Historical Consequences of STMD Funding Shortfalls

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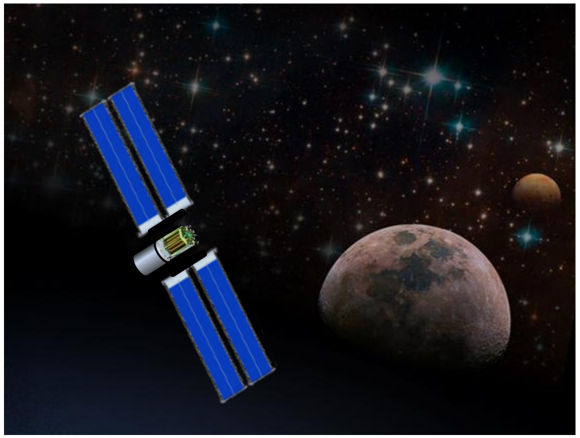
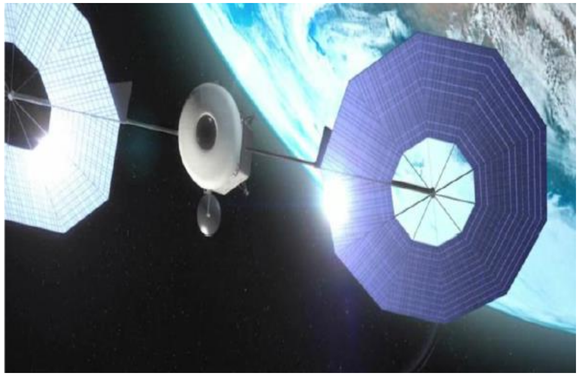
SEP DEMONSTRATION MISSION

Solar Electric Propulsion (SEP) is an essential capability for current Human Mars mission planning – to efficiently move large payloads to Mars





SEP has numerous other crosscutting applications

Communications Satellites and Government Missions
- more efficient orbit transfer
- increased maneuvering flexibility
- affordable power increase for communications or other payloads

Science and Exploration
- observatory placement and station keeping
- reaching distant destinations at less cost
- higher power for communications or other payloads
- transportation for cis-lunar, Mars, asteroid exploration

Satellite Servicing and Refueling

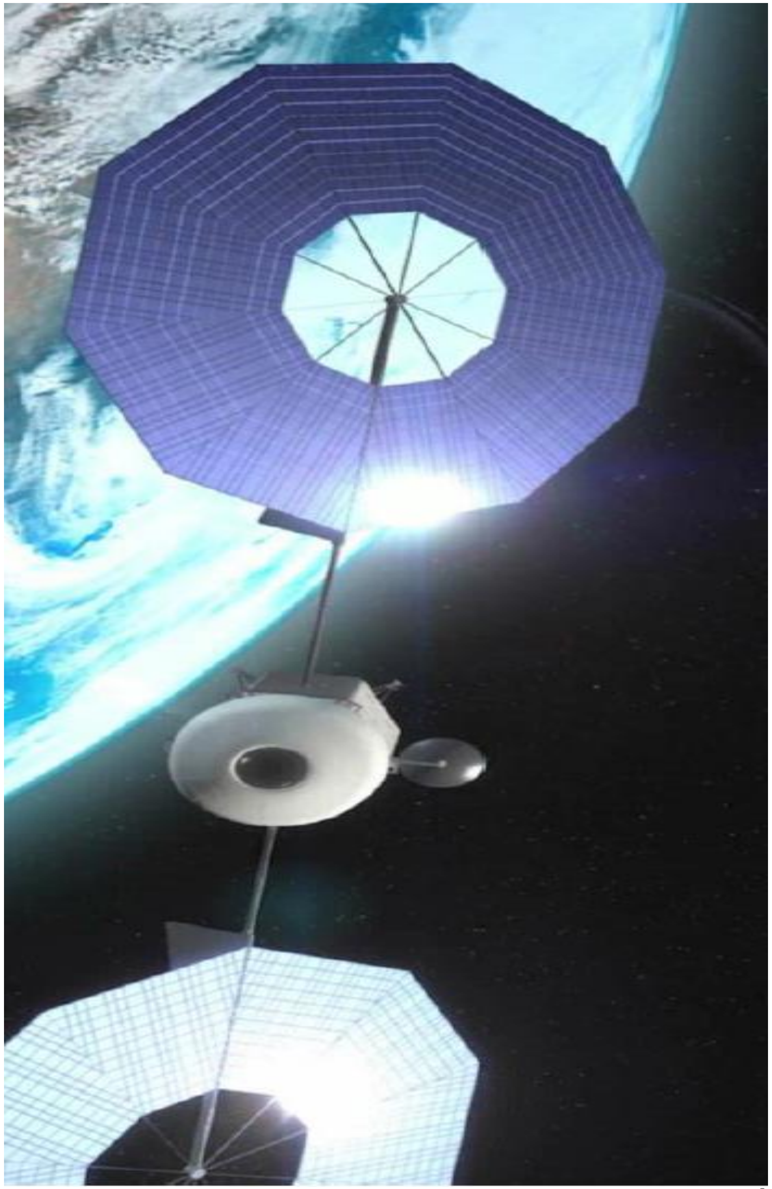
Space Tug between LEO, GEO or other Orbits
- single use or reusable
- multiple orbits and plane changes

Space Resource Access and Utilization

Orbital Debris Mitigation

Planetary Defense

Crosscutting Solar Electric Propulsion Development and Demonstration Objectives

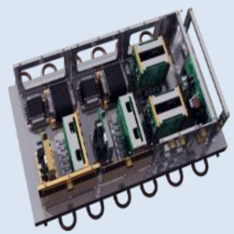


- Successful transition of matured and tested Game Changing technologies to flight demonstration project
- Develop and demonstrate 25kW to 50kW class Solar Electric Propulsion System
  - Extendable to 300kW for deep space human exploration
  - Directly applicable to Science Mission Directorate and missions for Other Government Agencies
  - A first demonstration mission targeted for the Asteroid Redirect Robotic Mission
- Develop & demonstrate Solar Electric Propulsion component technologies with commercial benefit
  - Reduced mass, efficient packaging, deployable solar arrays for improved commercial satellite affordability and potential ISS retrofitting
  - High power Hall thrusters for all electric commercial satellites

STMD Investments in SEP

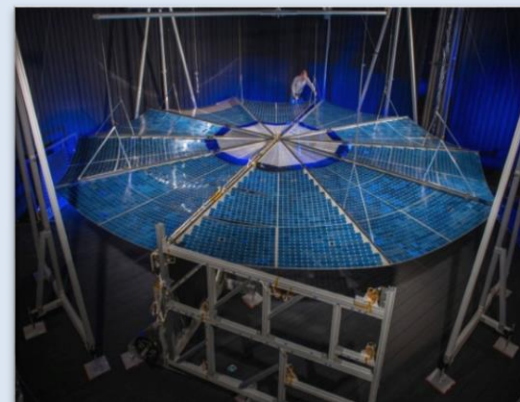
Thrusters

Power Processing Units



- Developed and tested high power Hall thruster 12.5 kW-class (2X current SOA)
- Magnetically shielded design to provide long life

Solar Arrays



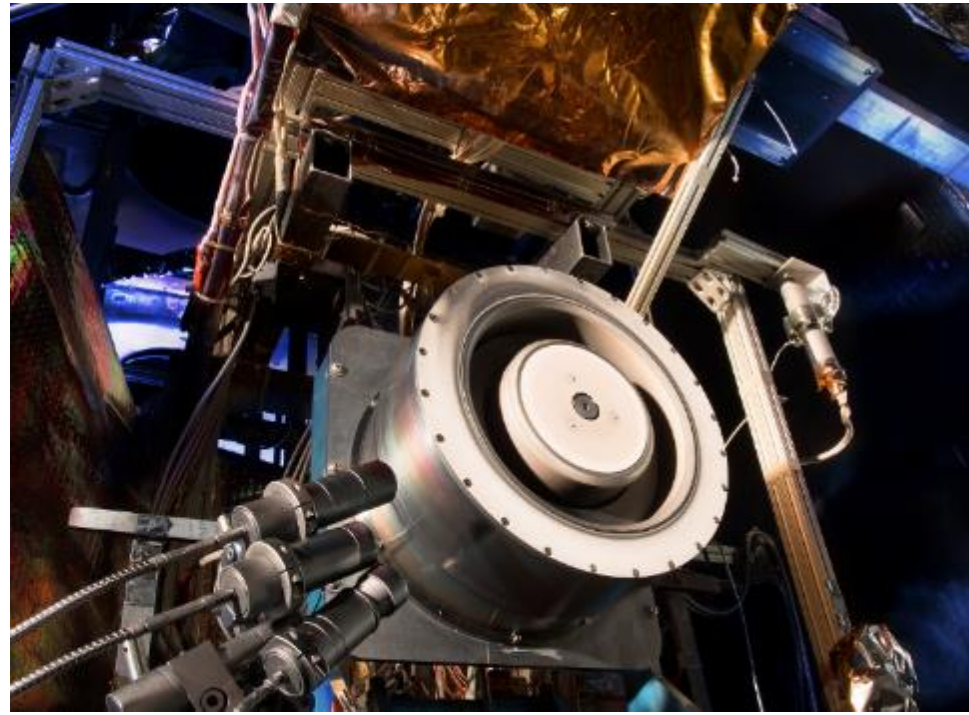
Designed, built and tested 25-kw-class advanced deployable Solar Array wings

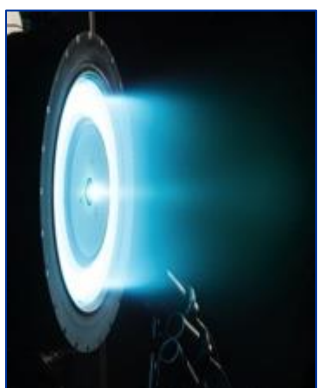
- MegaFlex "fold out" array (ATK)
- Mega-ROSA "roll out" array (DSS)

Hall Thruster & Power Processing Unit (PPU) Development and Risk Mitigation

- Two 12.5 kW Hall Thruster Technology Development Units
  - Validated design methodology & tools
  - Reduced mission and flight hardware development risks
- 2 Brassboard PPUs
  - 300Vin/800Vout (MFR reference)
  - 120Vin/800Vout (Post-MCR reference)

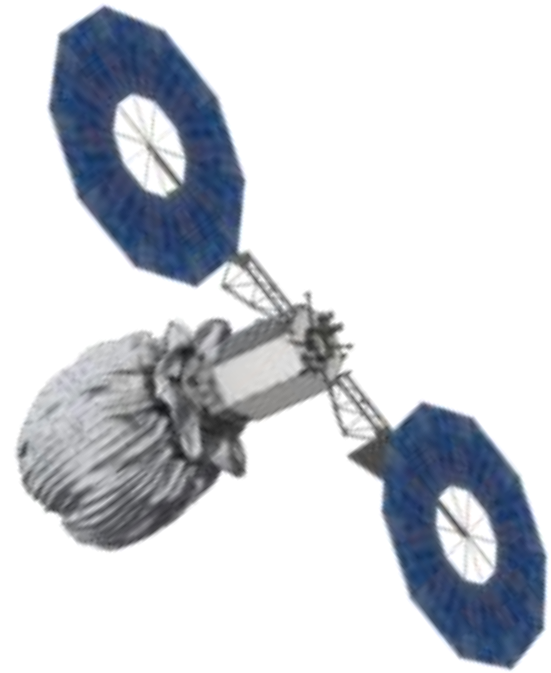
Demonstrated full, integrated performance compatibility of 120-V and 300-V PPUs with 12.5-kW Hall Effect Thruster





Post-test BN discharge chamber shows carbon deposition consistent with magnetically shielded operation

Technology Demonstration Missions



Asteroid Redirect Mission (ARM)
combining Technology Demonstration, Exploration and Science objectives

Mission Concept

- 40 kW-class SEP propels spacecraft to asteroid and returns material to Lunar Distant Retrograde Orbit
- Two 25 kW-class solar array wings and four 12.5-kW electric Hall thrusters
- Launch Date for Planning: December 2020
- Launch Vehicle: Delta IV or SLS

Alternate and Complimentary Demonstrations

- Functional space demonstration of large, advanced solar array on ISS
    - RFI for this approach issued in December 2014
- Commercial or OGA partnership on a modified all-electric bus with significant orbital maneuvering capability
- Possible SMD partnership in multiple first-use high-powered SEP demonstrations including: cis-lunar, asteroid, and planetary missions
- Mars exploration precursors or demonstrations

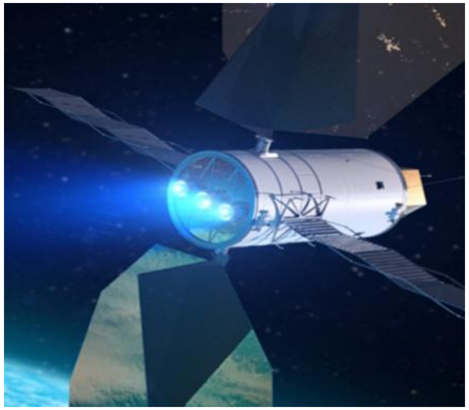
Budgetary Challenges in Conducting a Comprehensive Large-Scale Demonstration

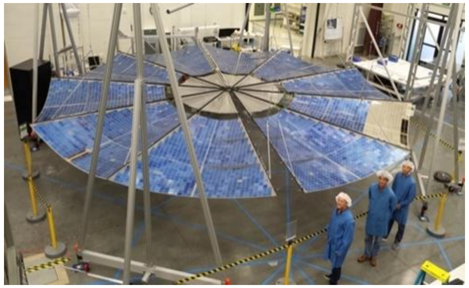
- Government-estimated SEP Module cost ($433M) significantly exceeds STMD in-guide budget profile ($229M)
- ARRM Budget Lifecycle and phasing presents significant challenges to timely perform mission. Launch initially June 2019, slipped to Dec. 2020.
- STMD in-guide covers: All SEP activities in FY15-16, all Ion Propulsion activities FY15-21, civil servant-only SEP mission design/studies FY15-21
- STMD in-guide gaps: SEP DDT&E - Power, Structures/mechanisms, Thermal, SE&I, RCS
    - Part of Power gap includes SEP Power Solar Array contract, not funded beyond FY16 (STMD funds are short $40M)
- <u>In general</u>, cost estimates from BAA studies indicate:
    - A 40 to 50 kW-class SEP demonstration requires approximately $400M
    - A 30 kW-class SEP demonstration requires approximately $250M
    - If less funding is available in the STMD budget, a major cost-sharing partnership is required to accomplish a demonstration of this scale.
- Continued lack of full funding for STMD and indecision on fully funding ARRM has delayed progress towards a high powered SEP demonstration

STMD SOLAR ARRAY DEVELOPMENT

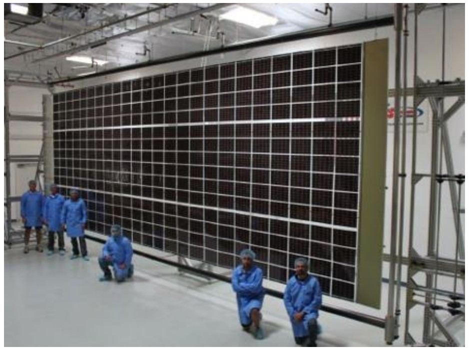
Need for Solar Electric Propulsion

- **Future exploration missions require high power Solar Electric Propulsion (SEP) to move cargo and humans beyond Low Earth Orbit**
- **SEP is more efficient than chemical propulsion**
  - SEP uses less fuel to the same destination reducing launch mass/cost (20% - 50% reduction)
- **STMD initiated a Solar Array Project in FY2011 as the first step towards complete capability**
  - Initial vision was a flight demonstration of entire SEP concept, but budget realities necessitated an array development project
  - Autonomously deployed large area arrays were identified as “long pole” in achieving goal
  - Project targeted development metrics of total power (1.5x SOA) and specific power (1.7x SOA)
  - Two contracts were awarded (ATK & DSS) for a total project budget of ~$11M
  - Both ATK & DSS successfully deployed solar arrays under thermal vacuum conditions (TRL 5)
  - Analytically demonstrated extensibility to 250 kW-class systems





ATK: *Megaflex*

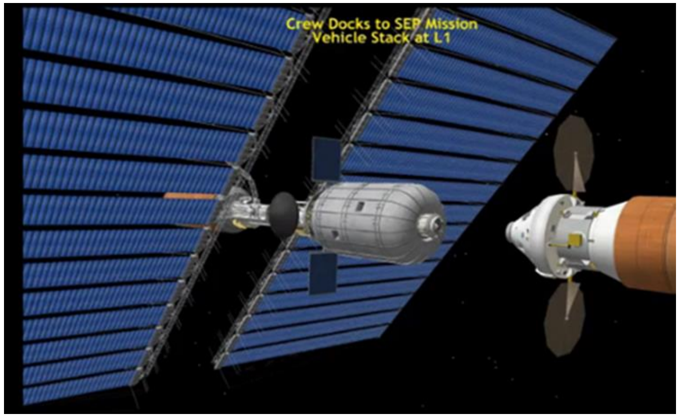


DSS: *Mega-ROSA*

Impact of STMD's Solar Array Investment

Technology has significant end-user interest & commercialization potential

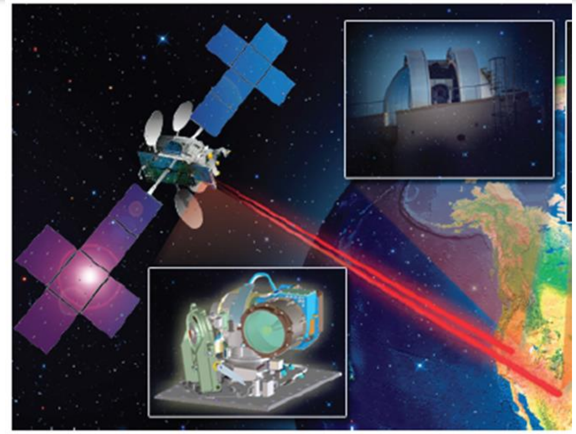
- **Enables NASA's future exploration missions**
  - Results in the fewest SLS launches & the least amount of payload that must be launched to orbit for multiple human exploration missions
- **Enables development of satellite servicing system**
- **Empowers US commercial satellite industry with larger & more capable systems**
- **Technology is being considered by every domestic prime contractor as an affordable & high-performance replacement to SOA arrays**
  - Space Systems Loral developing array with DSS for commercial satellites
  - Two proposers baselined DSS ROSA array for Discovery mission proposals
  - USAF funding ISS demonstration of small-scale ROSA
- **Under consideration as an upgrade for ISS solar power system**



LASER COMMUNICATIONS RELAY DEMONSTRATION

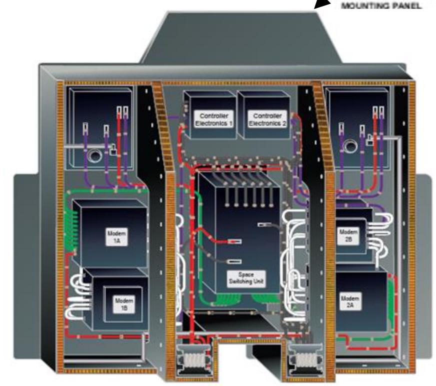
Laser Communications Relay Demonstration

- Demo Description:
  - A minimum two year flight demonstration to advance optical communications technology toward infusion into Deep Space and Near Earth operational systems, while growing the capabilities of industry sources.
- Objectives:
  - Demonstrate bidirectional optical communications between geosynchronous Earth orbit (GEO) and Earth
  - Measure and characterize the system performance over a variety of conditions
  - Develop operational procedures and assess applicability for future missions
  - Transfer laser communication technology to industry for future missions
  - Provide an on orbit capability for test and demonstration of standards for optical relay communications
- Anticipated Benefits:
  - A reliable, capable, & cost effective optical communication technology for infusion into future operational systems
- Anticipated NASA Mission Use:
  - Next Generation TDRS, Deep Space and Near Earth Science
  - ISS and Human SpaceFlight
- Attractive partnering arrangement with Space Systems/Loral as a hosted payload on a commercial telecom satellite and DoD partner for encryption.



LCRD is a hosted payload on an SSL commercial telecom satellite

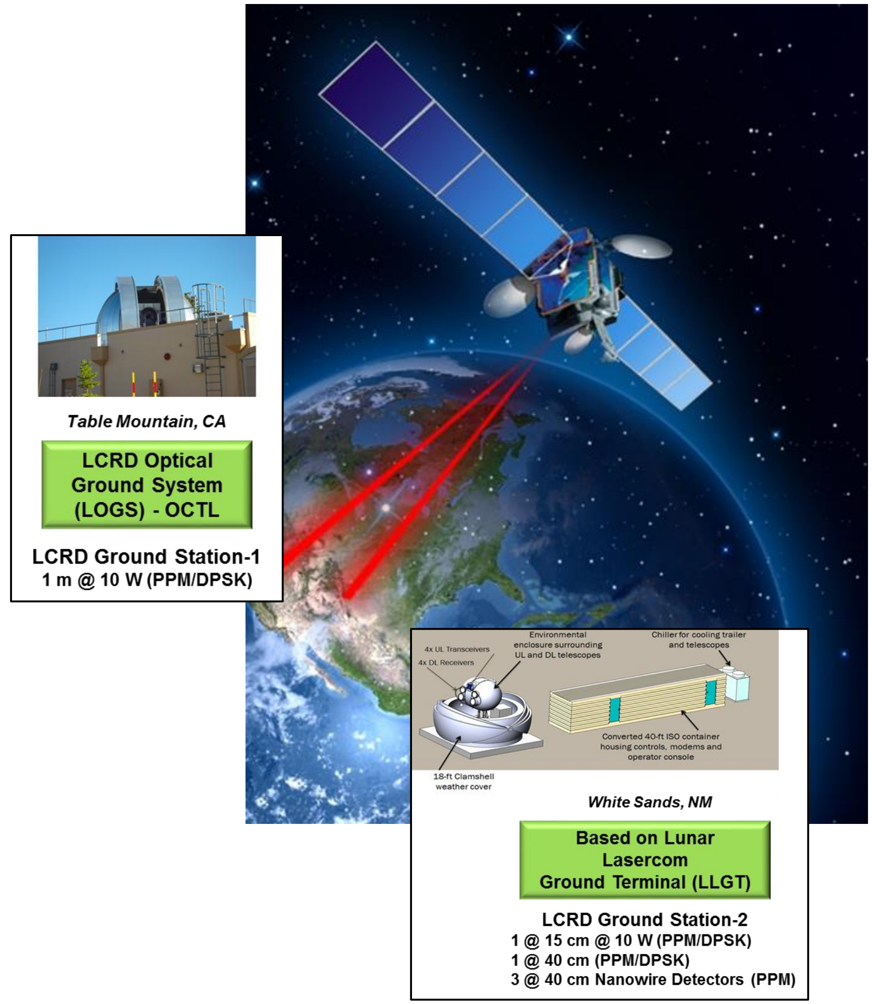
Payload Enclosure mounted on Earth Deck of typical SSL telecom satellite



Enclosure Rear View illustrates layout, structural, thermal maturity

LCRD KDP-A

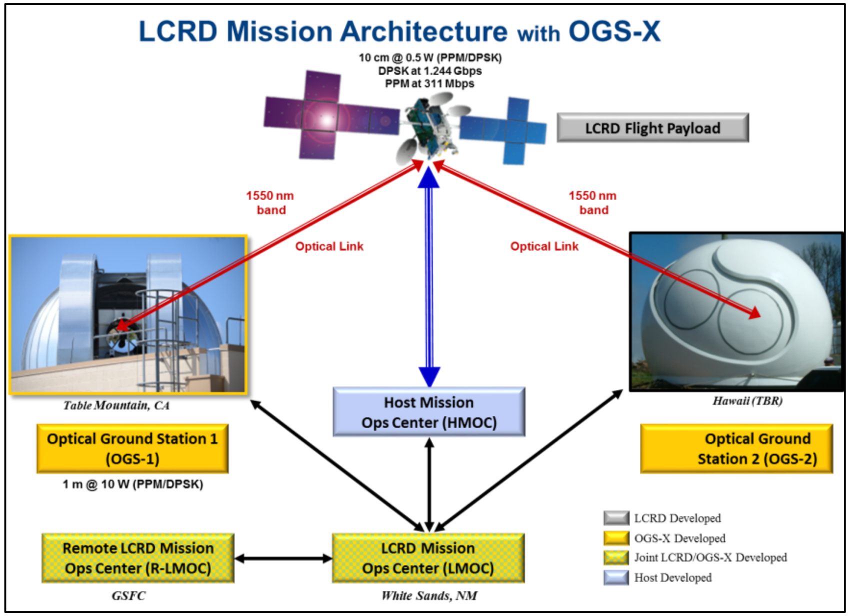
- KDP-A held December 2012
- Project de-scoped before KDP-A
  - On-Board Data Processing (Decoding, De-Interleaving, etc.), Store and Forward, DTN, Data Processing and DTN at Both Ground Stations
  - Networking Management
  - In-Band Commanding and No Telemetry on the Optical Downlink
  - Photon Counting Detector in Ground Station 2
  - Commercialization of the Photon Counting Detector
  - Delays GS2 delivery decision until end of FY13
- Notional Launch Readiness Date changed from December 2016 (from proposal) to December 2017 at KDP-A
- KDP-A LCC approved at $238.9M
- No change in LCC at KDP-B (May 2013), however additional funding was approved for PPM work, upping LCC to $239.2M (October 2013)

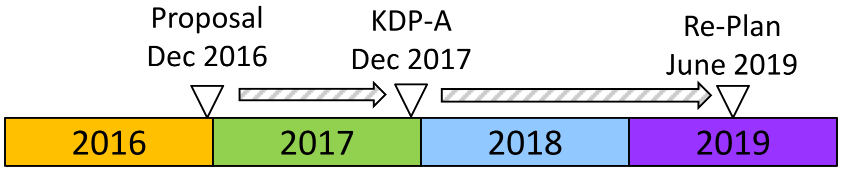


KDP-A/B architecture - LCRD on SSL commercial telecom satellite, with 2 ground stations (GS-1 at OCTL and GS-2 at White Sands)

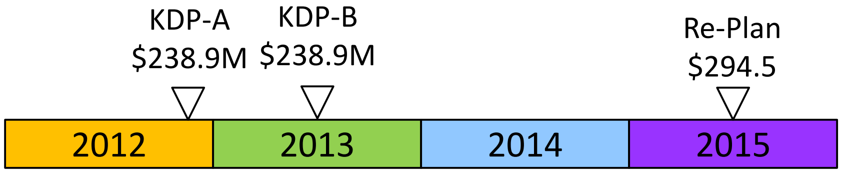
Current Effort After Post KDP-B Re-Plan

- In addition to the de-scopes taken prior to KDP-A, LCRD was directed to take additional de-scopes and other changes during the re-plan activity (directed February 2014 and completed March 2015)
  - Content removed/de-scoped from LCRD Budget:
    - JPL Ground Station 1 starting in FY15 – Moved to SCaN Optical Ground Station Extension (OGS-X), five years of operation (two years base plus three years extended operations)
    - De-scoped White Sands GS-2
    - Deviation approved for EVM
    - De-scoped E&PO
    - Payload I&T moved from GSFC to SSL after Electrical/Optic Integration Test Bed
    - Post launch checkout Science/Technology, Mission Ops, and LMOC Sustaining moved to SCaN OGS-X post checkout (L+60 days)
  - Encryption scope added October 2014 (no waiver for encryption requirements), to be funded through SCaN and tracked separately
- Re-plan budgets were constrained by STMD funding levels for FY15 and FY16, with LCC at $294.5M, including encryption
- Notional Launch Readiness Date slipped to June 2019





LCRD Notional Launch Readiness Date Change



LCRD LCC

DEEP SPACE OPTICAL COMMUNICATIONS

DSOC STMD/GCDP Funding History

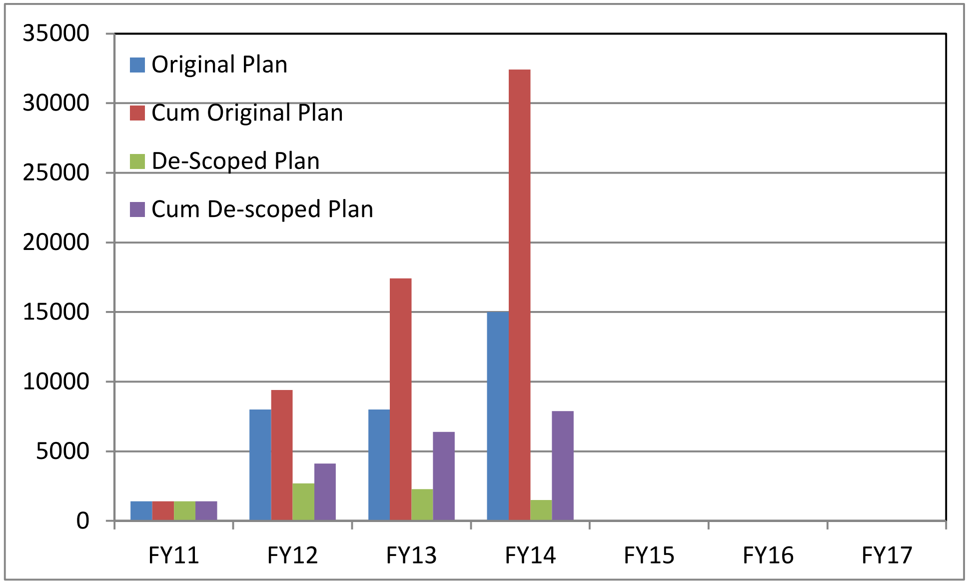
Introduction

- **STMD/GCDP has been funding DSOC since the end of FY11**
  - Original scope to mature key technologies (listed below) to TRL-5 by EO FY14
    - Isolation Pointing Assembly (IPA)
      - *Allows "dim-beacon" assisted low-bandwidth control for sub-micro-radian laser pointing accuracy*
    - Photon Counting Camera
      - *Combines "dim-beacon" acquisition tracking and data uplink functions*
    - Laser Transmitter assembly
      - *High peak-to-average power ratio and electrical-to-optical conversion for photon-efficient communication*
    - Deep-space Optical Transceiver
      - *Integrates IPA and PCC with electronics for functional Flight Laser Transceiver (FLT)*
    - Ground Receiver Detector Array
      - *Single photon counting arrays for detecting faint signal from deep-space using large area collectors*
- **Funding reduction in March 2013**
  - De-scoped DSOC Project
    - Three out of five technology elements pursued
      - Isolation Pointing Assembly
      - Photon Counting Camera
      - Ground Receiver Detector Array
    - Technology maturation to TRL-3/4 by EO FY14 instead of originally planned TRL-5
- **Re-Scoped DSOC at Feb-March 2014**
  - MOU between STMD/GCDP, HEOMD/SCaN, SMD/Discovery to fund DSOC through FY17
  - Mature integrated FLT to TRL-6
  - Ready for infusion into Discovery Mission to launch by Dec 2021

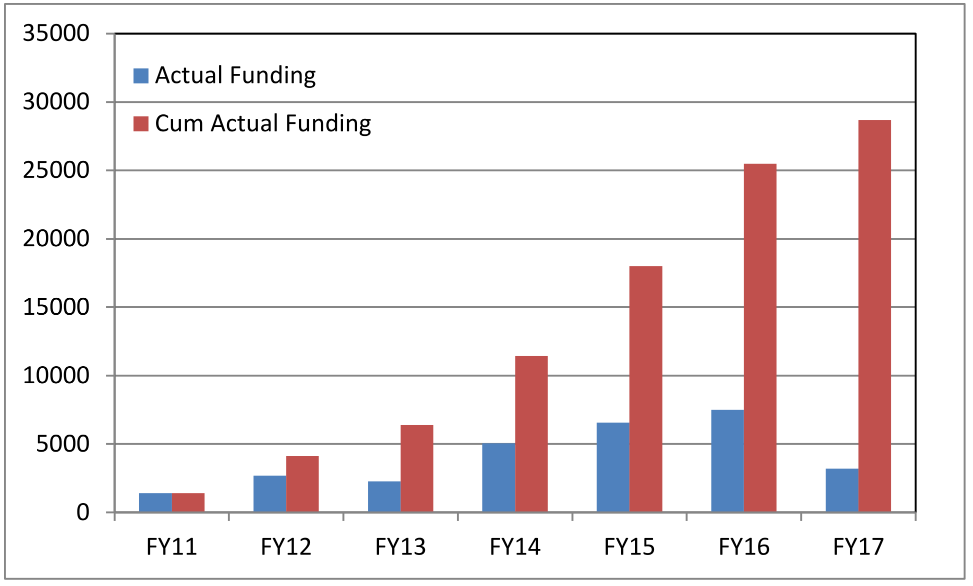
DSOC STMD/GCDP Funding History

Funding Profiles

- **Original Plan FY11-FY14**
  - TRL-5 maturation
    - Isolation Pointing Assembly (IPA)
    - Photon Counting Camera (PCC)
    - Laser transmitter Assembly (LTA)
    - Optical transceiver
    - Ground Detector Array
- **De-scoped Plan FY11-FY14**
  - TRL-3/4 Maturation
    - Isolation Pointing Assembly
    - Photon Counting Camera
    - Ground Detector Array



- **Actual Funding FY11-FY15 and FY16-FY17 plan**
  - Mature TRL-6 Flight Laser Transceiver and Ground Detector Array for 5m ground telescope
  - Ready to support Discovery Mission
  - IPA, PCC and LTA development benefitted from SBIR funding

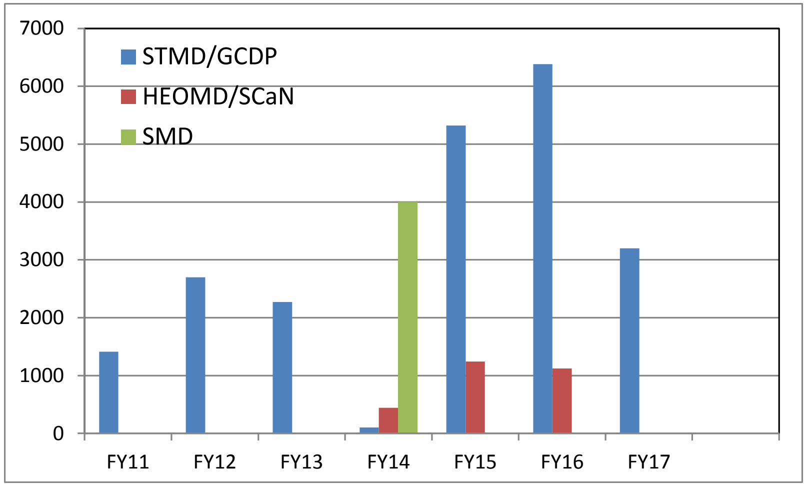


DSOC STMD/GCDP Funding History

Summary

- **How did shortage of funds early on keep DSOC from doing things in a full and timely manner**
  - **Early development and risk areas could not be fully addressed**
    - *Understanding why the WSi detectors work (to help design better detector4s with higher yield)*
    - *Developing larger than 32 x 32 flight detector arrays for DSOC*
    - *More efficient 1550 nm laser transmitter (as in resonantly pumped)*
  - **Other effects**
    - *Loss of focus resulted in loss of some key personnel*
    - *Originally planned involvement of LL-MIIT and NASA/GSFC was de-scoped*
  - **Stretching of DSOC Project schedule with identification of Discovery Mission as a potential host for Flight Transceiver has**
    - *Benefitted DSOC Project from developments elsewhere, such as*
      - *IPA technology from Control Dynamics under SBIR*
    - *Provided opportunity for advancing engineering development not included in original scope*
      - *Flight Electronics*
      - *Thermal design*
      - *Harnessing and umbilical development*

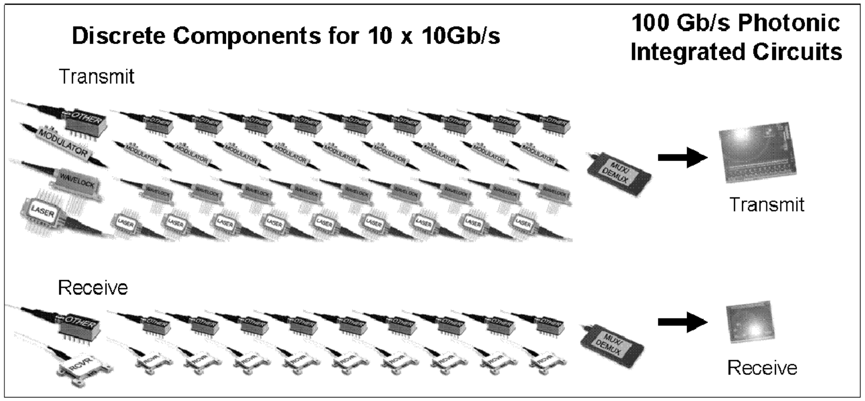
- **STMD/GCDP, HEOMD/SCaN and SMD funding distribution since MOU is shown in bar chart**



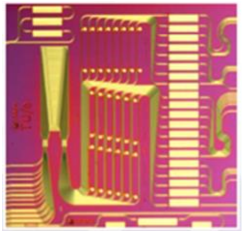
INTEGRATED PHOTONICS SMALL SPACECRAFT DEMONSTRATION

Proposed STMD/SCaN
Integrated Photonics Initiative Now Under Threat

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"

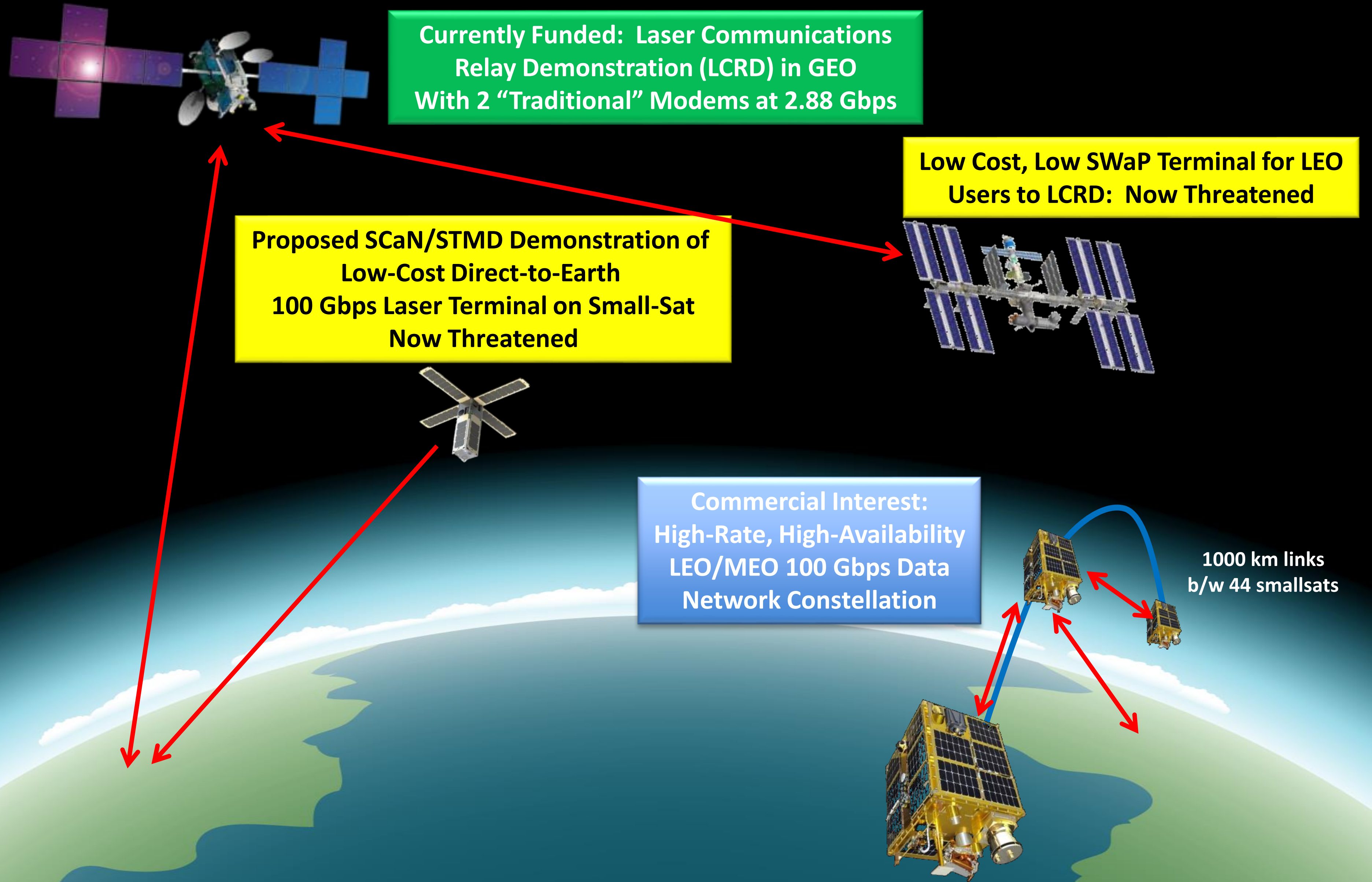


1 cm

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)

STMD and HEOMD/SCaN are working to fund a cubesat flight demo of integrated photonics in FY17 ($8M total), which is now under threat due to funding reductions to STMD…

Low-Cost Laser Comm Links Enabled by Integrated Photonics now Threatened by STMD Funding Reductions



CPST → eCryo

Evolvable Cryogenics – GRC

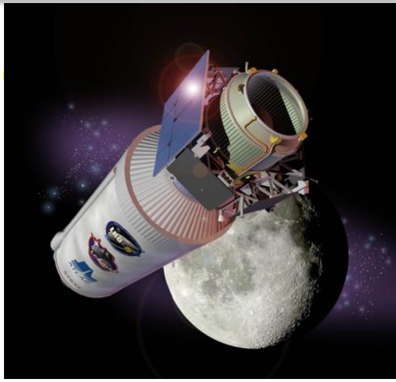
WAS:

Flight demonstration of cryogenic propellant storage and transfer technologies thereby advancing capabilities for deep space travel to serve both NASA exploration systems and commercial launch providers

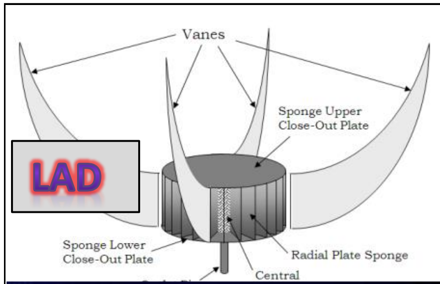
IS:

Portfolio of ground demos to validate cryogenic fluid technologies applicable to SLS and other exploration missions beyond LEO

Present Challenges for In-Space Cryogenic Systems



- We have no demonstrated capability to store cryogenic propellants in space for more than a few hours
  - SOA is Centaur's 9 hours with boil-off rates on the order of 30% per day
- We have no demonstrated, flight-proven method to gauge cryogenic propellant quantities accurately in microgravity
  - Need to prove methods for use with both settled and unsettled propellants



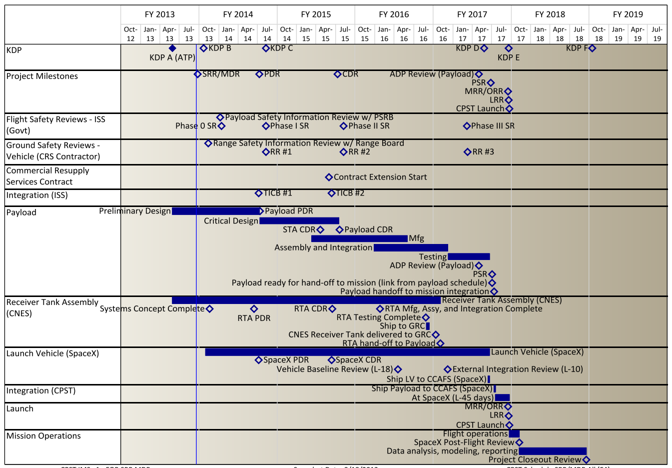
- We have no proven way to guarantee we can get gas-free liquid cryogens out of a tank in microgravity
  - Gas-free liquid is required for safe operation of a cryo propulsion system
  - Need robust surface-tension **liquid acquisition device (LAD)** analogous to those in SOA storable propulsion systems
  - Only known experience in the world is the single flight of the Russian Buran single flight (liquid oxygen reaction control system)
- We have no demonstrated ability to move cryogenic liquids from one tank (or vehicle) to another in space

Note

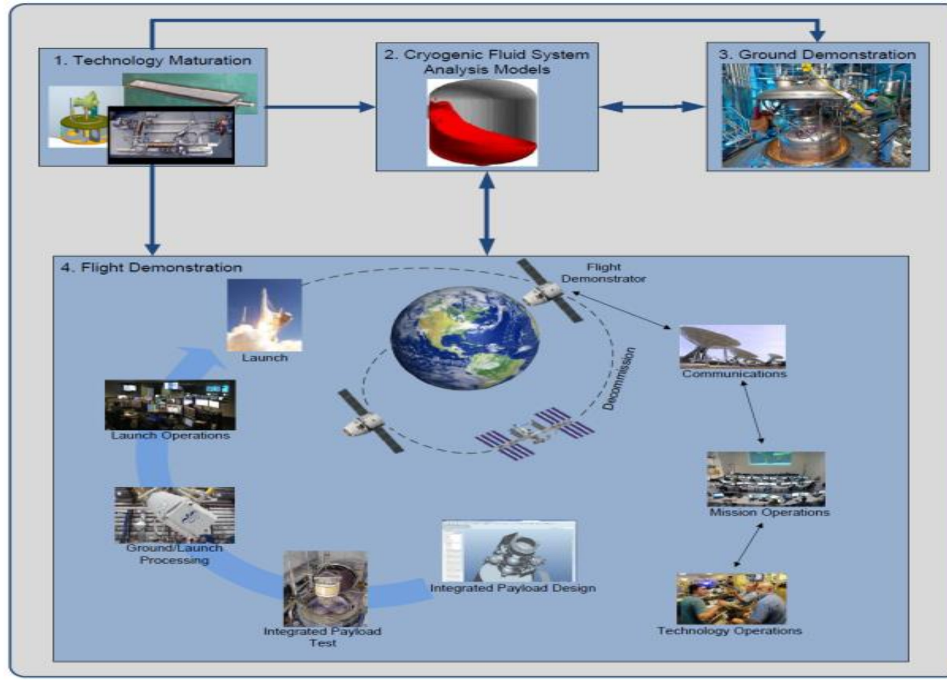
A flight demonstration with cryogenic propellant storage, expulsio
and transfer can remedy these problems (*and other more subtle on*

CPST Flight Demonstration

- CPST will:
  - Demonstrate long-duration storage
  - Demonstrate in-space transfer
  - Demonstrate in-space, accurate gauging



CPST IMS v1 - FOR SRR MDR.mpp   Snapshot Date: 9/18/2013   CPST Schedule SRR/MDR All [F4]



Description		2011	2012	Current FY2013	FY2014	FY2015	FY2016	FY2017	FY2018	FY2019	FY11-13 TOTAL	FY14-19 TOTAL	FY11-19 TOTAL
In-house NASA NOA Reqts (without reserve)	Full Cost ($M)	$4.007	$31.581	$26.033	$29.132	$39.054	$41.074	$27.846	$19.259	$7.547	**$61.620**	**$163.912**	**$225.532**
	Civil Servant Labor ($M)	$0.000	$13.781	$13.557	$15.078	$14.372	$14.153	$12.547	$9.411	$3.980	$27.338	$69.541	$96.878
	Procurement ($M)	$3.987	$17.663	$12.232	$13.703	$24.332	$26.571	$14.949	$9.499	$3.391	$33.881	$92.446	$126.327
	WYE Labor ($M)	$0.000	$7.087	$8.030	$9.356	$9.441	$9.835	$8.374	$5.695	$2.492	$15.117	$45.193	$60.309
	Materials ($M)	$3.987	$10.575	$4.202	$4.347	$14.892	$16.736	$6.575	$3.804	$0.899	$18.764	$47.253	$66.018
	Travel ($M)	$0.020	$0.137	$0.244	$0.350	$0.350	$0.350	$0.350	$0.350	$0.175	$0.402	$1.925	$2.327
	FTE	0.00	93.30	90.87	102.56	95.31	90.25	77.45	55.84	22.78	184.17	444.19	628.36
	WYE	0.00	41.35	44.86	48.73	45.83	46.35	38.32	25.30	10.75	86.21	215.27	301.48
Reserves	Full Cost ($M)	$0.000	$0.000	$0.000	$4.684	$5.700	$8.400	$7.100	$3.700	$1.675	**$0.000**	**$31.259**	**$31.259**
NASA In-house NOA Reqts (with reserve)	Full Cost ($M)	$4.007	$31.581	$26.033	$33.816	$44.754	$49.474	$34.946	$22.959	$9.222	**$61.620**	**$195.171**	**$256.791**
Launch Vehicle/Services Contract NOA Requirements	Full Cost ($M)	$0.000	$0.000	$2.000	$0.315	$36.000	$50.000	$50.000	$44.685	$0.000	**$2.000**	**$181.000**	**$183.000**
TOTAL CPST TDM NOA Requirements	**Full Cost ($M)**	**$4.007**	**$31.581**	**$28.033**	**$34.131**	**$80.754**	**$99.474**	**$84.946**	**$67.644**	**$9.222**	**$63.620**	**$376.171**	**$439.791**

CPST was baselined and approved for Phase B on Dec. 9, 2013

CPST VS. ECRYO

CPST

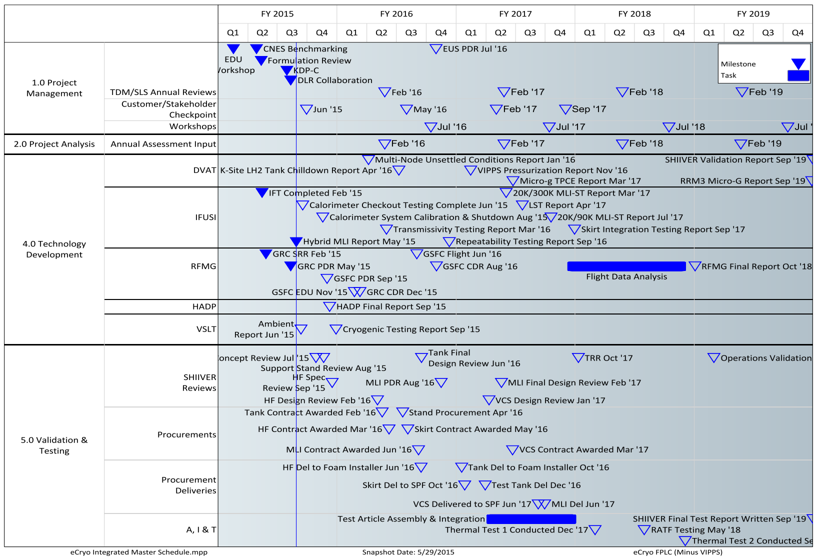
- Flight Demonstration utilizing SpaceX Dragon Trunk
- Technologies evolve from TRL 5 to 7
- Payload size: 224 kg LH2 (vs. 20 kg), 1.5 m diameter tank (vs. .3m diameter)
- Mission Duration: 1-2 months (vs. hours)
- Technologies Demonstrated on 1.5m tank:
  - Passive thermal control
  - 2 transfers using screen channel liquid acquisition devices
  - RFMG
- Technologies Developed:
  - High Accuracy Delta P Transducer
  - Valve Seat Leak Test
- Implementation
  - In-house payload build
  - Delivery Order on existing CRS Contract for the LV, S/C Bus, Mission Operations, and I&T
- Deliverables:
  - Micro-gravity data to anchor CFM models,
  - Industry workshops to share data,
  - Conference presentations

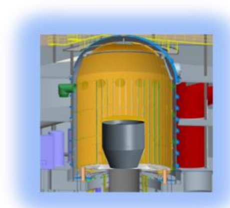
eCryo

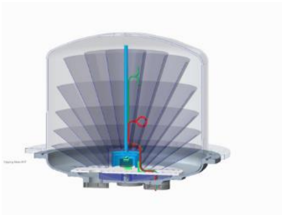
- Ground Demonstration of a CFM technology portfolio
- Technologies develop to a range from 3 to 6
- Ground Tank size: 4m diameter
- N/A.
- Technologies Demonstrated:
  - SHIIVER passive thermal control on 4m tank (MLI and Vapor Cooling)
  - RFMG on GSFC RRM3 Mission yielding flight data
- Technologies Developed:
  - High Accuracy Delta P Transducer
  - Valve Seat Leak Test
  - Super Insulation
  - IVF for SLS
- Implementation
  - In-house research and development
- Deliverables:
  - Industry workshops to share data,
  - Conference presentations,
  - Ground data to anchor CFM models

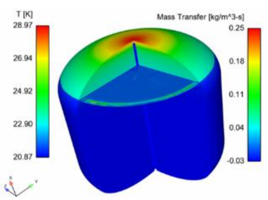
eCryo – Evolvable Cryogenics

- eCryo will:
  - Develop technology for extended in-space missions with near term gains geared toward industry.
  - Increase capabilities of analysis tools for predictive simulations of in-space cryogenic systems.




Structural Heat Intercept Insulation Vibration Evaluation Rig (SHIIVER)


Radio Frequency Mass Gauge (RFMG) for Robotics Refueling Mission 3 (RRM3)


CFM Analysis


Space Launch Systems (SLS) Stages support

eCryo Portfolio Products

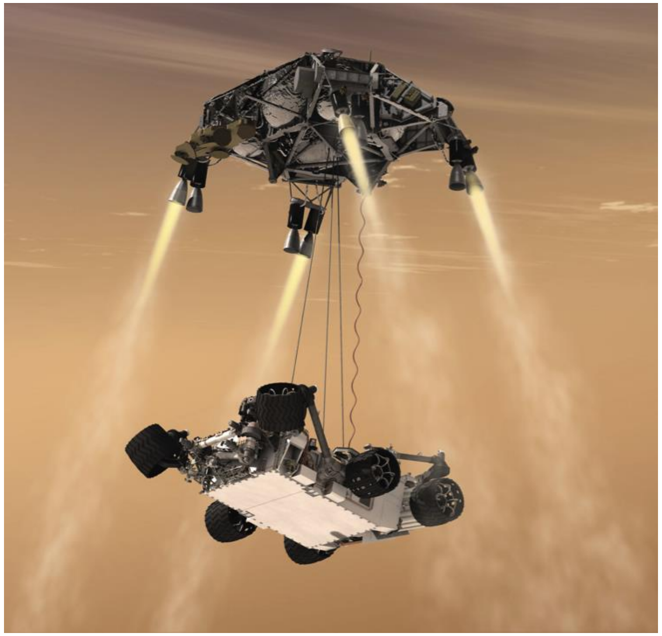
$M	FY15	FY16	FY17	FY19	FY20	TOTAL
STMD / TDM	**$ 13.356**	**$ 19.515**	**$ 10.792**	**$ 9.899**	**$ 4.996**	**$ 58.558**
KDP-C DM w/ Reserves (30 April 2015)	$ 12.001	$ 16.431	$ 10.792	$ 9.899	$ 4.996	**$ 54.119**
Total Increase (30 June 2015)	$ 1.355	$ 3.084	$ -	$ -	$ -	**$ 4.439**
- IVF Proposal w/o Sunk Costs	$ 1.046	$ 2.984	$ -	$ -	$ -	**$ 4.030**
- Additional FTE/ODC Adjustments	$ 0.309	$ 0.100	$ -	$ -	$ -	**$ 0.409**
Total LCC	**$ 13.356**	**$ 19.515**	**$ 10.792**	**$ 9.899**	**$ 4.996**	**$ 58.558**

eCryo was baselined and approved for Phase C on Apr. 30, 2015

EDL ARCHITECTURE DEVELOPMENT

Need for Advanced EDL Architectures

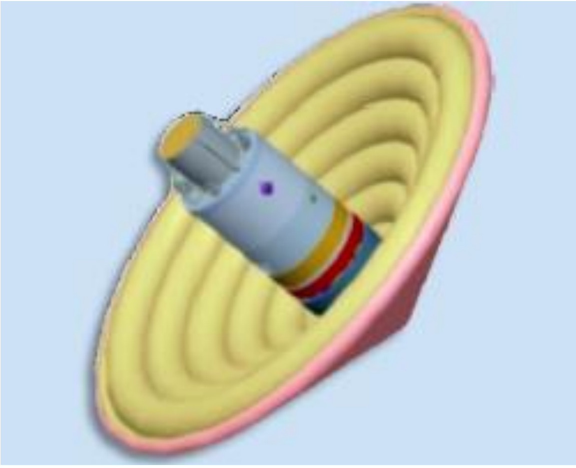
- **Mars' atmosphere results in significant EDL challenges**
  - Atmosphere causes vehicle to slow down
  - Atmosphere is dense enough to require a heat shield
  - Atmosphere is not dense enough to provide substantial drag necessitating large surface area heat shields
- **State of the Art EDL architectures are not sufficient for future human exploration missions to Mars**
  - Rigid aeroshells are constrained by launch shroud geometry
  - Current EDL technologies/approaches (MSL, Mars 2020, etc…) are limited to 1 mt payload mass to Mars' surface
  - Human exploration requires landed mass in excess of 18 mt



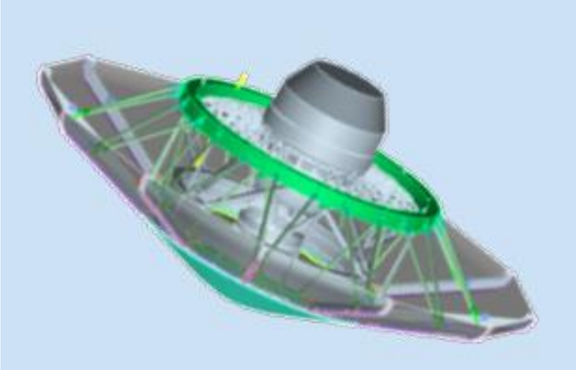
Mars Science Laboratory (MSL) Entry, Descent, and Landing Architecture

STMD's Advanced EDL Investments

- **STMD has initiated investments, and developed extensive expertise, in two deployable EDL architectures for human missions to Mars**
  - ***Hypersonic Inflatable Aerodynamic Decelerator (HIAD):*** Inflatable tori with overlaid, flexible TPS
  - ***Adaptable Deployable Entry and Placement Technology (ADEPT):*** Mechanically deployed structure with carbon fabric TPS
- **Both entry systems are folded for launch and deployed prior to Mars entry**
  - Provide rigid aerodynamic surface and thermal protection for hypersonic deceleration at scales in excess of 25 meters
  - HIAD & ADEPT can also be used for robotic exploration at diameters between 6 and 10 meters



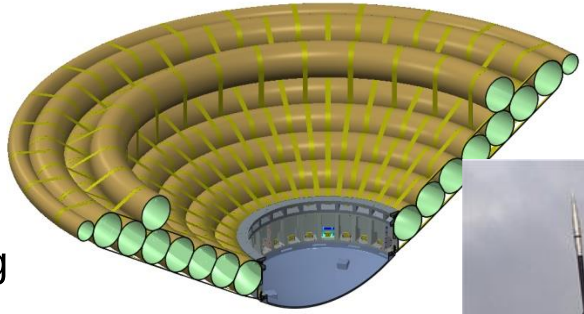
Hypersonic Inflatable Aerodynamic Decelerator (HIAD)

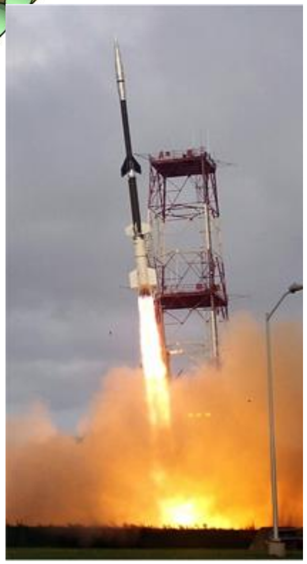


Adaptable Deployable Entry and Placement (ADEPT)

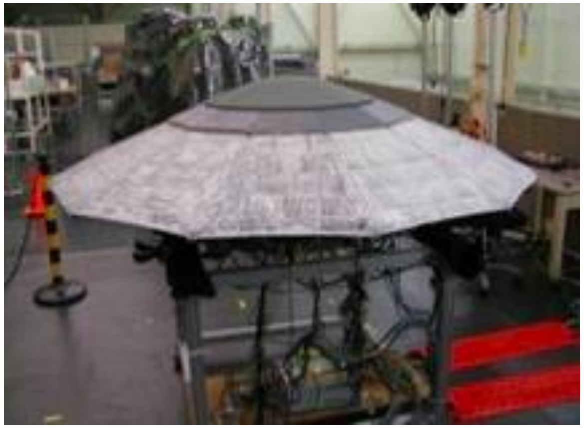
HIAD & ADEPT Opportunities & Accomplishments

- **Significant progress has been made maturing HIAD & ADEPT over the past decade**
  - HIAD successfully completed a 3 meter diameter flig test (IRVE-3 in 2012) & 6 meter wind tunnel test
  - ADEPT successfully completed a 0.7 meter diameter wind tunnel test campaign and fabrication of 2 meter diameter ground test article
- **Both EDL development activities have been impacted by budget reductions**
  - Potential HIAD development activity:
    - Execution of 3.7 meter diameter, high energy reentry flight test in partnership with ULA (asset recovery demonstration)
    - Ground-based maturation effort to improve aeroshell capabilities including scale up to >10 meter diameter
  - Potential ADEPT development activity:
    - Execution of six meter diameter ground test program
    - One meter diameter ADEPT test article sounding rocket flight test





HIAD architecture "cut-away" (top) and IRVE-3 sounding rocket flight demonstration (right)



ADEPT ground test article (2m dia.)

POWER GENERATION & STORAGE DEVELOPMENT

Power Generation & Energy Storage

Major NASA Power Capability Needs:

Mars Stationary Surface Power

- In order to live on Mars (or Lunar Surface) power generation is required under all scenarios, present goal is 40kW continuous power; technology baseline for capability satisfaction is nuclear fission, however solar power is possible

Mars Mobile Surface Power

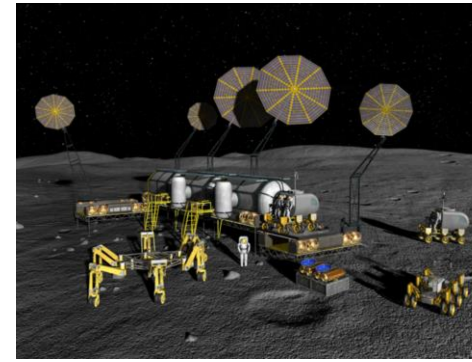
- In order to explore planetary surface; rovers are required technology baseline is 5-10kw fuel cell, however batteries are possible

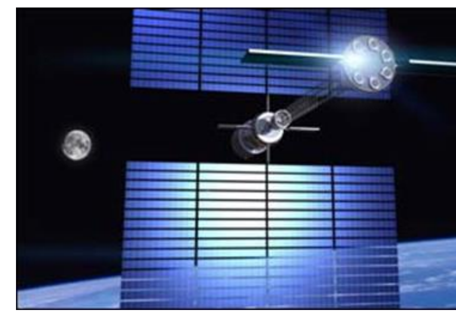
In-Space Propulsion for Mars Cargo

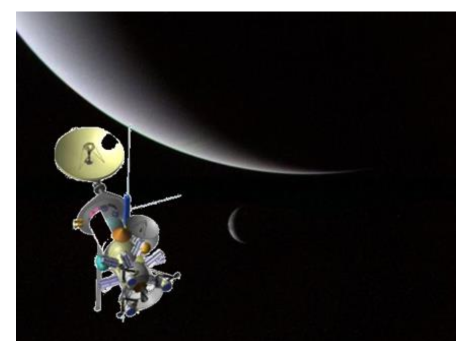
- Present Mars planning includes 400kw solar arrays for SEP propulsion system; Nuclear Thermal System is under consideration but not likely

Robotic Interplanetary Missions

- Beyond Jupiter, solar power is not viable, present Radio-Isotope Power Systems suffer from limited efficiency and the required use of PU-238; improvements to technology required to sustain Planetary Science Mission Capability







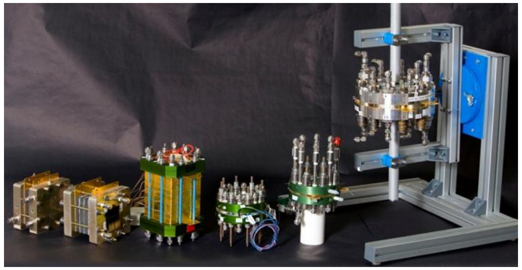
Major Power and Energy Technology Enhancements:

- Batteries with higher energy density required across multiple missions, result in reduced mass
- Radiation tolerant solar cells impact End of Life efficiency of solar arrays (mass) across all missions
- Radiation tolerant, along with high temperature/voltage, electronic components
- Wireless energy transfer allows dislocation of power generation and need across multiple missions

STMD Power & Energy Portfolio

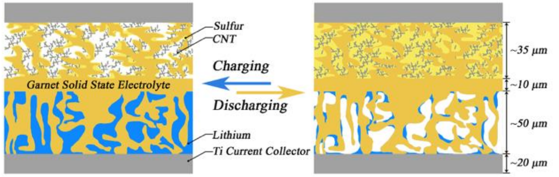
High Energy Density Batteries:

- NASA has a need for batteries with higher energy density (>300wh/kg @ cell level) than State of the Art Li+ technology can provide
- In FY14 STMD initiated a collaboration with ARPA E on advanced battery system. Project is beginning second year and hopes to deliver battery system for Adv. EVA Suit in 2017 (~$5M spent over 4 years)



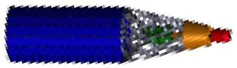
Fuel Cell Systems:

- NASA spacecraft and surface systems require fuel cells to generate power over intermediate time horizons and in conjunction with other energy sources, e.g. solar cells
- STMD took over an existing PEM Fuel Cell project when the Mission Directorate was established in 2011, delivered 1kw and 3 kw test articles to HEOMD/AES for testing on rovers (~$8M spent over 4 years); without pressing need STMD was forced to curtail work in FY14 and eliminate funding in FY15



Photovoltaics:

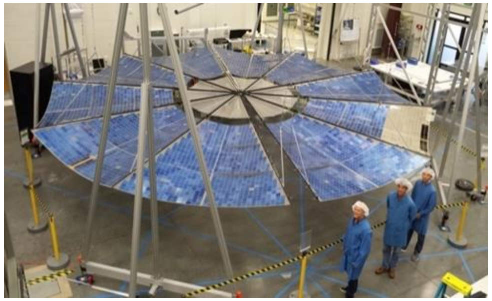
- Major photovoltaic effort in STMD has been Solar Array Systems project
- NASA has unique needs for Low Intensity, High Temperature, and High Radiation Tolerant solar cells however budget has limited ability to pursue research in this area



1 Kw Kilopower Fission System

Nuclear Systems:

- STMD Kilopower project is pursuing a 1kW fission system using U_{235} vs Pu_{238} (~$14M over 4 years), demonstration planned for 2018
- System will be extensible to 10kW x4 system capable of being used for Mars surface power requirement
- If successful system may also be used for Interplanetary Robotic Missions in the future



Power Beaming:

- STMD recently released an RFP for which Wireless Power Transfer was a topic for consideration

DEEP SPACE ATOMIC CLOCK DEMONSTRATION MISSION

DSAC Quad Chart

Multi-pole Trap

Quadrupole Trap

Titanium Vacuum Tube

Objective: Develop an advanced prototype mercury-ion atomic clock (TRL 7) and demonstrate for a year in space, providing the unprecedented performance needed for the next generation of deep space navigation and radio science. Identify steps to build a more power efficient and smaller infusible version.

Benefits to Space Navigation and Science

Enable shift to a more flexible/extensible 1-Way radio navigation architecture from the current 2-Way model

- Enables usable multiple spacecraft per aperture tracking
- Enables use of 1-Way uplink X-band tracking/open loop recording for robust gravity science solutions

Fundamental to autonomous radio navigation

- Contributes to smaller landing errors and to mass efficient pinpoint landing via propellant savings
- Needed for fully autonomous aerobraking operations

Increase navigation & radio science tracking data accuracy by 10 times and quantity by 2 times

- Improves Mars orbit determination to < 1 m with Ka band tracking

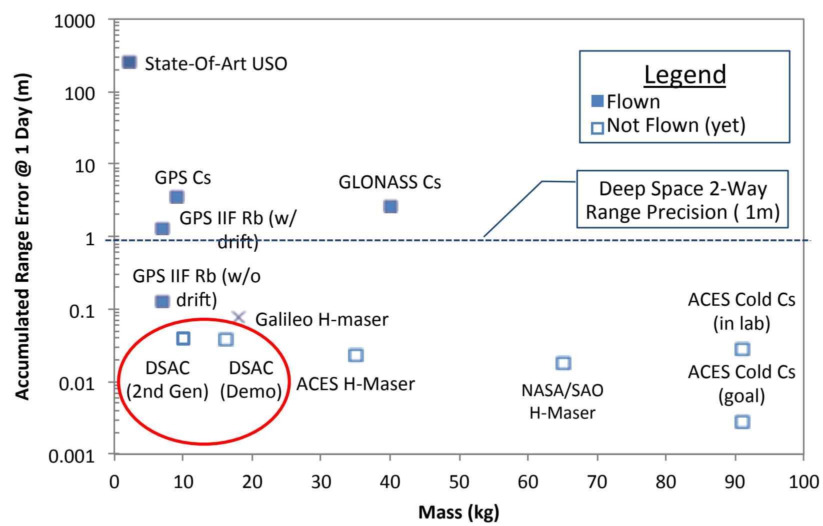
Potential to improve clock performance of the next GPS system by 50 x

Key Features for reliable in-space use

- No lasers, cryogenics, or other consumables → long life
- Existing vacuum technology and no microwave cavities → easier manufacturability
- Radiation tolerant at levels similar to GPS Rb Clocks

Technology highlights

- State selection via UV optical pumping using Hg ions
- Extreme stability via no wall collisions & high-Q microwave line
- Multi-pole trap yields insensitivity to disturbances

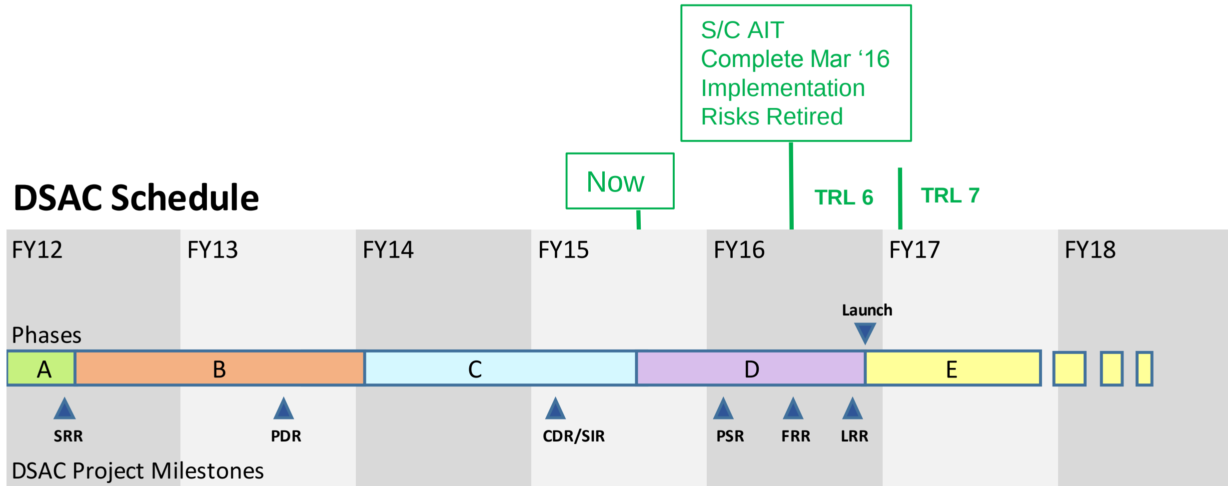


DSAC LCC and Schedule History

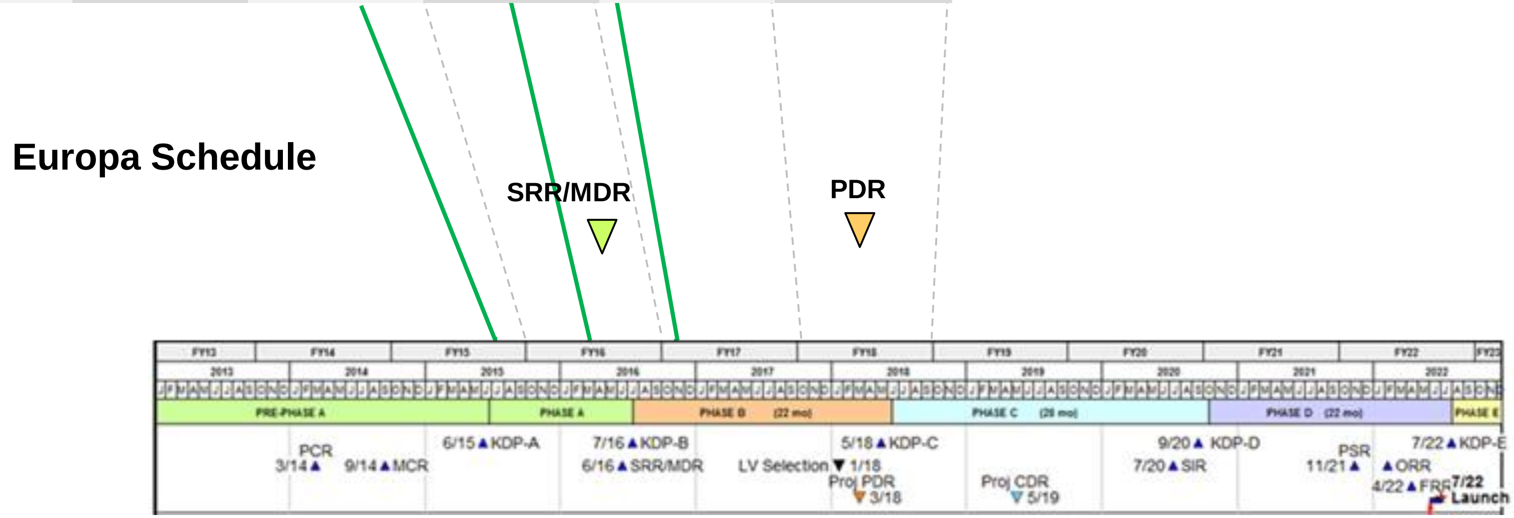
Date	Event	Planned Launch	LCC Total $M	HEOMD Share $M	SMD Share $M	Notes
9/15/2011	**Original JPL TA**	Mar 2015	59	15	0	
3/7/2012	**KDP B**	Mar 2015	59	15	0	Access to Space TBD after termination with Irridium
11/6/2013	**KDP C**	Sept 2015	67	19	0	Guideline error ($1M), Host Change to Surrey (4mo. Slip, $2.3M)
7/15/2015	**KDP D**	Sept 2016	73	21	4	GS costs ($0.4M), missed ONC ($0.8M), and launch slips ($0.8M) and overruns ($4M)

- 9% cost growth from KDP C baseline, due to technical issues with the clock and external events. DSAC project has managed to cost very well to date.
- Project on track to deliver demonstration unit/flight payload to Surrey host in December, following final environmental test sequence and final characterization.
- Customer support increasing as project has had successful implementation
  - Increased (HEOMD/SCAN) and new (SMD/PSD) cost sharing
  - Interest expressed in obtaining project ground assets when available (SMD)
  - Increased interest in mission and any non-recurring engineering necessary for infusion into Class B mission
    - DSAC accommodation study with Europa Clipper Pre-project began in June
    - DSAC briefed SMD PSD management on the current DSAC mission and development of a future DSAC for Clipper in July

Schedule Alignment with Europa

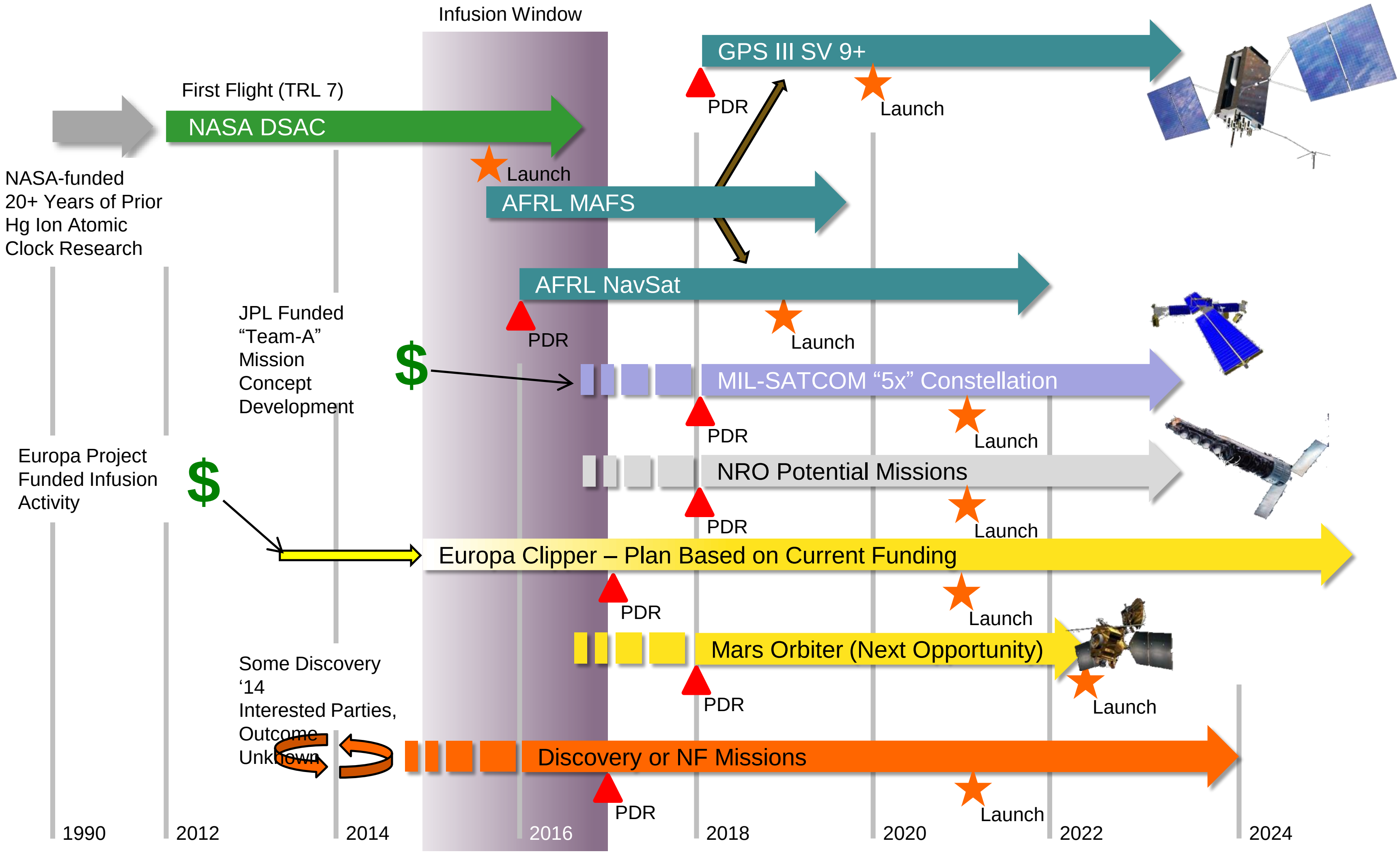


DSAC accommodation study with the Europa Clipper pre-project began in June.



DSAC is phased in advance of Europa, offering low implementation risk

Infusion Story

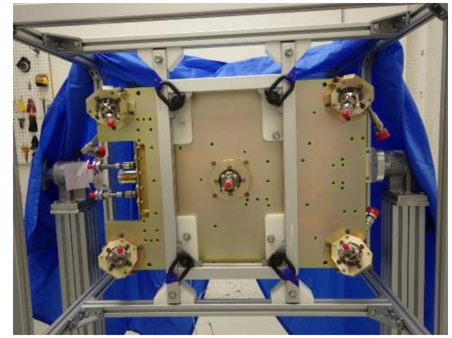


GREEN PROPELLANT INFUSION MISSION

Green Propellant Infusion Mission (GPIM) Project Performance

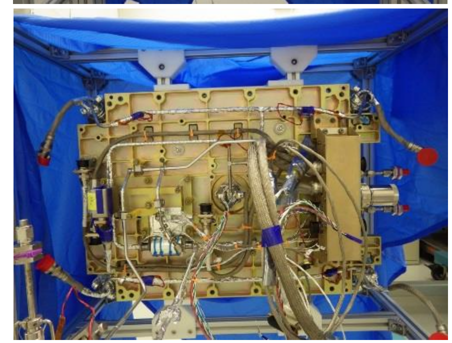
Technical / Test Performance:

- **GPIM will demonstrate the on-orbit use of the HAN-based green monopropellant AF-M315E as an alternative to hydrazine for attitude control and orbit change**
- **Green Propellant Propulsion Subsystem (GPPS) I&T is nearing completion**
  - Decision was made by STMD on 4/17 to use an all 1N thruster flight configuration, removing schedule and programmatic risk of 22N thruster from mission
  - All five 1N thrusters were manufactured and successfully completed their acceptance test sequence (functional testing, hot-fire, vibration testing and post vibration functional tests). This activity began in April and was completed in June.
  - All thrusters have been installed, electrically integrated, and successfully welded in the system
  - Fracture mechanics testing for the propellant tank completed
  - System testing planned for week of July 20
  - GPPS delivery from Aerojet to Ball planned for August 2015

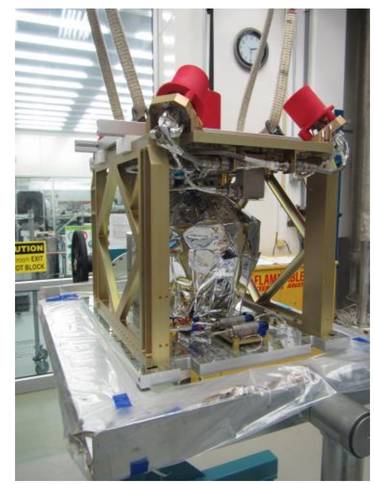


GPPS Propulsion Deck (top)

All 5 1N thrusters Welded



GPPS Propulsion Deck (bottom)

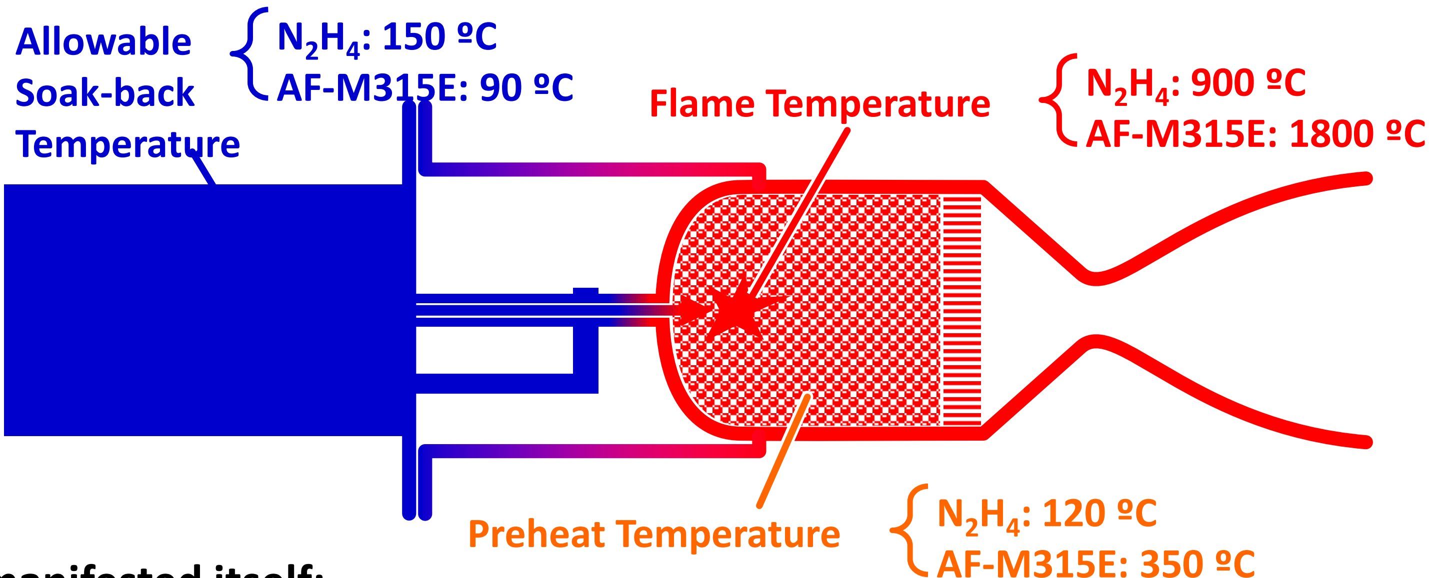


GPPS integration complete

Green Propellant Infusion Mission (GPIM) Challenges

Primary Challenges

- Much higher flame temperature and lower known allowable soak-back temperature made design of AF-M315E thrusters more challenging vs. conventional N_2H_4 thrusters



How it manifested itself:

- Flight-weight thruster design required refractory metals – leading to process development schedule delays, dissimilar material welding/brazing issues, significant catalyst bed heater development
- Detailed refractory materials properties at thruster operating temperatures not available – 22N thruster low cycle fatigue issues discovered in life test

Green Propellant Infusion Mission (GPIM) Challenges

Technology Challenges Have Driven Cost

- Aerojet was able to maintain schedule until life testing began
- Schedule delays driven by manufacturing readiness (immaturity of design going into CDR) delayed test readiness 5 months
- Test issues on 22N thruster caused another 3-4 months of delay
- Nine months of additional thruster development/testing has accounted for 70% of cost growth
- Launch vehicle-driven schedule delay has driven 20% of cost growth

Strategic Technology Readiness Assessment is Important

- Detailed assessment of readiness prior to committing to a flight schedule is vital
- Assessment needs to take into account not only the maturity level of the critical technologies, but also the readiness to integrate into flight hardware

Total LCC ($M)	**$56.9M**
Expected Completion	FY18
Cost Sharing	STMD, AF SMC (SERB P/Ls)
Participating Centers	GRC, KSC, GSFC
Participating Institutions	Ball (lead), AR, AF SMC, AFRL