Space Technology Mission Directorate

The 2022 NASA Strategic plan outlines the goals and objectives NASA will pursue to fulfill its mission (see Table 2). STMD has primary lead responsibility implementing Strategic Goal 3, Objective 3.1. Additionally, STMD contributes to achieving all NASA strategic goals and objectives through developing crosscutting technologies for multiple customers. The STMD Technology Portfolio is the vehicle by which Strategic Objective 3.1 is implemented.

Strategic Objective 3.1 **Innovate and advance transformational space technologies.**

Develop revolutionary, high-payoff space technologies driven by diverse ideas to transform NASA missions and ensure American leadership in the space economy.

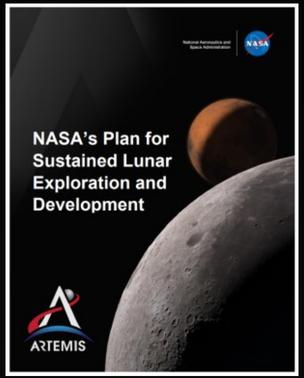
In addition, the 2020 National Space Policy provides the direction for NASA to lead in:

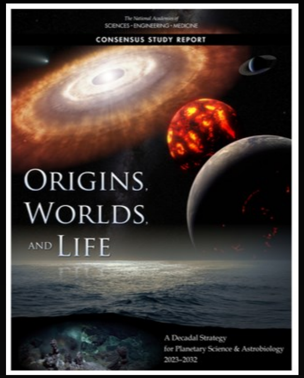
"the responsible and constructive use of space, promoting a robust commercial space industry, returning Americans to the Moon and preparing for Mars, leading in exploration, and defending United States and allied interests in space."

The policy emphasizes the importance of facilitating the growth of the commercial space sector, continuing the sustained US leadership in space. As NASA's technology mission directorate dedicated to developing state-of-the-art and advanced cross-cutting technologies, STMD develops technologies that enable science and human exploration goals and support the space economy, working with industry and academia ensuring a robust national space technology engine to meet national needs.

Strategic Technology Architecture Roundtable (STAR) Process

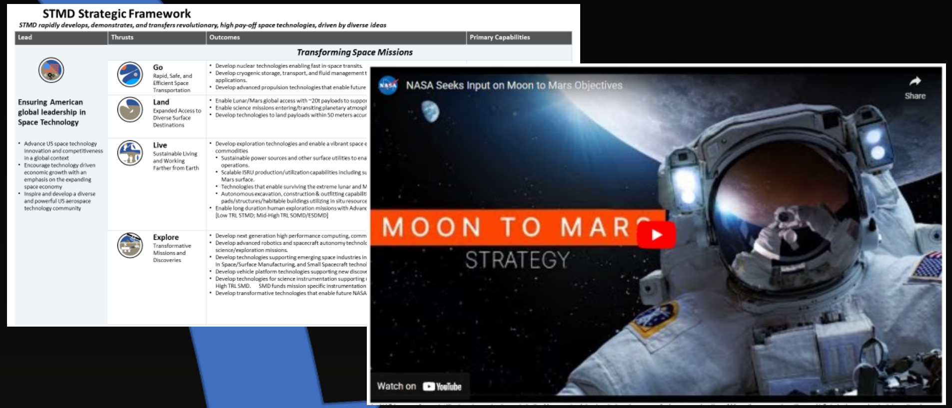
In order to achieve the NASA Strategic Objective led by the Space Technology Mission Directorate, the STAR process was implemented to bring together the various inputs from stakeholders to produce a set of gaps that can be closed through STMD investments.





Draws directly on Artemis architectures and Science Mission Directorate Decadal to identify technology gaps.

STMD Strategic Framework describes the STMD investment priority strategy. Strategic Technology Framework aligned to Agency Moon to Mars Strategy along with science and industry partner needs, prioritized by Agency Strategic Capability Leads (SCLs) and Principal Technologists (PTs).



STAR

Space Community' participation is obtained through Conferences and Requests for Information (RFIs) to validate envisioned futures, the current state of the art and the gaps between those two.

STAR process inclusive of Center Chief Technologists, ESDMD and SMD Representation.

Maps to OTPS Taxonomy.

STARPORT

STMD and ESDMD Gap database

+

Envisioned Future Priorities

PPBE Process

STARPort is the database of all Capability Area gaps for both STMD and ESDMD. Envisioned Future Priorities (EFPs) are written by SCL/PTs to show the future state envisioned and suggested path forward to inform Planning, Programming, Budgeting, and Execution (PPBE) process.

STMD Strategic Framework

STMD rapidly develops, demonstrates, and transfers revolutionary, high pay-off space technologies, driven by diverse ideas

Lead	Thrusts	Outcomes	Primary Capabilities
	Transforming Space Missions		
Ensuring American global leadership in Space Technology • Advance US space technology innovation and competitiveness in a global context • Encourage technology driven economic growth with an emphasis on the expanding space economy • Inspire and develop a diverse and powerful US aerospace technology community	**Go** Rapid, Safe, and Efficient Space Transportation	• Develop nuclear technologies enabling fast in-space transits. • Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications. • Develop advanced propulsion technologies that enable future science/exploration missions.	• Nuclear Systems • Cryogenic Fluid Management • Advanced Propulsion
	Land Expanded Access to Diverse Surface Destinations	• Enable Lunar/Mars global access with ~20t payloads to support human missions. • Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies. • Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards.	• Entry, Descent, Landing, & Precision Landing

	Live
	Sustainable Living and Working Farther from Earth
		• Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities
		  • Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.
		  • Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface.
		  • Technologies that enable surviving the extreme lunar and Mars environments.
		  • Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources.
		• Enable long duration human exploration missions with Advanced Habitation System technologies. [Low TRL STMD; Mid-High TRL SOMD/ESDMD]
			• Advanced Power
			• In-Situ Resource Utilization
			• Advanced Thermal
			• Advanced Materials, Structures, & Construction
			• Advanced Habitation Systems

	Explore Transformative Missions and Discoveries	• Develop next generation high performance computing, communications, and navigation. • Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions. • Develop technologies supporting emerging space industries including: Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft technologies. • Develop vehicle platform technologies supporting new discoveries. • Develop technologies for science instrumentation supporting new discoveries. [Low TRL STMD/Mid-High TRL SMD. SMD funds mission specific instrumentation (TRL 1-9)] • Develop transformative technologies that enable future NASA or commercial missions and discoveries	• Advanced Avionics Systems • Advanced Communications & Navigation • Advanced Robotics • Autonomous Systems • Satellite Servicing & Assembly • Advanced Manufacturing • Small Spacecraft • Rendezvous, Proximity Operations & Capture • Sensor & Instrumentation

STMD Strategic Framework Definitions

THRUSTS

Broad categories of strategic impact (Go, Land, Live, Explore).
Example: Go: Rapid, safe, & efficient space transportation

STRATEGIC OUTCOMES

High-level Goals under each Thrust.
Quantified Example: Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards.
Crosscutting Example: Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions.

CAPABILTY AREAS

Key technology focus areas aligned to NASA's System Capability Leads and Principal Technologists. Examples: Advanced Propulsion, Entry, Descent and Landing, ISRU, etc.

ENVISIONED FUTURE PRIORITIES

A document that communicates an Envisioned Future for a capability area, the current state of the art for that area, major gaps, and the plan on how to close these gaps. (i.e., Includes charts summarizing the technology development priorities to accomplish the envisioned future.)

TECHNOLOGY GAP

Technical hurdle(s) that needs to be overcome to enable an envisioned future.

TECHNOLOGY INVESTMENTS

Project/Investment that represents quantifiable unit(s) of work to address closing technology gap(s) in one or more capability areas.

STARPort database stores the technology gaps associated with a strategic capability and links them to the Thrusts and Strategic Outcomes. STARPort is part of the TechPort ecosystem and therefore has access to STMD and other Agency technology program data. This database provides the capability to trace investments from the highest levels of strategy, down through the capability areas and gaps, all the way to the individual projects and track progress over time. NASA is developing both public and government only facing STARPort common database.

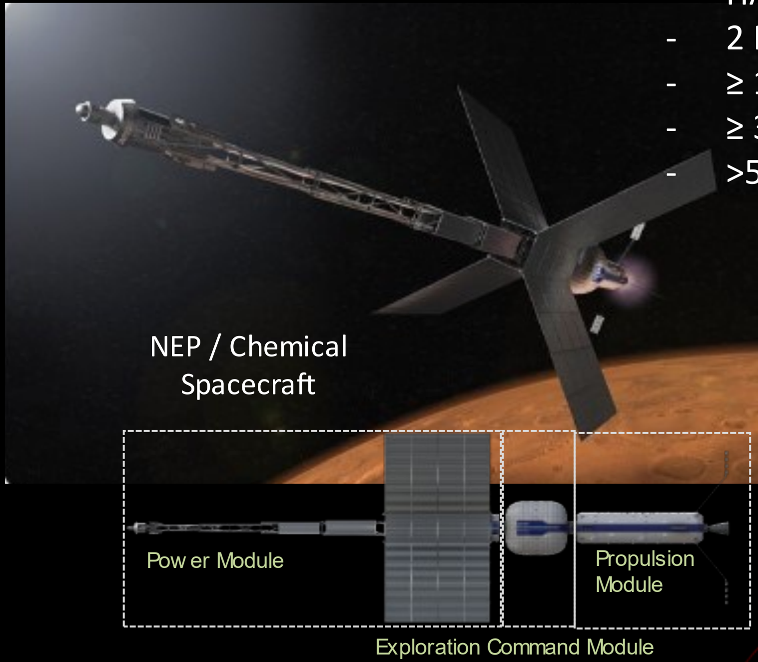
GO: Space Nuclear Propulsion
NASA Space Technology Mission Directorate
March 2022

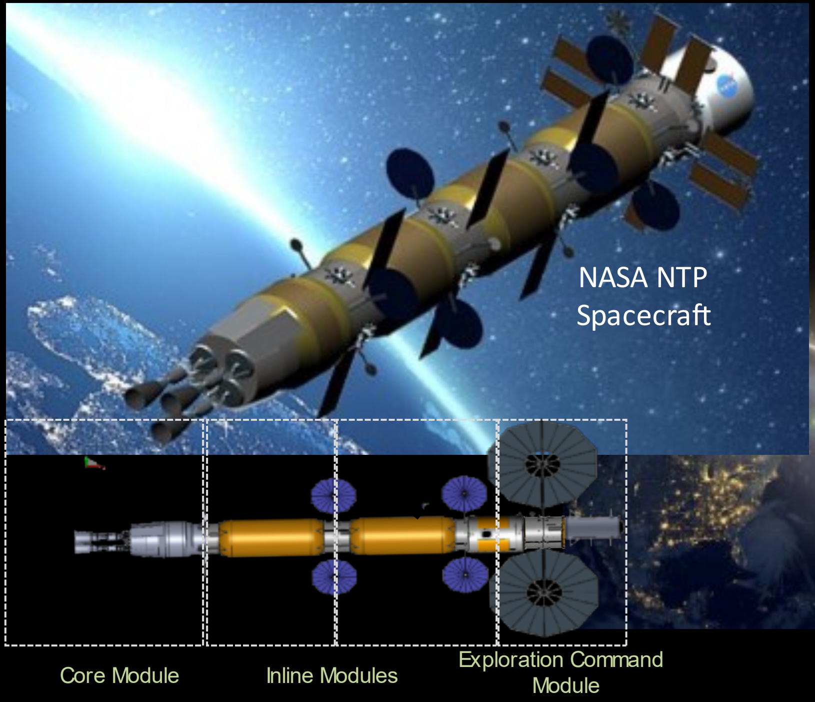
STMD welcomes feedback on this presentation
See RFI 80HQTR22ZOA2L-GO at nspires.nasaprs.com for how to provide feedback
If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

GO: Develop nuclear technologies enabling fast in-space transits.

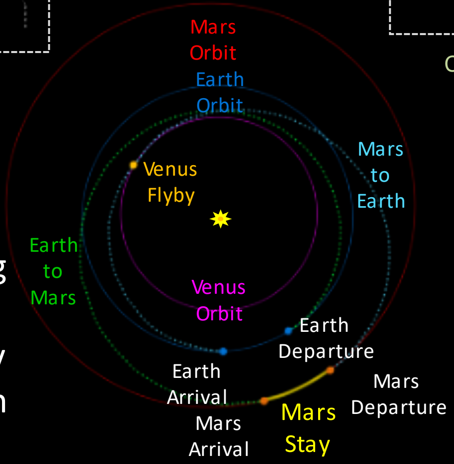
Initial Parallel Path for Nuclear Thermal Propulsion and Nuclear Electric Propulsion Technologies for future Cis-Lunar, Mars and Deep Space Exploration Missions.

- HALEU
- 2 MWe Class
- ≥ 1200 K Fuel
- ≥ 30% efficient Brayton
- >500 K heat rejection



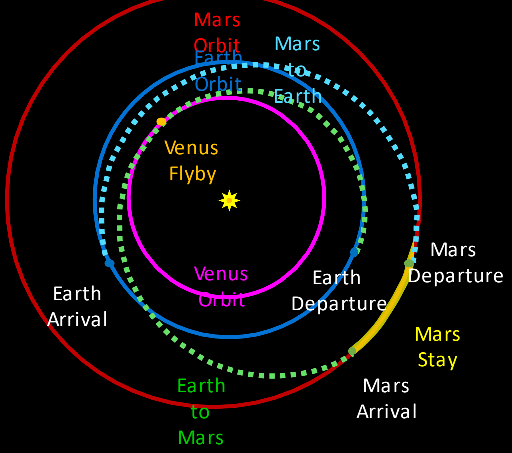


- HALEU
- > 2700 K Fuel to support > 900 s I_{SP}



- High Δ-velocity orbit maneuvering
- Strategic placement of space platforms
- Cis-lunar and Mars transportation staging
- Asteroid rendezvous and sample return
- Robotic and piloted deep space planetary missions including <750 day (TBR) Human Mars round trip
- MWe Class Nuclear Electric Propulsion

- Cis-lunar and Mars transportation including <750 day (TBR) Human Mars round trip
- Synergy with Department of Defense cis-lunar operations
- High thrust stage for fast outer planet, robotic science missions

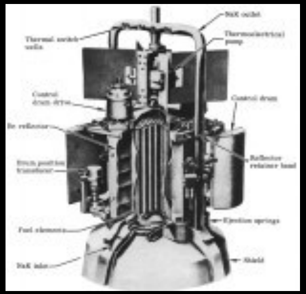


All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.

GO: Develop nuclear technologies enabling fast in-space transits: State of the Art

Space Heritage (TRL 9)

500 We Space Fission Reactor
4.5 kW Hall Effect Thruster Strings
25 kWe Space Station Freedom Brayton
70 kWt, 35 kWt per loop ISS System
290 K Radiators



500 W_e, 1965

4.5 kW Hall Thruster

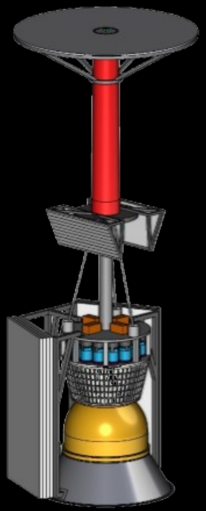
Radiators / Cooling Loop

Space Technology In Development

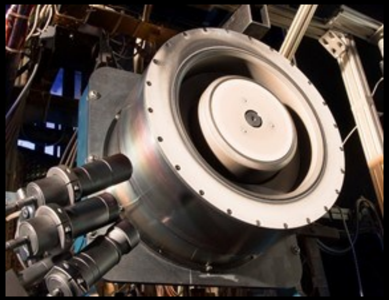
12.5 kW Hall Effect Thruster Strings – TRL 6
50 kW Solar Electric Propulsion System – PPE – TRL 5
Fission Surface Power – TRL 4 for 1 kWe, TRL 3 for 10 kWe
Design contracts released
HALEU Fuel Development:
- *TRL 2 for > 2700 K fuel*
- *TRL 5 for < 2500 K fuel*

1.1 GW Rover/NERVA engine – TRL 6
Subscale engine – reactor contracts – TRL 3
DARPA DRACO NTP Demonstration

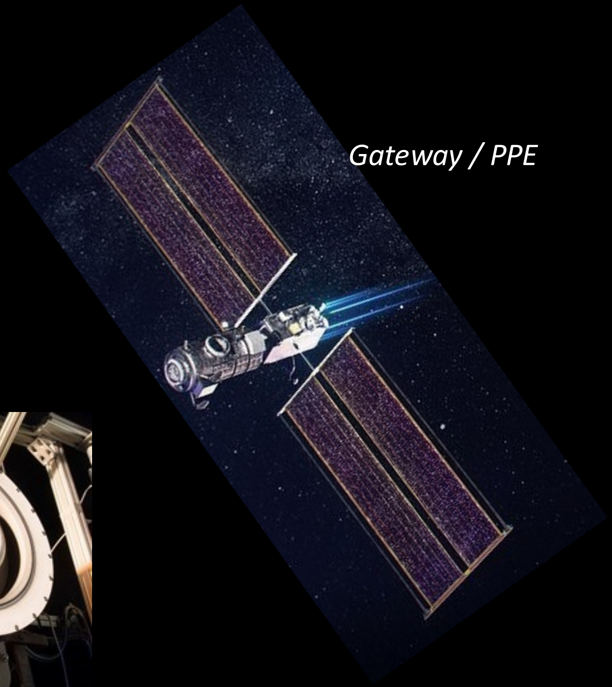
DRACO



Fission Surface Power



12.5kW Hall Thruster



Gateway / PPE

Terrestrial

Non-radiative cooled
Non-space environment

Nuclear Propulsion Roadmap Summary

Nuclear Electric Propulsion

- **Phase 1: Requirements Definition**
  - Define system requirements (e.g. system kg/kW threshold), identify industry opportunities with a make buy decision
- **Phase 2: Reactor Fuel & Moderator Development and Subsystem technology Maturation**
  - Industry and Government technology maturation efforts in parallel (Brayton, Radiators, PMAD, Thruster, etc.)
  - Reduce level of uncertainty on technical effort, program cost, and program schedule for an integrated system
  - DOE focus on fuel and moderated reactor design options

Nuclear Thermal Propulsion

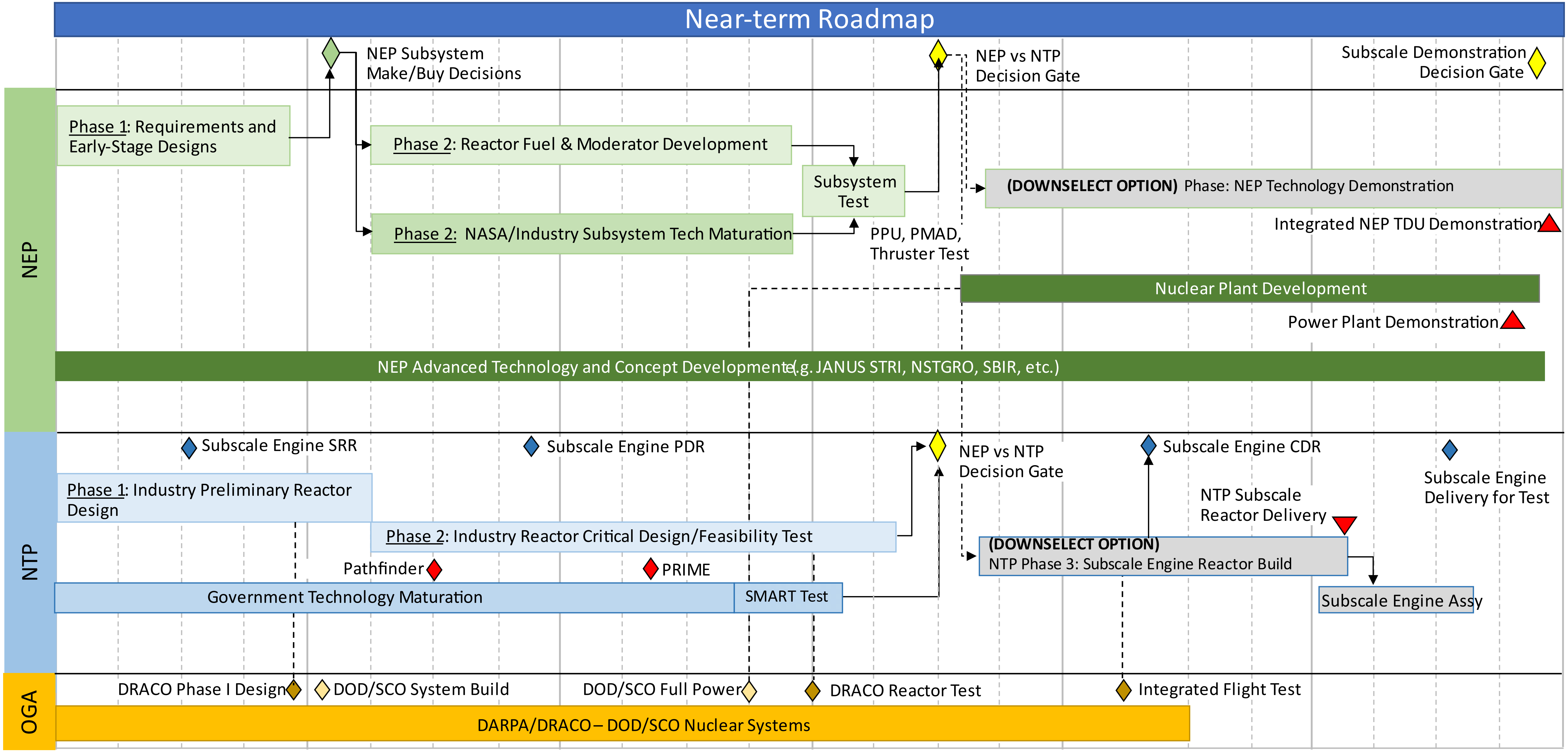
- **Phase 1: Industry Preliminary Reactor Design**
  - Preliminary reactor design industry efforts and high-temperature reactor fuel and materials development (Selected 7/21)
- **Phase 2: Industry Reactor Critical Design/Feasibility Test**
  - Critical reactor design and proof of concept tests from industry
  - Government PRIME test demonstration of reactor fuel and material maturity
  - Government SMART test of a fuel element in subscale reactor

NEP vs NTP Decision Point

- **OPTION: Phase 3: NEP Technology Demonstration**
  - Stepwise assembly of government and industry subsystems for a non-nuclear, integrated NEP TDU test
  - Independent Nuclear Power Plant Development

- **OPTION: Phase 3: NTP Subscale Engine Test**
  - Build subscale reactor and assemble subscale engine for a ground demonstration test

Nuclear Propulsion: Near-term Roadmap



Notional Timeline

Phase 1: Early Technology and Design Development Requirements

Nuclear Electric Propulsion

- Human Mars Architecture studies provide a reference point of departure.
  - Further engineering needed to define performance requirements, subsystem designs and qualification approaches
  - Incorporate industry and academic information gained through multiple technical interchange meetings held during FY21

Objectives / Deliverables:

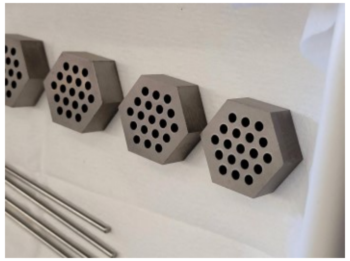
- Establish Level 1 (mission) and Level 2 (system) requirements
- Develop a government reference design
  - Develop detailed subsystem designs (industry and in-house); level 3 requirements (Design to Schedule): system design trades, interface definition, component designs
  - Reactor design (fuel and moderator) and primary heat transport
  - Power Conversion and PMAD
  - Heat rejection and thermal radiators
  - Electric propulsion (Thruster, PPU and Flow Control)
- Complete Make / Buy decision analyses
- Define Phase 2 priorities and risk assessment
- Identify rapid development investments for advanced propulsion concepts with defined proof-of-feasibility tests

Nuclear Thermal Propulsion

- Continue to advance the HALEU fuel and reactor materials development with DOE to support >2700 K reactor temperature
  - Establish industry preliminary reactor designs solutions for a subscale engine (Selected 7/21)
  - Determine design and testing options for various engine components and development activities

Objectives/Deliverables

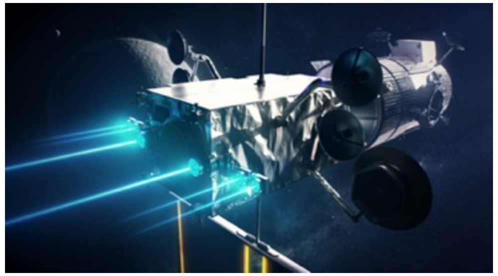
- Execute reactor preliminary design contracts with industry
- Subscale reactor and non-nuclear engine component PDR design
- Complete INL TREAT reactor modifications for PRIME reactor fuel and materials demonstration test.
- Define objectives, and design requirements for the SMART subsystem reactor test
- Develop requirements, determine location, and begin detailed engineering of a subscale ground demo facility.
- Begin build up of Hardware-in-the-loop software testing facility



Phase 2: Engineering Component and Subsystems Maturation

Nuclear Electric Propulsion

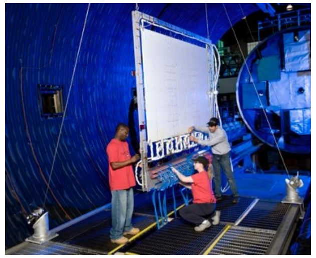
- Parallel investments from Industry and Government for multiple subsystem alternatives
- Leverage on-going NASA efforts on EP, FSP, and Electrified Aircraft
- Partner with DOE/DOD to adapt terrestrial reactor and power system technologies



Objectives:

- Assess current facility capabilities and required upgrades
- Perform risk reduction testing to evaluate materials and environments
- Develop subsystem prototypes for testing and analysis
- Down select advanced concepts with high potential for mid-TRL advancement and prototype demonstration

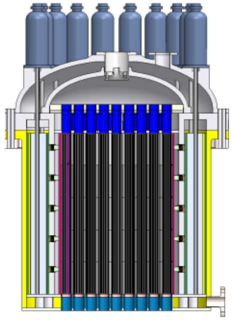
Deliverables:

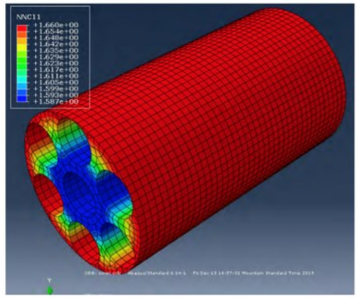


- Facility requirements and/or upgrades
- Reactor materials test results and recommendations
- Power conversion design and test plan
- Sub-scale radiator TVAC test with heat transfer loop
- Transformer demonstration, prototype high-voltage system model
- Prototype EP thruster testing
- DDU/PPU design and IEEE parts assessment

Nuclear Thermal Propulsion

- Completion of subscale engine design
- Begin work on software integration laboratory systems testing with hardware in the loop
- Begin development of subscale ground demo test facility and SMART reactor
- **Objectives/Deliverables**
- Execute industry reactor CDR designs and proof of concept test
- PRIME reactor fuel and materials demonstration test results
- SMART reactor licensing, environmental impact statement, and detailed engineering
- Engine component CDRs, Subscale engine CDR and DCR
- Preliminary design work for ground testing stand and scrubber system; facility licensing and environmental impact statement
- Non-nuclear component risk reduction tests





Moderator Block Reactor Core

Phase 3: Technology Capability Demonstration

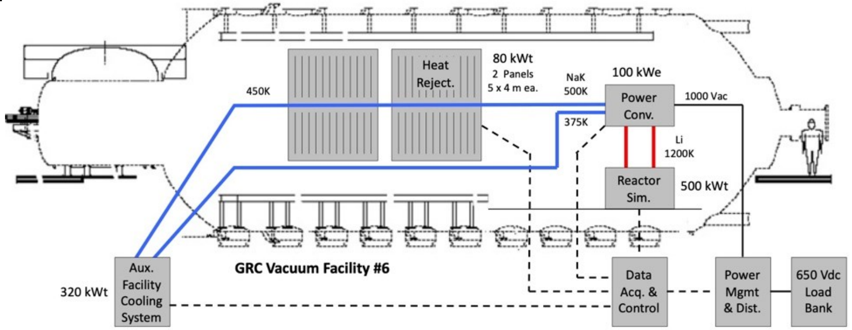
Nuclear Electric Propulsion

Objectives:

- Non-nuclear integrated TDU Test of major power subsystems at representative scale in relevant environment (To achieve TRL 5)
- Nuclear Testing of NEP fuel and moderator segments at operating temperature fluence & burnup
- Identify and prep nuclear reactor ground test facility
- High Power Propulsion Demonstration

Deliverables:

- High-fidelity reactor design and validation test plan
- Fabrication and acceptance testing of power subsystems at contractor facilities
- Delivery and integration of EP subsystems at NASA facility; Initial performance and erosion testing
- PMAD and DDU parts characterization and testing (temperature, voltage, and radiation)



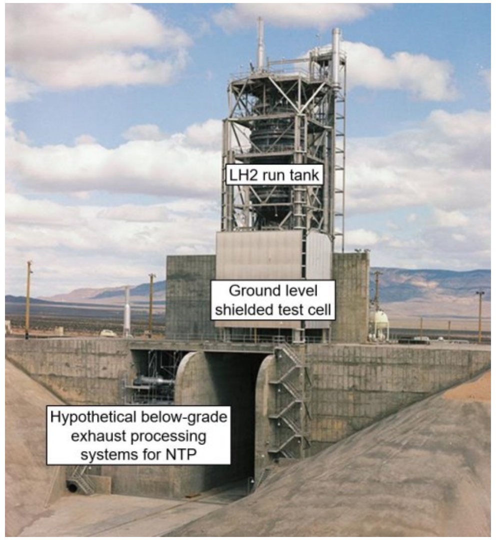
Nuclear Thermal Propulsion

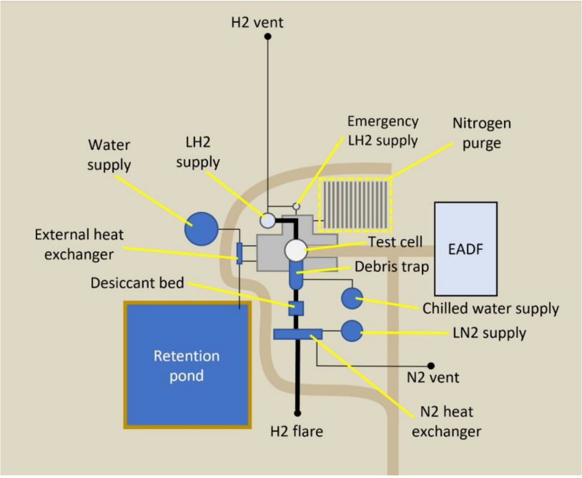
Objectives:

- Complete integration of non-nuclear turbomachinery, nozzle, and nuclear reactor into a full subscale system
- Perform integrated subscale engine demonstration and verify system performance capability including > 900 second I_{SP}

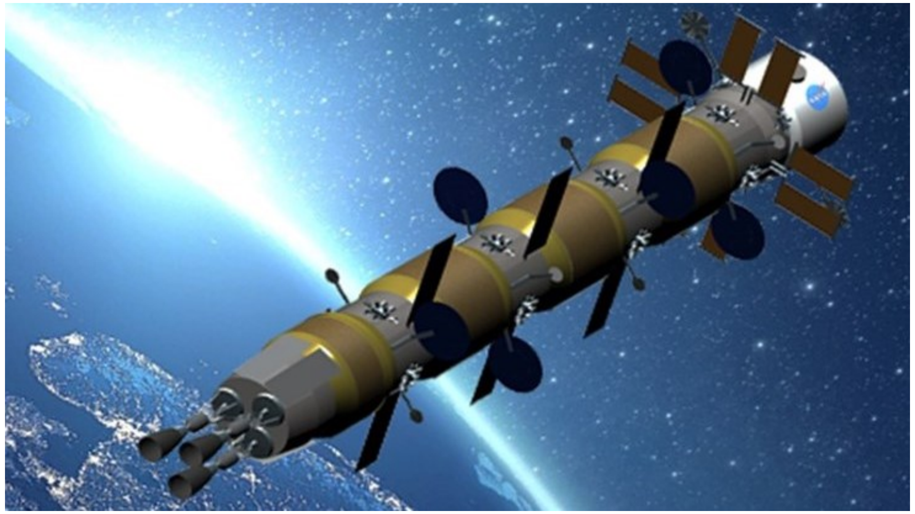
Deliverables:

- Complete reactor design specification and documentation
- Subscale engine performance capability and preliminary operational envelope
- Proof of design concept for a fully integrated NTP engine
- Ground demonstration of a subscale integrated system

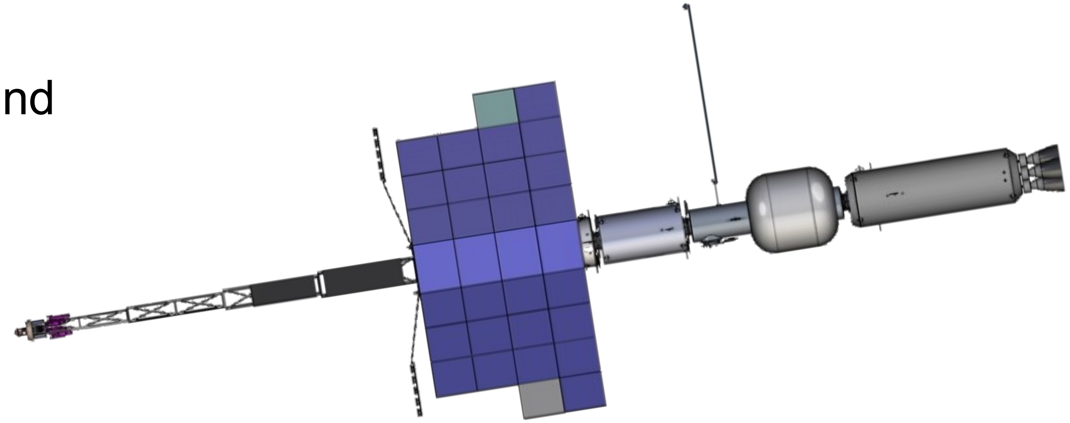




Flight Demonstration (Notional)



- Flight demonstration of nuclear propulsion capability
- Leverage of Department of Energy partnerships as appropriate
- Either NEP or NTP would be a fully integrated, mission relevant system
- Potential mission opportunity could include Mars EDL technology demonstration mission
- An NTP capability demonstration has potential partnership with DOD
  - Stakeholder / informed by DARPA DRACO partnership / products
- Demonstrate compliance with nuclear testing transportation and/or launch regulatory requirements
- Demonstrate active cooling through coordination with CFM and achieve CFM flight system test objectives



Capability Gap Priorities / Next Steps

Nuclear Electric Propulsion

Near-term
- HALEU Fueled 2 MWe Class Space Reactor Design ≥ 1200 K
- High voltage power system
- 2 MWe Class Propulsion system string prototype
  - Parallel / Leader follower approach w/ multiple thruster options
  - Steady State Thermal and ≥ 100 hrs
- Develop detailed subsystem designs (industry and in-house)
- IEEE Parts Topology Assessment

Mid-term
- ≥ 1200 K Fission Power Reactor, up to 10 MWt
- Brayton Power Demonstration ≥ 30% efficiency, up to 500 kW per unit
- Pumped Loop Heat Rejection, 1.5 MWt per loop, > 500 K
- 5 MW Class High temperature (> 500 K) radiator
  - ≤ 3 kg/m^2, < 1 kg/kW

Gap Closure
- NEP Integrated Pathfinder Flight Demonstration

Nuclear Thermal Propulsion

Near-term
- HALEU Fuel > 2700 K (2700 K Hydrogen) to support I_{SP} > 900 s
- Comparable reactor structural materials / hydrogen compatible
- 3 contractors selected for reactor PDR
  - Anticipating 2 contractors to proceed to CDR under Phase 2
- Prototypic Reactor Irradiation for Multicomponent Evaluation (PRIME) Test: CerCer fuel and insulated moderator in flowing hydrogen
- Design SMART and subscale ground test facility
- Subscale Maturation of Advanced Reactor Technologies (SMART) Test: Multiple NTP fuel and moderator elements into a driver core system.
  - Raise NTP material up to criticality with hydrogen flow testing

Mid-term
- 12.5 klbf non-nuclear engine (controls, cold flow, power pack)
- Ground Support & Ground Test Infrastructure Required for subscale ground demonstration and SMART
- Empirically Anchored Models & Simulation Capabilities Supporting NTP Engine System Design and Digital Twin Systems Engineering
- Begin development of long lead items required for full scale NTP certification ground test facility

Gap Closure
- NTP Integrated Pathfinder Flight Demonstration
  - Potentially w/ integrated CFM

Acronyms and Abbreviations

- ΔV : Delta-V; Change in Velocity
- Assy: Assembly
- CerCer: Ceramic-ceramic
- CDR: Critical Design Review
- DARPA: Defense Advanced Research Projects Agency
- DCR: Design Certification Review
- DDU: Data Display Unit
- DOD: Department of Defense
- DOE: Department of Energy
- DRACO: Demonstration Rocket for Agile Cis-lunar Operations
- EDL: Entry, Descent, and Landing
- EP: Electric Propulsion
- FSP: Fission Surface Power
- FY: Fiscal Year
- HALEU: High Assay Low Enriched Uranium
- IEEE: Institute of Electrical and Electronic Engineers
- INL: Idaho National Laboratory
- Isp: Specific impulse
- ISS: International Space Station
- NASA: National Aeronautics and Space Administration
- NEP: Nuclear Electric Propulsion
- NTP: Nuclear Thermal Propulsion
- OGA: Other Government Agencies
- PDR: Preliminary Design Review
- PMAD: Power Management and Distribution
- PPE: Power and Propulsion Element
- PPU: Power Processing Unit
- PRIME: Prototypic Reactor Irradiation for Multicomponent Evaluation
- SCO: Strategic Capabilities Office
- SMART: Subscale Maturation of Advanced Reactor Technologies
- SRR: System Readiness Review
- STMD: Space Technology Mission Directorate
- TBR: To Be Resolved
- TDU: Technology Demonstration Unit
- TREAT: Transient Reactor Test
- TRL: Technology Readiness Level
- TVAC: Thermal Vacuum

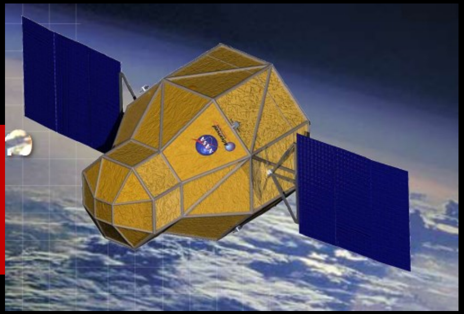
EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

GO: Cryogenic Fluid Management
NASA Space Technology Mission Directorate
March 2022

STMD welcomes feedback on this presentation
See RFI 80HQTR22ZOA2L-GO at nspires.nasaprs.com for how to provide feedback
If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

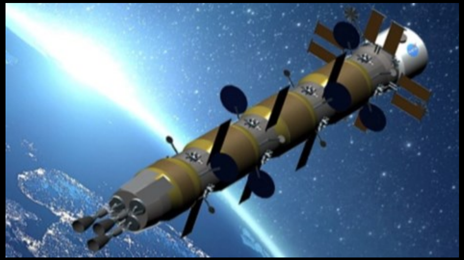
GO: Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications.

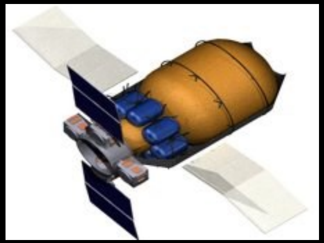
Developing technologies for near zero boil off storage, high efficiency chill-down and liquification, propellant transfer, and instrumentation to support Mars transportation and surface ISRU architectures.



STORAGE
- LOX, LCH4, LH2
- Near Zero Boil-off – Architecture / mission dependent

- **Critical Technologies**
  - Active Thermal Control
  - High Performance Insulation
  - Structural Heat Rejection/Intercept
  - Pressure Control
  - Operations
  - Near Zero Boil-off
  - Structural Multilayer Insulation
  - Low conductance structures
  - High Efficiency High Capacity 20 K and 90 K Cryocoolers
  - Destratification
  - Unsettled Mass Gauging
  - Thermal Control Coatings





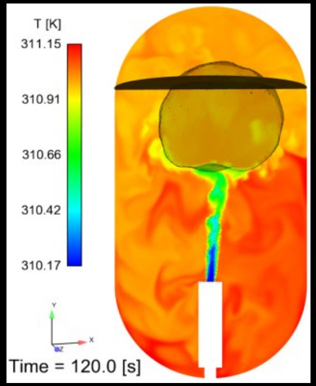
LIQUEFACTION
- H_2, O_2, CH_4
- Initial system performance:
  2 kg/hr of O_2 and 0.3 kg/hr of H_2
- Soft Vacuum insulation: 1.5 W/m2 at 250 K

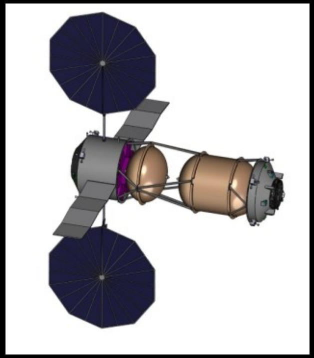
TRANSFER
- Propellant losses ≤1% during transfer
- <1% residual in supply tank

- **Critical Technologies**
  - Component Technologies
  - Operations
  - High efficiency chill down of tank and lines
  - Automated Cryo-Couplers
  - Low-leakage valves/actuators
  - Flow Meters
  - Efficient Liquid Acquisition Devices
  - Transfer pump

NON-PRIMARY PROPULSION
- Integrated RCS
- Fuel Cells
- ECLSS

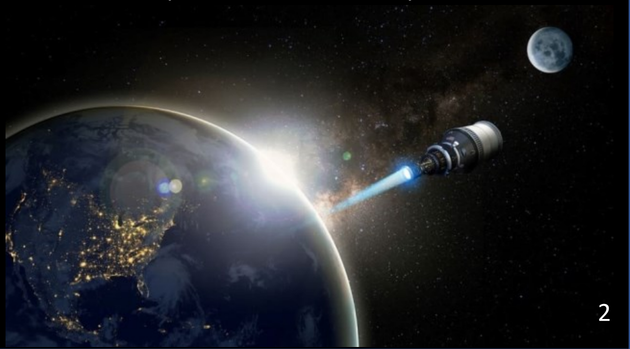
- Application Specific CFM Capabilities
- Uses components and processes from other categories





INTEGRATED OPERATIONS / PREDICTIVE PERFORMANCE
- Advanced instrumentation, data acquisition and signal processing
- Integrated Demonstration
- Accurate and robust a priori microgravity thermal-fluid predictions
  - Validated foundational physics in High Fidelity tools
  - High-to-Low Fidelity Model Integration

- Integrated System Performance Analysis
  - Low predictive uncertainty



CFM State of the Art

CFM capabilities must address the operational implementation and use of the technologies in a system, and the technical design of the CFM system. Many of the components required to close the gaps are the same but have diverging requirements or implementation strategies that change how the technology is used.

STORAGE

- Extensive experience in ground demonstration
- Longest H_2 cryogenic propulsion storage system has performed storage operations in space is 9 hrs
- Performed 4.5 Month CH4 subscale storage on RRM3

KEY Design Details

- Tank pressure regulation
- Methods of venting
- Structural heat load
- Total heat input over time
- Active cooling – **1W lift @ 20 K; 20W lift @ 90 K**

LIQUEFACTION

- **Ground based demonstration** and analytical performance model validation of **LN2**

KEY Design Details

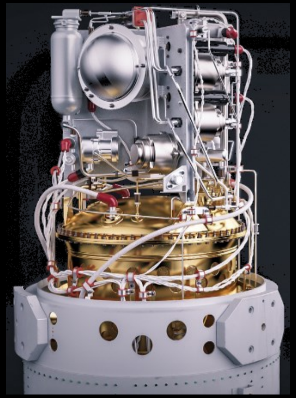
- Condensation, fluid physics, fluid purity
- Active cooling integration
- High performance insulation in appropriate environment

NON-PRIMARY PROPULSION

- **Ground based testing** of Integrated RCS in thermal vacuum

KEY Design Details

- Application specific technologies and operational processes

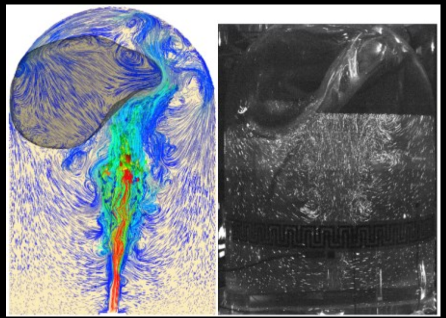


INTEGRATED OPERATIONS / PREDICTIVE PERFORMANCE

- Fluid property knowledge gaps
- Instrumentation
- Model development and validation for both high and low fidelity applications

KEY Design Details

- Zero-G Mass Gauging
- Operational and predictive fluid dynamics and thermodynamics

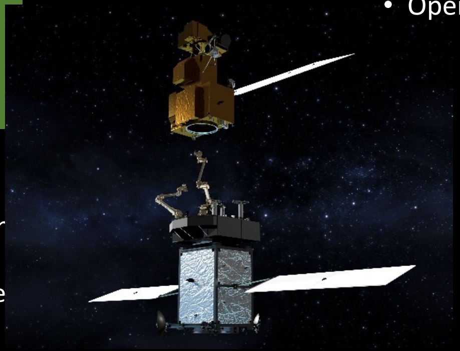


TRANSFER

- **Component brassboard** hardware **ground testing only**

Key Design Details

- Pump or pressure driven transfer
- High efficiency chill down of tank and lir
- Active cooling
- Low-leakage valves/actuators, leak dete
- Phase separation/Liquid acquisition



CFM Critical Technologies Current Investments

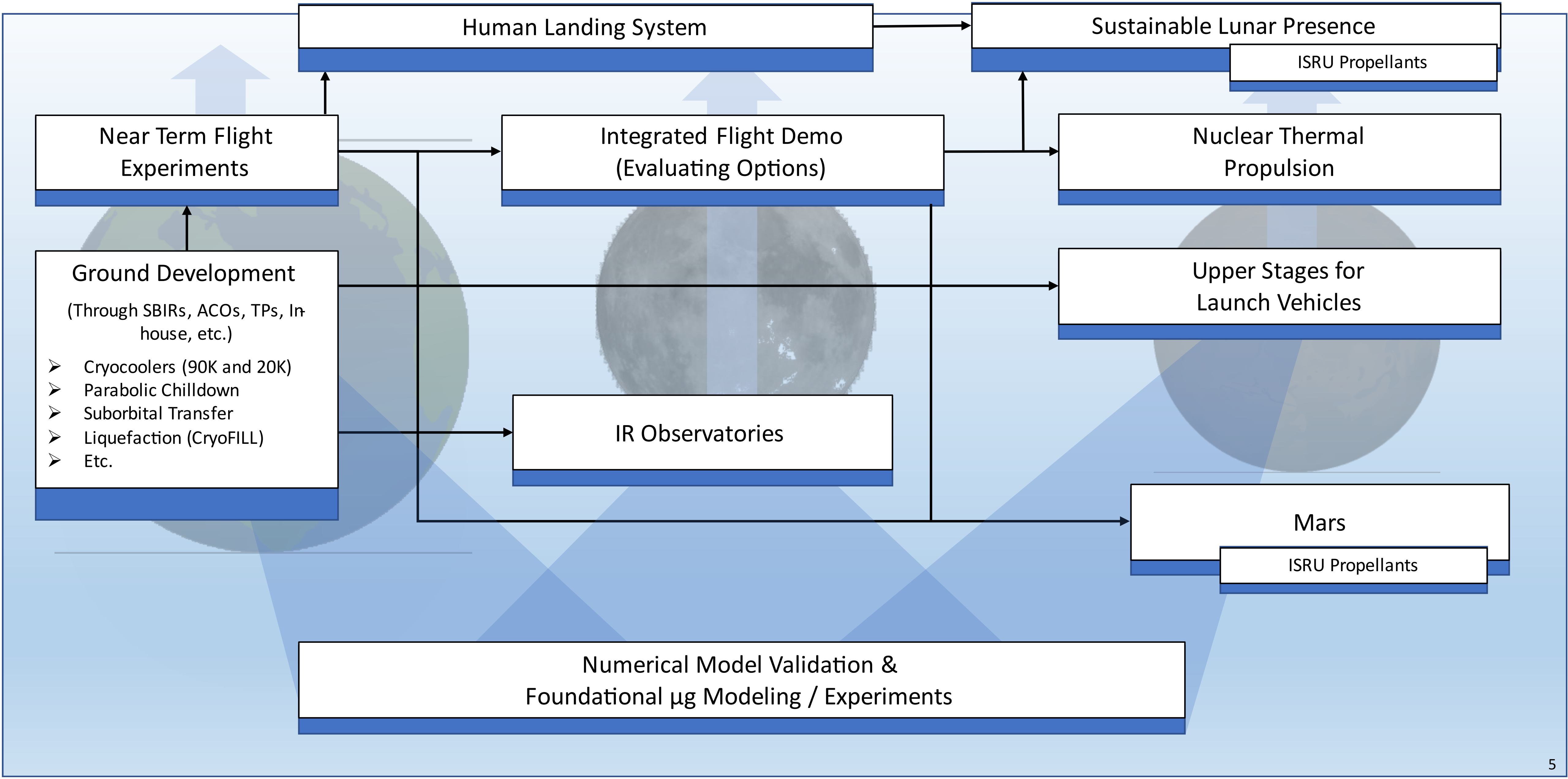
CFM Critical Technology Gaps	Cross Cutting or Fluid Specific	Current TRL	Gap Addressed**
Low Conductivity Structures	Cross Cutting	6	Tipping Point (TP)
High Vacuum Multilayer Insulation	Cross Cutting	6	FY20 TP
Sun Shields (deployment mechanism)	Cross Cutting	5	JWST / TP
Tube-On-Shield BAC	Cross Cutting	5	TP, In-house
Valves, Actuators & Components	Cross Cutting	4-5	TP, In-house
Vapor Cooling	Fluid Specific	6	TP, In-house
Propellant Densification	Fluid Specific	5	TP, In-house
Unsettled Liquid Mass Gauging, multiple methods	Cross Cutting	4-7	TP, ECI, FO, In-house
Sub-surface Helium Pressurization in Micro-g	Cross Cutting	5	ZBOT / TP
Line Chilldown (MPS, iRCS, Transfer)	Cross Cutting	5	TP
Pump Based Mixing	Cross Cutting	5	ZBOT / TP
Thermodynamic Vent System	Cross Cutting	5	TP
Tube-On-Tank BAC	Cross Cutting	5	In-house
Liquid Acquisition Devices	Fluid Specific	5	TP
Advanced External Insulation	Cross Cutting	4	Paragon / CELSIUS
Automated Cryo-Couplers	Cross Cutting	4	TPs, HLS, ECI
Cryogenic Thermal Coating	Cross Cutting	4	TP, In-house
High Capacity, High Efficiency Cryocoolers 90K	Cross Cutting	4	In-house
Soft Vacuum Insulation	Cross Cutting	3	MAV (MSR)
Structural Heat Load Reduction	Cross Cutting	3	CIF
Propellant Tank Chilldown	Cross Cutting	4	FY20 TP
Transfer Operations	Cross Cutting	4	FY20 TP
High Capacity, High Efficiency Cryocoolers 20K	Fluid Specific	4	In-house
Liquefaction Operations (MAV & ISRU)	Fluid Specific	4	TP / In-house
Para to Ortho Cooling	Fluid Specific	4	TP
Cryogenic Flow Meter	Cross Cutting	4	TP
Autogenous Pressurization in Micro-g*	Fluid Specific	4	ZBOT / TP
CFM Modeling Capability	Cross Cutting	2-9	ZBOT, In-house, STRG, FO

- NASAs CFM Portfolio has contributed extensively to bringing CFM critical technologies to TRL 4-6
- Significant SBIR program leverage
- Nearly all are receiving active investments
- Recent focus has been on advancing the CFM component and subsystem technologies beyond the mid-range TRL level and developing integrated flight demonstrations to support NASA's future missions
- Future focus will be closing out the current lower TRL investments and development of the near-term flight demonstrations
- HLS Leverage for multiple components
- Industry leverage (e.g. Lockheed Martin, Blue Origin, SpaceX, Eta Space, etc.)
- SMD ZBOT demonstrations and model validation
- High to low fidelity model development and validation to predict future mission capabilities

* Note: Traditional settled pressurization methods TRL 9

** Note: Addressing the gap does not in all cases equate to gap closure; some gaps are fluid or architecture specific; the goal is to develop high-fidelity models to support mission designs.

Long Term CFM Strategy and End User Applications



CFM Investment Approach

Ground Development (Current CFM Projects)

- Multiple ground-based component and subassembly projects addressing the CFM critical technologies
- Many of these lower-level capability demonstrations are advanced in technology readiness through the Tipping Point integrated system demonstrations
- CFM technologies supporting ISRU architectures do not require micro-g and TRL can be advanced to 6/7 in ground testing.

Near-Term Demonstrations (FY20 Tipping Points)

- STMD is sponsoring a significant Tipping point award to incentivize Industry to fly CFM experiments that will combine many of these CFM technologies to develop and raise the TRL level of storage and transfer
- Four flight demonstrations have been selected for award and are expected to fly by 2025
- Significant technology maturation is stalled in wait of integrated system and/or relevant environment testing

Large Integrated Flight Demonstration

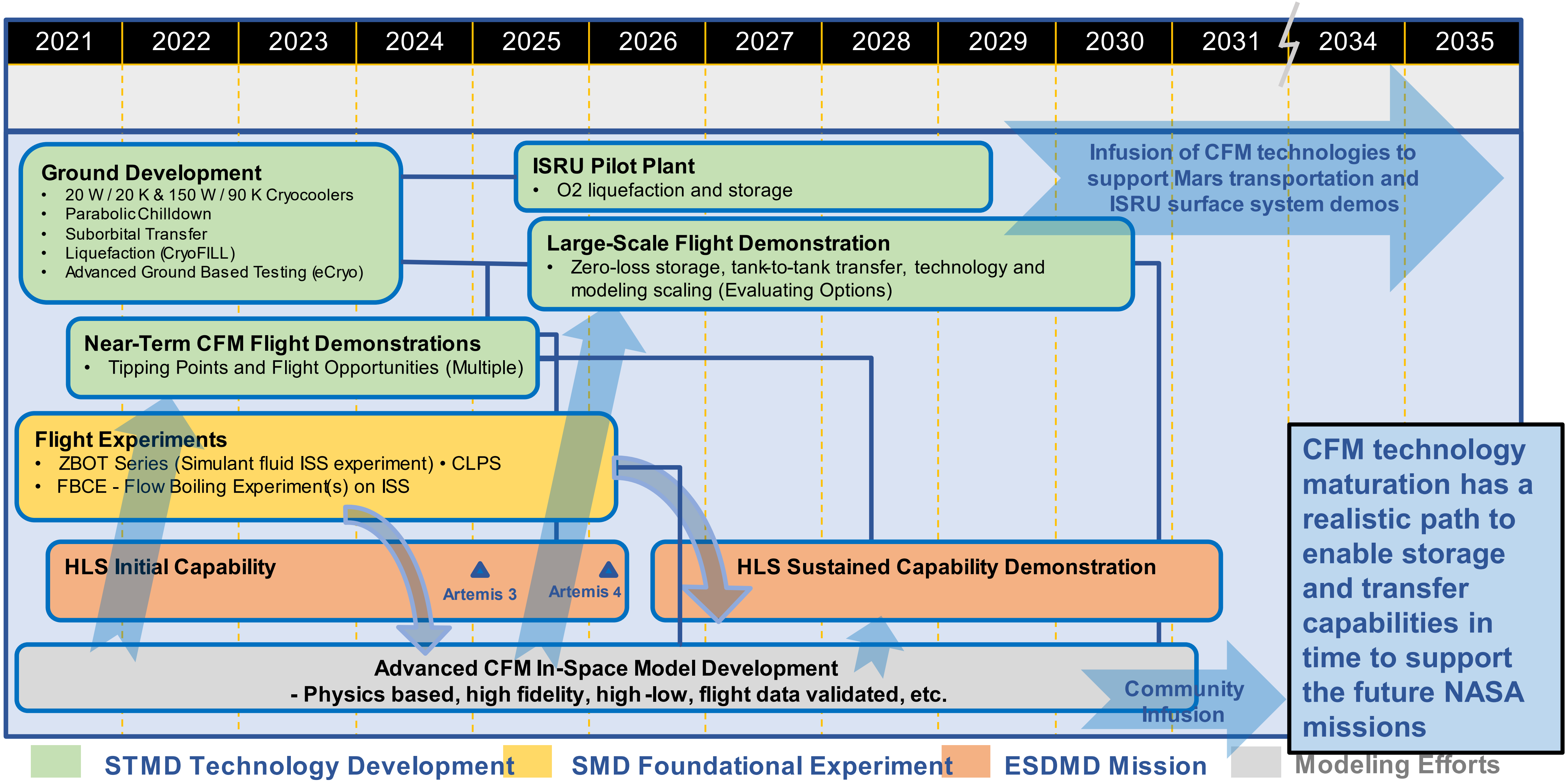
- Evaluating Options

Leverage the Human Landing System (HLS) Development and Demonstration

- Utilizing the data and performance gathered during the Near-Term Demonstrations and other mature enabling and enhancing technologies, the CFM individual systems will be demonstrated in a scalable flight experiment directly addressing the performance needs of CFM stakeholders.
- Post flight, CFM technologies will be ready to support NTP and other deep space Cryo stage missions

Operations Optimization

CFM Notional Near-Term Roadmap



Notional Timeline

Capability Gap Performance Goals

Storage

- Lunar Human Return/Exploration: Cryogenic propellant storage with near zero boil-off dependent on architecture and mission duration; LOx, LCH_4, LH_2
- Long Term Lunar/Mars/ISRU: Zero Boil-off (net head load of less than zero); LOx, LCH_4, LH_2; includes thermal insulation and structural interfaces limiting heat leak into tanks

Transfer

- Propellant losses of 1% (TBR) or less during transfer activity
- <1% (TBR) residual in supply tank

Liquefaction

- Integrated system performance of 2 kg/hr of O_2 and 0.3 kg/hr of H_2
- Fluids to demonstrate: LOx, LCH_4, LH_2

Predictive Model Validation

- Demonstrate that the relative difference between CFD or nodal model results and test data is less than 15% (TBR) for pressure time histories and less than 30% (TBR) for (fluid and/or wall) temperature time histories
  - Sufficient for acceptable performance margin (TBD) of operational systems

Acronyms and Abbreviations

- ACO: Announcement of Collaboration Opportunity
- BAC: Broad Area Cooling
- CELSIUS: Cryogenic Encapsulating Launch Shroud and Insulated Upper Stage
- CFM: Cryogenic Fluid Management
- CLPS: Commercial Lunar Payload Services
- Cryo: Cryogenic
- ECI: Early Career Initiative
- ECLSS: Environmental Control and Life Support System
- FBCE: Flow Boiling and Condensation Experiment
- FO: Flight Opportunities
- FY: Fiscal Year
- HEOMD: Human Exploration and Operations Mission Directorate
- HLS: Human Landing System
- IR: Infrared
- IRCS: Integrated Reaction Control System
- ISRU: In-Situ Resource Utilization
- ISS: International Space Station
- JWST: James Webb Space Telescope
- LCH_4: Liquid Methane
- LH_2: Liquid Hydrogen
- LOx: Liquid Oxygen
- MAV: Mars Ascent Vehicle
- Micro-g: Micro gravity
- MSR: Mars Sample Return
- NASA: National Aeronautics and Space Administration
- NTP: Nuclear Thermal Propulsion
- RCS: Reaction Control System
- RRM3: Robotic Refueling Mission 3
- SBIR: Small Business Innovation Research
- SMD: Science Mission Directorate
- STMD: Space Technology Mission Directorate
- STRG: Space Technology Research Grants
- TBD: To Be Determined
- TBR: To Be Resolved
- TP: Tipping Point
- TRL: Technology Readiness Level
- ZBOT: Zero Boil-Off Tank
- Zero-g: Zero gravity

EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

GO: Advanced Propulsion
NASA Space Technology Mission Directorate
March 2022

STMD welcomes feedback on this presentation
See RFI 80HQTR22ZOA2L-GO at nspires.nasaprs.com for how to provide feedback
If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

SPACE FLIGHT ARCHITECTURE DOMAINS

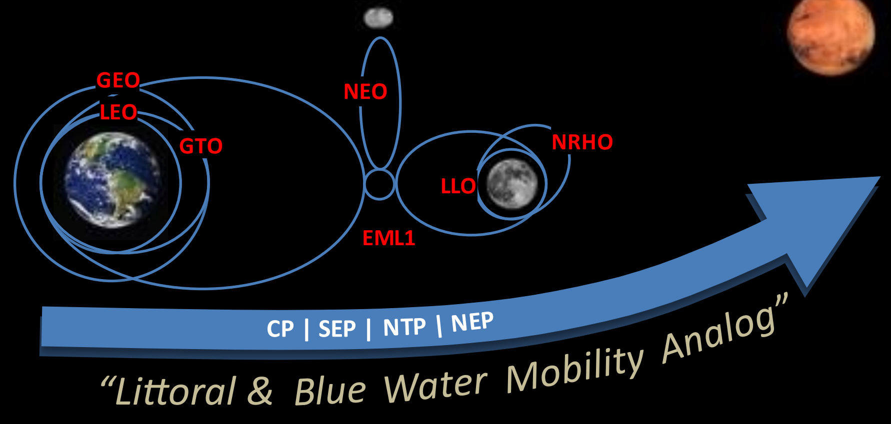
Exploration, Science, Commerce & Security

LEO TO CIS-LUNAR

CLPS/Artemis & Cis-Lunar Development

- Science Payloads
- Mining & Resource Extraction
- Manufacturing
- Fuel Depots / In Situ Derived Prop
- Space Solar Power
- Outposts (In-Space & Surface)
- Orbital Debris Mitigation and Remediation
- Planetary Defense Assets
- National Security Space Assets

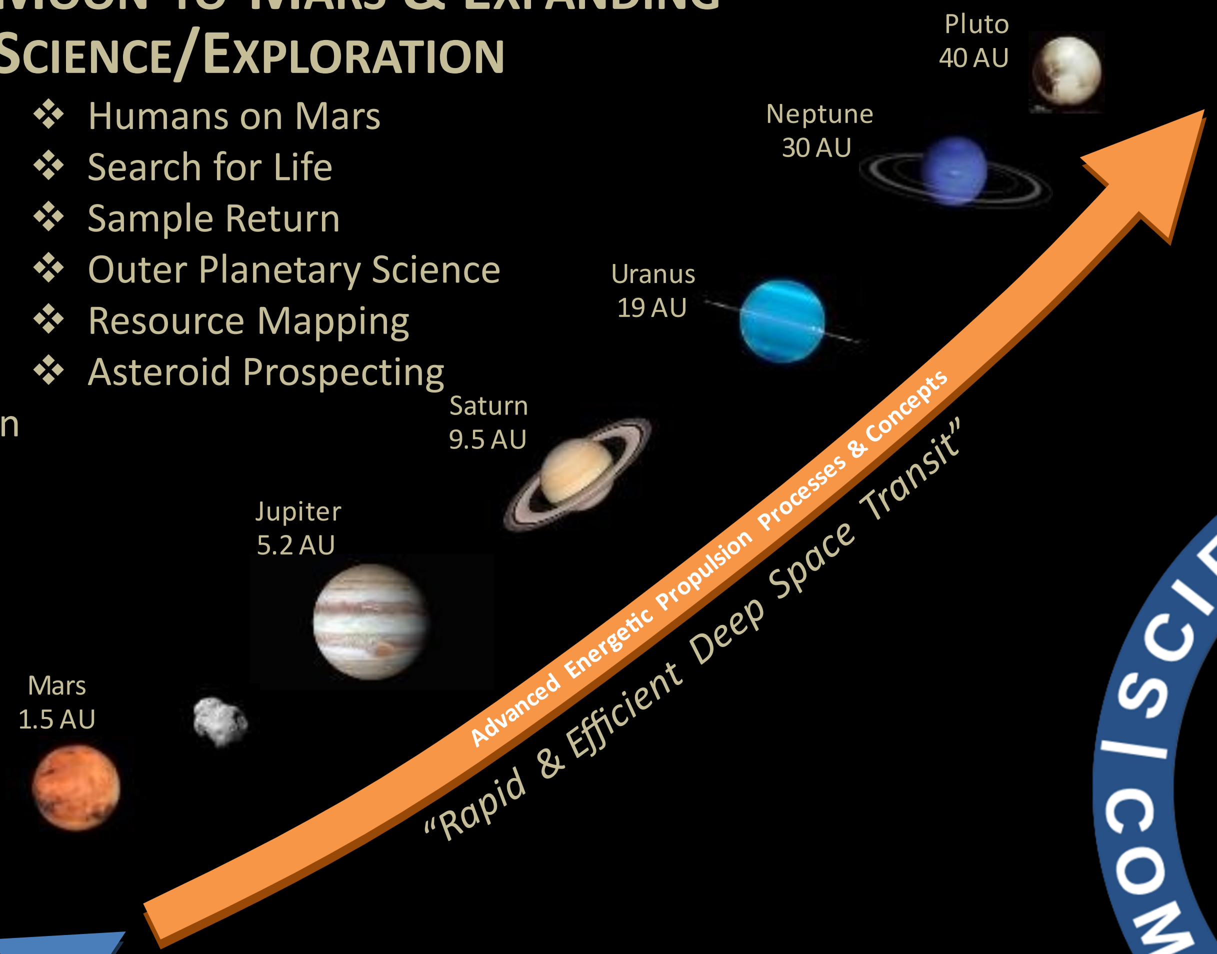
"Commercially Sustained Cis-Lunar Infrastructure"



MESO-SOLAR

Moon-to-Mars & Expanding Science/Exploration

- Humans on Mars
- Search for Life
- Sample Return
- Outer Planetary Science
- Resource Mapping
- Asteroid Prospecting



EXTRA-SOLAR

Outer Solar System & Interstellar

KBOs & Primitive Bodies	>50 AU
Heliosphere / Local ISM	100-200 AU
Pristine ISM	200-400 AU
Solar Gravity Lens	500-800 AU
Nearby Stars / Exoplanets	4.5-20 LY

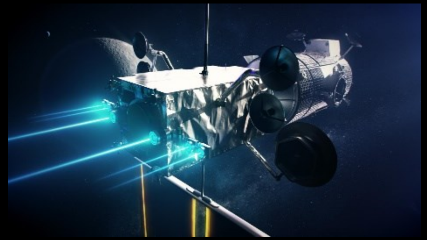
STMD STRATEGIC FRAMEWORK ENVISIONED FUTURE

GO Thrust – Advanced Propulsion Vision

Produce advanced propulsion technologies that enable future exploration/science/commercial missions

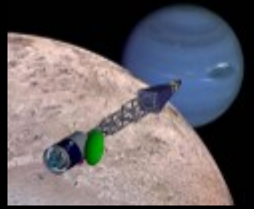
Developing advanced propulsion technologies to push the cutting edge farther and faster than ever before

ARCHITECTURE DRIVEN PROPULSION TECHNOLOGIES
SCIENCE/EXPLORATION/COMMERCE/SECURITY CAPABILITIES



High-ΔV EP Spacecraft

High-ΔV XX-kWe EP Capability
- 12-kWe Class HET → Gateway/PPE SEP
- 7-14-kWe Class GIT → Advanced NEXT
- 100-kWe Class Electric Thrusters including HET, MPD, VASIMR, & other options → Mars Transportation System



Outer Planetary Robotic NEP Spacecraft

Deep Space Nuclear Flagship Capabilities
- Propulsion Technologies Enabling Nuclear Propulsion Robotic Spacecraft
  - Fission Surface Power Derived NEP
  - Dynamic-RPS Derived NEP
  - Advanced LCF Derived NEP

Earth Pole Sitting Observatories

Sun Pole Sitting Observatories

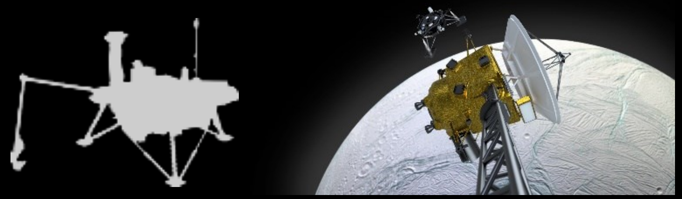
Observational Platforms for Science, Commercial & Security Missions Requiring Unlimited ΔV Capability
- Solar Sail Development & Demonstration
  - Monitor Solar Cruiser Project
  - Supplement SMD Technology Development as Warranted
  - Support Early-Stage Concept R&D

High-ΔV ESPA-Class Deep Space Spacecraft

Small Spacecraft Science, Commercial & Security Missions Requiring High-ΔV EP Capability
- Focus on ESPA-Class Sub-kW EP
- Flight Qualify & Demonstrate
- SMD SIMPLEx Mission Infusion

Green Propellant Deep Space Spacecraft

Green Propellant Adoption & Infusion into Missions of Opportunity
- Facilitate Provider/User Transition
- Incentivize Mission Opportunities
- Lunar Flashlight Mission Infusion

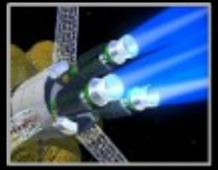


Thruster Advancement for Low Temperature Ops in Space

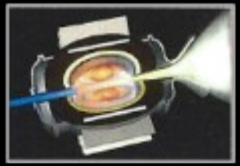
Deep Space Science Missions Requiring Cold Tolerant Storable Propulsion for Extreme Environments Access
- MON-25/MMH Bipropellant Thruster Technology
- Compact Lander Propulsion – TALOS → CLPS Infusion
- Deep Space Variant – Extensible TALOS → Enceladus

INSPIRATION DRIVEN RESEARCH
TRANSFORMATIONAL CAPABILITIES

Sustained investment in Advanced Energetic Propulsion research & innovation enables the possibility for new breakthrough technologies



Low-α NEP



Fission Gas Core or Advanced Solid Core

Pulsed Fission

Directed Energy & Sails

Fusion

Antimatter

Breakthrough Science

Capability Goals:
- $\alpha \leq 5$ kg/kW
- Thrust-to-Weight ≥ 0.6
- Relativistic S/C Velocity ≥ 0.1c

All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.

ADVANCED PROPULSION CAPABILITY OUTCOMES

Propulsion Technology Development Streams

Exploration Architecture Systems Development (TRL 6-8)

Lunar Gateway

Exploration (E)1: Gateway/PPE SEP

Develop 12.5-kWe SEP string and enable 50-kWe thruster array for lunar orbit maneuvering and NRHO station keeping

Artemis/Mars

E2: Cryogenic CP

Affordable, highly reusable cryogenic propulsion to providein-space transport and lunar surface access with extensibility to Mars

Mars Transport

E3-A: NEP/CP Hybrid

Multi-MW NEP to provide cruise ΔV plus affordable & highly reusable cryogenic propulsion to provide gravity well ΔV

E3-B: NTP

High thrust NTP to provide gravity well ΔV plus reactor integrated OMS to provide supplemental ΔV

Science, Commerce & Security Technology Development (TRL 6-8)

Flagship SEP

Science (S)1: High-ΔV SEP

Develop 7-14 kWe gridded ion EP string to enable more ambitious very high-ΔV deep space robotic missions

Extreme Access Storable Propulsion

S2-A: Baseline TALOS

Baseline TALOS: In-space cold tolerant storable pulse mode bi-propulsionto enable extreme environment surface access

S2-B: Extensible TALOS

Extensible TALOS: Deep space variant modifications & qualification for high-throughput, long-burn orbit transfer and extreme access

High-ΔV Small S/C

S3: ESPA Sub-kW SEP

Fully flight qualified high-throughput, radiation-tolerant sub-kW Xenon HET enabling high-ΔV ESPA-class deep space missions

Unique Platforms

S4: Solar Sail

Matured solar sail technology to provide essentially unlimited S/CΔV as an enabler of unique platform capabilities

Green Prop Adoption

S5: Green Propulsion

Facilitate green propellant infusion by incentivizing mission adoption and PPP opportunities to mature a wide range of thrust classes

Transformational Capability R&D (TRL 3-6)

Transformational CP

Transformational (T)1: RDRE

Early-stage R&D focused on RDRE maturation & prototype demonstrations to achieve transformational gains in CP performance for launch, in-space, and lander systems

Flagship NEP

T2: Robotic S/C NEP

Propulsion technologies enabling low-to-moderate power NEP transportation systems (FSP/Dynamic-RPS/LCF Derived NEP)

Rapid Transit Interstellar Probe

T3: Near Sun STP

Early-stage R&D focusing on transformational STP capability to enable solar perihelion burn Oberth maneuvers and the attainment of high solar system escape velocities

Advanced Energetic Propulsion

T4: Fusion/AEP Concepts

Early-stage R&D focused on rapid prototype demonstration of nuclear fusion propulsion technologies and AEP concepts to achieve transformational capabilities for fast & efficient solar system wide access

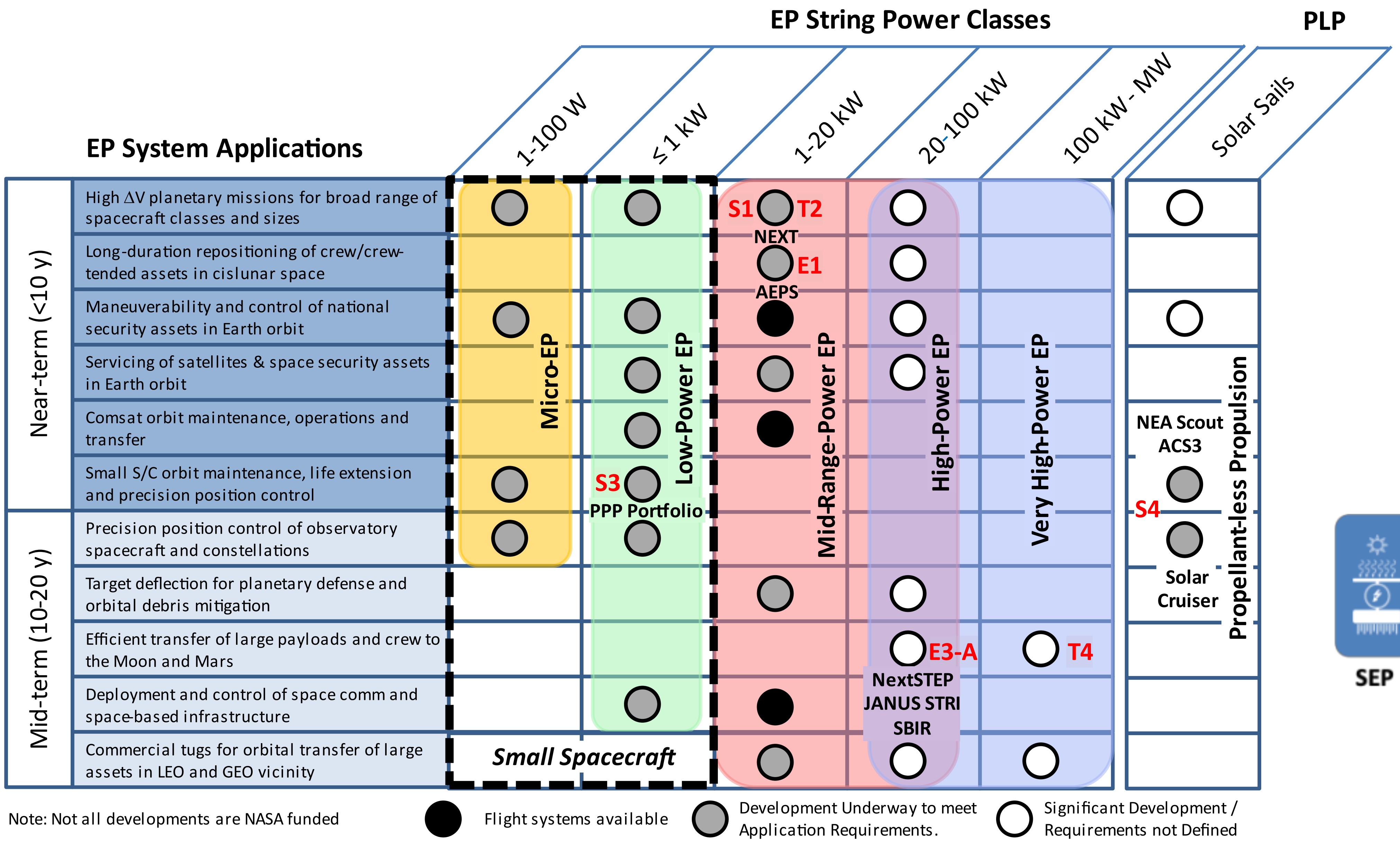
Near Term → Long Term

EXPLORATION ARCHITECTURES

SCIENCE, COMMERCE & SECURITY

INSPIRATION DRIVEN RESEARCH

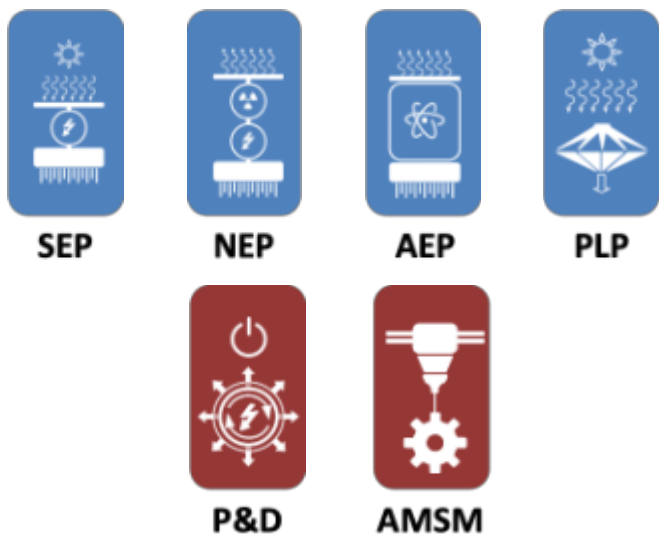
SOA – ELECTRIC PROPULSION SYSTEMS
Historical Developments & Projected Capabilities



Technology Objective Index

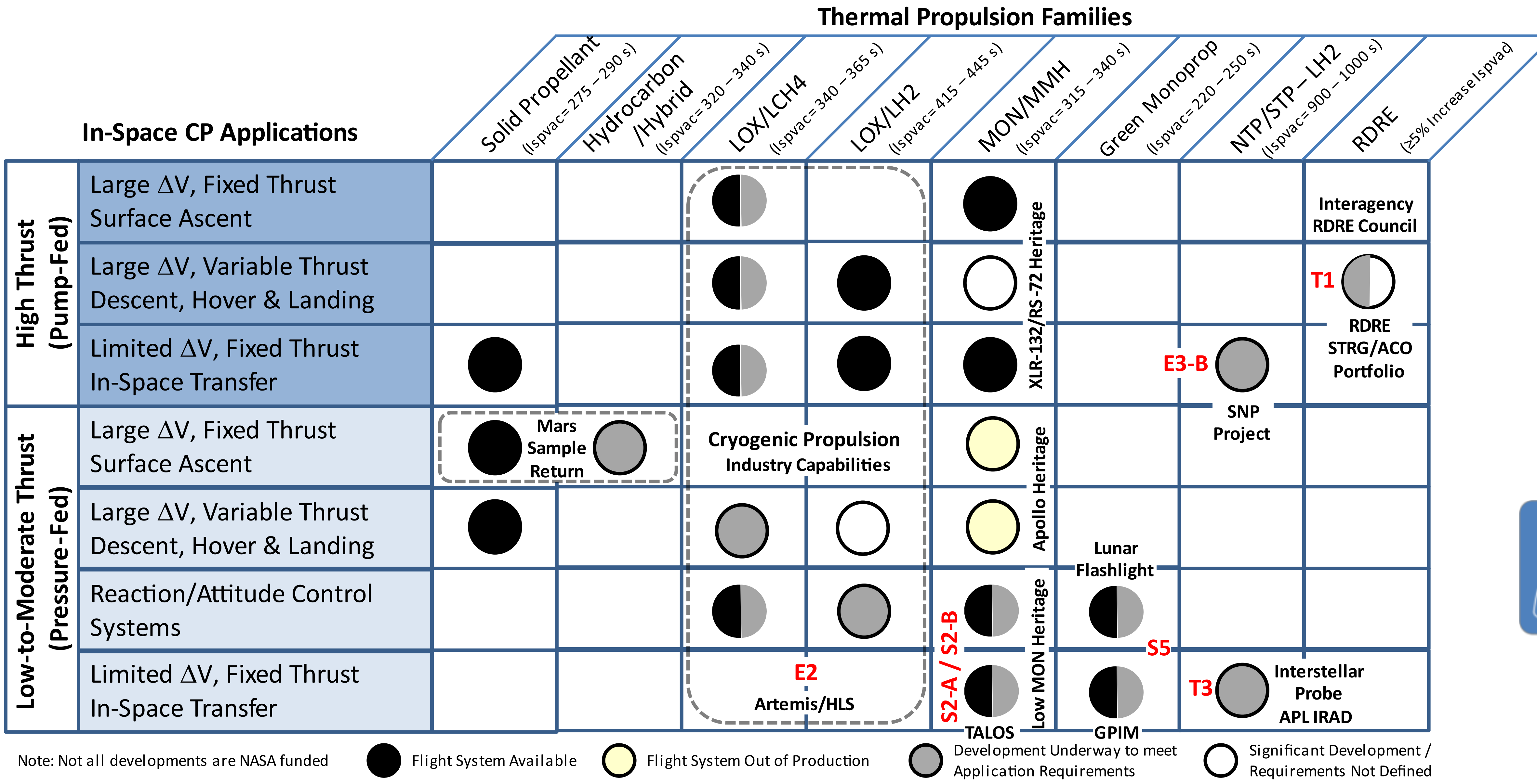
E1	Gateway/PPE SEP
E2	Cryogenic Propulsion
E3-A	Mars NEP/CP Hybrid
E3-B	Mars NTP
S1	High-ΔV SEP
S2-A	Baseline TALOS
S2-B	Extensible TALOS
S3	ESPA Sub-kW SEP
S4	Solar Sail Propulsion
S5	Green Propellant
T1	RDRE Propulsion
T2	Flagship NEP
T3	Interstellar Probe STP
T4	Fusion/AEP

Technology Elements



SOA – CHEMICAL & THERMAL PROPULSION SYSTEMS

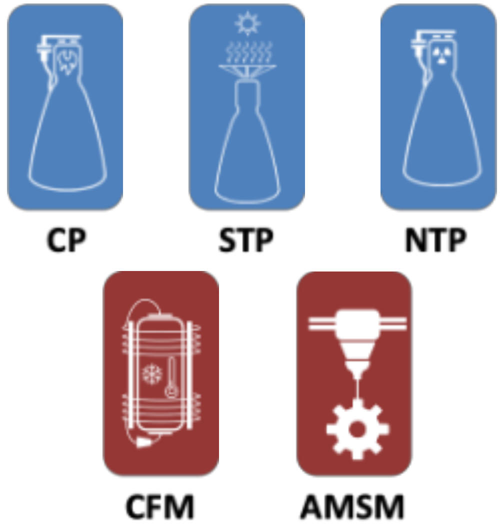
Historical Developments & Projected Capabilities



Technology Objective Index

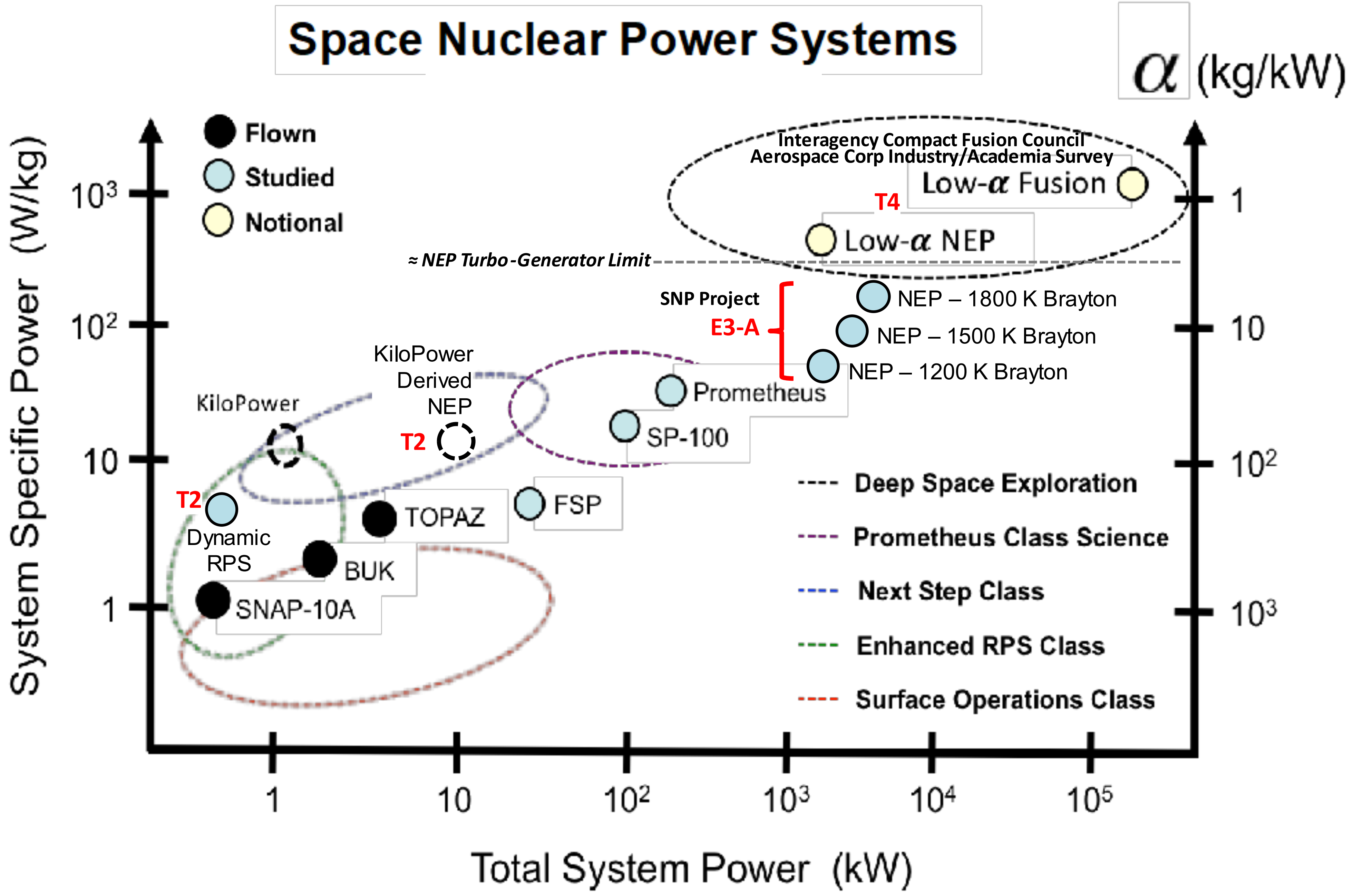
E1	Gateway/PPE SEP
E2	Cryogenic Propulsion
E3-A	Mars NEP/CP Hybrid
E3-B	Mars NTP
S1	High-ΔV SEP
S2-A	Baseline TALOS
S2-B	Extensible TALOS
S3	ESPA Sub-kW SEP
S4	Solar Sail Propulsion
S5	Green Propellant
T1	RDRE Propulsion
T2	Flagship NEP
T3	Interstellar Probe STP
T4	Fusion/AEP

Technology Elements



SOA – SPACE NUCLEAR PROPULSION & POWER SYSTEMS

Historical Developments & Projected Capabilities



Technology Objective Index

E1	Gateway/PPE SEP
E2	Cryogenic Propulsion
E3-A	Mars NEP/CP Hybrid
E3-B	Mars NTP
S1	High-ΔV SEP
S2-A	Baseline TALOS
S2-B	Extensible TALOS
S3	ESPA Sub-kW SEP
S4	Solar Sail Propulsion
S5	Green Propellant
T1	RDRE Propulsion
T2	Flagship NEP
T3	Interstellar Probe STP
T4	Fusion/AEP

Technology Elements

CONCLUSIONS & HIGH LEVEL DEVELOPMENT STRATEGY

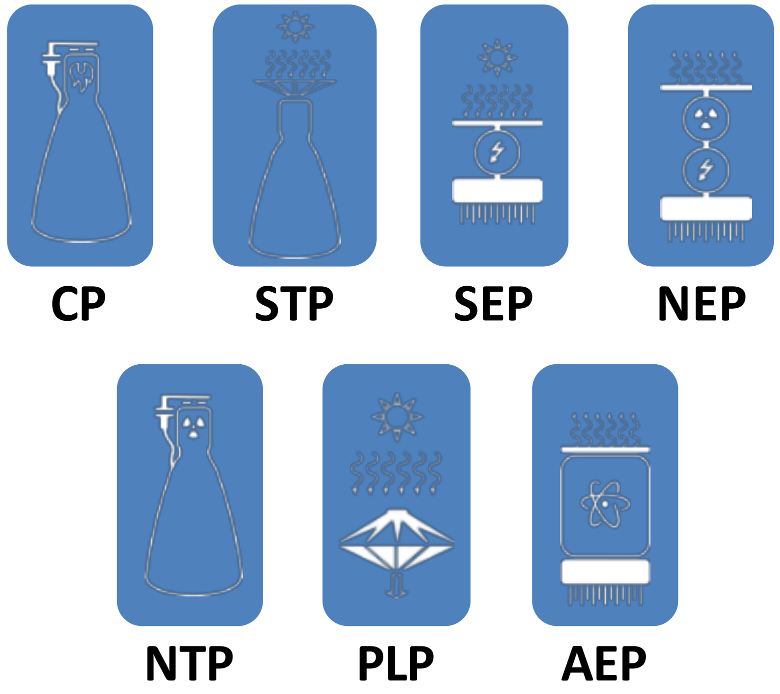
- **Architecture Driven Propulsion Technology Strategy is Essentially On Track**
  - Emphasis on sustained portfolio execution & commitment to deliveries, including accommodation of ground infrastructure impacts
  - Additional mid-TRL investment is needed in a few priority areas (e.g., ESPA-Class Sub-kW EP & Beyond NextSTEP High-Power EP)
- **Transformational Capability R&D Portfolio in need of Programmatic Restructuring & Significant Funding Augmentation**
- **High Level Development Strategy**

Architectural Outcome	Technology Capability Goal	Recommended Action	Investment Trend
Gateway/PPE SEP	12 kWe HET String / 50 kW SEP System	Sustain Execution & Commitment to PPE/Gateway Delivery	Sustain
Flagship High-ΔV SEP	7-14 kWe Gridded Ion EP String	Develop Advanced NEXT via Interagency Collaboration + SBIR + PPP	Augment
High-Power Exploration NEP	100 kWe HET, MPD, VASIMR, etc.	Industry Led Development/Qual via STRG + SBIR + PPP (i.e., Beyond NextSTEP)	Augment
ESPA-Class High-ΔV SEP	0.5-1 kWe (nominal) EP String	Industry Led Development/Qualification/Demo via SST/GCD PPP	Augment
Extreme Cold Environment CP	Baseline MON25/MMH TALOS	Sustain Execution & Commitment to PPP CLPS Delivery	Sustain
	Deep Space Variant TALOS	Commit to Industry Led Development/Qualification via PPP	Augment
Green Propellant CP	Reduced Cost / Expanded Thrust Range	Facilitate Infusion & Industry Led Development via SBIR/STTR + PPP + Incentives	Sustain
Unlimited ΔV Platforms PLP	Flight Demonstrated Solar Sail Technology	Monitor Solar Cruiser + Supplemental Tech Dev + SBIR/STTR + Early-Stage R&D	Sustain
RDRE CP	Transformative CP Performance	Sustain Early-Stage R&D & Transition to FY23 Mid-TRL Prototype Development	Augment
Flagship NEP	Transformative Robotic Science NEP	Evaluate/Facilitate FSP/Dynamic-RPS/LCF NEP System Integration & Maturation	Augment
Interstellar Probe Near Sun STP	Transformative Near Sun STP Capability	Sustain Early-Stage R&D & Transition to FY23 Mid-TRL Prototype Development	Augment
Fusion/AEP Concepts	Transformative Fusion/AEP Capability	Establish Comprehensive Nuclear Fusion/AEP Early-Stage R&D Portfolio	Augment

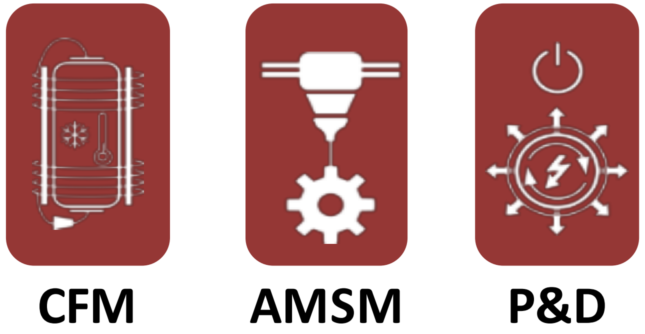
ADVANCED PROPULSION TECHNOLOGY DOMAIN

Taxonomy & Acronym Glossary

PROPULSION TECHNOLOGIES



CROSS-CUTTING SUPPORT TECHNOLOGIES



ACRONYMS

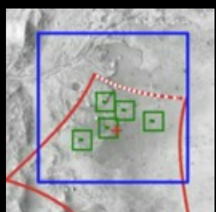
AEP – Advanced Energetic Propulsion
ACO – Announcement of Collaborative Opportunity
ACS – Attitude Control System
AMSM – Advanced Materials, Structures & Manufacturing
AU – Astronomical Units
BUK – Soviet Era Fast Fission Space Reactor (Derived from Bouk → “Beech Tree”)
CP – Chemical Propulsion
c – Speed of Light
CFM – Cryogenic Fluid Management
CLPS – Commercial Lunar Payload Services
EML1 – Earth Moon Lagrange Point 1
Enceladus – Icy Moon of Saturn
EP – Electric Propulsion
ESPA – Evolved Secondary Payload Adaptor
FSP – Fission Surface Power
GCD – Games Changing Development (Program)
GEO – Geo Synchronous Orbit
GIT – Gridded Ion Thruster
GPIM – Green Propulsion Infusion Mission
GTO – Geo Transfer Orbit
HET – Hall Effect Thruster
HLS – Human Landing System
IRAD – Internal R&D
ISM – Interstellar Medium
Ispvac – Vacuum Specific Impulse
LCF – Lattice Confined Fusion
LEO – Low Earth Orbit
LLO – Low Lunar Orbit
LOX – Liquid Oxygen
LY – Light Year
MMH – Mono-Methyl Hydrazine
MON – Mixed Oxides of Nitrogen
MPD – Magneto Plasma Dynamic (Thruster)
MPS – Main Propulsion System
NASA – National Aeronautics and Space Administration
NEA – Near Earth Asteroid
NEO – Near Earth Object
NEP – Nuclear Electric Propulsion
NEXT – Next Evolutionary Xenon Thruster
NRHO – Near Rectilinear Halo Orbit
NTP – Nuclear Thermal Propulsion
PLP – Propellant-Less Propulsion
PPE – Propulsion & Power Element (Foundational Gateway)
PPP – Public Private Partnership
PPU – Power Processing Unit
P&D – Power & Distribution
R&D – Research & Development
RCS – Reaction Control System
RDRE – Rotating Detonation Rocket Engine
RPS – Radioisotope Power System
SBIR – Small Business Innovation Research (Program)
S/C – Spacecraft
SEP – Solar Electric Propulsion
SIMPLEx – Small Innovative Missions for Planetary Exploration
SMD – Science Mission Directorate
SOA – State of Art
SNAP-10A – System for Nuclear Auxiliary Power
SNP – Space Nuclear Propulsion (Project)
SP-100 – Space Reactor Prototype
SST – Small Spacecraft Technology (Program)
STP – Solar Thermal Propulsion
STRG – Space Technology Research Grants
STTR – Small Business Technology Transfer
TALOS – Thruster Advancement for Low Temperature Operations in Space
TDM – Technology Demonstration Mission (Program)
TOPAZ – Soviet Era Thermal Fission Space Reactor
TP – Tipping Point
TRL – Technology Readiness Level
T/W – Thrust-to-Weight (ratio)
VASIMR – Variable Specific impulse Magnetoplasma Rocket
ZBO – Zero Boil Off
α – System Specific Mass (kg/kW)
ΔV – Spacecraft Velocity Change

LAND: Precision Landing and Hazard Avoidance
NASA Space Technology Mission Directorate
August 2022

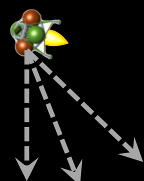
STMD welcomes feedback on this presentation
See 80HQTR22ZOA2L_EXP_LND at nspires.nasaprs.com for how to provide feedback
If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

LAND: Technologies to Precisely Land Payloads and Avoid Landing Hazards

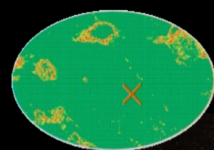
Developing entry, descent and landing technology to enhance and enable small spacecraft to Flagship-class missions across the solar system



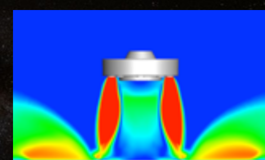
Terrain Relative Navigation



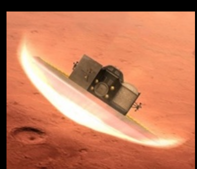
Ultra-Precise Velocity & Range



High-Resolution Surface Hazard Mapping

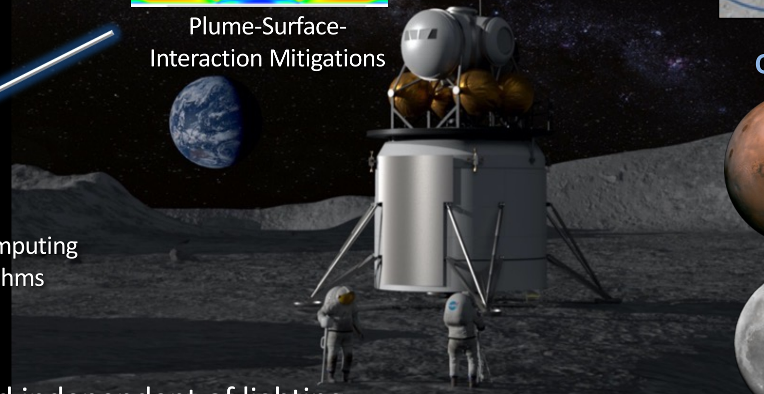


Plume-Surface-Interaction Mitigations

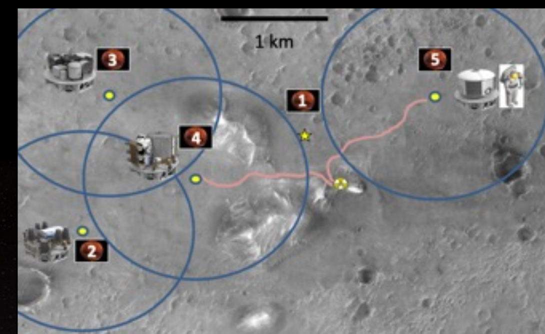


Highly-Controllable Entry/Deorbit Systems

Dedicated Computing and Algorithms



Aggregated and Sustainable Sites on the Moon and Mars



Capabilities evolvable for many solar-system destinations

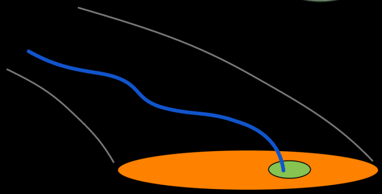
<u>Enable</u> anytime landings in treacherous terrains and independent of lighting
<u>Reduce the risk</u> of the landing for human and robotic missions to many destinations
<u>Reduce operations time</u> for a rover or human to reach an interesting site
<u>Aggregate resources</u> in one surface region for missions requiring multiple landings

Landing Precision: Description of Envisioned Future

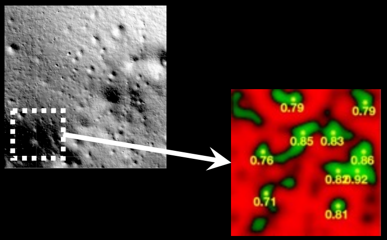
Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

EDL: Entry, Descent and Landing (solar bodies with atmospheres) **DDL: Deorbit, Descent and Landing** (airless solar bodies)
PL&HA: Precision Landing & Hazard Avoidance (general term for precise safe landing capabilities)

- **What are some of the challenges?**
  - Precise and safe landing is not yet possible away from Earth
  - Human & robotic PL&HA differs – **no one-size-fits-all** for all missions but capabilities are evolvable
  - Human-class missions currently target 50-100m precision, whereas some robotic-class missions target 10-50m precision
  - Anytime landing requires functionality independent of surface lighting conditions

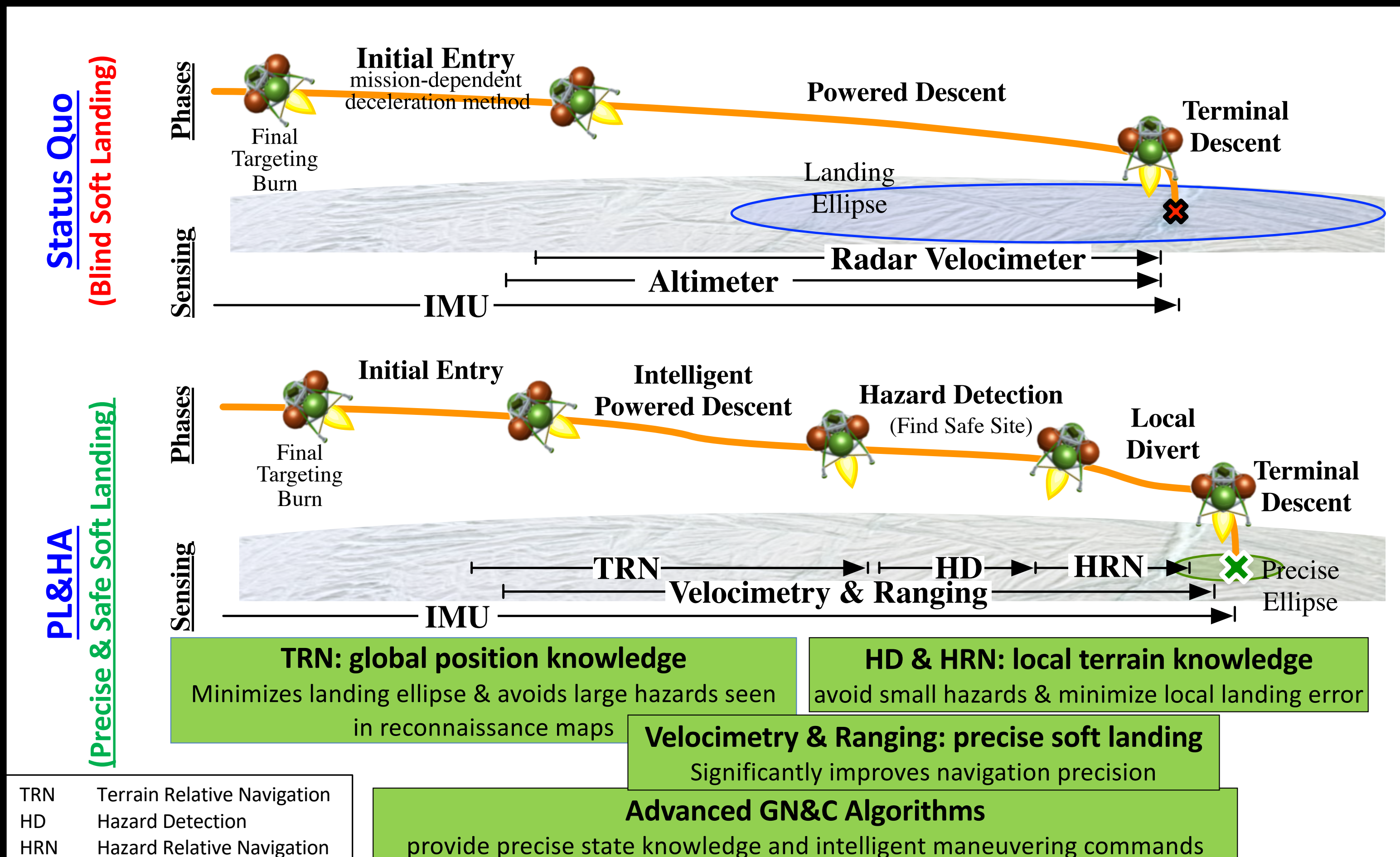


- **Description of Capability targets**
  - Highly-controllable EDL/DDL systems (hardware and algorithms) increase entry & descent maneuverability to facilitate fuel-efficiency and significant landing-ellipse minimization
  - Terrain relative navigation (TRN) facilitates propulsive/aero maneuvers to minimize landing ellipses and avoid large surface hazards identified in reconnaissance maps – global navigation without GPS
  - Precise velocity/range sensing facilitates soft landing and improves EDL/DDL navigation precision (current sensors are high size/mass/power, plus have high component/system-integration costs)
  - High-resolution terrain mapping during descent and landing facilitates hazard detection (HD) and avoidance of surface features not identifiable within reconnaissance maps – can also improve TRN maps in real time
  - Plume-Surface Interaction (PSI) mitigations facilitate improved landing sensing for soft, precise touchdown and minimize debris risks to the lander and other aggregated surface assets
  - Dedicated PL&HA computing minimizes processing-overload risks to primary flight computer during the critical EDL/DDL phase



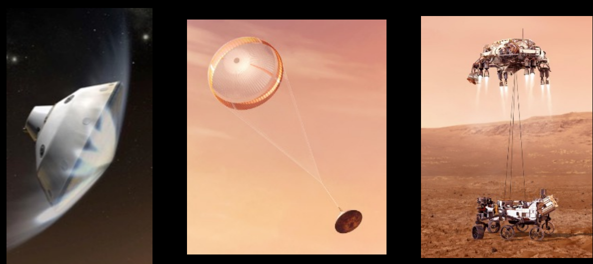
Landing Precision: Status Quo Vs. PL&HA

Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

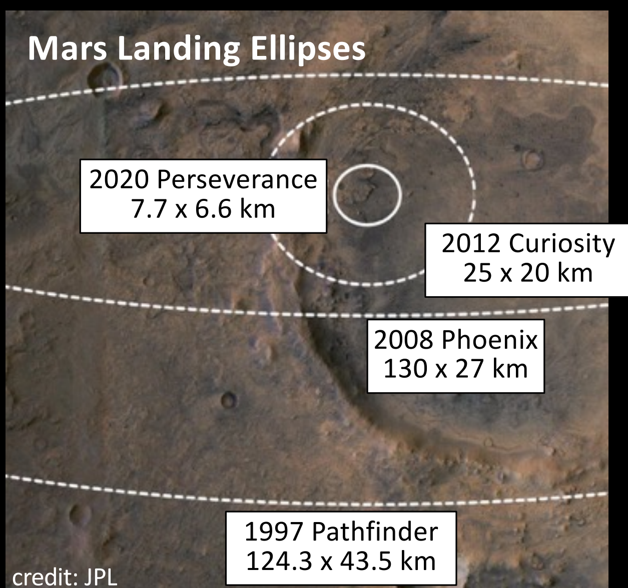


Landing Precision: State of the Art (SOA)

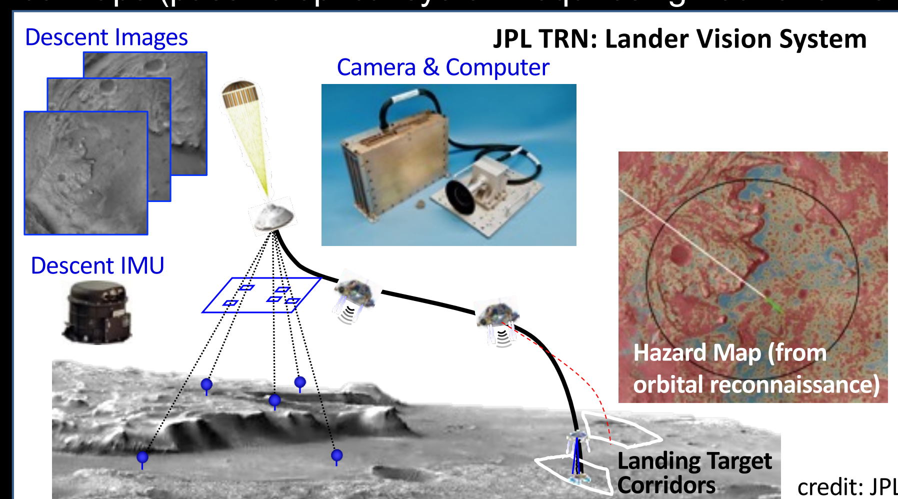
Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards



credits: JPL



- Mars 2020 Mission successfully landed the Perseverance rover within a 7.7 x 6.6 km landing ellipse on February 18, 2021
- EDL system: Viking-style entry body, parachute-deployment range trigger, Apollo-based entry guidance (bank-angle reversal maneuvers), camera-based TRN (JPL Lander Vision System), and JPL Doppler radar (velocity and range)
- JPL TRN fuses camera images and IMU data for precise position localization relative to a reconnaissance map → enabled landing at a location identified as safe within reconnaissance maps (passive optical system requires lighted terrain on descent)

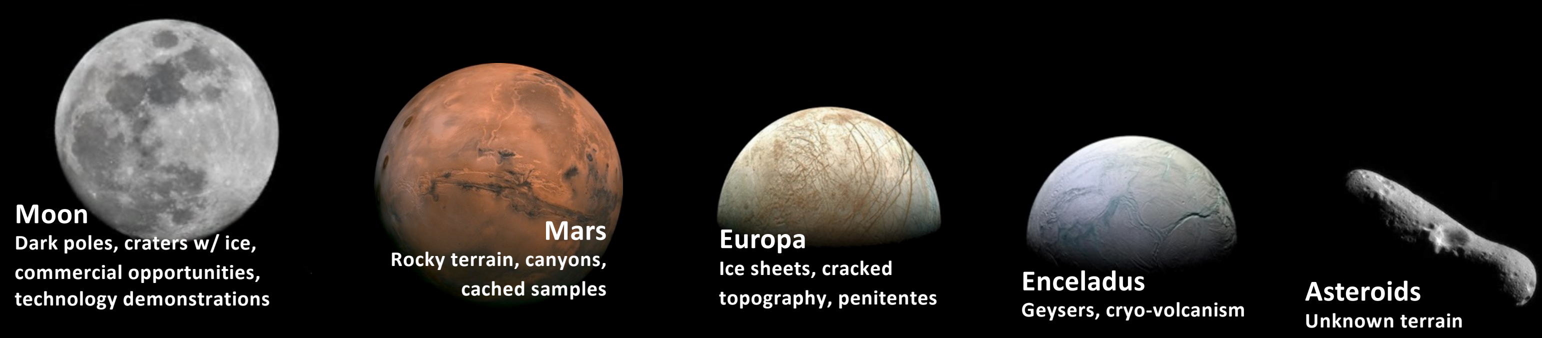


Note on TRN SOA: multiple commercial, passive-optical TRN systems are in development with planned demos onboard two different 2022 robotic lunar landers

Landing Precision: Development Strategy

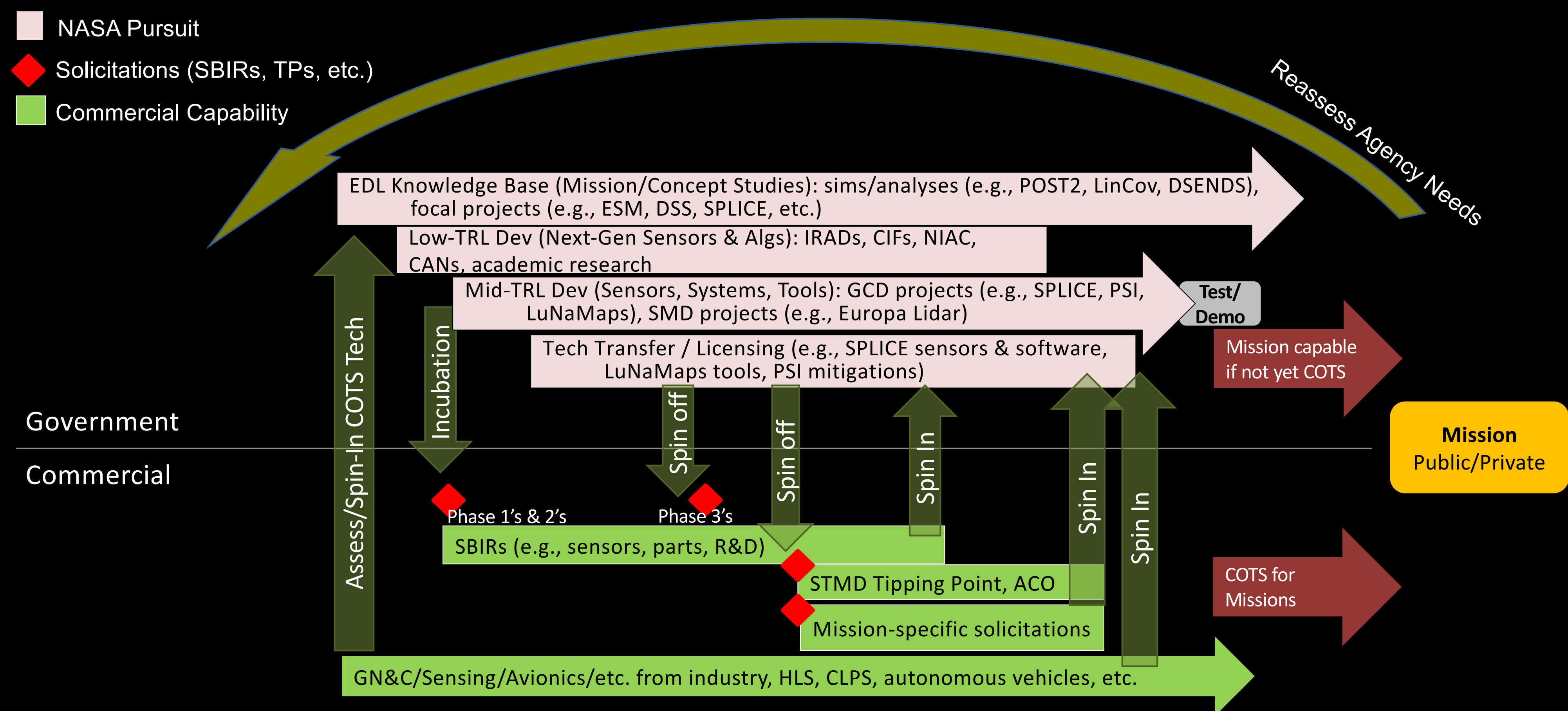
Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

- **Overarching Goal**
  - Develop, infuse, and commercialize technologies applicable to robotic and human landers that become part of the future suite of off-the-shelf GN&C (Guidance/Navigation/Control) capabilities for precise safe landing
- **Overview of Approach**
  - Sustain an EDL/DDL knowledge base and simulation to capture near-term and future human and robotic mission needs and the evolving commercial and government PL&HA capabilities
  - Prioritize development and infusion of cross-cutting EDL/DDL systems, sensors, avionics, and algorithms applicable to human and robotic missions
  - Leverage multiple test paradigms (lab, flight, suborbital, space) to accelerate TRL advancement and infusion
  - Pursue technology transfer, public-private partnerships, commercial spin-offs and spin-ins to promote closure of EDL/DDL capability gaps and the transition-into/leveraging-of commercial off-the-shelf (COTS) solutions



Landing Precision: Strategy Visualization with Focal Approaches

Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

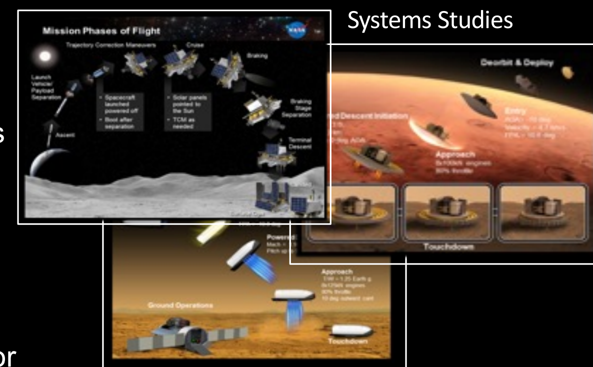


Landing Precision: Approach to Develop the Capabilities

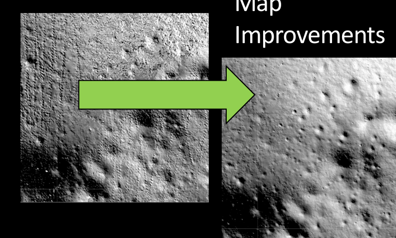
Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

Leverage focal agency projects, solicitations and partnerships to

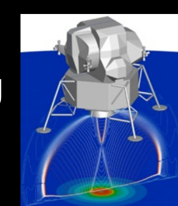
- **Evaluate highly-controllable EDL/DDL systems for future implementation**
  - study landing-precision improvements with novel aerodynamic bodies, new control architectures (e.g., dual-axis, direct-force) and GN&C advances
  - *closely coupled to separate EDL strategy package on "20t" landing capability*
- **Develop PL&HA hardware for anytime landing: TRN, HD, Velocimetry**
  - within NASA, initially pursue lidar development and commercialization to provide
    - active terrain sensing to enable TRN and HD during descent/landing over dark, shadowed, or illuminated surfaces
    - establish a baseline capability upon which to build future PL&HA approaches
  - solicit new sensor capabilities to facilitate technology transfer of NASA investments and to spin in industry advancements (e.g., advancements in radar, lidar, etc.)
  - following baseline approach, pursue future multi-function sensors, multi-capability systems based on lidar, radar or other active-sensing paradigms
  - pursue dedicated PL&HA computers for sensor fusion and algorithms processing in parallel with advancements in high performance spaceflight computing
- **Enable algorithms & processes supporting precise navigation & safe landing**
  - PSI modeling and validation via instrumentation to develop landing-system mitigations during terminal descent and touchdown
  - mapping tools/processes to improve TRN maps, surface ops, & mission planning
  - hazard detection and advanced guidance algorithms for landing-site identification and efficient descent/divert maneuvering



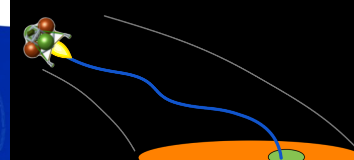
Systems Studies



Map Improvements



Plume Surface Interactions

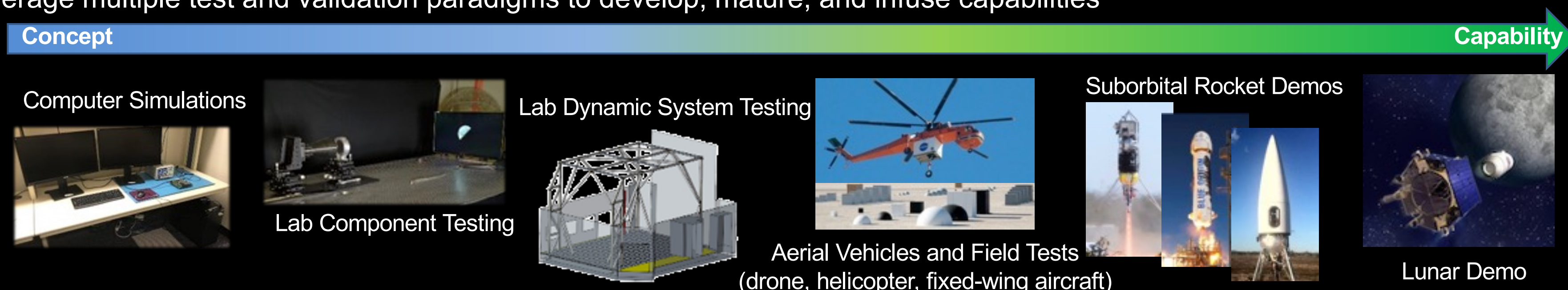


Advanced PL&HA Algorithms

Landing Precision: Approach to Mature & Transition the Capabilities

Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

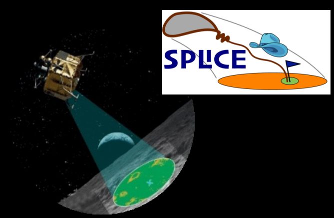
- Leverage multiple test and validation paradigms to develop, mature, and infuse capabilities

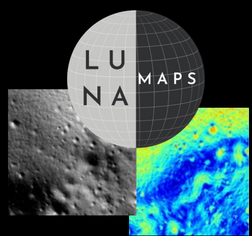


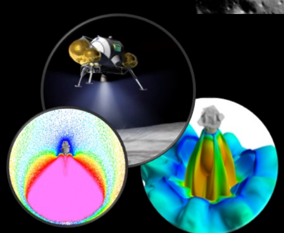
- Incubate public/private partnerships and technology commercialization/dissemination for TRL maturation and to maximize infusion/availability to government and commercial spaceflight missions
  - **Academic partnerships** (cooperative agreements, ECF/ESI, NSTGRO) continue to foster new innovations and incubate low-TRL concepts, plus mature the next generation of technologists and engineers
  - **SBIR/STTR solicitations** have been and will continue to develop PL&HA component supply chains and commercial solutions for current and next-generation sensors, including incubate and mature new low-TRL innovations
  - **Tipping Point solicitations** have promoted and will continue PL&HA commercialization and infusion
    - 2018 Tipping Point has promoted multiple commercial TRN implementations
    - 2020 Tipping Point is developing a next-generation suborbital capability for closed-loop GN&C/PL&HA testing
    - Discussing future solicitations for commercial Hazard Detection and integrated PL&HA systems
  - **Flight Opportunities 2022 Nighttime Precision Landing Challenge** will help promote commercial development of terrain mapping sensors for hazard detection – targeting general field of active sensors (lidar, radar, IR, etc.)
  - Open **NASA/industry workshops** are promoting ideas incubation for public-private partnerships and infusion
    - 2021 Lunar Mapping Workshop discussed mapping tools/processes, capabilities, and needs

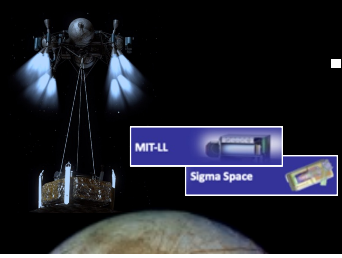
Landing Precision: NASA Projects Implementing the Approach

Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards









- **STMD/GCD SPLICE (Safe & Precise Landing – Integrated Capabilities Evolution) Project**
  - Developing and field testing lidar for active terrain sensing during descent/landing over dark, shadowed, or illuminated surfaces
  - Implementing dedicated computing for sensor fusion and advanced algorithms processing in parallel with advancements in the NASA High Performance Spaceflight Computing (HPSC) initiative
  - Commercializing technologies: Phase 3 SBIR for NDL commercialization, flight software going into NASA Software Release System, partnering with CLPS/HLS companies on TRN dev and HD infusion/commercialization
- **STMD/GCD LuNaMaps (Lunar Navigation Maps) Project**
  - Developing mapping tools and processes to provide a capability critical to future lunar missions with feedforward to Mars and beyond (Open NASA/industry workshop occurred in 2021 to discuss tools/processes/needs)
  - Will generate navigation-quality lunar maps from orbital reconnaissance imagery for onboard uses
  - Will enhance maps with analog field data & synthetic surface features for ground-based algorithms assessments
- **STMD/GCD PSI (Plume Surface Interaction) Project**
  - Implementing simulation models and tools to predict PSI environments and enable smart design and risk analysis of EDL architectures
  - Developing instrumentation for ground testing (at relevant scales), collecting flight data, predicting PSI effects, and validating models → goal is to enable future PSI mitigation strategies
- **SMD** Europa Lander Concept: **ILS (Intelligent Lander System)**
  - Developing integrated TRN, Hazard Detection & Velocimetry capabilities for the unique environment of Europa
  - Technologies likely have broader mission applicability beyond Europa
  - Lidar-specific investments have potential for TRN and HD applications in other missions

Landing Precision: Transition Status of NASA Investments (SPLICE)

Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

STMD/GCD SPLICE (Safe & Precise Landing – Integrated Capabilities Evolution) Project – Developing and Commercializing multiple sensors, algorithms, and a computing architecture for a broadly-applicable PL&HA baseline

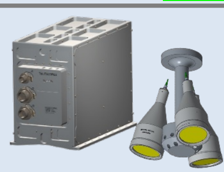
(Commercialization/Licensing Statuses are Highlighted)

Sensors/Scanners

Passive TRN
(Imaging & Inertial)

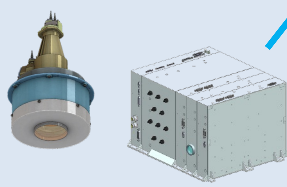
Camera + IMU (both COTS)

Ultra-Precise Velocity & Range



Doppler Lidar
(Transitioning to COTS – Phase 3 SBIR)

Surface Hazard Imaging
(Map Generation)



Scan-Array Lidar
(Early licensing/infusion discussions)

Dedicated Computing

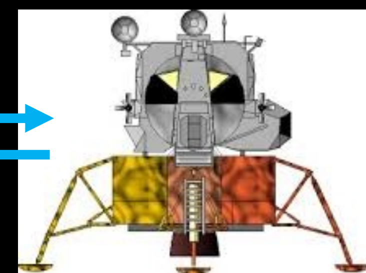
Precise EDL Navigation
PL&HA Guidance
Safe Site

Pre-EDL Navigation
Master Clock

Descent & Landing Computer
(Early component licensing discussions)

Software Functions
(Licensable or Listable in NASA SW Catalog)
TRN: Image Processing and Map Comparisons
Hazard Detection (Safe Site ID)
PL&HA Guidance
PL&HA Navigation

Architecture
SpaceVPX Architecture (Industry Standard)
HPSC-Surrogate (COTS + rad-tolerance provisions)
and Kintex FPGA (COTS) for I/O & co-processing

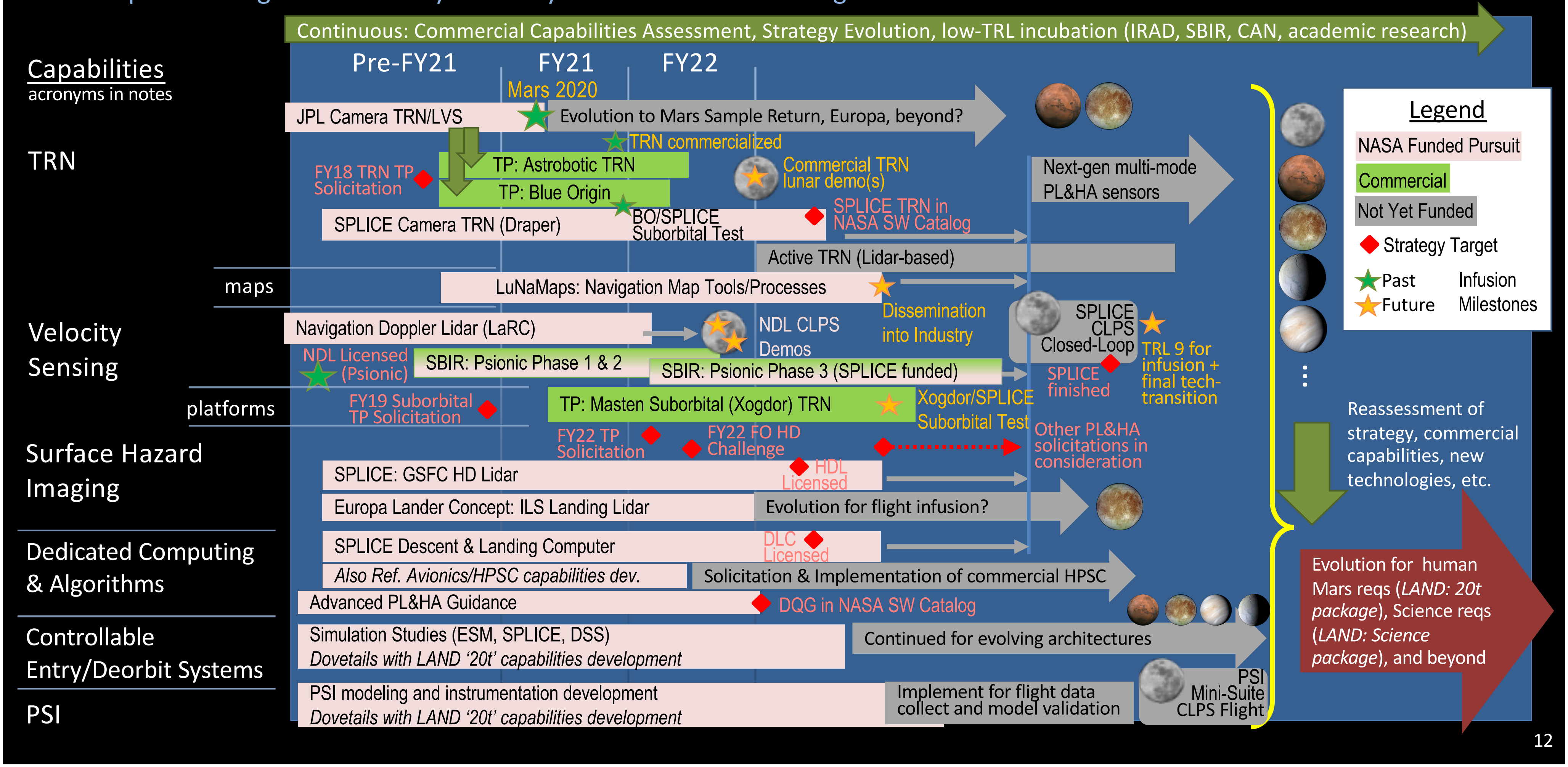


Lander & Primary Computer

EDL Functions
Vehicle Control
Non-PL&HA Guidance & Nav

Landing Precision: Development, Evolution & Infusion Roadmap

Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards



Landing Precision: Highest-Priority Technology Gaps & the Closure Path

Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

Current project investments are poised to address the highest-priority gaps with safe and precise landing

Current Investment (on closure path) | **Current Investment (follow through)** | **Unfunded (Future Ask)**

LuNaMaps Project

- **Gap: High-Resolution, Continuous Lunar Maps for Precise Landing**

PSI Project

- **Gap: Validated Prediction of Plume Surface Interaction (PSI) for Vehicles Landing on the Moon**
- **Gap: Flight Instrumentation to Acquire Plume Surface Interaction Performance Data**

SPLICE Project

- **Gap: Navigation and guidance technologies that provide precise knowledge and maneuver planning for Lunar missions**
- **Gap: Precision Landing and Hazard Avoidance Test Platform** (on closure path with Masten Tipping Point award for Xogdor platform development)
- **Gap: Dedicated high-performance computing for precise landing and hazard avoidance algorithms and sensor fusion** (tied to Avionics Gap for HPSC – High Performance Spaceflight Computing)
- **Gap: Real-time mapping technologies for active terrain relative navigation (TRN) and hazard detection and avoidance during lunar descent toward landing** (active TRN is increasing in priority for lunar South Pole landings)

Landing Precision: Logical Next-Steps

Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

Current Investment | Maintain | Future Need

Summary of current approach

- SPLICE: developing sensors, computing and software for a baseline integrated capability for precise and safe landing
- LuNaMaps: developing and disseminating lunar mapping tools/processes for use by government and industry with lunar landing
- Europa Lander Concept Study: developing EDL technologies for the unique environment of Europa with potential for broader infusion
- Modeling and Architecture Studies: high-fidelity EDL simulations are continuing mission concept studies to evaluate highly-controllable EDL systems, model PSI, and assess PL&HA technologies that enable the closure of EDL gaps and the strategy evolution
- Commercialization: solicitations for public-private partnerships, SBIRs, Tipping Points, etc. are accelerating technology commercialization (spin off and spin in) plus infusion into CLPS missions and non-space applications (consider incentivizing certain EDL/PL&HA technologies for various mission classes)

What are the next steps?

- Maintain concept studies, low-TRL investments, EDL-focused SBIR solicitations, STRG/academic awards, public-private partnerships, and commercialization to identify new technologies and evolve the development strategy
- Conduct planned demonstration tests to validate models, raise TRL, and mitigate infusion risks for EDL technologies
  - Conduct testing and then disseminate PSI-mitigation approaches for landing systems
  - Conduct a lunar demonstration of the SPLICE technologies being actively used (in closed loop) within a landing system
- Continue development toward future generations of EDL and Avionics Technologies
  - HPSC: continue development & commercialize → radiation-hard, multicore processing is critical to future envisioned missions
  - Europa Lidar: monitor advancement of systems for commercialization and broader-infusion prospects
  - Active TRN: develop lidar-based TRN for anytime, anywhere global access (e.g., EDL/DDL for dark/shadowed lunar regions)
  - Pursue multi-mode EDL/PL&HA sensors that further advance and miniaturize integrated capabilities

Landing Precision: Summary

Develop Technologies to Land Payloads Within 50 m Accuracy and Avoid Landing Hazards

- **Strategy**
  - Develop safe and precise landing capabilities that increase surface accessibility for anytime and anywhere global access to locations that pose significant landing risk to missions
- **Goal**
  - Infuse and commercialize technologies to become part of the future suite of COTS (Commercial Off-The-Shelf) GN&C capabilities for human and robotic landing missions
- **Approach**
  - Prioritize development of cross-cutting systems, sensors, avionics, and algorithms
  - Sustain EDL knowledge base and simulation to capture and assess human and robotic mission needs
  - Implement via NASA centers, academic partnerships, solicitations, public-private partnerships, etc.
  - Leverage the NASA technology transfer process, publishing, licensing, etc. to transition technologies to COTS

Acronyms for Precision Landing Technologies

Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

- CAN: Cooperative Agreement Notice
- CLPS: Commercial Lunar Payload Services
- DDL: Deorbit, Descent and Landing
- DLC: Descent and Landing Computer
- DSS: Descent Systems Study (project)
- DQG: Dual Quaternion Guidance
- ECF: Early Career Faculty
- EDL: Entry, Descent and Landing
- ESI: Early Stage Innovation
- ESM: Entry Systems Modeling (project)
- HD: Hazard Detection
- HDL: Hazard Detection Lidar
- HPSC: High Performance Spaceflight Computing
- IRAD: Internal Research and Development
- LVS: Lander Vision System
- NDL: Navigation Doppler Lidar
- NSTGRO: NASA Space Technology Graduate Research Opportunity
- PL&HA: Precision Landing and Hazard Avoidance
- PSI: Plume-Surface Interaction
- SBIR: Small Business Innovative Research
- SW: Software
- TP: Tipping Point (commercial partnership projects)
- TRN: Terrain Relative Navigation

EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

LAND: Entry, Descent, and Landing to Enable Planetary Science Missions
NASA Space Technology Mission Directorate
August 2022

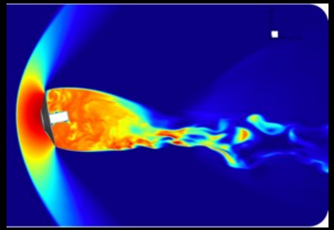
STMD welcomes feedback on this presentation
See 80HQTR22ZOA2L_EXP_LND at nspires.nasaprs.com for how to provide feedback
If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

LAND: Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies

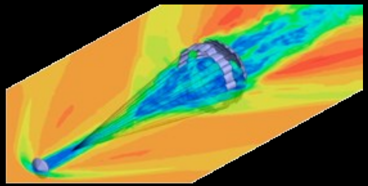
Developing atmospheric entry technology to enhance and enable small spacecraft to Flagship-class missions across the solar system

Entry Systems Modeling & Testing

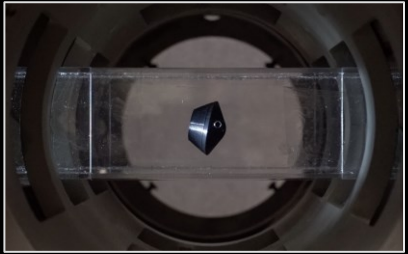
Reducing entry system mass and risk by developing advanced, validated models



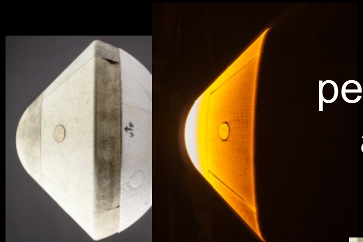
"DESKTOP WIND TUNNEL"



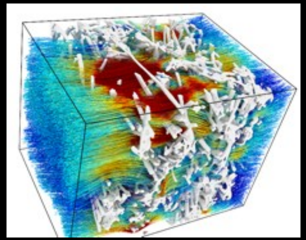
PARACHUTE MODELING



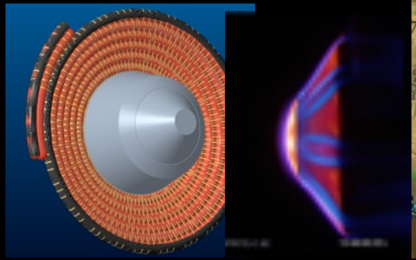
MAGNETIC SUSPENSION WIND TUNNEL



CONFORMAL MATERIALS



IN-DEPTH MATERIAL RESPONSE



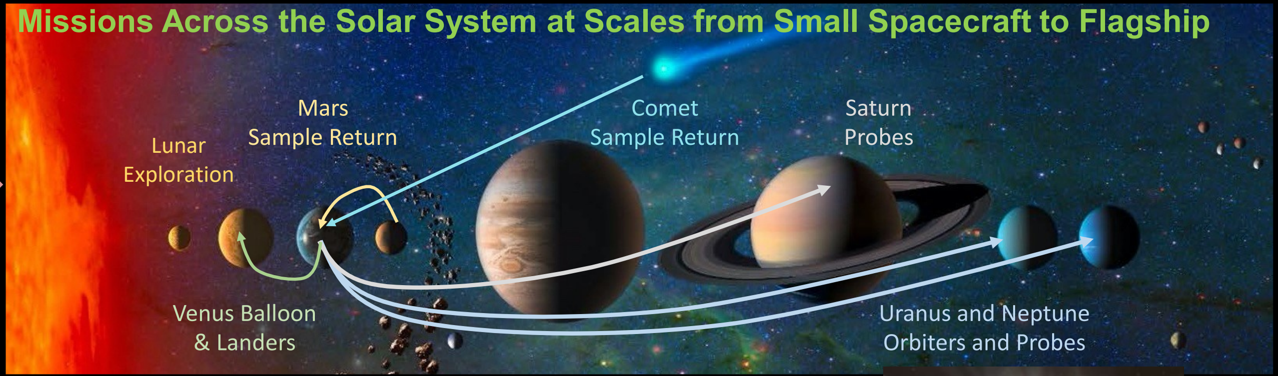
DEPLOYABLE DECELERATORS

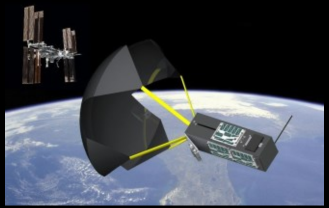
3D WOVEN HEATSHIELDS

to enable

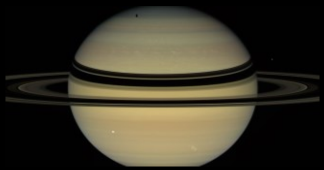
Hardware Development

Maturing new materials and systems to fill performance gaps and enable new missions



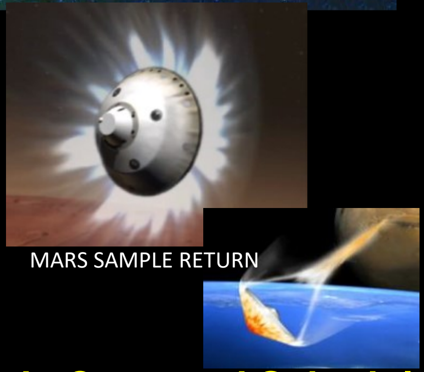


PRECISION DEORBIT



SATURN PROBE

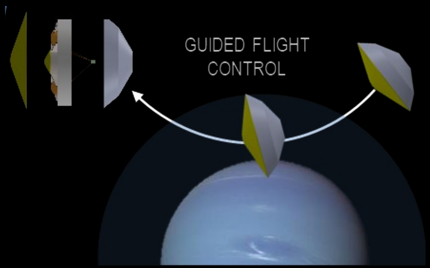
TITAN PINPOINT LANDING



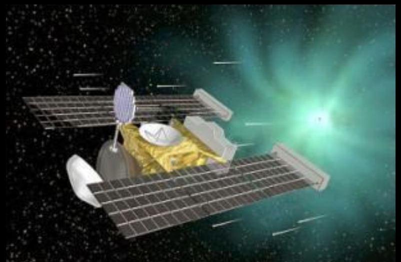
MARS SAMPLE RETURN

Increasing Science Return, Decreasing Risk, Cost, and Schedule

ICY MOON PRECISE LANDING



ICE GIANT AEROCAPTURE



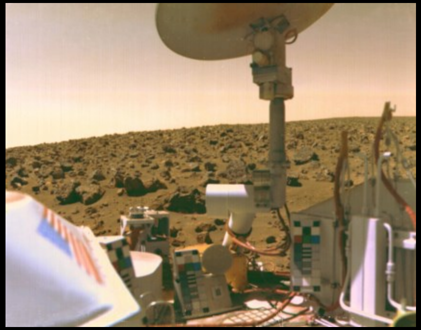
HIGH-SPEED SAMPLE RETURN

Not all activities depicted are currently funded or approved. Depicts "notional future" to guide technology vision.

State-of-the-Art: EDL for Planetary Science Missions

Mission	Destination	EDL Date(s)	Capability Demonstrated/SOA Established
Apollo	Earth return	1967-1972	Packed Avcoat TPS, precision guidance
Viking	Mars	1976	Sphere-cone aeroshell, supersonic parachute, pallet
Pioneer Venus	Venus	1978	Carbon Phenolic TPS (SOA no longer available)
Galileo	Jupiter	1995	Carbon Phenolic TPS, ablation sensor (SOA no longer available)
Pathfinder	Mars	1997	Landing Airbags
Genesis	Earth Return	2004	Carbon-Carbon TPS
MER	Mars	2004	Angular rate control
Stardust	Earth Return	2006	One-piece PICA TPS; fastest Earth entry
Phoenix	Mars	2007	Viking-style pallet lander (no new features)
MSL	Mars	2012	Hypersonic guidance, Sky-crane, MEDLI
InSight	Mars	2018	Viking-style pallet lander (no new features)
Mars2020	Mars	2021	TRN, EDL cameras, MEDLI2
Orion (11 km/s)	Earth return	*2022*	Block Avcoat TPS, precision guidance
OSIRIS-REx	Earth Return	2023	Stardust entry system (no new features)
MSR SRL	Mars	2028-2029	Highest Mars entry/landed mass, largest parachute
MSR-EES	Earth Return	2031	Class V reliability required; passive capsule w/3MDCP
DAVINCI	Venus	(2032)	Genesis-type aeroshell/TPS at Venus
Dragonfly	Titan	2034	Titan EDL; thermal management over long descent

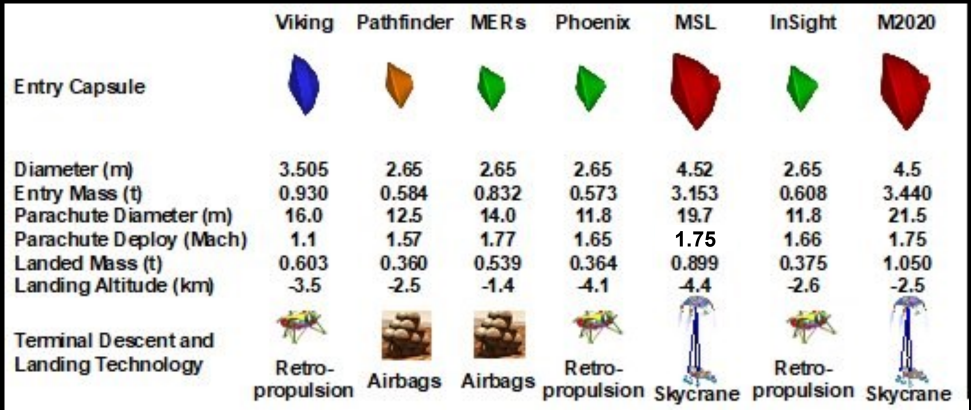
Viking 2



Galileo

Stardust

Mars Program



	Viking	Pathfinder	MERs	Phoenix	MSL	InSight	M2020
Entry Capsule							
Diameter (m)	3.505	2.65	2.65	2.65	4.52	2.65	4.5
Entry Mass (t)	0.930	0.584	0.832	0.573	3.153	0.608	3.440
Parachute Diameter (m)	16.0	12.5	14.0	11.8	19.7	11.8	21.5
Parachute Deploy (Mach)	1.1	1.57	1.77	1.65	1.75	1.66	1.75
Landed Mass (t)	0.603	0.360	0.539	0.364	0.899	0.375	1.050
Landing Altitude (km)	-3.5	-2.5	-1.4	-4.1	-4.4	-2.6	-2.5
Terminal Descent and Landing Technology	Retro-propulsion	Airbags	Airbags	Retro-propulsion	Skycrane	Retro-propulsion	Skycrane

- EDL design & technologies are specialized for each destination/mission
- Newer missions tend to be more complex; push existing technologies to or beyond their limits
- Conservativism used to minimize risk (to accommodate large uncertainties), but also limits performance

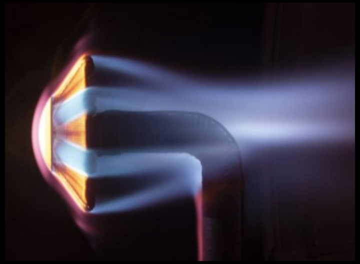
Purple = Future EDL, in development

Planetary EDL Subsystem SOA

TPS

- Investments over the past ~15 years have produced materials that span the expected planetary mission space for the next 1-2 decades

HEEET

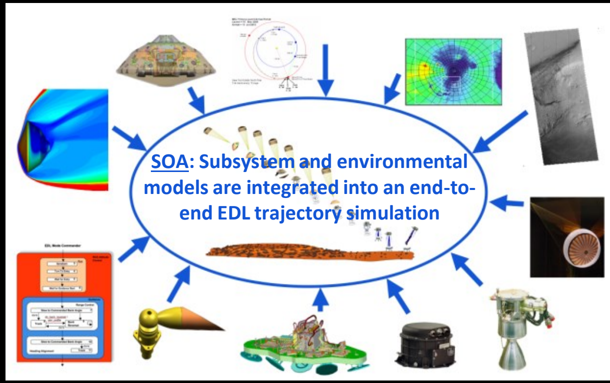


ADEPT/Spiderweave

PICA

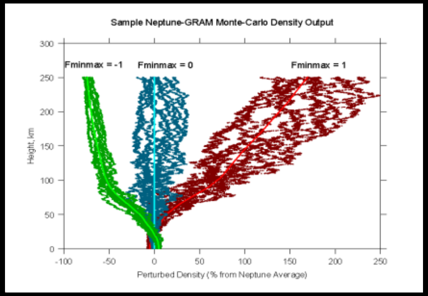
GN&C Modeling

- Baseline models under development for expected planetary mission space; Quantified uncertainty forthcoming



Atmosphere Models

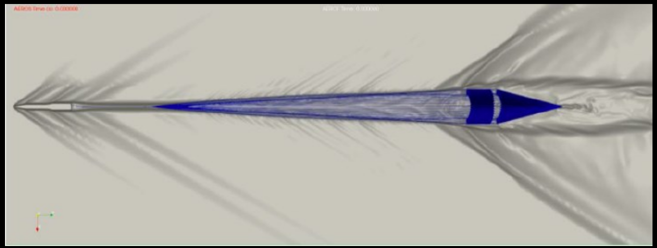
- GRAM update for PSD destinations of interest nearing completion; New data inclusion forthcoming



Parachutes

- Mars2020 flew largest supersonic chute to date; MSR plans even larger. Modeling SOA lags hardware/testing, but is under active development

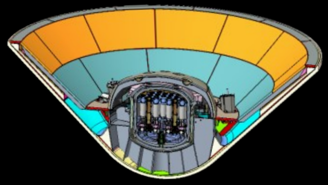
M2020 Parachute



Aero/FS Simulation of ASPIRE

Architecture/System

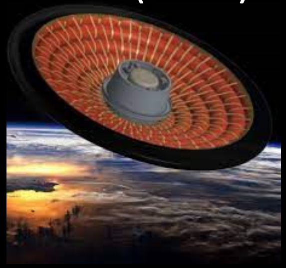
- EES designed for high reliability. ADEPT & HIAD provide scalability beyond rigid capsules, SRP provides extensibility beyond parachutes



EES

ADEPT

HIAD (LOFTID)

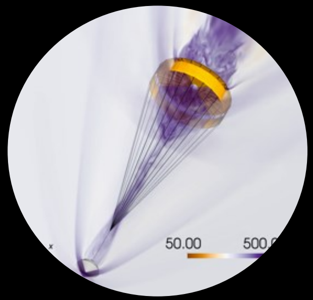


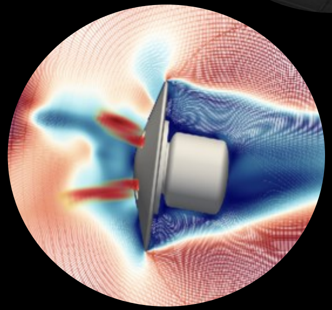
SRP Simulation

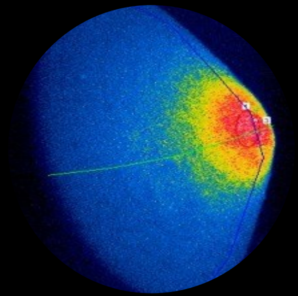
EDL Modeling and Simulation is Critical to Planetary Science

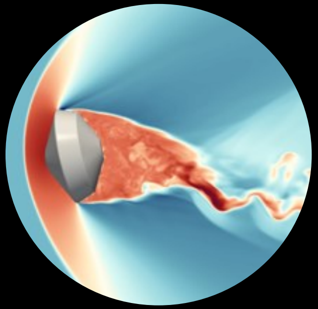
Planetary entries cannot be practically tested end-to-end on Earth; flight performance assessment and certification RELIES on robust EDL Modeling and Simulation capabilities.

- **Models, particularly in aerosciences and material response, have largely undefined uncertainty levels for many problems (limited validation)**
  - Without well-defined uncertainty levels, it is difficult to assess system risk and to trade risk with other subsystems, leading to increased schedule and cost
- **Missions get more ambitious with time**
  - Tighter mass and performance requirements
  - More challenging EDL conditions requires that models evolve or the missions of tomorrow will remain out of our grasp
- **Even reflights benefit from improvement**
  - Reflights are never truly reflights; changing system performance requires new analysis, introduces new constraints
  - ‘New physics’ still rears its head in these disciplines
- **Some of the most challenging problems have the “worst” models**
  - Parachute dynamics, separation dynamics, TPS failure modes, backshell radiation









Focused investment in development and validation of EDL Modeling and Simulation (M&S), *guided by mission challenges*, ensures that NASA is ready to execute the challenging planetary science missions of tomorrow.

Context: Mission Priorities from the 2022 Planetary Decadal Survey
List of Missions that Include Entry, Descent and/or Landing (EDL)

	2022 Decadal Survey Priority	Enabling/Enhancing EDL Capability Advancement
Flagship	Uranus Orbiter and Probe*	Potential Aerocapture for orbiter; atmospheric modeling, aero/aerothermal modeling, mass-efficient entry system
	Enceladus Orbilander*	*Precision landing/hazard avoidance?*
	Europa Lander*	*Hazard detection and avoidance*
	Mercury Lander*	*Precision landing/hazard avoidance?*
	Neptune-Triton Odyssey	Aerocapture for orbiter(?); atmospheric modeling, aero/aerothermal modeling, mass-efficient entry system
	Venus Flagship*	Atmospheric modeling, aero/aerothermal modeling, mass-efficient entry system, precision landing?

New Frontiers 5 (2024 AO)
- Comet Surface Sample Return (CSSR)*
- Lunar South Pole-Aitken Basin Sample Return*
- Ocean Worlds (only Enceladus)
- Saturn Probe*
- Venus In Situ Explorer*
- Io Observer
- Lunar Geophysical Network (LGN)*

New Frontiers 6
- Centaur Orbiter and Lander (CORAL)*
- Ceres Sample Return*
- Comet Surface Sample Return (CSSR)*
- Enceladus Multiple Flyby (EMF)
- Lunar Geophysical Network (LGN)*
- Saturn probe*
- Titan orbiter
- Venus In Situ Explorer (VISE)*

New Frontiers 7

New Frontiers 6 list, plus
- Triton Ocean World Surveyor

**Missions potentially involving EDL*

Reference: https://www.nationalacademies.org/our-work/planetary-science-and-astrobiology-decadal-survey-2023-2032

High-Priority Gaps and Current STMD/SMD Investments

There are 26 identified gaps mapped to the "Planetary EDL" outcome. Highest-priority gaps, as ranked by the EDL System Capability Leadership:

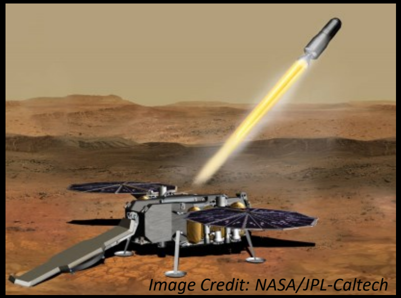
Current/Recent STMD Investments	
▪ Entry Systems Modeling (ESM) Project* ▪ ACCESS STRI (5 yrs, $15M) ▪ ECF and ESI Awards: Modeling, Chutes ▪ Plume Surface Interaction (PSI) Project ▪ Global Reference Atmospheric Models*	**Modeling & Simulation (includes UQ across the breadth of models)** ▪ Validated Aerothermodynamic Prediction for Robotic Mission EDL ▪ Thermal Protection System Performance Modeling & Optimization for Robotic Missions ▪ Validated Static/Dynamic Aerodynamics Prediction from Supersonic to low Subsonic Speed ▪ Validated Wake Models, Including Reaction Control Thruster Effects ▪ Atmospheric Model Development
▪ SPLICE† ▪ MEDLI and MEDLI2 Flight Instruments* ▪ DrEAM Flight Instrumentation* ▪ Parachute Sensors (ECI, SBIR) ▪ SCALPSS*, SCALPSS 1.1 (for PSI)	**Performance Validation** ▪ Integrated, Multi-Function Precision Landing Sensors for Robotic Missions† ▪ EDL Flight Vehicle (Aeroshell) Flight Performance Data for Robotic Missions ▪ Flight Instrumentation to Acquire Parachute Performance Data ▪ Planetary Aerothermodynamics Test Facility
▪ Entry Systems Modeling (ESM) Project* ▪ ACCESS STRI ▪ 3-D Woven TPS (HEEET, 3MDCP) ▪ Multiple SBIR awards	**EDL Hardware Technologies** ▪ High-Reliability Earth Entry Vehicles for Robotic Missions ▪ Supersonic Parachute Systems and Modeling
▪ Exo-Brake ▪ Additively-Manufactured TPS (ECI) ▪ Deployable Decelerators (HIAD, ADEPT)	**Enabling Small Spacecraft Missions** ▪ Small Spacecraft EDL ▪ Small Spacecraft Aerocapture with feed forward to Ice Giant missions

†NOTE: Precision Landing Technologies apply to several missions and are found in the "Land within 50 m" Outcome package.

*Funded/Co-funded by Science Mission Directorate

Enabling the Mars Sample Return Mission

EDL Challenges



Sample Retrieval Lander (SRL)

- Heaviest Mars payload to date
- Required volume may lead to new aerodynamics
- Largest supersonic parachute ever flown
- Precise landing needed, to efficiently recover cache
- Pallet-style lander will see increased PSI effects

Earth Entry System (EES)

- Category V payload → high reliability requirements against containment loss on entry or impact
- Capsule released 3 days before entry (MMOD risk)
- Extreme mass constraints (round trip multiplier)
- G-sensitive core samples

Forward Plan/Approach

- Continue investments in Entry Systems Modeling (ESM) and ACCESS to reduce uncertainties in aerodynamics and aerothermodynamics, integrate material response, quantify risk, reduce entry system mass. Infuse tools and methods to mission.
- Test materials and sensors, continue parachute modeling advances through ESI, ECI projects, and ESM. Collaborate with ASPIRE2 to gather flight data. Infuse models to mission.
- Develop and commercialize precision landing and hazard detection sensors to infuse as needed. *(see Land - 50 m)*
- Conduct Mars-relevant ground tests and advance PSI models. Apply models to mission; quantify uncertainty/risk.
- *****Gather flight data through MEDLI3 and EDL cameras to validate predictions and inform future missions.*

- Continue investments in Entry Systems Modeling (ESM) and ACCESS to reduce uncertainties in aerodynamics and aerothermodynamics, quantify risk, reduce entry system mass. Infuse tools and methods to mission.
- Use 3MDCP TPS material for efficient insulation, robust heat tolerance, and MMOD resilience. Infuse characterization and modeling tools to mission.

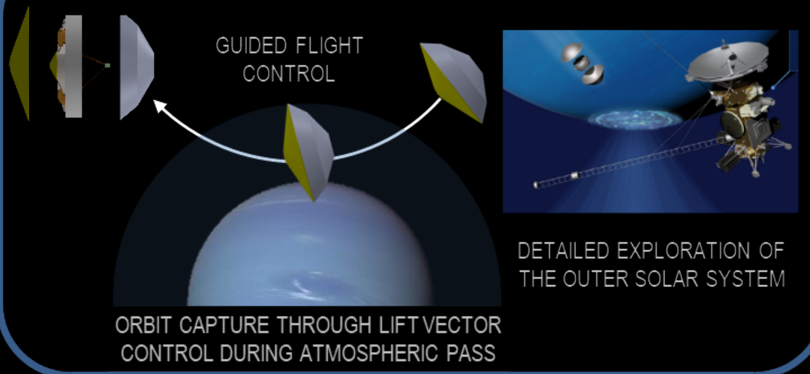
Orange = summary of infusion path

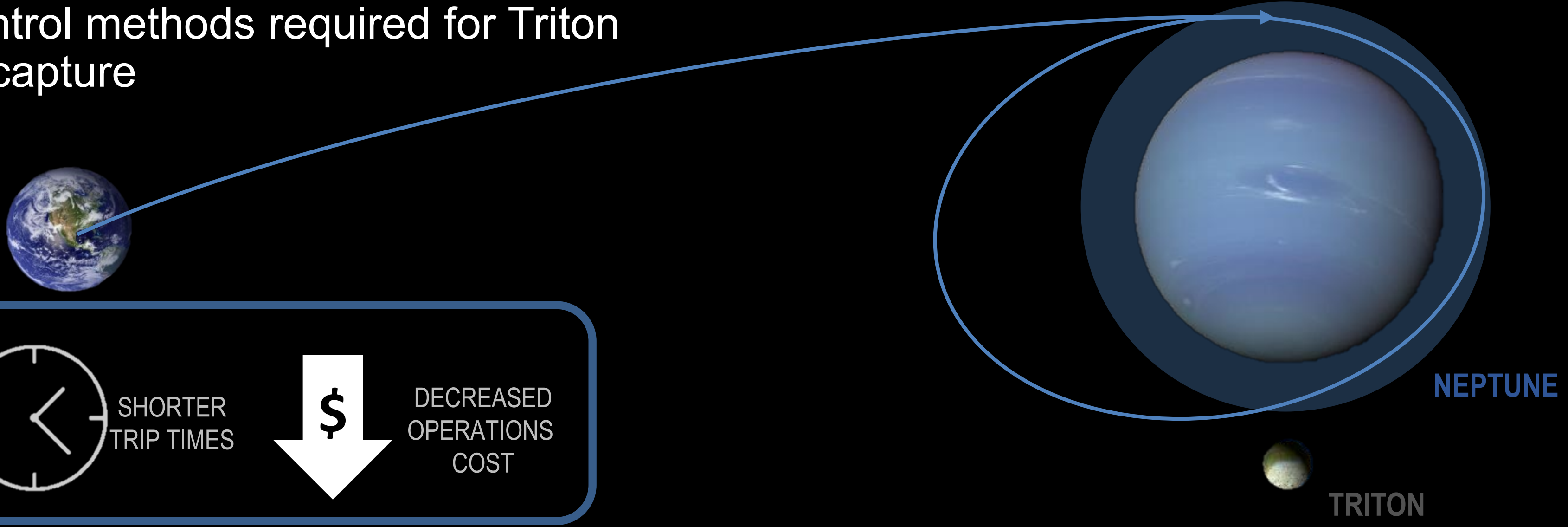
**Does not enable MSR, but inclusion on largest-ever SRL will inform and feed forward to future large-scale missions (see LAND 20 t package)*

Benefits of Aerocapture for Ice Giant Missions

- Missions to Uranus and Neptune are mass-constrained and have cruise times of several years
- An orbiter can AEROCAPTURE and use the planet's atmosphere to remove up to 95% of its arrival velocity, drastically reducing the propellant requirements, shortening the trip time, and/or allowing additional science (such as one or more probes) to be included in the mission.
- Aerocapture has never been performed but employs validated entry system design methods and leverages hypersonic guidance and control demonstrated by Apollo, Orion, MSL, and Mars 2020.
- 3-D woven TPS systems (TRL6) are well-suited for Uranus and Neptune entry speeds (>=29 km/s) and high heat loads of long atmospheric passes
- An Earth-based aerocapture demonstration will reduce perceived risk and mature guidance and control methods required for Triton observations and/or Uranus aerocapture

ICE GIANT AEROCAPTURE: NEPTUNE & TRITON





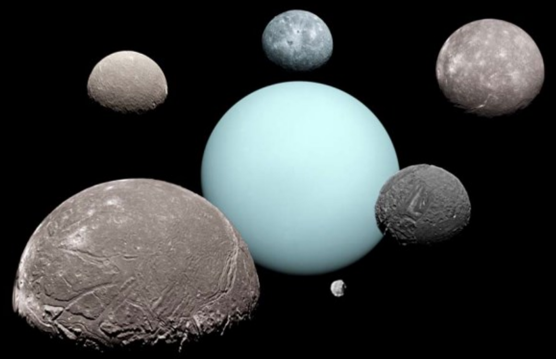
AEROCAPTURE PERFORMANCE BENEFITS:

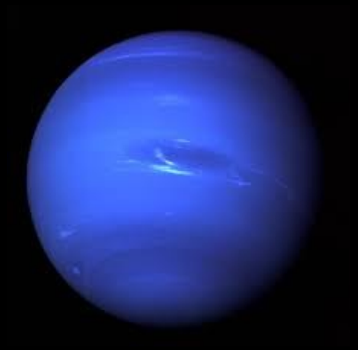
- INCREASED PAYLOAD MASS
- INCREASED SCIENCE
- SHORTER TRIP TIMES
- DECREASED OPERATIONS COST

Enabling Aerocapture for Ice Giant Missions

Challenges

- High entry speed leads to high heat rates
- Long atmospheric pass leads to high heat loads
- Aerothermodynamic uncertainties result from H_2/He atmosphere
- Atmospheric uncertainties are significant
- **Uranus:** Precision approach/maneuvering needed to avoid rings
- **Neptune:** High exit velocity required, for Triton observation orbit





Forward Plan/Approach

- Pursue focused H_2/He investments in Entry Systems Modeling (ESM) and leverage ACCESS STRI to reduce uncertainties in aerodynamics and aerothermodynamics, integrate material response, quantify risk, reduce entry system mass. Infuse tools and methods to mission.
- Establish atmospheric models, including Uranus-GRAM and Neptune-GRAM
- Perform Earth demonstration of aerocapture, including applicable aerodynamic shape and guidance and control methods
- Use advanced TPS materials appropriate for efficient insulation, robust heat tolerance.
- Infuse characterization and modeling tools to mission.
- Gather flight data through DrEAM and MEDLI3 to validate predictions and inform future missions.
- Develop low-SWaPc instrumentation for Ice Giant entry systems.

Orange = summary of infusion path

Enabling Probes for Outer Planet Missions

Challenges

- High entry speed leads to high heat rates
- High pressure during entry and descent
- Aerothermodynamic uncertainties result from H_2/He atmosphere
- Aerodynamic stability characteristics
- Atmospheric uncertainties are significant
- Parachute deployments in different atmospheres; long descent phases
- **Uranus:** Precision approach/maneuvering needed to avoid rings

Forward Plan/Approach

- Pursue focused H_2/He investments and parachutes in Entry Systems Modeling (ESM), ESI, and ECI; leverage ACCESS STRI to reduce uncertainties in aerodynamics and aerothermodynamics, integrate material response, quantify risk, reduce entry system mass. Infuse tools and methods to mission.
- Establish and maintain atmospheric models, including Saturn-GRAM, Uranus-GRAM and Neptune-GRAM
- Use HEEET or 3MDCP TPS material for efficient insulation, robust heat tolerance. Infuse characterization and modeling tools to mission.
- Gather flight data through DrEAM and MEDLI3, and on DAVINCI, to validate predictions and inform future missions. Develop low-SWaPc instrumentation for Ice Giant entry systems.

Orange = summary of infusion path

Forward Plans to Close High-Priority Gaps

Gap Area	Near to Mid-Term Approach
Modeling & Simulation	• Continue investment in Entry Systems Modeling (ESM) project focusing on development and validation of integrated, higher-fidelity modeling capabilities to support next Decadal missions • Continue successful history of investments in Early Stage portfolio, including ECI, ESI/ECF, and ACCESS STRI • Complete and sustain upgrades to GRAM models for all relevant destinations • Initiate simulation retooling efforts to improve efficiency and take advantage of GPU-based and exascale computing architectures
Performance Validation	• Complete Mars 2020/MEDLI-2 post-flight analysis, including ESM deep dive • Implement DrEAM and DAVINCI instrumentation suites • Implement and conduct post-flight analysis from SCALPSS and SCALPSS 1.1 on CLPS; begin multi-sensor CLPS PSI suite • Begin development of MEDLI-3 for Mars Sample Return • Continue to support/improve Engineering Science Investigation (ESI) requirement on upcoming competed missions • Perform OSIRIS-REx airborne observation during Earth Return • Leverage SBIR/STTR for new sensor development, including for landing systems and parachutes • Advocate for new planetary aerothermodynamics facility as defined via ongoing HEAC study
EDL Hardware Technologies	• Maintain prior-developed (now SOA) TPS materials (e.g. PICA, HEEET) to ensure capability for all classes of future missions • Continue development of Mars Sample Return Earth Entry System (EES) with a focus on overall reliability. Leverage ESM and ACCESS capabilities to better determine reliability of as-built system. • Push the state of the art for supersonic decelerators via a combined modeling and experimental validation effort. Leverage advanced modeling tools to better understand physics drivers. • Leverage SBIR, CIF, ECI, and other Early Stage investments
Enabling Small Spacecraft Missions	• Conduct an aerocapture flight test with direct applicability to Ice Giants and retire technical and “perceived” risk of adoption • Enable small spacecraft deorbit/EDL via compact, low-SWAPc deorbit/entry systems and thermal protection materials development

Green = currently funded/planned; Yellow = not yet funded

Acronyms

- ADEPT – Adaptable, Deployable Entry and Placement Technology
- CLPS – Commercial Lunar Payload Services
- CFD – Computational Fluid Dynamics
- CORAL – Centaur Orbiter and Lander
- CSSR – Comet Surface Sample Return
- DrEAM – Dragonfly Entry Atmospheric Measurements
- ECF – Early Career Faculty
- EDL – Entry, Descent and Landing
- EES – Earth Entry System (specifically, that for Mars Sample Return)
- EMF – Enceladus Multiple Flyby
- ESI – Early Stage Innovation
- FEM – Finite Element Model
- FS – Fluid/Structural
- GN&C – Guidance, Navigation and Control
- GPU – Graphical Processor Unit
- GRAM – Global Reference Atmospheric Models
- HEAC – Hypersonic Environment Aerothermal Capability
- HEEET – Heatshield for Extreme Entry Environment Technology
- HIAD – Hypersonic Inflatable Aerodynamic Decelerator
- LGN – Lunar Geophysical Network
- LOFTID – Low Earth Orbit Flight Test of an Inflatable Decelerator
- MEDLI2 – Mars Entry, Descent and Landing Instrumentation (2)
- MSR – Mars Sample Return
- PICA – Phenolic Impregnated Carbon Ablator
- PSD – Planetary Science Division
- PSI – Plume Surface Interaction
- SBIR – Small Business Innovation Research
- SCALPSS – Stereo Cameras for Lunar Plume Surface Studies
- SOA – State of the Art
- SPLICE – Safe, Precise Landing Integrated Capabilities Evolution
- SRL – Sample Retrieval Lander (specifically for Mars Sample Return)
- SRP – Supersonic Retropropulsion
- STRI – Space Technology Research Institute
- SWAPc – Size, Weight, Power and Cost
- TPS – Thermal Protection System
- TRN – Terrain Relative Navigation
- VISE – Venus In Situ Explorer
- 3MDCP – 3-Dimensional Carbon Phenolic

EXPLORESPACE TECH

TECHNOLOGY DRIVES EXPLORATION

LAND: Enable Lunar/Mars Global Access and ~20t Payloads

NASA Space Technology Mission Directorate

August 2022

STMD welcomes feedback on this presentation

See 80HQTR22ZOA2L_EXP_LND at nspires.nasaprs.com for how to provide feedback

If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

Entry, Descent and Landing (EDL) Definition

- Process of delivering a vehicle from the top of an atmosphere to the surface and landing safely
- For bodies without an atmosphere, sequence referred to Deorbit, Descent and Landing (DDL)
- Three phases of atmospheric flight
  - Entry – Hypersonic flight: Decelerate, dissipate heat, guide to the target
  - Descent – Supersonic flight: Engage additional deceleration (parachutes/engines)
  - Landing – Subsonic flight: Sense the surface, expose landing hardware and reduce engine thrust for touchdown
- EDL is a critical mission phase, with extreme environments and complex dynamics, that cannot be fully tested end-to-end on Earth
- To date, all US Mars landings have utilized the same EDL technology developed for the Viking missions: rigid, 70˚ sphere-cone aeroshells and supersonic parachutes – suitable for < ~2t landed

Photo Credits: NASA/JPL-Caltech

LAND: Enable Lunar/Mars global access and ~20t payloads to support Mars human surface missions.

Developing landing capabilities that support unique requirements for both the Moon and Mars, to allow for landing greater payload capacity with greater accuracy

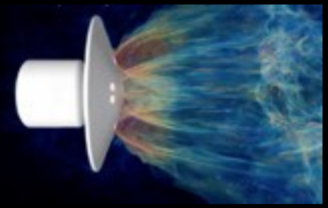
Lunar Capabilities (feeding forward to Mars)

Precision Landing and Hazard Avoidance

Safely and precisely land near science sites or pre-deployed assets *(see details in separate package)*

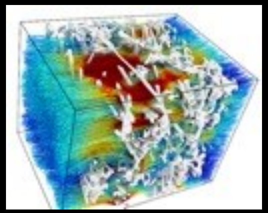
Retropropulsion

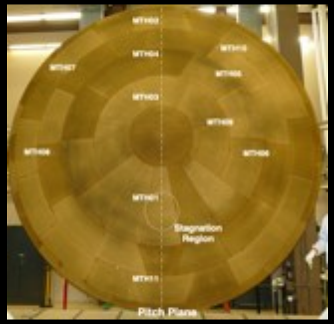
Understand flow physics and vehicle control through wind tunnel testing of Mars-relevant configurations; advance CFD modeling



Plume Surface Interaction

Reduce risks to landers and nearby assets by understanding how engine plumes and surfaces behave





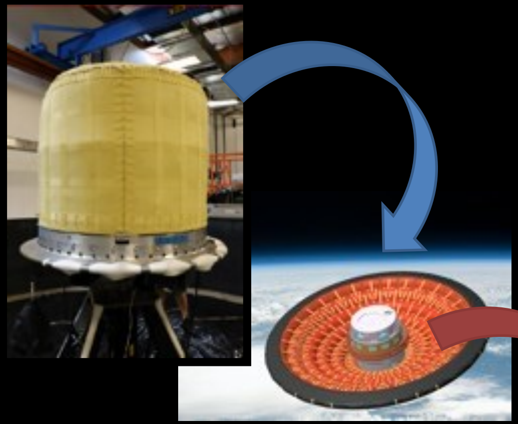
Foundational Modeling, Testing, Instrumentation, and Computing

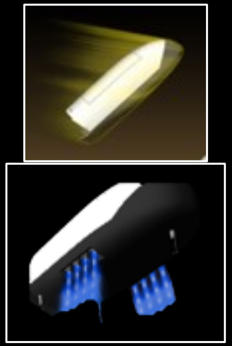
Measure EDL flight system performance and update/develop unique, critical simulations for EDL/DDL systems

Mars Capabilities

Large Scale Demonstrations

Large structures, including deployables, that can slow down a 20t payload in the thin Mars atmosphere

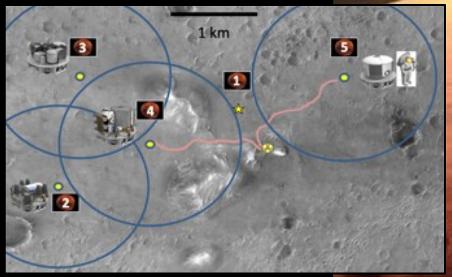




Assess Alternatives

Earth Flight Tests, such as LOFTID

Aggregate Assets



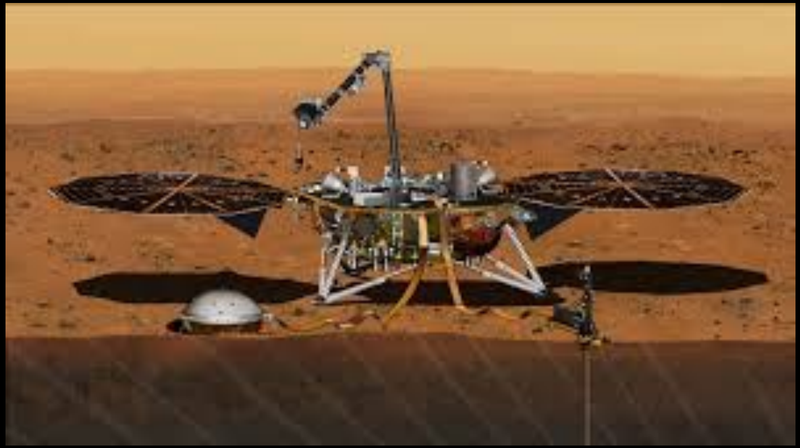
NASA's Mars Landing Missions – State-of-the-Art

Photo Credit: NASA

Viking 1 & 2
1976
(600 kg)

Spirit and Opportunity – 2004 (539 kg)

Phoenix – 2008 (364 kg)



InSight – 2018 (375 kg)

Pathfinder
1996
(360 kg)

Curiosity – 2012 (899 kg)

Mars 2020 – Perseverance (1,050 kg)

Artist Concept Credits:
NASA/JPL-Caltech

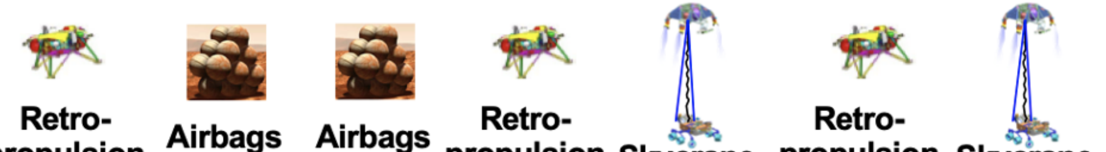
Landing 20t on Mars Requires A Leap in Scale and Capability

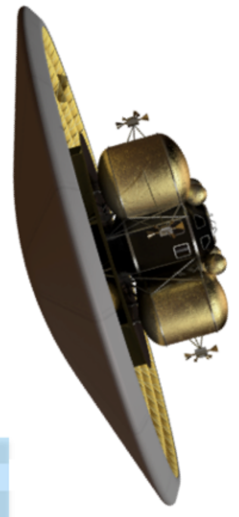
Landing 20t payloads represents a 20-30x increase in delivered mass capability, over the SOA

- Viking-derived rigid sphere-cone aeroshells with cross sections that fit in a launch vehicle shroud are not large enough to decelerate heavy payloads in the thin Mars atmosphere – a larger entry system is needed (“E”)
- Supersonic parachutes cannot be used; high-speed propulsive descent is enabling (“D”)
- Precise Lunar landings require and will demonstrate integrated GN&C for the landing and prediction/knowledge of large-engine plume surface interaction (PSI) effects. Both feed forward to large Mars missions (“L”)
- Robust guidance and control throughout entry and descent is required for safe, precise landing (“EDL”)

Entry Capsule *(shown to scale)*

	Viking	Pathfinder	MERs	Phoenix	MSL	InSight	M2020	Human-Scale Lander (Projected)
Diameter (m)	3.505	2.65	2.65	2.65	4.52	2.65	4.52	16 - 19
Entry Mass (t)	0.930	0.585	0.840	0.573	3.153	0.608	3.368	49 - 65
Parachute Diameter (m)	16.0	12.5	14.1	11.8	21.5	11.8	21.5	N/A
Parachute Deploy (Mach)	1.1	1.71	1.67	1.65	1.75	1.66	1.8	N/A
Landed Mass (t)	0.603	0.360	0.539	0.364	0.899	0.375	1.050	26 - 36
Landing Altitude (km)	-3.5	-2.5	-1.4	-4.1	-4.4	-2.6	-2.5	+/- 2.0
Terminal Descent and Landing Technology	Retro-propulsion	Airbags	Airbags	Retro-propulsion	Skycrane	Retro-propulsion	Skycrane	Supersonic Retropropulsion





Steady progression of “in family” EDL — *Payloads up to ~1 t*

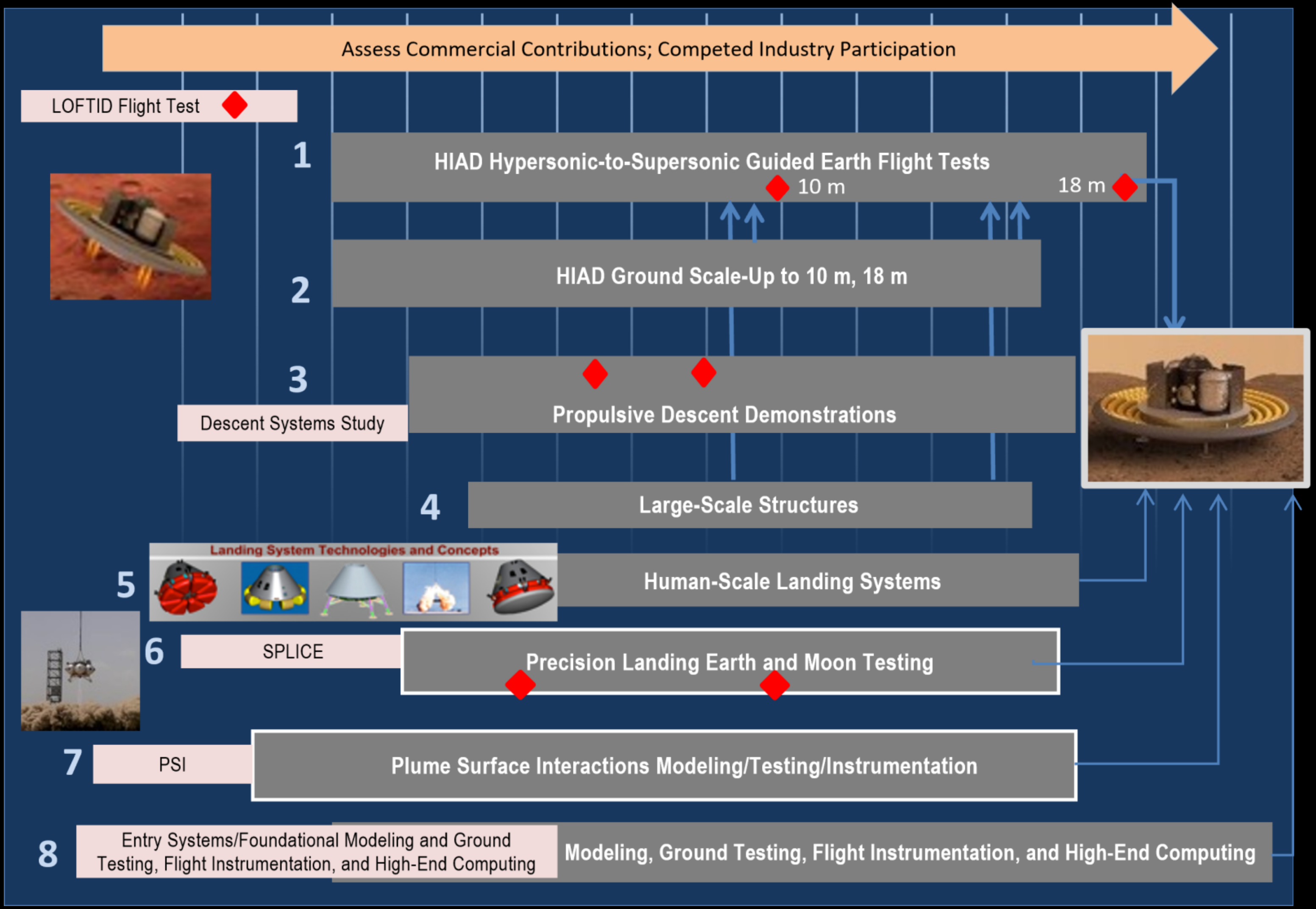
New EDL Paradigm — *Payloads 20-30* t*

*actual payload requirements differ with architecture assumptions

Mars Crew / Cargo Landers for 20t Payloads

Notional Development Plan (Current STMD Investments Noted in Pink Bars)

NOTE: Numbered items correspond to highest-priority gaps (see page 8). Activity duration and timing are success-oriented and require significant investment increases.

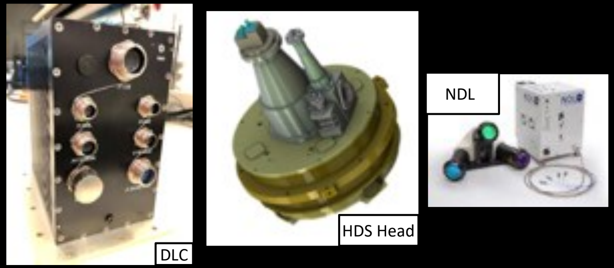


- *The large-scale Mars EDL system is comprised of multiple long-lead elements that all need to be matured in parallel.*
- *Flight tests of "E," "D," and "L" components occur at Earth. Precision Landing is demonstrated on the Moon. End-to-end Mars validation is performed computationally (as with current vehicles), and the Mars cargo missions serve as the system certification for humans.*

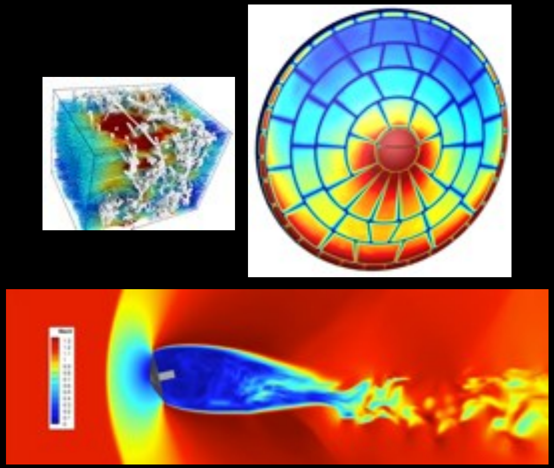
Legend
- Current Funded Activity
- Risk Reduction / Capability Maturation
- Demonstration/experience at Moon
- Commercial activity/leveraging
- Launch (test flight LVs TBD)
- Feed-in

Current Investments to Achieve 20t Landings

LOFTID
6m inflatable aeroshell test with United Launch Alliance (ULA) - 2022

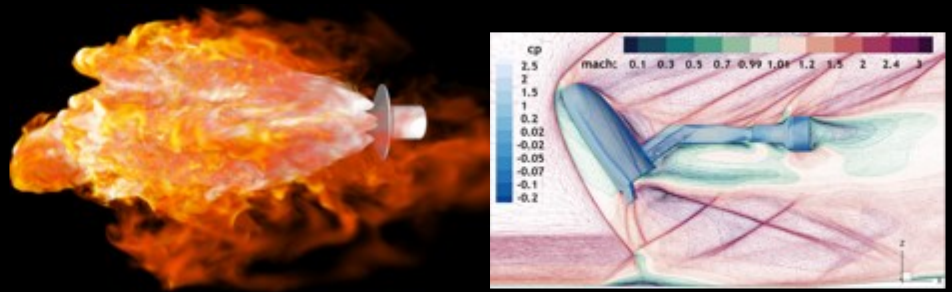


***SPLICE**
Precision Landing/Hazard Detection sensor, computing, and algorithm development, flight testing, and commercialization
(see separate package for "50 m" outcome)

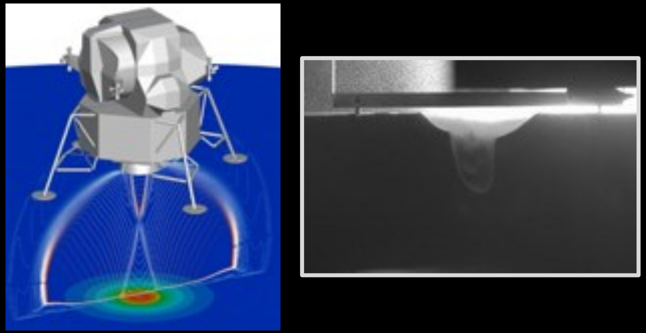


Entry Systems Modeling (ESM)
Advancing core capabilities and reducing mission risk through validation (Aerodynamics, Aerothermal, TPS, GN&C)

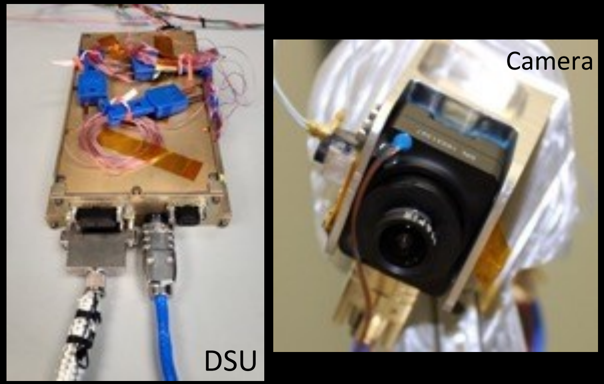
MEDLI2
Heating and pressure sensors on Mars 2020 aeroshell; provides aero/aerothermal model validation data (post-flight data analysis in progress)



Descent Systems Study
Mid L/D ground testing complete
HIAD and all SRP testing FY22-23



***Plume Surface Interaction (PSI)**
Model Advancement and Validation through Ground Testing, Flight instrument maturation



***SCALPSS**
Stereo Cameras to measure Plume Surface Interaction under CLPS landers; provides PSI model validation data

Early-Stage investments such as SBIR and academic efforts contribute to most projects shown
**Orange = Demonstration for Lunar missions in Near Term; Lunar-focused investments feed forward directly to Mars*

Highest-Priority Technology Gaps

There are 20 identified gaps mapped to the "Land 20t" outcome. Below are the highest-priority gaps, as ranked by the EDL System Capability Leadership. The major bullets trace to the numbered grey bars on the schedule (page 6.)

- **Aeroshell (Hypersonic Deceleration) System (1)**
  - Flight Test Validation of Integrated High-Mass Mars Entry and Descent Architectures
  - Control Technologies for Exploration Class Inflatable Decelerator
  - Aeroshell/TPS Reliability Prediction
- **Ground Development and Scale-Up of Inflatable Decelerators and Large Structures (2)**
- **Retropropulsion (Supersonic Deceleration) System (3)**
  - Supersonic Retropropulsion (SRP) Modeling & Simulation
  - Supersonic Retropropulsion (SRP) Guidance, Navigation and Control
- **Validated Prediction of Plume-Surface Interaction (PSI) for Vehicles Landing on Mars (7)**
- **Entry Systems/Foundational Modeling and Testing, Instrumentation, and Computing (8)**
  - High-End Computing Capability for EDL Modeling
  - Multi-disciplinary / coupled EDL Performance Models
  - Validated Aerothermodynamic Prediction for Human Mars EDL
  - Thermal Protection System Performance Modeling & Optimization for Human Mars Exploration
  - EDL Flight Vehicle (Aeroshell) Flight Performance Data for Human Mars Entry and Earth Return
  - Low Cost EDL Flight Instrumentation Data Acquisition System
  - Planetary Aerothermodynamics Test Facility

**Note that all Precision Landing gaps are mapped to the "Land within 50 m" outcome and are therefore not included here. These are CRITICAL to implementing the Artemis architectures. See the separate package on that outcome.*

Forward Plans to Close High-Priority Gaps

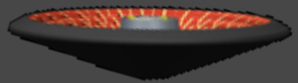
System/Area	Near- to Mid-Term Approach
Aeroshell (Hypersonic Deceleration) System (1), including Ground Development & Scale-Up, Large Structures (2) *(see graphic on following page)*	• **Complete current investments in LOFTID 6 m flight test, data analysis and dissemination. Assess alternate Mars architectures via analysis.** • Advance towards Commercial Rocket Stage Reuse capability (increased size, payload mass) – ground scale-up work must proceed in parallel to support this application, including materials, gas generators, and model advancement and validation • Formulate large-scale Earth flight tests through Pre-Phase A to establish objectives, estimate schedule and budget. Determine SRP requirements • Use LOFTID EDU to advance control strategies • Advance gas generator technology needed for large-scale systems, and materials with improved volume/handling characteristics (industry) • Perform large-scale Earth flight tests to demonstrate performance and functionality needed for human Mars mission implementation
Retropropulsion (Supersonic Deceleration) System (3) *(see graphic on following page)*	• **Complete current investments in Descent Systems Study wind tunnel testing and data analysis, including academic participation (ESI21)** • Initiate hot-fire wind tunnel testing at GRC to further characterize aerodynamic parametric data • Perform scaled (sounding rocket-based) Earth flight tests to validate in-flight performance • Integrate with large-scale decelerator Earth-based flight tests (if flight conditions can be met)
Plume Surface Interactions (PSI) (7) *(see graphic on following page)*	• **Complete foundational PSI ground testing and Early Stage investments to support improved prediction capability (SBIR, STRG)** • Instrument CLPS landers to gather Lunar validation data (SCALPSS, PSI Mini-Suite); also leverage data collected by lander providers, other P/Ls • Develop low-SWaPc flight instrumentation (in-house, SBIR, and other competitive opportunities) for larger-scale Lunar missions that will feed forward to Mars. Leverage Artemis landings. • Gather dedicated PSI data from future Mars robotic landers to support improved understanding of landing environments and further gaps
Foundational Modeling, Testing, Instrumentation, and High-Performance Computing (8)	• **Continue investments in Entry Systems Modeling, focusing on development and validation of integrated, higher-fidelity modeling capabilities, including academic efforts (ACCESS STRI, ECF, ESI)** • Facilitate advanced computing implementation of key EDL models through code transfer, workforce development efforts, and OGA partnerships • Conduct ground facilities maintenance and construction as necessary to fill high-priority gaps • Instrument entry systems on future Mars robotic landers (MEDLI-3), invest in new sensors and low-cost DAS (SBIR), obtain data from Artemis I and II Earth return
Precision Landing and Hazard Avoidance	• **Complete SPLICE for sensor and algorithm development and terrestrial testing; continue SBIR and FO use. Obtain NDL data from CLPS flights.** • Perform integrated CLPS lunar demonstration(s); commercialize for infusion to human and cargo landers • Implement and demonstrate integrated capabilities on future Mars robotic landers *See package dedicated to the LAND precision landing outcome, for more details*

NOTE: Large-Scale Structures and Human-Scale Landing Systems require initial in-house exploration followed by solicitations, when funding is available.

Hypersonic Inflatable Aerodynamic Decelerator (HIAD)
Scale-Up and Flight-Testing Approach

IRVE-3 (3 m) – 2012 successful flight test from Wallops Flight Facility - SOA

Established the aerodynamic performance and stability of inflatable heatshield approach

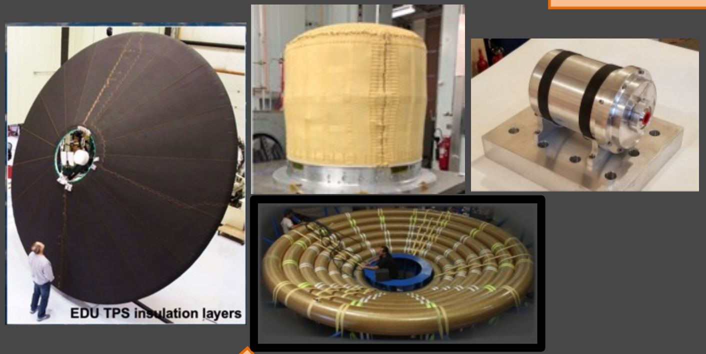


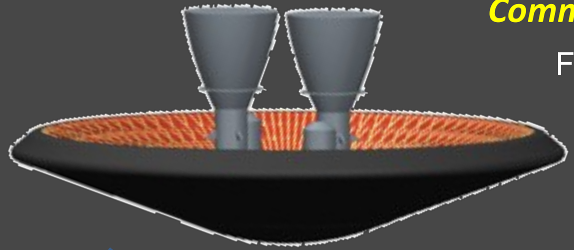
LOFTID Flight Test (6 m) – 2022 flight test in partnership with United Launch Alliance (ULA)

Vandenburg launch with JPSS-2. ***HIAD will experience human Mars mission-relevant heating and g-load.***

Ground Scale-up Demonstration

- Mass-efficient materials for structure and TPS
- Improved handling and packing density
- Gas generators: volume-enabling





Commercial Rocket Engine Recovery (12 m) – 2024-25+

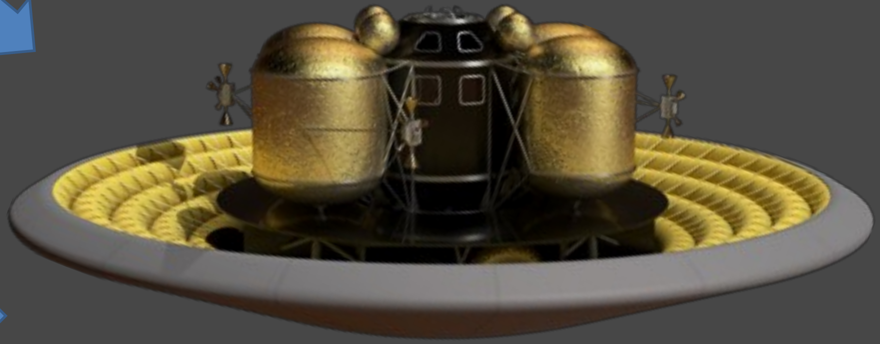
Frequent industry use will solidify HIAD technology

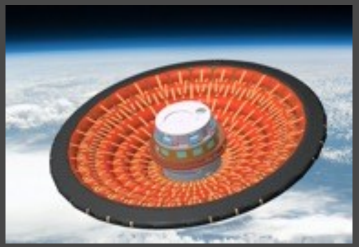
- Establish large-scale (12 m+) production
- Maintain specialized vendor base
- Return multiple sets of flight data for validation
- Reduce risk for human Mars mission implementation

Perform integrated demonstration

Sustain commercial base

Human Mars Lander (~18 m)





Guided HIAD, SRP Earth Flight Testing (10-15 m)

- Demonstrates closed-loop G&C and transition to propulsive deceleration
- Includes large-scale, mass-efficient structures

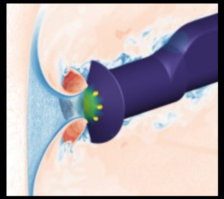
Ready for Mars infusion

Green = currently funded; Yellow = not yet funded

Retropropulsion Advancement Approach

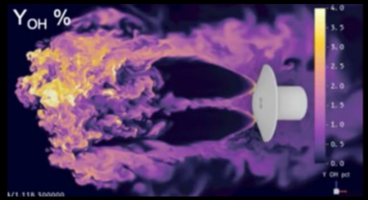
Commercial Demonstration of Supersonic Retropropulsion (SpaceX, high-altitude Earth stage return – 2013) - SOA

- Established viability of rocket engine restart in oncoming flow conditions. NASA received flight data for CFD assessment.
- Geometry/configuration dramatically different than NASA Mars EDL concepts, but general feasibility established.



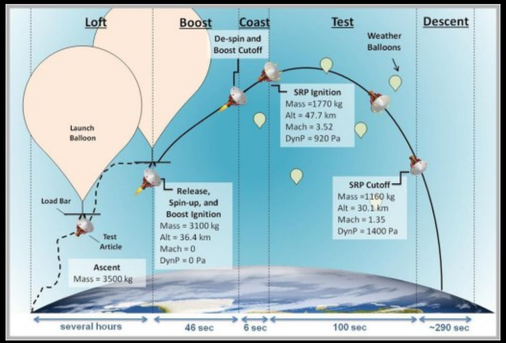
Wind Tunnel Testing with Cold Gas Thrusters (Langley Unitary Plan Wind Tunnel – 2010, 2021-23) - SOA

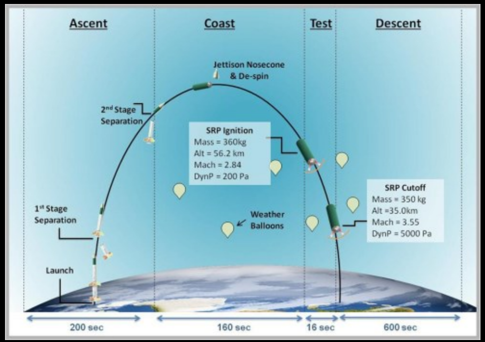
- Various nozzle/shape configurations, uncertainty quantification, inert gas subscale validation data
- Establishes aerodynamic databases for simulations to assess performance of Mars EDL alternatives



Wind Tunnel Testing with Combustion Engines (Glenn Supersonic and Transonic Tunnels)

- First hot-fire test with chemistry effects, hot-fire subscale validation data
- Establishes aerothermal environments, refines aerodynamics for iterative vehicle design; input to end-to-end flight dynamics simulations of 20 t Mars EDL



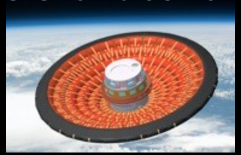


High-Altitude Suborbital Testing (~1m diameter scale)

- Series of tests at larger scale in Mars-relevant environment (density, Mach)
- Continuity in transitions across flight regimes, verifies stability
- Flight-relevant configurations, combustion, system integration

Integration with Hypersonic Decelerator, Transition Test

- Test transition from aerodynamic to propulsive deceleration at Mars-relevant conditions and configurations



(see previous page)

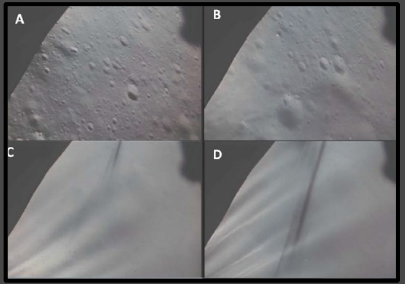
Gradual increase in test fidelity retains flexibility and supports configuration decisions.

Rapid analysis of large datasets is key challenge – requires new tools, computing architectures

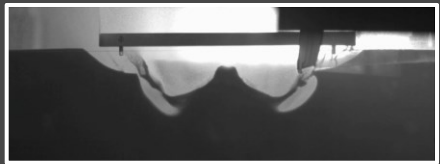
Plume Surface Interaction (PSI) Advancement Approach

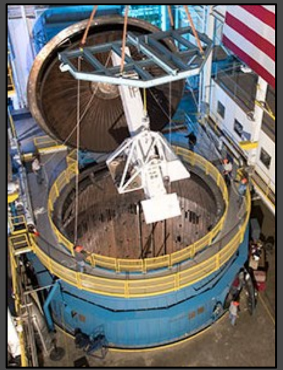
The Challenge: **Engine plumes of landing (and ascending) vehicles will disturb the surface below, potentially causing (1) cratering, (2) heating of the vehicle base and legs, and (3) high-speed ejecta impacts on nearby surface assets. Little test or flight data exist to develop and validate predictive models.**

MSL Skycrane Plume-Induced Surface Cratering



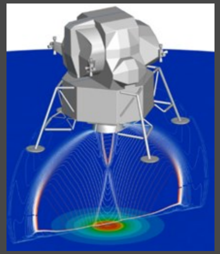
Apollo 15 camera obscuration (Metzger, 2011)


Physics-Focused Ground Test, annular crater in sand (2021)


Large-Scale Ground Test, Armstrong Test Facility (OH)


Crater Observation Camera


mm-Wave Doppler Radar


PSI Prediction Model

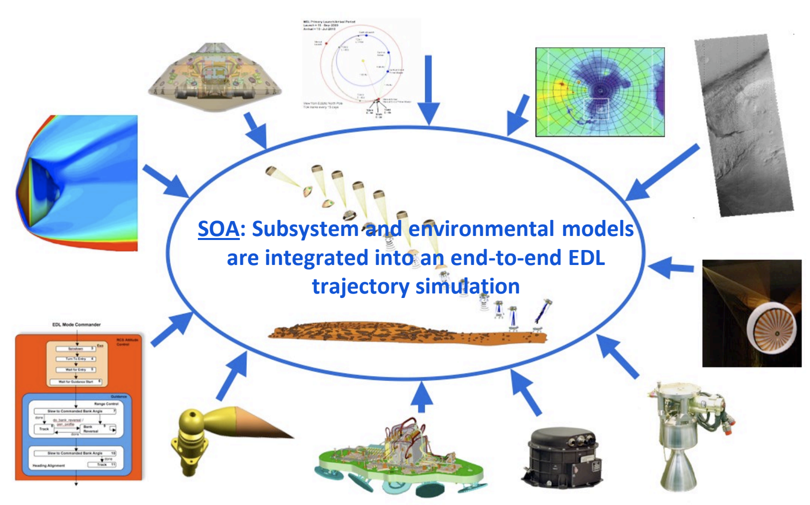
Advancement Approach (captured in gaps):

- Mature predictive modeling capability, currently unvalidated (results are qualitative; need to mature towards quantitative)
  - Complex, multi-physics problem requiring high-end computing resources to achieve required throughput
  - Key environment that will drive lander and surface asset design **and create dust that requires mitigation**
  - *Obscuration during PSI event may affect precision landing sensor performance/data, in high-thrust cases*
- Conduct vacuum ground tests with regolith/bedrock simulants to generate initial model validation data
  - Small-scale, warm-gas tests varying simulants, vacuum levels (Moon and Mars), nozzle heights and mass flows
  - Large-scale (1000 lb_f+) vacuum tests with simulants, combustion – more relevant to human-scale systems
  - *Limited vacuum facilities exist, to handle both regolith and combustion, at any scale*
- Develop instrumentation to measure (1), (2), and (3) above
  - Implement in ground tests to demonstrate instruments and measure relevant quantities for model validation
  - Instrument CLPS landers (100's of lb_f) for single and multiple PSI phenomena
  - Instrument larger lunar and robotic Mars landers with low-SWaPc multi-sensor suites to obtain flight data

Green = currently funded; Green-Yellow = partially funded; Yellow = not yet funded

Modeling/Testing/Instrumentation Advancement Approach

- Planetary EDL/DDL cannot be practically tested end-to-end at Earth; system acceptance relies heavily on a combination of ground testing (wind tunnels, arcjets, ballistic ranges, drop tests, etc.) and computer modeling and simulation (CFD, material response, FEM, atmosphere, H/W and S/W, etc.)
  - Flight data has been historically sparse, for vehicles flying at planets other than Earth
  - Heatshield instrumentation on Mars Science Laboratory and Mars 2020 have helped validate models and improve design practices for future vehicles, but uncertainties still exist and risk tolerance will be lower, for human systems
- Aging and inadequate facilities, combined with high reliability requirements, create gaps in our ability to readily certify human-rated, large-scale planetary landers.
- Human-rated landing systems will require high-fidelity, closed-loop modeling and simulation, along with ground test and flight data with quantified uncertainties, gathered by precision instrumentation



Advancement Approach (captured in gaps):

- Continue robust modeling capability within each subsystem development
- Develop coupled, multi-scale models for lander systems and environments, utilizing advanced computing architectures (GPU, exascale) to achieve schedule (requires new skills and tools)
- Ensure flight regime is adequately replicated in test facilities
- Develop and implement low-SWaPc instrumentation to gather critical model validation data from ground tests, flight tests, and EDL missions

This content builds upon the Entry Systems Modeling project and a vibrant Early-Stage academic community. Progress requires a long-term, sustained commitment to foundational capabilities: tools, facilities, and high-end computing.

Summary

- The EDL systems required for landing 20 t payloads are significantly larger and different than those used in the past to land up to one tonne on Mars. A comprehensive set of ~20 high-priority gaps defines the needed near-term advancements.
- Human Mars architecture studies over the past 5 years indicate that a HIAD/SRP-based EDL system is most likely to be able to close the architecture *under the current Agency assumptions*. Alternative approaches must continue to be assessed as the space economy and available technologies evolve.
- Large-scale, human-rated EDL vehicles require maturing multiple systems in parallel, each with ground development and/or flight testing needed
- Landing-related technologies such as precision landing and hazard avoidance, and the prediction of plume-surface interactions, will heavily leverage development, testing, and implementation on lunar landers of increasing scales.
- Mars entry and descent technologies are long-pole developments that will remain untested by Artemis lunar missions. Given the Agency's current lunar priority, major investments in these areas are few.
- The modeling and simulation used for end-to-end EDL certification will require significant modeling advances and computing efficiencies to achieve high reliability on the current manifested schedules.
- Ground and flight test will continue to be a foundation of EDL development. Modern instrumentation is critical, and new/upgraded test facilities will be required to secure this envisioned future.

Acronyms

- CLPS – Commercial Lunar Payload Services
- CFD – Computational Fluid Dynamics
- DDL – Deorbit, Descent and Landing
- ECF – Early Career Faculty
- EDL – Entry, Descent and Landing
- ESI – Early Stage Innovation
- FEM – Finite Element Model
- GN&C – Guidance, Navigation and Control
- GPU – Graphical Processor Unit
- HIAD – Hypersonic Inflatable Aerodynamic Decelerator
- H/W – hardware
- LOFTID – Low Earth Orbit Flight Test of an Inflatable Decelerator
- MEDLI2 – Mars Entry, Descent and Landing Instrumentation (2)
- PSI – Plume Surface Interaction
- SBIR – Small Business Innovation Research
- SCALPSS – Stereo Cameras for Lunar Plume Surface Studies
- SOA – State of the Art
- SPLICE – Safe, Precise Landing Integrated Capabilities Evolution
- SRP – Supersonic Retropropulsion
- STRI – Space Technology Research Institute
- S/W – software
- TPS – Thermal Protection System

EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

LIVE: Advanced Habitation Systems (AHS)
NASA Space Technology Mission Directorate
May 2022

STMD welcomes feedback on this presentation
See RFI 80HQTR22ZOA2L_LIVE at nspires.nasaprs.com for how to provide feedback
If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

AHS Investments Support Multiple Strategic Outcomes and Primary Capabilities

Thrusts	Outcomes	Primary Capabilities
Go Rapid, Safe, and Efficient Space Transportation	• Develop nuclear technologies enabling fast in-space transits. • Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications. • Develop advanced propulsion technologies that enable future science/exploration missions.	• Nuclear Systems • Cryogenic Fluid Management • Advanced Propulsion
Land Expanded Access to Diverse Surface Destinations	• Enable Lunar/Mars global access with ~20t payloads to support human missions. • Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies. • Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards.	• Entry, Descent, Landing, & Precision Landing

Live Sustainable Living and Working Farther from Earth	• Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities
	  • Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.
	  • Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface.
	  • Technologies that enable surviving the extreme lunar and Mars environments.
	  • Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources.
	• Enable long duration human exploration missions with Advanced Life Support & Human Performance technologies.
		• Advanced Power
		• In-Situ Resource Utilization
		• Advanced Thermal
		• Advanced Materials, Structures, & Construction
		• Advanced Habitation Systems

Explore Transformative Missions and Discoveries	• Develop next generation high performance computing, communications, and navigation. • Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions. • Develop technologies supporting emerging space industries including: Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft technologies. • Develop vehicle platform technologies supporting new discoveries. • Develop transformative technologies that enable future NASA or commercial missions and discoveries	• Advanced Avionics Systems • Advanced Communications & Navigation • Advanced Robotics • Autonomous Systems • Satellite Servicing & Assembly • Advanced Manufacturing • Small Spacecraft • Rendezvous, Proximity Operations & Capture

Major AHS Interfaces to Other Capabilities

In Space Transportation SCLT
AHS technology improvements in CO_2 reduction (O_2 recovery), food, and other AHS areas along with increased reliability, reduce cargo mass ~5 MT x propulsion gear ratio

Entry Descent and Landing SCLT
AHS technology improvements in CO_2 reduction (O_2 recovery) and food technologies reduce landed cargo mass

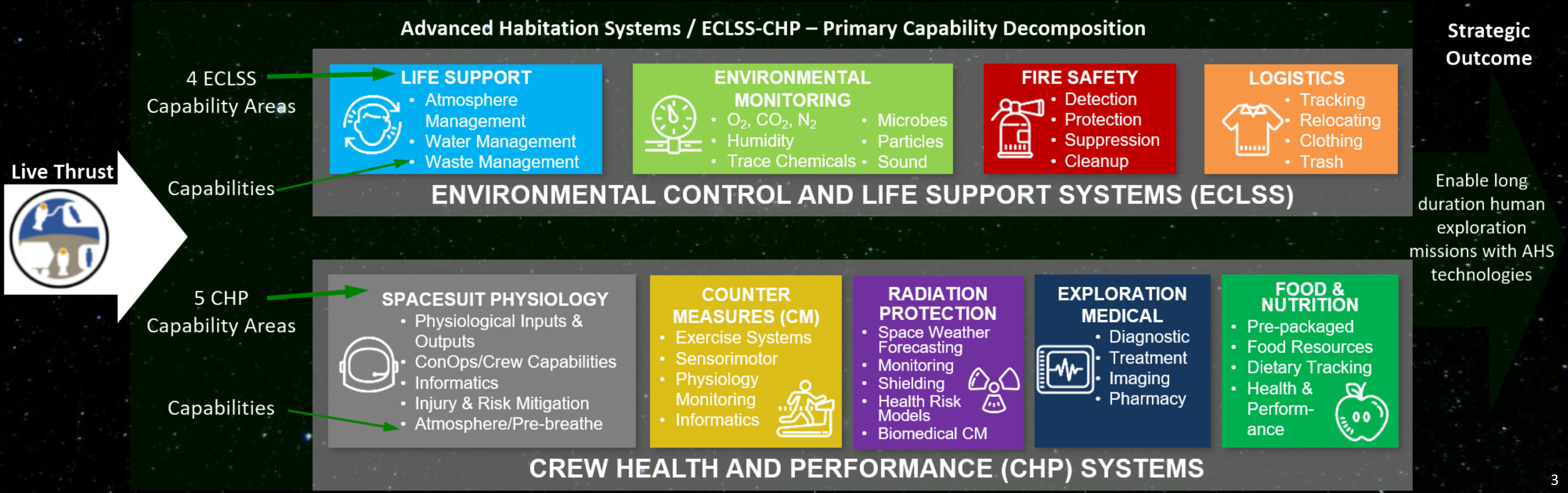
ISRU SCLT
AHS investments in CO_2 reduction (O_2 recovery), gas–phase contaminant separations, water contaminant removal, and monitoring are extensible to ISRU resource production

AHS capabilities captured in NASA taxonomy in TX06 & TX07
Largest technology challenges: CO_2 reduction (O_2 recovery), in-flight food nutrition, GCR shielding, and reliability (spares mass)

Autonomous Systems SCLT
Advances in robotics and autonomy support AHS system maintenance/operation to prepare for crew arrival, allow crew to focus on science, and allow ECLSS processing during uncrewed periods (smaller/lower power systems)

Advanced Habitation Systems Capability Areas and Capabilities

- AHS capabilities keep astronauts healthy and productive while living in space and planetary vehicles
- Broadly characterized into vehicle Environmental Control and Life Support Systems (ECLSS) and Crew Health and Performance (CHP) Capability Areas
  - Capability Areas are further decomposed to capabilities and sub-capabilities to define gaps
  - Useful to discuss state of the art and envisioned futures for each capability area/capability
  - LIVE Thrust will evolve to include EVA suits In the future



Mission Characteristics That Drive AHS Capability Needs

- Mission Duration
  - Crew consumables and waste generation are fixed kg/crew-day
  - Duration needs to be long enough to offset system closure mass
- Crew safety and mission success goals
  - Longer duration increases risk
  - Increased Probability of Sufficiency (POS) - increase spares & certainty of spares life
  - Increased ability for Earth independent diagnostics and repair

- Microgravity vs Surface
  - μg adds complexity to address liquid-gas-solids separation and other phenomena
- Frequent planned EVAs
  - Loss of water and oxygen (less available for recycling)
  - Increased crew fatigue and injury risk
  - Reduced cabin pressure to reduce pre-breathe time, impacts 14.7 psia/23% O_2 systems
  - Mitigating surface dust from EVA
- Number of crew members
  - Crew consumables are fixed kg/d
- Planetary protection and science integrity
  - Monitoring/sterilization/treatment/containment adds mass
- Long uncrewed periods
  - Adds mass to prevent or recover from microbial upset
  - Importance of habitat autonomy and robotic caretaking increases

- Availability of In-Situ Resource Utilization (ISRU) products (water and gases)
  - Influences recycling break-even point, possible ISRU-ECLS sensor and processor commonalities

AHS Envisioned Future Decomposition by Capability Area

(Mission need)
- L = Lunar surface
- T = Transit to Mars
- M = Mars surface

LIFE SUPPORT

- Reliable long-duration life support with Earth independent diagnostics and repair (L,T,M)
- >20% reduction in spares and installed mass (T)
- Enable single missions >800 days w/o resupply (T)
- Repeated missions with >9 months dormancy (L,T,M)
- >75% oxygen recovery at 2 mm-Hg CO_2 (T)
- High pressure oxygen recharge for EVA (L,M)
- >98% water recovery (L,T,M)
- Remove respirable lunar and Mars dust (L,M)
- Planetary protection compatible ECLSS venting (M)

ENVIRONMENTAL MONITORING

- Identify and quantify chemical (>12 water, >33 air) and microbial species in-mission with out sample return (L,T,M)
- Ability to detect unknown constituents (T,M)
- Distinguish between fire, habitat dust, and surface dust particles (L,M)
- Support forward and backward planetary protection detection (both microbial and non-DNA techniques) (M)

FIRE SAFETY

- Test-verified partial gravity flammability characteristics and countermeasures (L,M)
- ECLSS compatible fire suppression (L,T,M)
- Reduce post fire clean-up time (L,T,M)
- Common fire safety strategy across element architectures (L,T,M)

LOGISTICS

- Jettison >90% of trash mass during Mars transit (T)
- Mars trash disposal compatible with planetary protection (M)
- In-flight autonomous logistics (L,T,M)
- Reducing clothing and wipes mass by >50% (L,T,M)
- Clothing flammability (and other non-metallics) >36% O2 (L,M)

SPACESUIT PHYSIOLOGY

- 100% of tasks within human performance (L,T,M)
- Predict and mitigate decompression sickness for surface EVA (L,M)
- Predict and mitigate suited injury (L,M)
- 6 Major physiological informatics parameters provided in-suit to enable real time self-assessment or loss of communication areas (L,M)

COUNTER-MEASURES

- Reduce mass and volume (L,T,M)
- Maintain/monitor fitness in-flight to enable unassisted landing egress & EVA (L,T,M)
- Validated lunar and Mars fitness standards (L,M)

RADIATION PROTECTION

- 24-hr prediction of solar storm duration and intensity to >90% (L,T,M)
- High energy neutron detectors (L,T,M)
- Earth independent monitoring/forecasting (T,M)
- GCR shielding (T,M)

EXPLORATION MEDICAL

- In-mission diagnostics and treatment for 100 of 120 medical risk conditions (L,T,M)
- Autonomous medical skill and & decision support systems (T, M)
- Integrated data architecture (L,T,M)

FOOD & NUTRITION

- 100% of nutrient stability >5-year shelf life (T,M)
- Food acceptability >90% (L,T,M)
- <30% launched water content (T,M)
- Exploration counter-measure in-mission nutrition intake monitoring (L,T,M)

Advanced Habitation Systems State-of-the-Art by Capability Area

LIFE SUPPORT

- ISS life support demonstrations have identified required system reliability issues – fixes in work
- ~21,700 kg spares + food, 4 crew x 860days x Probability of Sufficiency (POS)=0.99
- Resupply every 2-6 months
- Nearly uninterrupted use of wetted systems
- ~47% oxygen recovery at 2 mm-Hg CO_2
- No in-flight EVA oxygen recharge capability
- ~93% water recovery
- HEPA filters require frequent manual cleaning

ENVIRONMENTAL MONITORING

- Detailed gas/water chemical, microbial identification, and particle analysis only with samples returned to ground
- Major air constituents & limited targeted trace gases in flight
- Water analysis limited to total organic carbon
- Culture based microbial sample return, DNA sequencing limited to surface microbes
- Limited particle measurement capability demonstrated
- Mass intensive passive acoustic adsorption/damping

FIRE SAFETY

- Partial understanding of large ug fire propagation and properties
- Very limited knowledge of partial gravity fire properties
- Obsolete monitoring
- Cleanup by depress/repress
- Limited mask emergency response
- CO_2 based fire extinguishers

LOGISTICS

- Manual trash compaction, short storage time, module level jettison only
- No planetary protection compliance for waste disposal
- Manual & limited In-flight autonomous logistics tracking
- Disposable & flammable clothing, towels, & wipes

SPACESUIT PHYSIOLOGY

- Physiological inputs/outputs adequately known for ISS EVA only
- Limited informatics; primarily ground-monitored
- Ground, ISS, and Apollo suit injuries occur (27 injury mechanisms identified)
- Prebreathe protocols for 14.7 and 10.2 psia microgravity only

COUNTER-MEASURES

- 3+ large devices, large mass
- Returning crew egress from landing vehicle requires ground team assistance
- Exercise planning and monitoring via ground
- Limited sensorimotor countermeasures

RADIATION PROTECTION

- Mature shielding design tools
- Reconfigurable SPE shielding & limited GCR shielding
- Crew radiation monitoring
- Short term space weather using earth centric assets

EXPLORATION MEDICAL

- Evacuate <8 hrs
- Resupply 2-3 months
- Limited in-mission diagnostic, treatment
- Ground medical data & decision support systems

FOOD & NUTRITION

- ~1.5 year shelf life, fresh food resupply every 2-3 months
- Only ~215 standard food items, µg plant experiments
- ~47% launched water content
- In-mission nutrient intake monitoring in development

Advanced Habitation Systems – Examples of Current Investments (1/2)

(There are many SBIR/STTR/ECI/ECF/CIF/STRG investments supporting lower TRL innovation not list below)

LIFE SUPPORT

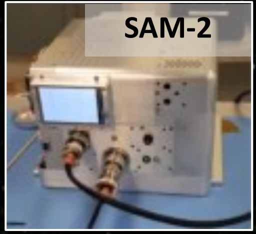

Advanced Oxygen Generator


Urine Brine Processor Assembly


Compact Toilet System

- Long duration reliability testing on ISS & ground
- Oxygen generation improved maintainability
- High Pressure O_2 EVA resupply
- Sabatier enhancements
- 4-bed, Thermal amine, and CapiSORB CO_2 scrubbers
- Bosch CO_2 Reduction
- Methane Pyrolysis
- Hydrogen Separation
- Medical oxygen
- Long life condensing heat exchangers
- Wetted systems dormancy tolerance and recovery
- I_2 and Ag water biocides
- Partial-g water systems
- Compact toilet and lower mass fecal containers
- Urine pretreat storage and delivery
- Trace gas catalytic oxidizer
- Scroll & cyclone particulate filtration

ENVIRONMENTAL MONITORING


SAM-2


MiniTOCA


Airborne Particle Monitor


MinIon/ Biomole

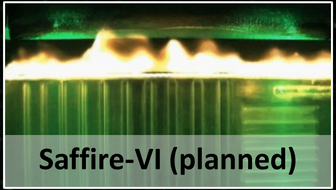
- Long duration reliability testing on ISS
- MinIon-DNA sequencer
- Air and water microbial sequencing sample preparation
- Air Particle Monitor
- Miniature air monitor
- Spacecraft Atmosphere Monitor (SAM)
- Potable Water Total Organic Carbon Analyzer
- Spacecraft Water Impurities Monitor (SWIM)
- Acoustic monitors, low mass acoustic materials, and quiet fan modeling

FIRE SAFETY

- Anomaly Gas Analyzer
- Water Spray mist fire extinguisher
- Smoke cleanup device
- Improved realistic fire training
- Saffire VI on Cygnus – ug (varies ~2000-3700 cm^2)
- CLPS partial-g (~150 cm^2)
- Blue Origin partial-g (~40 cm^2)
- Partial gravity drop tower spin test and development of non-spin capability


Drop tower spin rig


Combustion Product Monitor

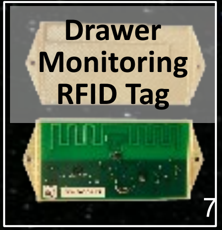

Saffire-VI (planned)

LOGISTICS

- Trash Compactor Processing System (TCPS)
- Trash-to-gas / OSCAR
- RFID Enabled Autonomous Logistics Management (REALM)
- Long wear clothing / laundry
- In-flight disinfectant solution generation for reusable wipes
- ISS Bishop airlock jettison bag
- Exploration trash jettison trade study
- Lunar vacuum cleaner testing


REALM-2 on Astrobee


TCPS Tile


Drawer Monitoring RFID Tag

Advanced Habitation Systems – Examples of Current Investments (2/2)

(There are many SBIR/STTR/ECI/ECF/CIF/STRG investments supporting lower TRL innovation not list below)

SPACESUIT PHYSIOLOGY

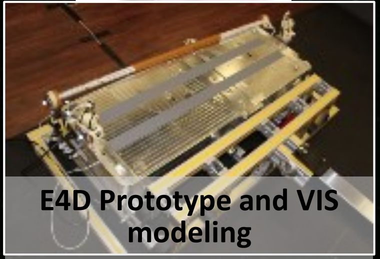
- Suit-independent analytics tool
- Suit user injury tracking system
- MEDPRAT
- Contingency CO_2 limits
- Crew state model & risk tool
- Physical & cognitive EVA simulations
- Personalized EVA informatics and decision support
- JARVIS informatics display
- Exploration Atmospheres pre-breathe validation
- Decompression sickness risk tool

Suit-human load modeling

Real-time NBL-suit expired CO2 informatics

COUNTER-MEASURES

- Exploration exercise device (E4D) development
- Vibration isolation systems
- No-Treadmill (T2) exercise ISS evaluation
- EVA muscle/aerobic standards
- EPIC informatics tools
- Heart rate/blood pressure/OCT monitors
- In-flight sensorimotor balance trainer validation
- In-flight bone assessment

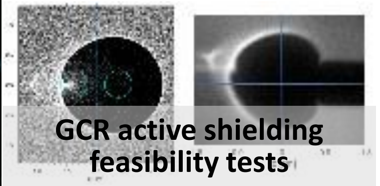


E4D Prototype and VIS modeling

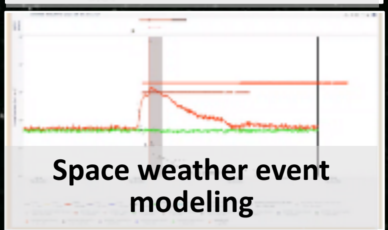
RADIATION PROTECTION

- Lunar/Mars space weather forecasting
- Solar particle event (SPE) forecasting ML
- HERMES Gateway suite
- Orion-HERA
- EVA-ARD
- Active electrostatic shielding modeling study
- ISS-RAD and Adv Neutron Spectrometer
- Bio-dosimetry Polaris Project

HERA



GCR active shielding feasibility tests



Space weather event modeling

EXPLORATION MEDICAL

- Impact analysis tool
- Exploration medical risk database
- Medical levels of care tool
- Handheld microscope
- Multi Med device
- Mini IntraVenous-fluid Generation (mini-IVGen)
- HoloLens MedTED
- Integrated Sim test bed
- Exploration Formulary
- Stability/toxicity study
- Automated med inventory tool dev
- CHP Integrated Data Architecture

FOOD & NUTRITION

- Crew Health And Perform-ance Analog (CHAPEA)
- Ohalo/ROSbio plant growth facility
- Hurdle processing/ storage/temp study
- BPS crop evaluations
- CUBES & Synthetic Bio
- NextSTEP Xroots aeroponics
- Deep Space Food Challenge

CHAPEA

Synthetic nutrient production

Advanced Habitation Systems – SCLT Top Priorities – indicated by white text

(Gray text goals are still important but not a top priority)

LIFE SUPPORT

- Reliable long-duration life support with Earth independent diagnostics and repair (L,T,M)
- >20% reduction in spares and installed mass (T)
- Enable single missions >800 days w/o resupply (T)
- Repeated missions with >9 months dormancy (L,T,M)
- >75% oxygen recovery at 2 mm-Hg CO_2 (T)
- High pressure oxygen recharge for EVA (L,M)
- >98% water recovery (L,T,M)
- Remove respirable lunar and Mars dust (L,M)
- Planetary protection compatible ECLSS venting (M)

ENVIRONMENTAL MONITORING

- Identify and quantify chemical (>12 water, >33 air) and microbial species in-mission with out sample return (L,T,M)
- Ability to detect unknown constituents (T,M)
- Distinguish between fire, habitat dust, and surface dust particles (L,M)
- Support forward and backward planetary protection detection (both microbial and non-DNA techniques) (M)

FIRE SAFETY

- Test-verified partial gravity flammability characteristics and countermeasures (L,M)
- ECLSS compatible fire suppression (L,T,M)
- Reduce post fire clean-up time (L,T,M)
- Common fire safety strategy across element architectures (L,T,M)

LOGISTICS

- Jettison >90% of trash mass during Mars transit (T)
- Mars trash disposal compatible with planetary protection (M)
- In-flight autonomous logistics (L,T,M)
- Reducing clothing and wipes mass by >50% (L,T,M)
- Clothing flammability (and other non-metallics) >36% O2 (L,M)

SPACESUIT PHYSIOLOGY

- 100% of tasks within human performance (L,T,M)
- Predict and mitigate decompression sickness for surface EVA (L,M)
- Predict and mitigate suited injury (L,M)
- 6 Major physiological informatics parameters provided in-suit to enable real time self-assessment or loss of communication areas (L,M)

COUNTER-MEASURES

- Reduce mass and volume (L,T,M)
- Maintain/monitor fitness in-flight to enable unassisted landing egress & EVA (L,T,M)
- Validated lunar and Mars fitness standards (L,M)

RADIATION PROTECTION

- 24-hr prediction of solar storm duration and intensity to >90% (L,T,M)
- High energy neutron detectors (L,T,M)
- Earth independent monitoring/forecasting (T,M)
- GCR shielding (T,M) – active shielding feasibility study

EXPLORATION MEDICAL

- In-mission diagnostics and treatment for 100 of 120 medical risk conditions (L,T,M)
- Autonomous medical skill and & decision support systems (T, M)
- Integrated data architecture (L,T,M)

FOOD & NUTRITION

- 100% of nutrient stability >5-year shelf life (T,M)
- Food acceptability >90% (L,T,M)
- <30% launched water content (T,M)
- Exploration counter-measure in-mission nutrition intake monitoring (L,T,M)

Acronyms

- AHS – Advanced Habitation Systems
- ARD – Active Radiation Dosimeter
- CHAPEA – Crew Health and Performance Analog
- CHP – Crew Health and Performance
- CIF – Center Innovation Fund
- CM – Counter Measures
- E4D – Exploration Exercise Device
- ECI – Early Career Initiative
- ECF – Early Career Faculty
- ECLS - Environmental Control and Life Support
- ECLSS – Environmental Control and Life Support System
- EPIC – Exercise and Performance Information Console
- EVA – Extravehicular Activity
- GCR – Galactic Cosmic Rays
- HEPA – High Efficiency Particulate Air
- HERA - Hybrid Electronic Radiation Assessor
- HERMES - Heliophysics Environmental and Radiation Measurement Experiment Suite
- ISRU – In-situ Resource Utilization
- ISS – International Space Station
- IVGen – IntraVenous Generation
- JARVIS – Joint Augmented Reality Visual Informatics System
- MEDPRAT - Medical Extensible Dynamic Probabilistic Risk Assessment Tool
- MedTED – Medical Technology Demonstration
- ML – Machine Learning
- NBL – Neutral Buoyancy Laboratory
- OCT - Optical coherence tomography
- OSCAR - Orbital Syngas/Commodity Augmentation Reactor
- POS – Probability of Sufficiency
- RAD - Radiation Assessment Detector
- REALM – RFID Enabled Autonomous Logistics Management
- SAM – Spacecraft Atmosphere Monitor
- SBIR – Small Business Innovative Research
- SCLT – System Capability Leadership Team
- SPE – Solar Particle Event
- STRG – Space Technology Research Grants
- STTR – Small Business Technology Transfer
- SWIM – Spacecraft Water Impurities
- TCPS – Trash Compactor Processing System
- TRL – Technology Readiness Level

EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

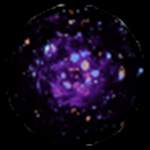
LIVE: In Situ Resource Utilization
NASA Space Technology Mission Directorate
May 2022

STMD welcomes feedback on this presentation
See RFI 80HQTR22ZOA2L_LIVE at nspires.nasaprs.com for how to provide feedback
If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

LIVE: Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities

Scalable ISRU production/utilization capabilities including <u>sustainable commodities</u> on the lunar & Mars surface*

Commercial Scale Water, Oxygen, Metals & Commodity Production



- Lunar resources mapped at meter scale for commercial mining
- 10's of metric tons of commodities per year for initial goal commercial usage
- Scalable to 100's to 1000's metric tons per year

Commodities for Habitats & Food Production

- Water, fertilizers, carbon dioxide, and other crop growth support
- Crop production habitats and processing systems
- Consumables for life support , EVAs, and crew rovers/habitats for growing human space activities

In Situ Derived Feedstock for Construction, Manufacturing, & Energy

- Initial goal of simple landing pads and protective structures
- 100's to 1000's metric tons of regolith-based feedstock for construction projects
- 10's to 100's metric tons of metals, plastics, and binders
- Elements and materials for multi-megawatts of energy generation and storage
- Recycle, repurpose, and reuse manufacturing and construction materials & waste

Commodities for Commercial Reusable In-Space and Surface Transportation and Depots

- 30 to 60 metric tons per lander mission
- 100's to 1000's metric tons per year of for Cis-lunar Space
- 100's metric tons per year for human Mars transportation

<u>All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.</u>

*Commodities are items and consumables that can be eventually sold

In Situ Resource Utilization (ISRU) Capability – *'Prospect to Product'*

ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create commodities* for robotic and human exploration and space commercialization

Destination Reconnaissance & Resource Assess

Assessment and mapping of physical, mineral, chemical, and water/volatile resources, terrain, geology, and environment

Resource Acquisition, Isolation, & Preparation

Atmosphere constituent collection, and soil/material collection via drilling, excavation, transfer, and/or manipulation before Processing

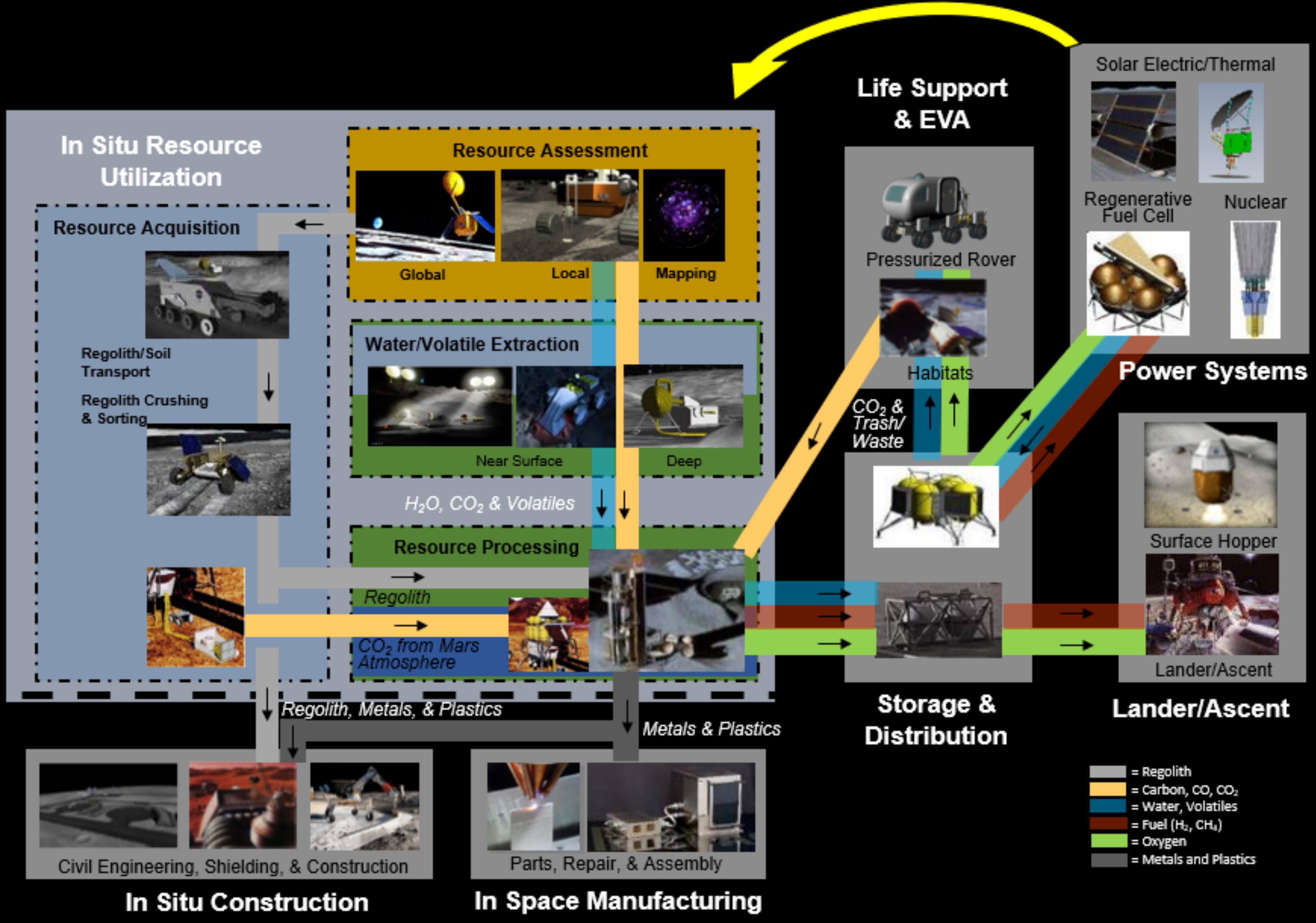
Resource Processing

Chemical, thermal, electrical, and or biological conversion of acquired resources and intermediate products into

- Mission Consumables
- Feedstock for Construction & Manufacturing

Water/Volatile Extraction

A subset of both Resource Acquisition and Processing focused on water and other volatiles that exist in extraterrestrial soils



- **ISRU is a capability involving multiple disciplines and elements to achieve final products**
- **ISRU does not exist on its own. It must link to users/customers of ISRU products**

*Commodities are items and consumables that can be eventually sold

ISRU Functional Breakdown And Flow Diagram

Destination Reconnaissance and Resource Assessment

- Site Imaging/Terrain Mapping
- Instruments for Resource Assessment
- Orbital Resource Evaluation
- Local Surface Resource Evaluation
- Resource/Terrain/Environment Data Fusion and Analyses

Resource Acquisition, Isolation, and Preparation

- Resource Excavation & Acquisition
- Resource Preparation before Processing
- Resource Transfer
- Resource Delivery from Mine Site and Removal

Resource Processing for Production of Mission Consumables

- Resource Storage and Feed To/From Processing Reactor
- Regolith Processing to Extract Oxygen
- Regolith Processing to Extract Water
- Carbon Dioxide Processing
- Water Processing
- Instrumentation to Characterize Processing Performance
- Product/Reactant Separation
- Contaminant Removal from Reagents/Products

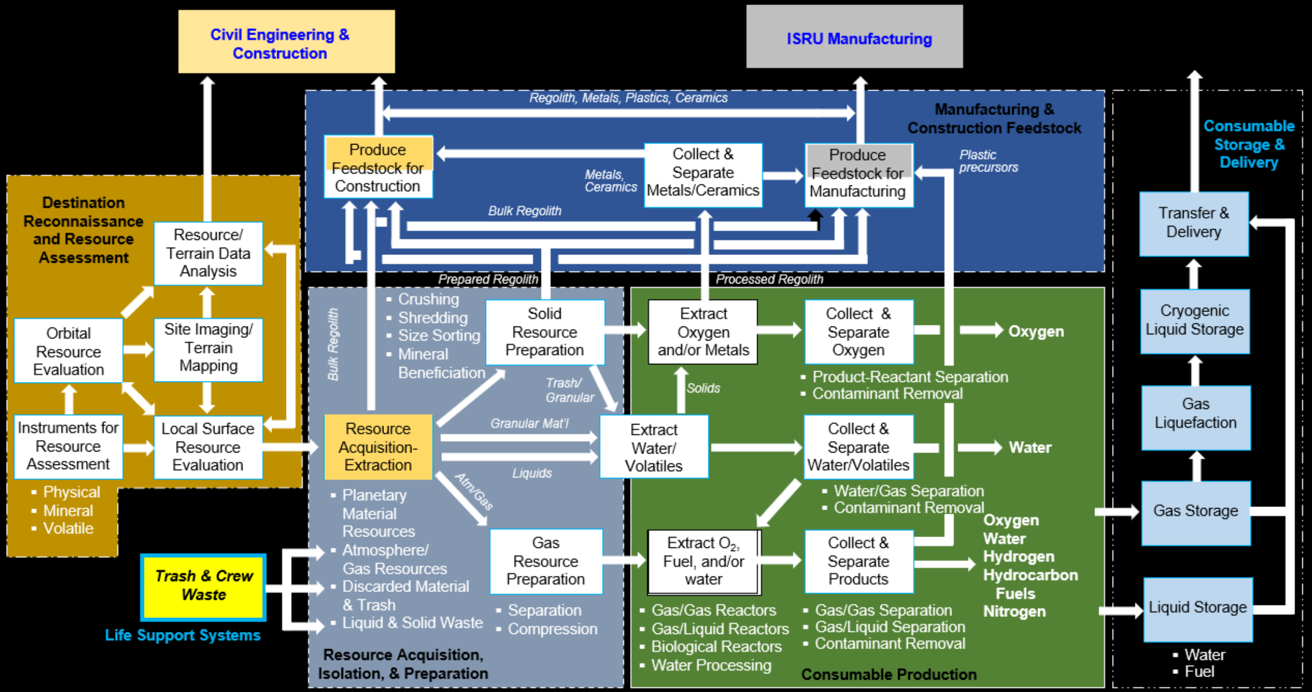
Resource Processing for Production of Manufacturing and Construction Feedstock

- In Situ Excavation and Movement for Construction
- Resource Preparation for Construction Feedstock
- Material transfer
- Resource Processing to Extract Metals/Silicon
- Resource-Trash/Waste Gas Processing to Produce Methane/Plastics

Cross Cutting

- Planetary Simulants for Test & Verification
- Planetary Regolith/Environment Test Chambers

- Functional Breakdown and Flow Diagram used to understand:
  - Technology State of the Art and gaps
  - Connectivity Internally and with other disciplines
  - Influence of technologies on complete system and other functions
- ISRU functions have shared interest with Autonomous Excavation, Construction, & Outfitting (AECO)
  - Destination Reconnaissance
  - Resource Excavation & Delivery
  - Construction Feedstock Production



ISRU Must Operate as Part of A Larger Architecture

P = Provided to ISRU
S = Supplied by ISRU
Italic = Other Disciplines

- Architecture elements must be designed with ISRU product usage in mind from the start to maximize benefits
- Infrastructure capabilities and interdependencies must be established and evolve with ISRU product users and needs
  - Transition from Earth-supplied to ISRU-supplied

Power:
- Generation, Storage, & Distribution (P)
- ISRU-derived electrical /thermal (S)

Advanced Power Systems

Transportation to/from Site:
- Delivery (P)
- Propellants & Depots (S)

Advanced Propulsion
Entry Descent and Landing

Communications & Navigation (P)
- To/From Site
- Local

Adv. Communication & Navigation

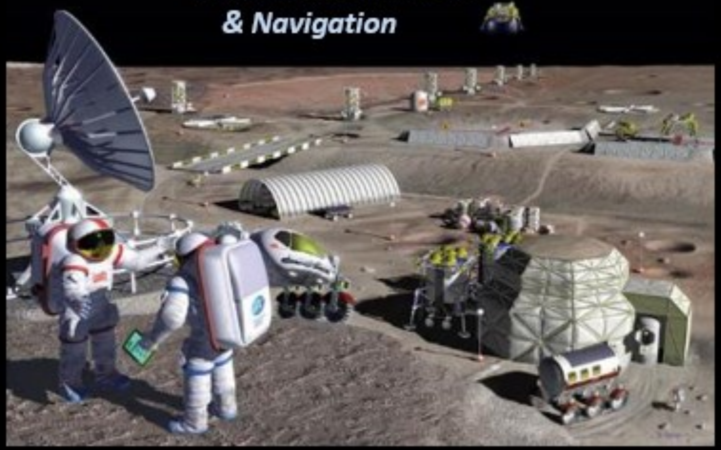
Maintenance & Repair

Logistics Management
- Replacement parts (P)
- Feedstock (S)

In Space/Surface Manufacturing

ISRU

Coordinated Mining Ops:
Areas for:
i) Excavation
ii) Processing
iii) Tailings
iv) Product Storage

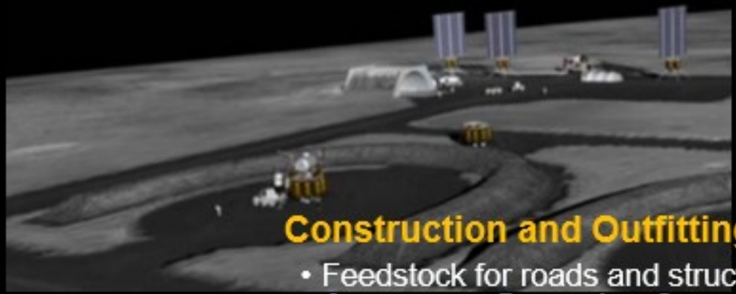


In situ Instruments/Sensors
Autonomous Systems
Adv. Thermal Management

Living Quarters & Crew Support Services
- Water, O_2, H_2, Gases (S)
- Trash/waste (P)
- Nutrients(S)

Commodity Storage and Distribution:
- Water & Cryogenic Fluids (CFM)
- Manufacturing & Construction Feedstock

Cryogenic Fluid Management
Autonomous Systems & Robotics
Autonomous Excavation, Construction, & Outfitting

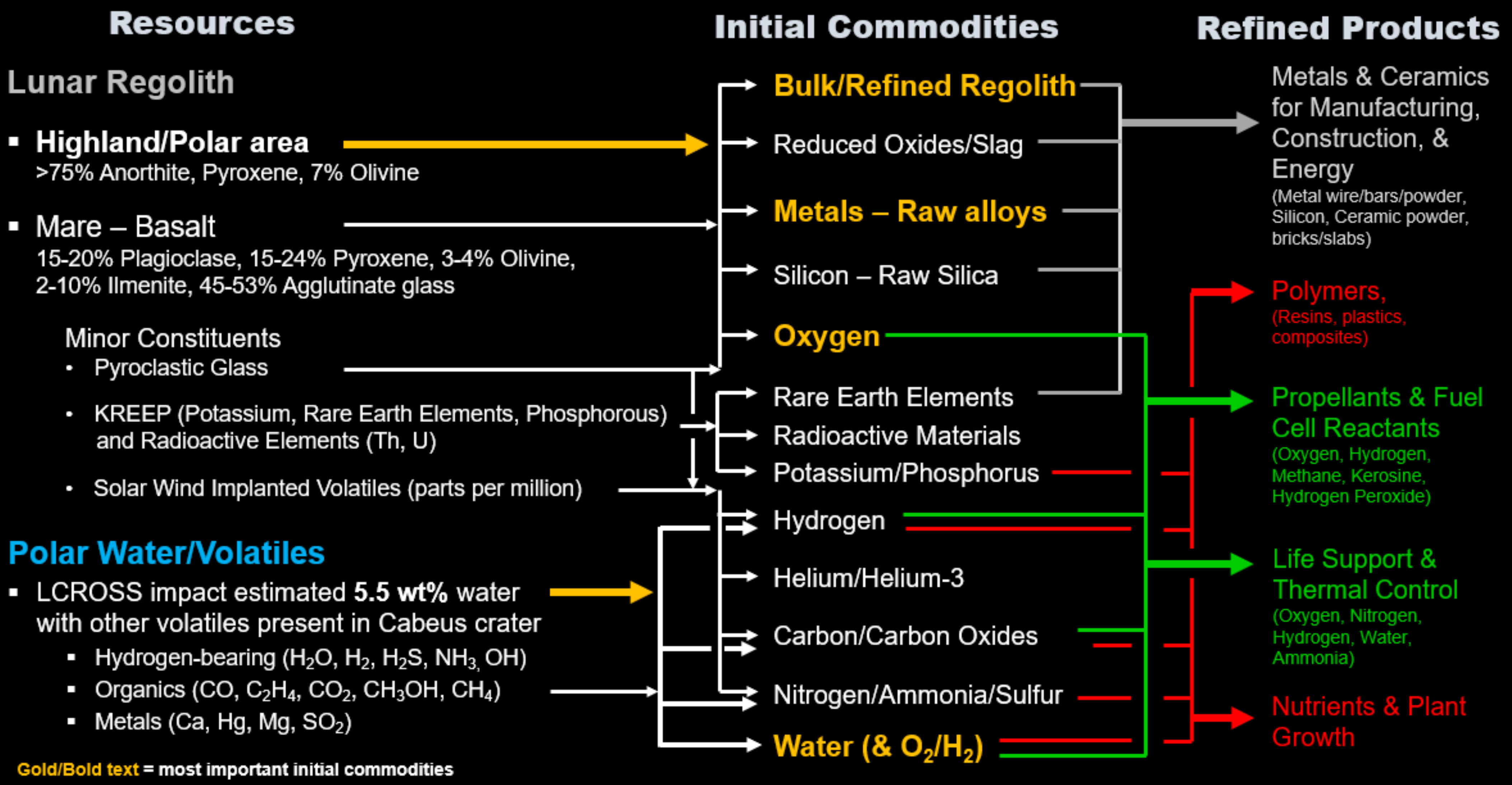


Construction and Outfitting
- Feedstock for roads and structures (S)

Autonomous Excavation, Construction, & Outfitting
Autonomous Systems & Robotics

Lunar Resources and Commodities

- ISRU starts with the easiest resources to mine, requiring the minimum infrastructure, and providing immediate local usage
- The initial focus is on the lunar South Pole region (highland regolith and water/volatiles in shadowed regions)
  – ISRU will evolve to other locations, more specific minerals, more refined products, and delivery to other destinations



Plan to Achieve ISRU Outcome

Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface

- **Know Customer Needs (Type and Quantity of Commodities) & Develop Suppliers**
  - Work with Artemis elements, Moon/Mars Surface Architecture, and International Partners
  - Work with Commodity users: Life Support & Food Production, Propulsion, Manufacturing, Construction
  - Understand all processing system wastes (life support, ISRU, manufacturing, construction) as potential new resource
  - ➢ Work with Terrestrial/Space Industry & Lunar Surface Innovation Consortium for Commercial Involvement & Opportunities

- **Perform Ground Development of Hardware and Systems until Ready for Lunar Flight**
  - Initiate a full range of ISRU & other discipline technologies across all TRLs (Technology Pipeline) to enable ISRU capabilities
  - Perform gravity related research (short duration & ISS) on material handling, resource processing, and feedstock behavior
  - Integrate lunar ISRU technologies and subsystems into systems for environmental and operational testing
  - Develop lunar ISRU components, subsystems, and operations (including autonomy) applicable to Mars ISRU systems
  - ➢ **Engage Industry, Academia, and the Public** to lay the foundation for long-term lunar economic development

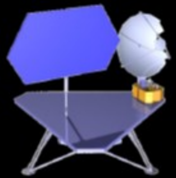
- **Reduce Risk of ISRU for Human Exploration & Space Commercialization thru CLPS Missions**
  - Understand lunar polar resources for technology development, site selection, mission planning (SMD and ESDMD)
  - Obtain critical data (ex. regolith properties, validate feasibility of ISRU processes)
  - Demonstrate critical ISRU technologies in lunar environment, especially those that interact with and process regolith

- **Perform End-to-End ISRU Production of Commodities & Demonstrate Usage**
  - Production at sufficient scale to eliminate risk of Full-scale system
  - Initially use ISRU-derived commodity in non-mission critical application; examples include non-crewed ascent vehicle or hopper, extra fuel cell power, extra crew and EVA oxygen, construction demonstration, etc.
  - ➢ **Involve industry in ISRU Demos and Pilot Plant to transition to Full-scale commercial operations**

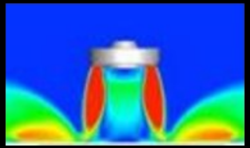
➢ **ISRU must be demonstrated on the Moon before mission-critical applications are possible**
- NASA STMD is breaking the 'Chicken & Egg' cycle of past ISRU development priority and architecture insertion issues by developing and flying ISRU demonstrations and capabilities to the Pilot Plant phase

Near-Term Envisioned Future:
Evolve from STMD Demonstrations to Sustained Lunar Surface Operations

STMD Leads *Individual* Technology Development and Flight Demonstrations


ISRU Demo & Pilot Plant


ISRU Pilot Excavator



Precision Landing (SPLICE) & Plume Surface Interaction

Cryo Fluid Management TP & Flight Demos

Autonomous Robotics, LIDAR, and Navigation

In Situ Construction Demos


Vertical Solar Array Technology (VSAT)

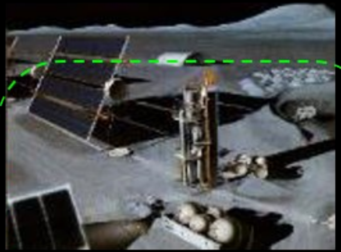

Power Beaming


40 KWe Nuclear Reactor Demo

Regenerative Fuel Cell Power Demo

ESDMD/SOMD Evolve STMD Capabilities into Sustained Artemis Base Camp Infrastructure and Commercial Operations

Large Scale Power Generation & Distribution



Complex, Multi-Element ISRU Operations

Landing Pad & Infrastructure Construction



Cryogenic Consumables & Propellant Depots

Human and Robotic Maintenance & Repair

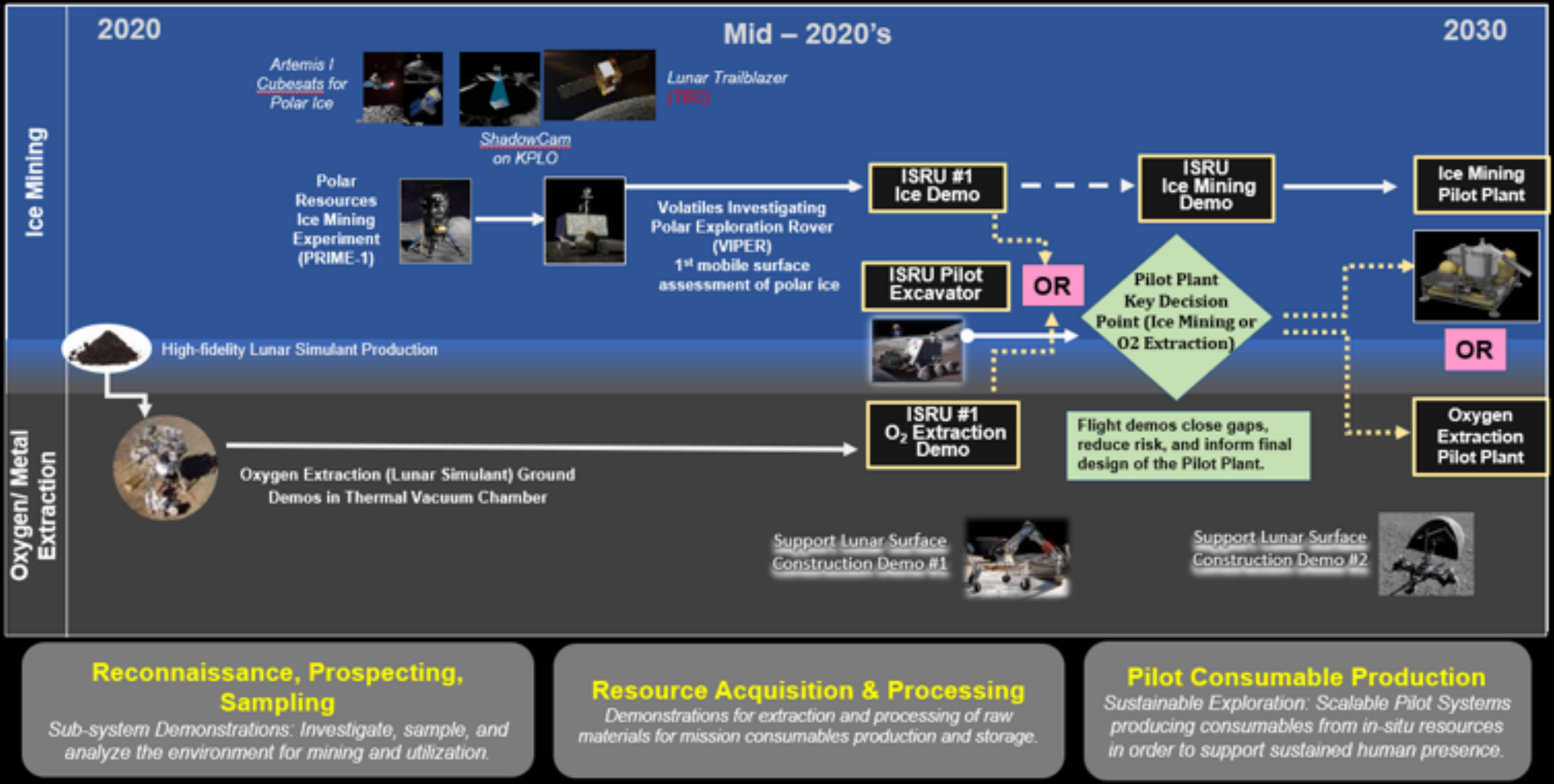


Offloading, Deployment, and Repurposing



Lander, Habitat, and Surface Vehicle Servicing

ISRU Path to Full Implementation & Commercialization



Full-scale implementation & Commercial Operations
(see next chart)

- Dual Path that includes both Water Mining and Oxygen/Metal from Regolith
  - O_2/Metal Path supports Surface Construction as well
- Ground development of multiple critical technologies in both pathways underway to maximize success and industry involvement
- Resource assessment missions to obtain critical data on mineral and water/volatile resources have started
  - PRIME-1 validates critical VIPER instruments and lunar highland material properties (for subsequent ground development)
- Demonstrations are aimed at reducing the risk of Pilot Plant design and operation (and subsequent Full-scale implementation)
  - Pilot Plant demonstrates performance, end-to-end operations, and quality of product for implementation and use

NASA ISRU Capability State of the Art and Current Work

Resource Assessment – Flight Development (TRL 4-6)
- Multiple instruments under development by SMD and STMD for resource collection and assessment
- Instruments to be flown on CLPS missions – PRIME-1 and VIPER for lunar ice characterization

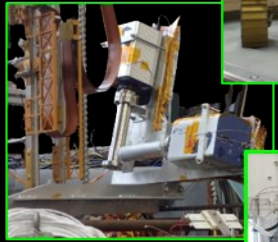
Water Mining – Proof of Concept (TRL 2/3)
- 3 mining approaches and 6 water extraction technologies under development
- Challenges: Space Robotic, Break the Ice Lunar

Oxygen Extraction from Regolith – Engineering Breadboards/Field Test Units (TRL 4/5)
- Two Hydrogen Reduction systems built and tested at Pilot scale; terrestrial operations, non-flight mass/power, mare regolith, days/weeks operation (2008)
- Carbothermal Reduction system with solar concentrator built and tested as Sub-Pilot scale; terrestrial operations, mare regolith, non-flight mass/power, days/weeks operation (2010)
- Carbothermal & Hydrogen Plasma Oxygen extraction methods now reducing Highland simulants under laboratory conditions (TRL 3)

Oxygen/Metal Extraction from Regolith – Laboratory Proof of Concept
- Laboratory type/scale hardware: Molten Regolith Electrolysis (TRL 3/4); Ionic Liquid Reduction (TRL 2/3); International development of Molten Salt Electrolysis-ESA (TRL 3/4) and MRE-Israel (TRL 3/4)
- Bio-mining for oxygen/metal extraction (TRL 2/3)

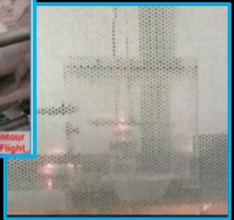
Construction Feedstock (Low TRL: 2-4)
- Feedstock (blends of simulant and plastic) used in manufacturing & construction lab. demonstrations
- Mars concrete and soil/binders demonstrated: ACME & 3D Hab, Construction Centennial Challenge
- Size sorted lunar simulants being used for sintering construction tests
- Ilmenite beneficiation demonstrated on lunar-g aircraft
- 3D printer with simulant feedstock was tested on the ISS in the Additive manufacturing Facility
- Trash-to-Gas as start to conversion to fuels/plastics

Cross Cutting/System Level Resources
- 9 water electrolysis projects in 3 different types (PEM, SOE, Alkaline)
- NASA lunar simulant project initiated; Highland regolith simulant characterization & limited production
- External simulants available for purchase
- NASA Large dirty vacuum chamber almost ready at JSC; 2nd chamber at MSFC being modified



PRIME-1

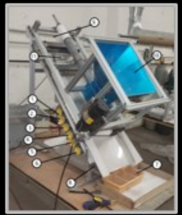
VIPER

LightWAVE

Lunar Auger Dryer ISRU (LADI)

Radiant Gas Dynamic Mining

PILOT H_2 Reduction


Molten Regolith Electrolysis

Carbothermal Reduction

MMOST Size Separation & Beneficiation

JSC 15' Dia. Dirty TVac


Simulants

ISRU Capability Gaps to Achieve Initial Full-Scale Production*

*Estimates from Internal NASA and APL Lunar Surface Innovation Consortium Supply/Demand Workshop 9/17/2020)

Resource Assessment (Lunar Water/Ice) Capability Gaps
- Surface features and geotechnical data on regolith outside and inside permanently shadowed craters (PSRs)
- Understanding of water and contaminants as a function of depth and areal distribution
- Understanding of subsurface water/volatile release with heating
- Resolution of hydrogen and subsurface ice at <10s m scale (or less) for economic assessment & mine planning (orbital/surface)
- Instrument for polar regolith sample heating and released volatile characterization (minimum loss during transfer/evaluation)

Water Mining Capability Gaps
- Feasibility and operation of downhole ice/water vaporization and collection in cold-trap under lunar PSR conditions
- Feasibility and operation icy regolith transfer (low loss) and processing in reactor under lunar PSR conditions; min. 15,000 kg/yr; 3 years nom.
- Water and other volatile capture and separation; contaminant removal
- Electrical power & Thermal energy in PSRs for ice mining/processing (10s of KWs) – *Power System Gap*

Oxygen Extraction Capability Gaps
- Industrial-scale of regolith processing for oxygen (minimum of 10 mT O_2/yr; 3 years nom. with min./no maintenance)
- Regenerative oxygen & product gas clean-up (10,000 kg/yr)
- Measuring mineral properties/oxygen content before and after processing

Manufacturing & Construction Feedstock Capability Gaps
- Metal and metal alloy extraction from regolith: Post oxygen extraction or separate/multi-step refining
- Crushing, size sorting and mineral beneficiation of 100s mT per project for extraction and manufacturing/construction feedstock
- Production of 10s mT per project of plastic/binders and cement for manufacturing and construction

Regolith Excavation, Handing, & Manipulation Capability Gaps
- Long-life, regolith transfer (100s of mT) and low leakage regolith inlet/outlet valves for processing reactors (10s of thousands of cycles)
- Excavation and delivery of granular regolith (O_2/Metal) and icy regolith (Water Mining) – *Autonomous Excavation, Construction, & Outfitting (AECO)*
- Extensive Traversibility (100s of km in sunlit and PSR locations and ingress/egress – *Autonomous & Robotic Systems Gap*

Cross-Cutting/System Level Resource Gaps
- Gravity-related research (short duration & ISS) to better understand impact on material handling, resource processing, and feedstock behavior
- Long-duration (100s of days) and Industrial-scale (10s of mT) operations under lunar vacuum and at <100 K temperatures
- Sensors and autonomous process monitoring and operations
- Industrial-scale water electrolysis water electrolysis, clean-up, and quality measurement for electrolysis or drinking (10s of mT/yr)

ISRU Commodity Production Investment Status (1 of 2)

- **Develop Critical Technologies for Lunar Oxygen Extraction**
  - ☑ Close coordination with Autonomous Excavation, Construction, and Outfitting (AECO) on excavation and delivery
  - ☑ 6 different O_2 extraction technologies in development
  - ☑ 9 development projects for 3 different water electrolysis approaches (with Life Support and Regenerative Power)
  - ☐ Interface and internal technologies/functional areas require further investment
- **Develop Critical Technologies for Lunar Resource Assessment and Water Extraction**
  - ☑ Significant number of SMD and STMD instrument technologies for resource assessment down to 1 m.; University/Public Challenges
  - ☒ Need to consider technologies for deeper >3 m assessment for water/volatiles based on some water deposit theories
  - ☑ Close coordination with AECO on excavation in Permanently Shadowed Regions (PSRs); Break the Ice Lunar Challenge
  - ☐ 6 water mining development projects for 3 different approaches
  - ☑ 9 development projects for 3 different water electrolysis approaches (with Life Support and Regenerative Power)
  - ☐ Interface and internal technologies/functional areas require further investment
  - ☒ No dedicated robotic polar water/volatile resource assessment surface missions beyond VIPER currently in planning
  - ☒ No dedicated funded effort to develop resource maps for site selection
- **Develop Critical Technologies for Manufacturing and Construction Feedstocks/Commodities**
  - ☐ Technologies for raw metal/alloy extraction in work as part of O_2 extraction; work required to further separate and refine metals
  - ☐ Technologies for regolith size sorting, mineral beneficiation, and regolith manipulation in work
  - ☐ Development and evaluation feedstocks to support manufacturing and construction techniques
  - ☒ Limited plastic/binder production from in situ resources; synthetic biology technologies in work for bio-plastic and some commodity feedsocks
- **Evaluate and Develop Integrated Systems for Extended Ground Testing; Tie to Other Discipline Plans**
  - ☑ NASA and APL performed/performing ISRU system evaluations
  - ☐ Dedicated modeling, evaluation criteria, and Figures of Merit (FOMs) established
  - ☐ Approach/approval for NASA and/or Industry-led System development and testing
  - ☑ Facilities and simulants to support lunar environmental testing with regolith simulants
  - ☐ Facilities and approach for extended mission analog operation and evaluation ground testing

Green = Significant Funded Activities
Yellow = Partially Covered; More Required
Red = Limited/No Funded Activities

ISRU Commodity Production Investment Status (2 of 2)

- **Develop/Fly Resource Assessment & ISRU Demonstrations Missions leading to Pilot Plant operations by 2030**
  - ☑ Orbital missions, PRIME-1, & VIPER funded and under development for launch
  - ❑ Lunar Trailblazer launch date and mission data later than desired. Actual spacecraft ready for launch in 2022
  - ☒ No clear plan for polar water/volatile resource assessment leading to Base Camp site selection – predicated on success of VIPER
  - ❑ At least one demonstration planned for each ISRU commodity path

- **Involve Industry/Academia with Goal of Commercial Space Operations at Scale**
  - ☑ 25, NIACs, SBIRs, BAAs, ACOs, & TPs led by industry underway for ISRU
  - ☑ 9 STTRs, NIACs, LuSTR, NSTRF, ESI/ECF led by Academia underway for ISRU
  - ☑ Lunar Surface Innovation Consortium – ISRU Focus Group underway and active; Supply/Demand Workshop
  - ☑ Center for the Utilization of Biological Engineering in Space (CUBES)
  - ☑ NASA prize competitions and university challenges: BIG Idea, Moon-Mars Ice Prospecting, Break the Ice Lunar, Lunabotics, CO_2 Conversion Challenge, Space Robotics Challenge
  - ❑ Selection/Competition strategy for ISRU demonstrations and Pilot Plant in work for industry involvement and commercialization

Green = Significant Funded Activities
Yellow = Partially Covered; More Required
Red = Limited/No Funded Activities

ISRU Commodity Production Summary and Next Step Priorities

- **Complete Development of Water/Oxygen Mining Paths and Close Technology Gaps**
  - Continue oxygen extraction of Highland regolith
  - Continue water extraction/mining approaches in parallel until mission data allows for down-selection
    - Work with life support on oxygen and water cleanup technologies and requirements
- **Expand Development of Metal/Aluminum Extraction & other Feedstock for Manufacturing & Construction**
  - Continue and expand work on combined oxygen and metal extraction technologies;
  - Initiate work focused on metal extraction and processes leading to more pure/refined metals
  - Consider wider range of regolith options: Mare regolith, Pyroclastic Glasses, and KREEP
  - Continue and expand construction feedstock/commodity development with in-space manufacturing and construction
  - Evaluate synthetic biology technologies for bio-mining, bio-plastic, and some commodity feedstocks
- **Coordinate Polar Resource Assessment with SMD and ESD/SOMD for Artemis Base Camp site selection**
- **Initiate Internal and Industry-led System-level integration of ISRU and infrastructure capabilities**
  - Expand ISRU system engineering, modeling, integration, and testing to enable technology and system selections
  - Begin combining power, excavation, ISRU, storage & transfer, comm/nav, autonomy/avionics, maintenance/crew.
- **Initiate solicitations with Industry to progress ISRU technologies to Demonstration & Pilot-scale flights**
  - Pursue oxygen and metal extraction demonstrations; delay water mining demonstration until better knowledge is obtained
  - Provide feedstock technologies and capabilities to support construction demonstrations

Acronyms

- ACME - Advanced Construction with Mobile Emplacement
- ACO - Announcement of Collaborative Opportunity
- Adv. - Advanced
- AECO - Autonomous Excavation, Construction, & Outfitting
- Al - Aluminum
- BAA - Broad Agency Announcement
- BIG Idea - Breakthrough, Innovation, and Game-changing
- BRACES - Bifurcated Reversible Alkaline Cell for Energy Storage
- Ca - Calcium
- CFM - Cryogenic Fluid Management
- C2H4 - Molecular formula for ethylene
- CH4 - Molecular formula for methane
- CH3OH - Molecular formula for methanol
- CIF - Center Innovation Fund
- CLPS - Commercial Lunar Payload Services
- CO - Molecular formula for carbon monoxide
- CO2 - Molecular formula for carbon dioxide
- COPR - Carbothermal Oxygen Production Reactor
- CY - Calendar Year
- Demo - Demonstration
- Dia - Diameter
- ECF - Early Career Faculty
- ESI - Early Stage Innovation
- EVA - Extra Vehicular Activity
- FLEET - Fundamental Regolith Properties, Handling, and Water Capture
- FY - Fiscal Year
- G - Gravity
- GRC - Glenn Research Center
- H2 - Molecular formula for hydrogen
- H2O - Molecular formula for water
- H2S - Molecular formula for hydrogen sulfide
- Hg - Mercury
- ICICLE - ISRU Collector of Ice in a Cold Lunar Environment
- IHOP - ISRU-derived H2O Purification and H2-O2 Production
- IL - Ionic Liquid
- ISRU - In Situ Resource Utilization
- ISS - International Space Station
- JPL - Jet Propulsion Laboratory
- JSC - Johnson Space Center
- K - Kelvin temperature
- kg/yr - Kilograms per year
- KPLO - Korean Pathfinder Lunar Orbiter
- KREEP - Potassium (K), Rare Earth Elements, Phosphorous
- KSC - Kennedy Space Center
- KWe - Kilowatt electric
- LADI - Lunar Auger Dryer ISRU
- LCROSS - Lunar Crater Observation and Sensing Satellite
- LIDAR - Light Detection and Ranging
- LIRA - Lunar In-situ Resource Analysis
- LightWAVE - Light Water Analysis and Volatile Extraction
- LP3 - Lunar Propellant Production Plant
- LuSTR - Lunar Surface Technology Research
- LSII - Lunar Surface Innovation Initiative
- Lunar WETS - Lunar Water Extraction Techniques and Systems
- M - Meter
- Mat'l - Material
- min. - Minimum
- MMOST - Moon to Mars Oxygen and Steel Technology
- MRE - Molten Regolith Electrolysis
- MSFC - Marshall Space Flight Center
- mT - Metric Tonne
- NASA - National Aeronautics and Space Administration
- NIAC - NASA Innovation Advanced Concepts
- nom. - Nominal
- NH3 - Molecular formula for ammonia
- NSTRF - NASA Space Technology Research Fellowship
- O2 - Molecular formula for oxygen
- O2/yr - oxygen per year
- OH - Molecular formula for hydroxyl
- PEM - Proton Exchange Membrane
- PILOT - Precursor ISRU Lunar Oxygen Testbed
- PRIME - Polar Resources Ice Mining Experiment
- PSR - Permanently Shadowed Region
- SAA - Space Act Agreement
- SBIR - Small Business Innovation Research
- SO2 - Molecular formula for sulfur dioxide
- SOE - Solid Oxide Electrolysis
- SMD - Science Mission Directorate
- SPLICE - Safe and Precision Landing – Integrated Capabilities Evolution
- STMD - Space Technology Mission Directorate
- STTR - Small business Technology Transfer
- Th - Thorium
- TP - Tipping Point
- TRL - Technology Readiness Level
- TVac - Thermal vacuum
- U - Uranium
- VIPER - Volatiles Investigating Polar Exploration Rover
- VSAT - Vertical Solar Array Technology
- wt% - Weigh percent

EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

LIVE: Power and Energy Storage Systems
NASA Space Technology Mission Directorate
May 2022

STMD welcomes feedback on this presentation
See RFI 80HQTR22ZOA2L_LIVE at nspires.nasaprs.com for how to provide feedback
If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

ADVANCED POWER SYSTEMS SUPPORT MULTIPLE STRATEGIC OUTCOMES AND REQUIRE SUPPORT

Primary outcome supported: "Sustainable power" under "LIVE" thrust.

Secondary outcome supported: "Platform Technologies" under "EXPLORE" thrust

Go *Rapid, Safe, & Efficient Space Transportation*	• Develop nuclear technologies enabling fast in-space transits. • Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications. • Develop advanced propulsion technologies that enable future science/exploration missions.
Land *Expanded Access to Diverse Surface Destinations*	• Enable Lunar/Mars global access with ~20t payloads to support human missions. • Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies. • Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards.

Live
Sustainable Living and Working Farther from Earth
	• Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities
	  • Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.
	  • Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface.
	  • Technologies that enable surviving the extreme lunar and Mars environments.
	  • Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources.
	• Enable long duration human exploration missions with Advanced Life Support & Human Performance technologies.

Explore *Transformative Missions and Discoveries*	• Develop next generation high performance computing, communications, and navigation. • Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions. • Develop technologies supporting emerging space industries including: Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft technologies. • Develop vehicle platform technologies supporting new discoveries.

Led by Advanced Propulsion PT TX 2.0

Power PT

TX 3.0 Power and Energy Storage

Envisioned Future - *LIVE*

Sustainable Living and Working Further from Earth

Developing sustainable power sources and other surface utilities to enable continuous Lunar and, ultimately, Mars surface operations.

Power Generation

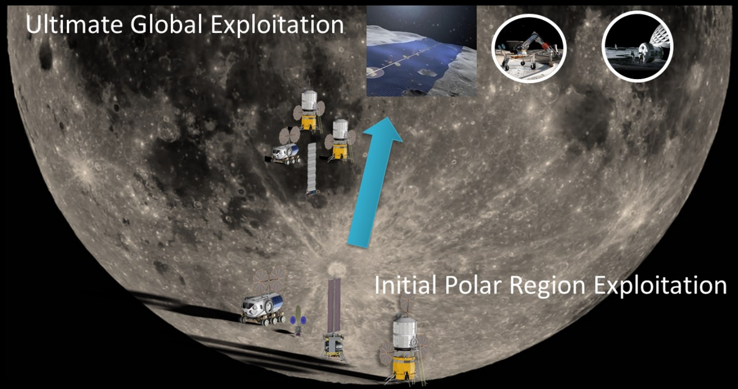
- Up to 50 kW_e-class modular Earth-sourced Photovoltaic Arrays for Lunar Polar surface outposts and ISRU prospecting/production plants.
- 40 kW_e-class mobile Fission Power Systems to support Lunar Polar operations, bootstrap a global Lunar surface power grid to support Lunar industrialization at lower latitudes, and support Mars surface exploration

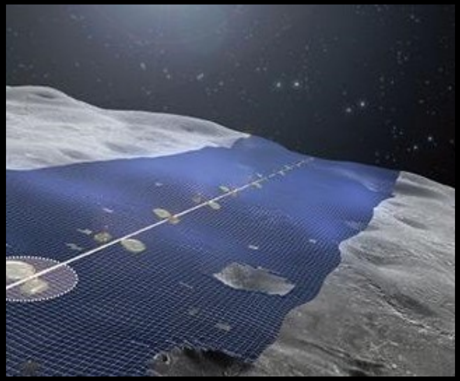
Energy Storage

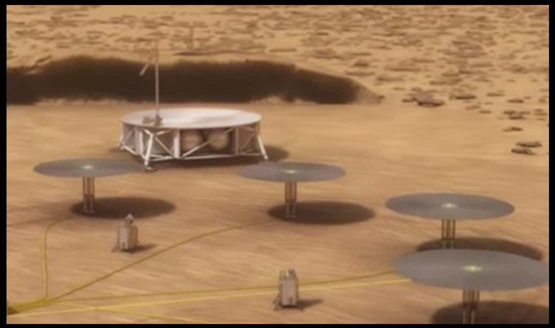
- Up to 50 kW_e-hr Secondary Batteries for mobility
- Up to 1 MW_e-hr Regenerative Fuel Cells for Polar Outpost/ISRU energy storage
- Large scale energy storage systems gathered from Lunar-sourced minerals

Power Distribution

- 1000 V, radiation-hard, high reliability power electronics
- Up to 10 kW_e–class low mass Cables and spools for multi-km power distribution grids
- Up to 10 kW_e-class Power Beaming for up to 5 km line-of-sight.
- High power, long distance transmission lines printed from Lunar-sourced aluminum.







All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.

Envisioned Future: Gaps to Close to Enable Outcomes

LIVE: Sustainable Power

	Gap	Polar Ice Mining	Polar Regolith O_2	Global Regolith Mining
A	Mobile Fission Surface Power	●	●	●
B	Reliable, Rad-Hard Power Electronics*	●	●	●
C	Transmission Cable Systems	●	●	●
D	Photovoltaic Arrays	●	●	●
D	Long Life, Grid-Scale Secondary Energy Storage	●	●	●
E	Wireless Power Transmission*	●		●
E	Dynamic Conversion for Radioisotope GPHS*	●		
E	Low Temperature Secondary Battery Modules*	●		
F	CH_4/O_2 Primary Fuel Cell Power			

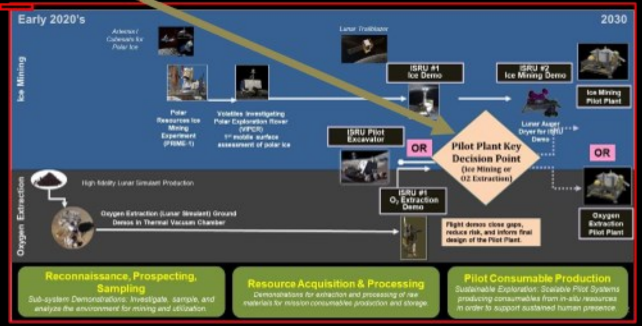
* *Also supports "EXPLORE: Platform Technologies"*

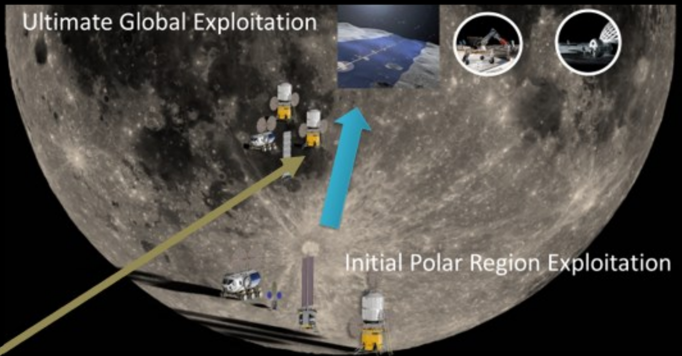
Needed for:
- Polar Ice Mining ● (blue)
- Polar Regolith O_2 ● (red)
- Global Regolith Mining ● (green)

"Killer App" for highest priority LIVE gap closures is support to industrial-scale Lunar ISRU production and construction in the early 2030's at the South Pole and expansion toward the equator 2035+
- *Mission architects need to know what capabilities will be available when*

Overall sustainable power gap priorities are affected by a key decisions related to Lunar resource extraction:
- ~2026: Will initial industrial-scale capability at the South Pole focus on ice mining in PSRs or extracting oxygen from regolith in insolated regions?
- ~2030's: Will power demand away from the Pole grow beyond the capability of Earth-launched assets?

ISRU Pilot Plant Key Decision 2026: Ice Mining vs. Regolith O_2





Global power grid planning: 2030

Gap A: Fission Surface Power

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.1.2.1, 3.1.4.1

Definition: No multi-kW_e-scale power sources have been developed to be capable of providing sun-independent, mobile power on the Lunar or Martian surface. Such power is needed not only to supplement solar power for sustainable operations on the Lunar pole but also to bootstrap the printing of power system components from Lunar regolith as infrastructure expands toward lower latitudes.

SOA: Though fission reactors have been operated on Earth land and sea for many decades, no reactors have been operated in space since the Soviet Topaz I (~5 kW_e) flight in 1988. The Soviet TOPAZ II development unit (~6 kW_e) was briefly ground tested in the US in 1994. A space fission reactor development unit (~ 1 kW_e) was tested in the US in 2018.

CURRENT INVESTMENTS

NASA:

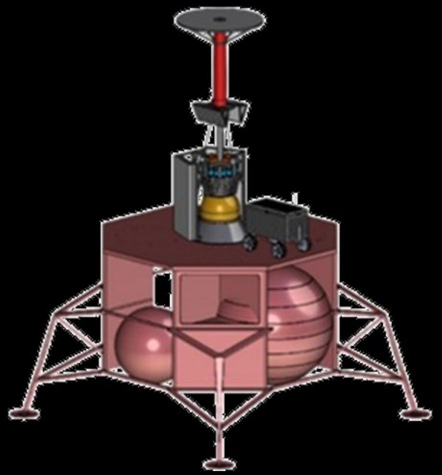
- Energy Conversion
  - *SBIR/STTRs (Stirling, Brayton, ATEG, Heat Ex, Radiators)*
- Radiation Shielding
  - *SBIR (materials)*
- Systems
  - *TMD (FSP)*
-

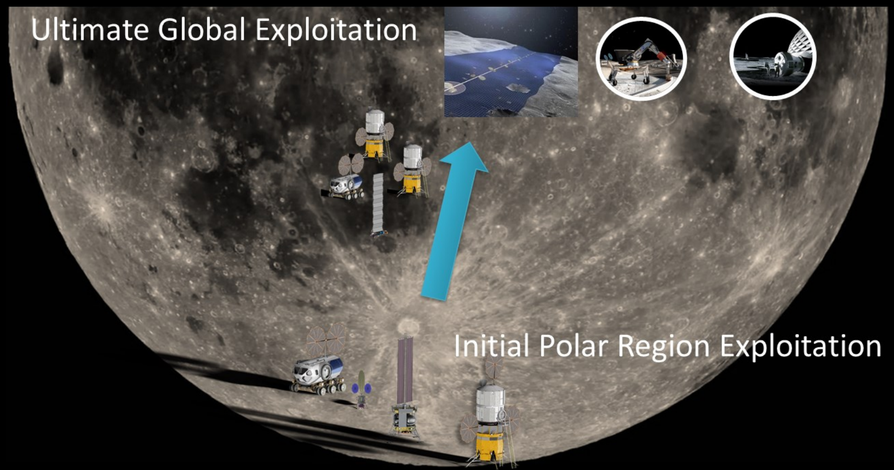
OGA

- Nuclear fuels
  - DoE SMR
  - DoD Project Pele

CLOSURE:
Bring to TRL 6 a 40 kW_e-class mobile fission power system suited for the Lunar polar environment in time to support a TDM on the Moon in 2028. Lower power (e.g., 10 kW_e) units may be developed for Mars.

CLOSURE PLAN:
- Complete NASA TDM FSP Project





Gap B: Reliable, Rad-Hard Power Electronics

Thrust: **LIVE**
Outcomes: **Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations**
Taxonomy Elements: **3.3.1, 3.3.3, 3.3.4**

Definition: SOA power management and control electronics do not provide sufficient reliability and durability to support full scale ISRU operations in the Lunar Pole thermal, dust , and radiation environment and are not maintainable in that environment. Mission architects must know what capability will be available to them once full-scale ISRU production operations are to start in the 2030s

SOA: Power electronics of sufficient reliability for current missions are at TRL 9 for near Earth, geosynchronous, and deep space missions at <200 V.

CURRENT INVESTMENTS

NASA:

- Materials:
  - *SBIRs (SiC, Ga_2O_3, shielding)*
  - *LuSTR grant (SiC)*
- Circuitry and Devices
  - *SBIR (switches)*
  - *STTR (controller)*
  - *LuSTR grant (router)*
  - *GCD TP (Apogee RPCD)*
  - *GCD TP (TYMPO)*
  - *GCD TP (BDPA)*
  - *GCD TP (MIPS)*
- Dust compatibility
  - *GCD (LO-DuSST)*

OGA (DoD & DoE):

- Materials & Devices

CLOSURE:

Bring to TRL 6 by 2030 a suite of power management, control, and regulation circuits & software operating at up to 1000 V and at maximum specific power and which are maintainable in the Lunar dust environment and 0.99 reliable for 10 years in the relevant Lunar radiation and thermal environments and in the Lunar hard vacuum and Mars atmosphere environments.

CLOSURE PLAN:

- LuSTR or ECF project for integrated subsystem (material, device, circuit) reliability modeling
- GCD efforts to bring optimized suite of circuits with dust tolerant connectors to TRL 6
- TDM project to demo circuits and software on CLPS and/or for ISRU Pilot plant(s) in 2030

Gap C: Transmission Cable Systems

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.3.2

DEFINITIONS:
CA: SOA Earth-sourced power cables and load connection and deployment systems do not provide capability at specific power and dust-tolerance levels sufficient to support power distribution among Lunar pole surface elements. Flight-qualified technologies for cables, connectors and deployment spools are not optimized for the Lunar polar environment.
CB: The technology required to print long distance (100's of km) on the Lunar surface from locally-sourced aluminum has seen little conceptual development.
Mission architects must know what capability will be available to them once full-scale ISRU production operations are to start in the early 2030s and once large-scale Lunar surface operations expand toward the lower latitudes in the late 2030s.

SOA: Cables, dust-tolerant load connection systems, and cable deployment systems for the Lunar surface have been developed only to the "bench-top" level.

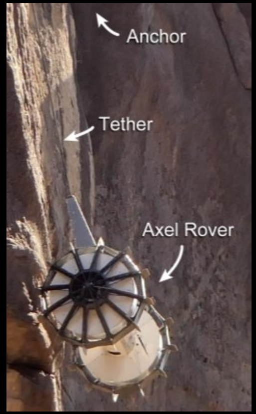
CURRENT INVESTMENTS NASA:

- Cable & Spooling system
  - *SBIR*
  - *PCC (WOTM)*
  - *GCD TP (TYMPO)*
- Connector
  - *GCD TP (UFPC)*
  - *GCD (Lo-DuSST)*

GAP CA CLOSURE:

Bring to TRL 6 by 2030 an electrically insulated transmission cable, spooling, and load connection systems that can be unrolled and deliver power point-to-point with 0.99 reliability at 1000 V (source and load) and at 10 kW_e scale in the Lunar polar dust, MMOD, and thermal environments (both insolated and PSR), losing no more than 3% per km and at maximized delivered power per unit of cable system mass.

Closure Plan:
- Further SBIR and ESI efforts for load connection and cable/spooling systems
- GCD project to bring full-scale system to TRL 6
- TDM projects to demonstrate components (cable/spool, connectors, proximity charging) on CLPS



GAP CB CLOSURE:

Bring to TRL 6 by 2035 MW_e, 100 km-scale power transmission systems, printed on the Lunar surface from Lunar-sourced aluminum and with minimal material brought from Earth.

Closure Plan:
- STRG and SBIR efforts for Lunar aluminum mining and conductor printing
- GCD efforts to bring integrated, printed power conductor systems to TRL 6 by 2035
- TDM project to fly and operate power conductor production equipment on the Lunar surface by 2037

Gap D1: Photovoltaic Arrays

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.1.1

Definition:
D1A: SOA Earth-sourced solar array blankets do not provide sufficient durability or scale to support full scale ISRU production in the Lunar Pole thermal, dust , and radiation environment. Flight-qualified technology for deployment towers and reflectors is not optimized for gathering sunlight low on the horizon as at the Lunar poles.
D1B: The technology required to print photovoltaic arrays on the Lunar surface from Lunar silicon has seen little conceptual development.
Mission architects must know what capability will be available to them once full-scale ISRU production operations are to start in the early 2030s and once large-scale Lunar surface operations expand toward the lower latitudes in the late 2030s.

SOA: Photovoltaic arrays (<200 V) and deployment mechanisms suitable for LEO operations are at TRL 9. Vertical array deployment mechanisms for Lunar gravity are at a benchtop level of development. Large 10's kW_t-scale reflectors/mirrors are at a concept-level of development. Large scale, surface-level photovoltaic arrays, at a GW_e scale and printed from Lunar-sourced silicon, are at a very early stage of conceptual development.

CURRENT INVESTMENTS

NASA:

- Earth-sourced PV Blankets:
  - *SBIR (composite Blanket)*
  - *GCD ACO (FSAP)*
  - *CLPS (PILS)*
- Earth-sourced Deployment Structures
  - *SBIR*
  - *STRG (BYU)*
  - *GCD (VSAT)*
- Earth-sourced Reflectors
  - *none*
- Dust compatibility
  - *GCD (LO-DuSST)*
  - *GCD ACO (DMFlex)*
- Lunar-sourced PV blankets
  - *None*

OGA (DoD & DoE):

- Earth-sourced PV Blankets

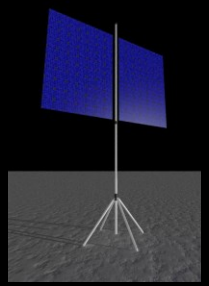
Gap D1A CLOSURE:

Bring to TRL 6 by 2030 50 kW_e-scale photovoltaic arrays, deployed vertically or horizontally (with reflector towers), providing power at >200 V at 200 W_e/kg BOL and exhibiting no more than 10% degradation over ten years in the Lunar polar environment (including shadowed periods). Deployment solutions must maximize effective low-horizon insolation within limits of specific power.

Closure Plan

- SBIR efforts for rad-hard photovoltaics, blanket, and reflector/concentrator designs
- GCD efforts to bring optimized blankets (with concentrators, dust tolerance, and rad-hardened PV) to TRL 6
- Continue GCD VSAT Project
- TDM project to fly 10 KW_e-scale VSAT or reflector tower to support PSR prospecting in ~2025
- TDM project to fly ~50 kW_e arrays to support pilot plant ops in 2030

Full-Scale Polar Power Demand Assumptions	kWe
Outpost Module	10
Initial Full-Scale O_2-from Regolith (7 t/year system - Carbothermal	15
Initial Full-Scale Ice-Mining , Rim (10 t/year system)	46
Initial Full-Scale Ice-Mining, in PSR (10 t/year system)	22

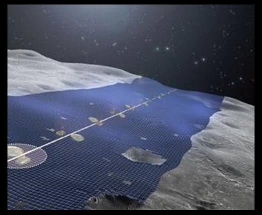


Gap D1B CLOSURE:

Bring to TRL 6 by 2035 GW_e-scale photovoltaic blankets, printed horizontally on the Lunar surface from Lunar-sourced silicon and with minimal material brought from Earth.

Closure plan

- STRG and SBIR efforts for Lunar silicon mining and PV array printing
- GCD efforts to bring integrated, printed PV generation systems to TRL 6 by 2035
- TDM project to fly and operate PV production equipment on the Lunar surface by 2037



Gap D2: Long Life Grid-Scale Secondary Energy Storge

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.2.2

Definition:
D2A: **Eclipse-period support of industrial scale ISRU production facilities and a crewed outpost at the Lunar pole will require Earth-sourced, large-scale, long life, maintenance-free electrical energy storage** at a MW_e scale.
D2B: Expansion of Lunar infrastructure toward the Equator will require large scale electrical and thermal energy storage sourced from Lunar regolith..
Mission architects must know what capability will be available to them once full-scale ISRU production operations are to start in the early 2030s and once large-scale Lunar surface operations expand toward the lower latitudes in the late 2030s.

SOA: For Earth-sourced, electrical energy storage, H_2/O_2 Primary fuel cells are nearing TRL 6/7 at a 1 kW_e-scale with ~5000-hour operating life. High pressure electrolyzers of similar life and scale will be at TRL 5 at completion of NASA STMD's RFC project. Electrical and thermal energy storage sourced from Lunar regolith, such as metal-oxygen flow batteries and thermal "wadis", remain at only a conceptual level of development.

CURRENT INVESTMENTS

NASA:
- PEM Primary and Regen FC
  - *GCD ACO (AARC)*
  - *GCD ACO (AMPES)*
  - *GCD ACO (LFC-Blue Origin)*
  - *GRC (RFC)*

DoD NUWC:
- PEM Primary FC
  - *Various (SNC, Teledyne)*

Gap D2A CLOSURE:

Bring to TRL 6 by 2030 a H_2/O_2 regenerative fuel cell energy storage system in up to MWh_e and 10 kW_e increments with maximum specific energy and maintenance-free life in the Lunar polar environment of 50,000 hours and 500 charge/discharge cycles.

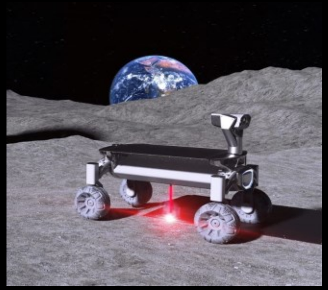
Closure Plan
- LuSTR or STRG effort for reliability/life modeling
- SBIR efforts for highly durable membranes and fluid components
- GCD project for ultra-long life RFC system
- TDM project to fly ~10 kW_e RFC to support Outpost and ISRU pilot plant operations in 2030

Full-Scale Power Demand Assumptions	kWe
Outpost Module	10
Initial Full-Scale O_2-from Regolith (7 t/year system – Carbothermal	15
Initial Full-Scale Ice-Mining , Rim (10 t/year system)	46
Initial Full-Scale Ice-Mining, in PSR (10 t/year system)	22

Gap D2B CLOSURE:

Bring to TRL 6 by 2035 GWh_e-scale secondary flow batteries formed from Lunar-sourced chemicals and large-scale thermal wadis printed from sintered regolith.

Closure plan
- STRG and SBIR efforts for mining Lunar minerals suitable for secondary electrochemical batteries and for sintering of regolith for thermal energy storage
- GCD efforts to bring integrated electrical and thermal energy storage systems to TRL 6 by 2035
- TDM project to fly and operate energy storage equipment on the Lunar surface by 2037



Gap E1: Wireless Power Transmission up to 10 kW_e Increment

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.3.2

Definition: ISRU ice mining operations in PSR (from prospecting to full-scale industry) will require power transmitted from insolated regions to mobile assets in the PSR interior.

SOA: Subscale wireless power transmission systems have been developed to the bench-top level. Relevant pointing mechanisms have been developed for terrestrial applications.

CURRENT INVESTMENTS

NASA:

- Power Beaming
  - *SBIR*
  - *PCC (WOTM)*
  - *LuSTR grant (UCSB)*

DoD:

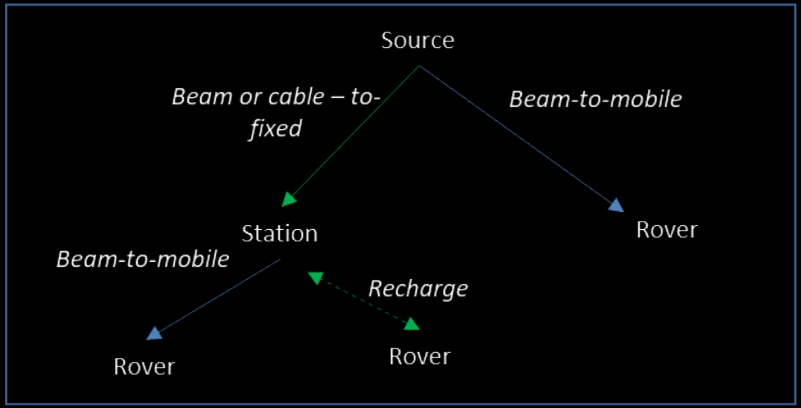
- Power Beaming
  - *Various*
- Pointing Mechanisms
  - *Various*

Gap E1 Closure:

Bring to TRL 6 by 2030 a wireless transmission system delivering power at up to ~10 kW_e scale from a 1000 V source in either an isolated region or a PSR to a mobile load in a PSR, losing no more than 75% source-to-load over 5 km and at maximized delivered power per unit of system mass.

Closure Plan:

- Further SBIR efforts for beaming and pointing mechanisms
- ~100 W_e subscale demos may support CLPS applications.
- GCD project to bring full-scale system to TRL 6
- TDM projects to demonstrate 1 kW_e for 2028 PSR ice mining demo, 10 kW_e for 2030 PSR Ice Mining pilot plant



PSR Distribution/Storage Trade

Gap E2: Dynamic Conversion for Radioisotope GPHS in 500 W_e Increment

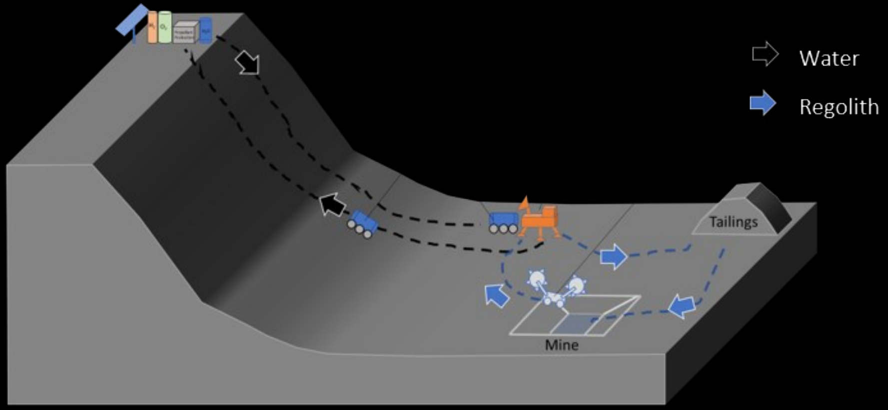
Thrust: **EXPLORE**
Outcomes: **Develop vehicle platform technologies supporting new discoveries**
Taxonomy Elements: **3.1.2, 3.1.4**

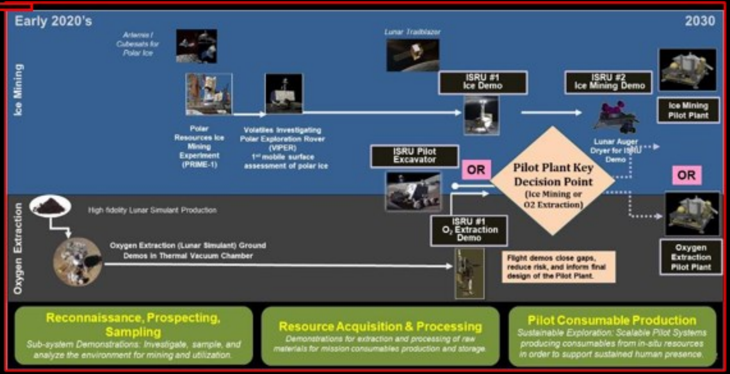
Definition: A key strategic mission for NASA's Science Mission Directorate (SMD) is an understanding of the distribution of resources in the permanently shadowed regions of the Lunar South Pole. A multi-100 W_e, sun-independent power source is required for mobility assets to conduct through prospecting in the 2026 timeframe. Smaller power sources (~100 We) required for CLPS-class science exploration missions in PSR

SOA: The current MMRTG can deliver ~125 W_e BOL from ^{238}Pu General Purpose Heat Sources (GPHS).

CLOSURE:
Bring to TRL 6 by 2024 a 500 W_e-class radioisotope power source with Stirling conversion from the ^{238}Pu GPHS.

CLOSURE PLAN:
- Accelerate SMD's DRPS project





CURRENT INVESTMENTS NASA/DoE:
- SMD RPS program
  - *DRPS Project*

Gap E3: Low Temperature Secondary Battery Modules up to 50 kWh_e Increment

Thrust: LIVE

Outcomes: **Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations**

Taxonomy Elements: 3.2.1

Definition: The principal challenge from Artemis for battery technology is mobility energy storage for ISRU operations in PSRs. SOA (Li-ion) batteries lose 75% of their room temperature (295 K) capacity when operating at 235 K. Battery modules that can deliver SOA 295 K performance in a 70 K environment can thus increase specific energy for batteries in PSRs by well over a factor of three. Such performance might be achieved with a combination of cells developed to perform better at lower temperatures, improved insulation/thermal management hardware, and supplemental radioisotope heat sources.

SOA: Li-ion battery modules at 50 kWh-scale can deliver ~500 cycles at 150 Wh_e/kg at 290 K. Insulation and active thermal management hardware are required to maintain the cells in this temperature range when operating in colder environments.

CURRENT INVESTMENTS

NASA:

- Cells
  - *ECF (various)*

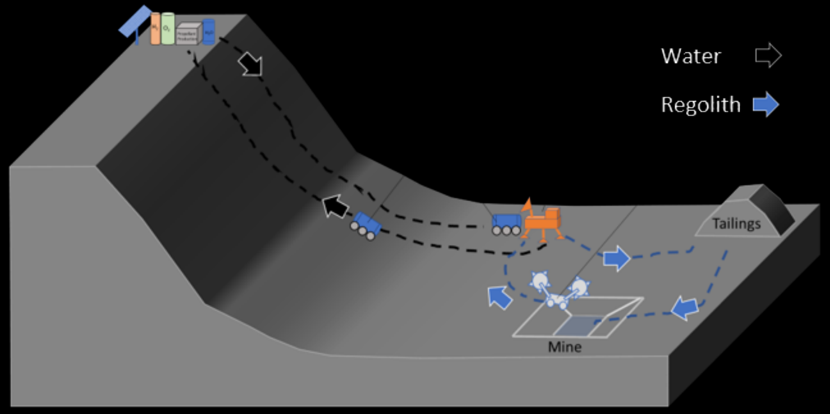
CLOSURE:

Bring to TRL 6 by 2030 a 50 kWh-class battery module with capability to provide greater than net* 150 Wh_e/kg specific energy at 1 kW_e discharge for 500 cycles in a 70 K environment and to survive with full operational capability after long-duration cold soak at 70 K.

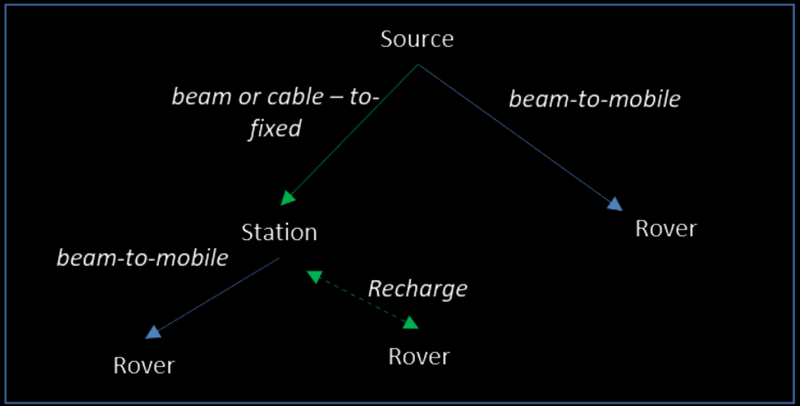
**net of module insulation, extra heat sources, or extra cells to feed heaters.*

CLOSURE PLAN:

- Further SBIR efforts for cell development, thermal management systems, and supplemental (e.g., radioisotope) heat sources.
- GCD project to bring full-scale system to TRL 6
- TDM projects to demonstrate 1 kW_e for 2028 ice mining demonstration



PSR Distribution/Storage Trade



Gap F: CH_4/O_2 Primary Fuel Cell Power up to 10 kW_e Increment

Thrust: LIVE
Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations
Taxonomy Elements: 3.2.2

Definition: Primary power from LO_2/LCH_4 reactant storage may be the mass-optimal solution for certain Lunar/Mars mobility assets and Landers

SOA: Air/Natural Gas Solid Oxide Fuel Cells are in common terrestrial use up to ~50 kW_e scale. Multi-kW_e-scale Jet Fuel/O_2 power plants tested by USN NUWC in operational configurations. NASA and vendors have tested LO_2/LCH_4 SOFC 1 kW_e-scale in breadboard configurations.

CURRENT INVESTMENTS

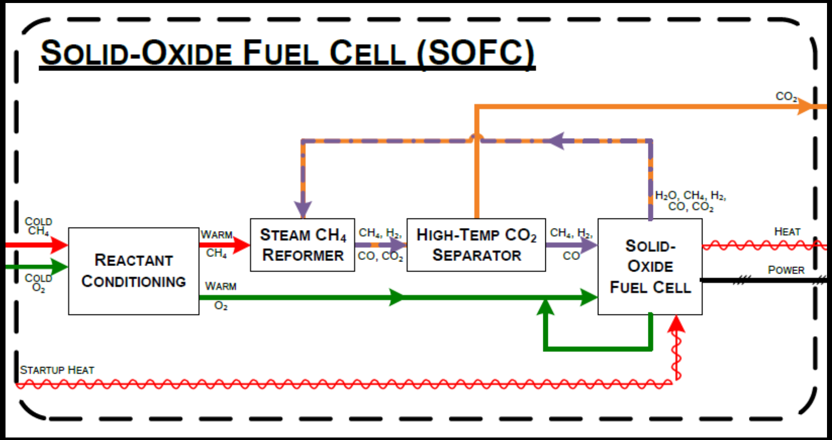
NASA:

- SOFC
  - *SBIR Ph 3 (Precision Combustion)*

CLOSURE:
Bring to TRL 6 LO_2/LCH_4 primary fuel cell power generation systems in up to 10 kW_e increments with maximum specific energy and maintenance free life in the Lunar polar or Martian environments of 10,000 operating hours

CLOSURE PLAN:

- Further SBIR efforts for cell development and thermal management systems
- GCD project to bring full-scale system to TRL 6



Envisioned Future - *EXPLORE*

Transformative Missions and Discoveries

Vehicle platform technologies supporting new discoveries

Power Generation

- Low Irradiance, Low Temperature (LILT) photovoltaic arrays operating at > 300 V and providing > 8 W/kg EOM in Jovian orbital environment
- LILT photovoltaic arrays operating with red-shifted spectrum at 750 K and 90 atm (e.g., Venusian surface mission)
- Improved efficiency/durability thermoelectric power conversion for ^{238}Pu GPHS
- Chemical or wind power generation operating at 750 K and 90 atm (e.g., Venusian surface mission)

Energy Storage

- Primary battery storage surviving to 35 K and operating (high rate) at 200 K with specific energy >200 Wh_e/kg. (e.g., Lunar PSR mission)
- Primary battery storage operating at 750 K and ~10 W for 3000 hrs. (e.g., Venusian surface mission)
- Passive thermal control at low mass for secondary batteries(2)

Power Distribution

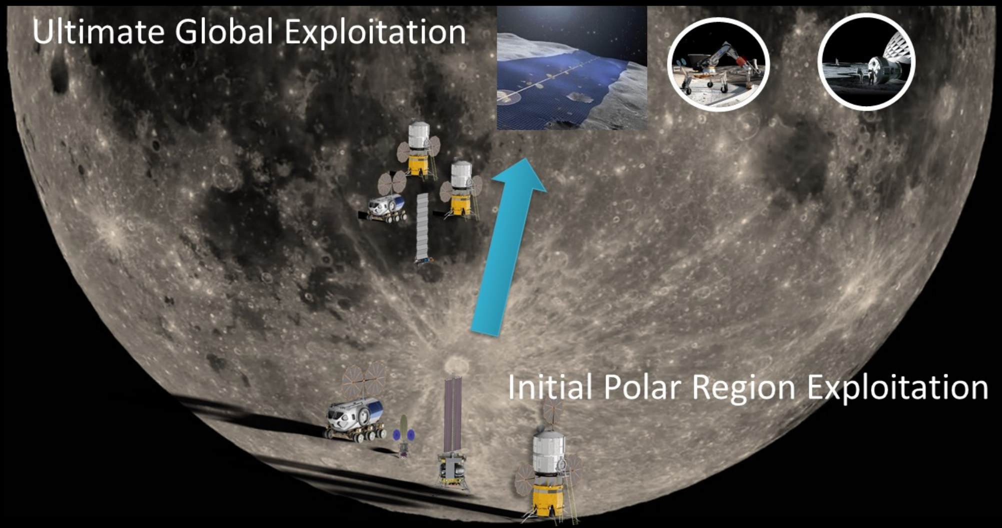
- Reliable, Rad-hard power electronics for extreme (e.g., Jovian) radiation and high temperature (e.g., Venusian surface) environments(1)
- Beamed power at ~100 W_e-scale (3)

(1)Possible augmentation to closure of LIVE Gap B: Power Electronics.
(2)Probable inclusion with closure of LIVE Gap E3: Low Temperature Secondary Batteries
(3)Probably inclusion with closure of LIVE Gap E1: Wireless Power Transmission

All activities depicted not currently funded or approved. Depicts “notional future” to guide technology vision.

Conclusions

- The immediate focus is on advancing TRL for power system components brought from Earth, defining performance which surface system architects can assume when designing sustainable exploration systems for the Moon and Mars.
  - The future priority should be advancing the technology to manufacture power system components from In-situ Lunar resources, with such systems bootstrapped with power systems brought from Earth.
- Continuation of several mid-stage investments is required to drive toward achieving desired outcomes.



Acronyms

- ACO – Announcement of Collaboration Opportunity
- BPDA – Breakthrough Distributed Power Architecture
- BOL – Beginning of Life
- BYU – Brigham Young University
- CLPS – Commercial Lunar Payload Services
- DMFlex –Dust Mitigation for Flexible solar arrays
- DoD – Department of Defense
- DoE – Department of Energy
- DRPS – Dynamic Radioisotope Power System
- ECF – Early Career Faculty
- EOM – End of Mission
- ESI – Early Stage Innovation
- FC – Fuel Cell
- FSAP – Flexible Solar Array qual Protocols
- FSP – Fission Surface Power
- GCD – Game Changing Development program
- GPHS – General Purpose Heat Sources
- GRC – Glenn Research Center
- ISRU – In-situ Resource Utilization
- kW_e – kilo-Watt electric
- LEO – Low-Earth Orbit
- LILT – Low Irradiance, Low Temperature
- LO-DuSST – Lunar Occupancy Dust- Surface Separation Technologies
- LuSTR – Lunar Surface Technology Research
- MIPS – Micro-grid Definition and Interface Converter for Planetary Surface
- MMOD – Micro-Meteoroid and Orbital Debris
- NUWC – Naval Undersea Warfare Center
- OGA – Other Government Agencies
- PCC – Prizes, Challenges, and Crowdsourcing
- PEM – Proton Exchange Membrane (fuel cell)
- Ph - Phase
- PILS - Photovoltaic Investigation on the Lunar Surface
- PSR – Permanently Shadowed Region
- PT – Principal Technologist
- PV - Photovoltaic
- RFC – Regenerative Fuel Cell
- RPCD - Rad-hard Power Controller Development
- RPS – Radioisotope Power System
- SBIR – Small Business Innovation Research
- SCLT – System Capability Leadership Team
- SOA – State of the Art
- SMD – Science Mission Directorate
- SMR – Small Modular Reactor
- SNC – Sierra Nevada Corporation
- SOFC – Solid Oxide Fuel Cell
- STRG – Space Technology Research Grants
- STTR – Small Business Technology Transfer Program
- TDM – Technology Demonstration Missions Program
- TP – Tipping Point
- TRL – Technology Readiness Level
- TX – Taxonomy (area)
- TYMPO – Tethered power sYstems for in-situ lunar Mobility and Power transmisison
- UCSB – University of California, Santa Barbara
- UFPC – Ultra-Fast Proximity Charging
- US – United States
- USN – United States Navy
- VSAT – Vertical Solar Array Technology
- WOTM – Watts on the Moon

EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

LIVE: Thermal Management Systems
NASA Space Technology Mission Directorate
May 2022

STMD welcomes feedback on this presentation
See RFI 80HQTR22ZOA2L_LIVE at nspires.nasaprs.com for how to provide feedback
If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

Advanced Thermal Management Technologies to Enable Lunar and Martian Missions

Thermal management technologies that enable surviving the extreme lunar and Mars environments

Thermal Control for In-Space Transportation Systems

"Develop nuclear technologies enabling fast in-space transits"

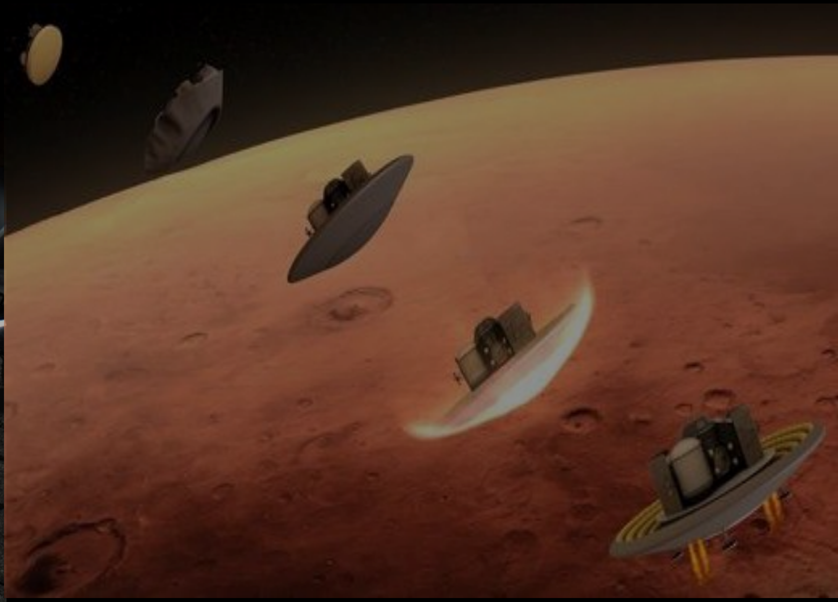
"Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications"

Thermal Control for Surface Environment Survival

"Technologies that enable surviving the extreme lunar and Mars environments"

Science Instrument Survival
Power Systems
Spacesuits
Habitats
Cold Tolerant Mechanisms
ISRU Commodity Production

Thermal Control for Entry, Descent, and Landing Systems

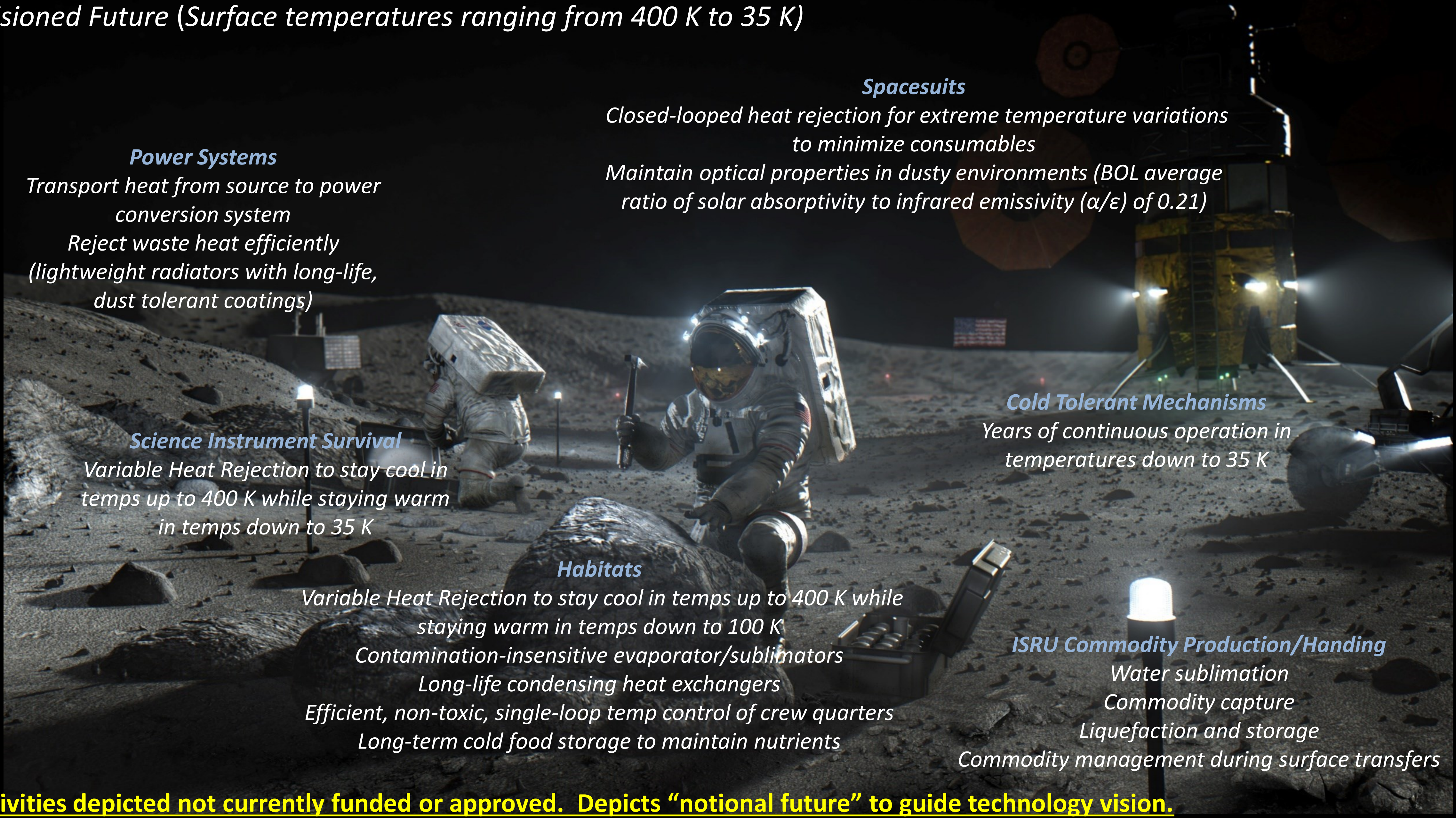


"Enable lunar/Mars global access with 20t payloads to support human missions"

"Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies"

Advanced Thermal Management Technologies to Enable Lunar and Martian Missions

Envisioned Future (Surface temperatures ranging from 400 K to 35 K)



Spacesuits

Closed-looped heat rejection for extreme temperature variations to minimize consumables

Maintain optical properties in dusty environments (BOL average ratio of solar absorptivity to infrared emissivity (α/ε) of 0.21)

Power Systems

Transport heat from source to power conversion system

Reject waste heat efficiently (lightweight radiators with long-life, dust tolerant coatings)

Cold Tolerant Mechanisms

Years of continuous operation in temperatures down to 35 K

Science Instrument Survival

Variable Heat Rejection to stay cool in temps up to 400 K while staying warm in temps down to 35 K

Habitats

Variable Heat Rejection to stay cool in temps up to 400 K while staying warm in temps down to 100 K

Contamination-insensitive evaporator/sublimators

Long-life condensing heat exchangers

Efficient, non-toxic, single-loop temp control of crew quarters

Long-term cold food storage to maintain nutrients

ISRU Commodity Production/Handing

Water sublimation

Commodity capture

Liquefaction and storage

Commodity management during surface transfers

All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.

Advanced Thermal Management Technologies to Enable Lunar and Martian Missions

Current State of the Art and Progress Toward Goals

Technology Area	SoA (Flight Heritage)	Current NASA Investments (Technologies in Development)			Goal
		TRL 1-3	TRL 4-6	TRL 7-9	
Variable Heat Rejection	Turn Down Ratio ~3:1 (Human class)	✓	✓	--	Turn Down Ratio > 12:1
	Turn Down Ratio ~30:1 (Rover class)				Turn Down Ratio > 100:1
Advanced Radiators	19 kg/m^2 (Deployable)	✓	--	--	< 6 kg/m^2 (Deployable)
	6 kg/m^2 (Body Mounted)				< 3 kg/m^2 (Body Mounted)
Thermal Control Coatings	$\alpha = 0.35$, $\varepsilon = 0.87$ after 5-year life	✓	--	--	$\alpha < 0.25$, $\varepsilon > 0.88$ after 10-year life
Advanced Heat Pipes	Medium heat fluxes	✓	✓	--	High heat fluxes
Dust Tolerant Thermal Systems	Intolerant (oversized)	✓	--	--	90% pristine surfaces after 10-year life
Freeze Tolerant Thermal Components	0.067” ID Tube (Radiator)	✓	--	--	> 0.125” ID Tube (Any TCS component)
Advanced Heat Exchangers	Standard Manufacturing	✓	✓	--	Non-standard manufacturing for optimization
Novel Heat Transfer Fluids	Two fluid loops	--	--	--	Efficient, non-toxic, freeze resistant single loop
	Traditional working fluids				Fluids with improved thermophysical properties
Cold Tolerant Mechanisms	Heated lubrication	✓	✓	--	Cold tolerant lubrication or lubrication-free
Advanced Cooling for Electronics	6.5 W/in^2, 30 kg/m^2	✓	✓	--	> 12 W/in^2, < 9 kg/m^2
Integrated Structural/Thermal Elements	Independent elements	✓	✓	--	Integrated elements with reduced system mass
Advanced Modeling Techniques	Independent analysis	✓	--	--	Integrated analysis

Current Investments Summary (1 of 3)

Novel Heat Transfer Fluids

Applications: Surface Functions

Existing Funding: NONE

Planned Funding:

NA

Recommendations:

- More STRG Solicitations to increase opportunities for success (ECLSS applications)
- Continue seeding new low TRL work for any application, including fluids in high temp applications, such as fission power
- Invest in solid-state solutions such as leveraging of Shape Memory Alloy elastocaloric properties

Dust Tolerant Systems

Applications: Surface Functions

Existing Funding: STMD Investment – Autonomous, active vibration coupled with anti-static coating

Planned Funding:

- GCD: Lunar Dust Affects on Radiators (LDAR)
- CLPS Demonstration - Active electrodynamic shielding on radiator-like coupon
- SBIR subtopic focus areas for thermal considerations in dust mitigation

Recommendations:

- Integrate active dust mitigation on optical surfaces and study impacts/effectiveness
- Initiate development of passive solutions
- Expand dust work to include Mars regolith and environments

Advanced Radiators

Applications: Surface, SmallSats, and Planetary Missions

Existing Funding:

- STMD & SST Investments
- Advancements In - Additive Manufacturing, Deployability, Integration of Advanced Heat Pipes

Planned Funding:

- ESI21 Advanced Heat Rejection Technologies for Space-Flight Radiators

Recommendations:

- Expand surface power radiator portfolio
- Increased collaboration with materials development (integrate advanced materials and processes)

Thermal Control Coatings

Applications: Surface, SmallSats, and Planetary Missions

Existing Funding:

- SMD & STMD Investments
- Advancements In – Dust resistance, optimization of optical properties, impact resistance

Planned Funding:

- NA

Recommendations:

- Solicitations to address high temperature applications
- Solicitation to extend life of coatings
- Development of fully integrated solutions
- Increased collaboration with advanced materials/processes

Current Investments Summary (2 of 3)

Freeze Tolerant Thermal Components

Applications: Surface, SmallSats, and Planetary Missions

Existing Funding:
- STMD & SMD Investments
- Advancements In - Advanced manufacturing and multi-phase flow

Planned Funding:
- NA

Recommendations:
- Advancement of existing developments to mid-TRL levels
- Increased collaboration with materials development

Advanced Modeling Techniques

Applications: Surface, SmallSats, Aerospace, and Planetary Missions

Existing Funding:
- STMD Investment
- Advancements In - Human thermal loads

Planned Funding:
- NA

Recommendations:
- Solicitations to address integrated thermal loads on-surface
- Structural/thermal modeling advancements
- Incorporate AI/ML for reduced processing times

Integrated Structural/Thermal Elements

Applications: Surface, SmallSats, Aerospace, and Planetary Missions

Existing Funding:
- STMD & ARMD Investments
- Advancements In - Additive Manufacturing & Structural Aerogels

Planned Funding:
- Thermal SBIR subtopic focus area for thermal topology optimization approved

Recommendations:
- Solicitations to seed new ideas and advance existing developments
- Increased collaboration with ARMD and materials/process developers
- Develop self-sensing and self-healing technologies

Advanced Heat Exchangers

Applications: Surface, SmallSats, Aerospace, and Planetary Missions

Existing Funding:
- STMD, SMD, ESDMD, SOMD, & ARMD Investments
- Advancements In - Advanced manufacturing, Novel fluid control techniques

Planned Funding:
- NA

Recommendations:
- Investments to drive potential solutions toward a flight ready state
- Increase collaboration between Mission Directorates
- Closed-loop systems for EVA

Current Investments Summary (3 of 3)

Advanced Heat Pipes

Applications: Surface, SmallSats, Aerospace, and Planetary Missions

Existing Funding:
- STMD, SMD, & SST Investments
- Advancements in - hybrid, oscillating, and variable conductance heat pipes (including advanced manufacturing techniques)

Planned Funding:
- NA

Recommendations:
- Continue seeding new advancements including miniaturization
- Push existing advancements toward tech demo

Variable Heat Rejection

Applications: Surface and Planetary Missions

Existing Funding:
- Primarily STMD Investments
- Advancements in - variable emissivity/view factors, thermal switches, supplemental heat rejection, multi-phase flow, insulation, and integration

Planned Funding:
- NA

Recommendations:
- Continue seeding new advancements
- Push existing advancements toward tech demo

Cold Tolerant Mechanisms

Applications: Surface and Planetary Missions

Existing Funding:
- STMD & SMD Investments
- Advancements in - magnetic gears, phase change lubricant, bulk metallic glass gears

Planned Funding:
- NA

Recommendations:
- Continue seeding new advancements
- Push existing advancements toward tech demo

Advanced Cooling for Electronics

Applications: Surface, SmallSats, Aerospace, and Planetary Missions

Existing Funding:
- STMD & SMD Investments
- Advancements in – coldplates, textured cooling loops, electrohydrodynamic control, and microgap coolers

Planned Funding:
- NA

Recommendations:
- Continue seeding new advancements
- Push existing advancements toward tech demo

Planned Development Approach

Order listed shows priorities for new starts due to missing or limited existing investments and descends to top priorities for continued development, demonstration, and infusion.

Technology	Current NASA Investments			Recommendation
	TRL 1-3	TRL 4-6	TRL 7-9	
Novel Heat Transfer Fluids	--	--	--	Initiate STRG Solicitation
Dust Tolerant Thermal Systems	✓	--	--	Fund LDAR, Initiate new advancements
Advanced Radiators	✓	--	--	Continue to develop low TRL ideas & Solicit mid TRL advancements
Thermal Control Coatings	✓	--	--	Continue to develop low TRL ideas & Solicit mid TRL advancements
Freeze Tolerant Thermal Components	✓	--	--	Solicit mid TRL advancements
Advanced Modeling Techniques	✓	--	--	Solicit mid TRL advancements
Integrated Structural/Thermal Elements	✓	✓	--	Expand mid TRL portfolio
Advanced Heat Exchangers	✓	✓	--	Expand mid TRL portfolio
Advanced Heat Pipes	✓	✓	--	Consolidate OHP work – move toward demos
Variable Heat Rejection	✓	✓	--	Stay the course – move toward demo
Cold Tolerant Mechanisms	✓	✓	--	Stay the course – move toward demo
Advanced Cooling for Electronics	✓	✓	--	Stay the course – move toward demo

Conclusions/Recommendations

- Near-term focus on novel fluids and dust tolerance is required to achieve surface goals
- The next priority after novel fluids and dust tolerant systems is the development of advanced radiators & radiator coatings for surface applications
- Late mid-stage investments are crucial for buying down risk for flight program infusion
- Increase collaboration with CLPS, Small Sats, and Flight Opportunities to increase flight demonstration opportunities
- Thermal Management technologies are highly integrated and support many outcomes and could therefore benefit from increased collaboration among developers
- Development of system-level performance requirements is needed to push component level solutions into integrated system-level solutions
- Continuous infusion of new thermal management ideas can significantly enhance planned architectures leading to enabling of future architectures

Acronyms and Symbols

- α – solar absorptivity
- ε – emissivity
- AI/ML - Artificial Intelligence/Machine Learning
- ARMD – Aeronautics Research Mission Directorate
- BOL – Beginning Of Life
- CLPS – Commercial Lunar Payload Services
- ECLSS – Environmental Control and Life Support Systems
- ESDMD – Exploration Systems Development Mission Directorate
- ESI – Early Stage Innovations
- EVA – Extravehicular Activity
- GCD – Game Changing Development
- ID – Inner diameter
- ISRU – In-situ Resource Utilization
- LDAR – Lunar Dust Affects on Radiators
- OHP – Oscillating Heat Pipes
- SBIR – Small Business Innovative Research
- SMD – Science Mission Directorate
- SoA – State of the Art
- SOMD – Space Operations Mission Directorate
- SST – Small Spacecraft Technologies
- STMD – Space Technology Mission Directorate
- STRG – Space Technology Research Grants
- TCS – Thermal Control Systems
- TRL – Technology Readiness Level

EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

LIVE: Excavation, Construction, and Outfitting
NASA Space Technology Mission Directorate
May 2022

STMD welcomes feedback on this presentation
See RFI 80HQTR22ZOA2L_LIVE at nspires.nasaprs.com for how to provide feedback
If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

LIVE: Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources

Thrusts	Outcomes
Go Rapid, Safe, and Efficient Space Transportation	• Develop nuclear technologies enabling fast in-space transits. • Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications. • Develop advanced propulsion technologies that enable future science/exploration missions.
Land Expanded Access to Diverse Surface Destinations	• Enable Lunar/Mars global access with ~20t payloads to support human missions. • Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies. • Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards.

Live Sustainable Living and Working Farther from Earth	• Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities
	  ◦ Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.
	  ◦ Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface.
	  ◦ Technologies that enable surviving the extreme lunar and Mars environments.
	  ◦ Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources.
	• Enable long duration human exploration missions with Advanced Life Support & Human Performance technologies.

Explore Transformative Missions and Discoveries	• Develop next generation high performance computing, communications, and navigation. • Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions. • Develop technologies supporting emerging space industries including: Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft technologies. • Develop vehicle platform technologies supporting new discoveries. • Develop transformative technologies that enable future NASA or commercial missions and discoveries

- **TX 07.2 Mission Infrastructure, Sustainability, and Supportability** - Provide landing sites, blast containment shields, landing aids.
- **TX 03 Advanced Power** – Receive power; Provide excavation and construction services necessary for power infrastructure
- **TX 07.1 In-Situ Resource Utilization** – Provide regolith for commodities and feedstock production; receive resource information and manufacturing/construction feedstock.
- **TX 07.2.5 & TX 12.1 Advanced Materials and Dust Mitigation** – providing and using technologies for surviving extreme environments
- **TX 10 Autonomous Systems** – Receive Autonomous Systems & Robotics technologies for complex Excavation, Construction, & Outfitting operations
- **TX07.2 Assembly, TX12.3 Mechanical Systems** - Shared capability areas with Servicing & Assembly (OSAM)
- **TX 12.4 Manufacturing** – Receive manufactured parts for Lunar surface Construction and Outfitting from Adv. Manufacturing

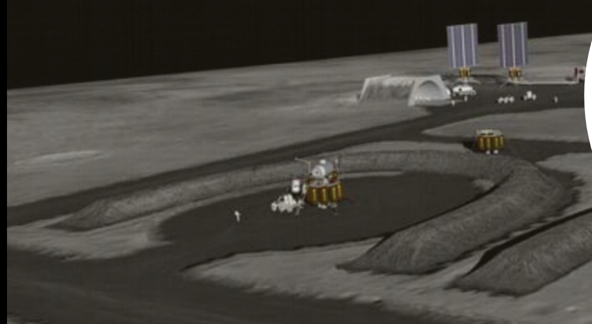
Autonomous Lunar Excavation, Construction, & Outfitting

targeting landing pads, structures, habitable buildings utilizing in-situ resources

Excavation for ISRU-based Resource Production

- Site surveying, resource prospecting
- Ice mining & regolith extraction for 100s to 1000s metric tons of commodities per year

Excavation for Construction



- Site preparation for construction: obstacle clearing, leveling & trenching
- Construction materials production utilizing in-situ resources
  - 100s to 1000s metric tons of regolith-based feedstock for construction projects
  - 10s to 100s metric tons of metals and binders

Construction and Outfitting

- Landing pad construction demo scaling to human lander capable landing pads
- Unpressurized structure evolving to single and then multi-level pressurized habitats
- Outfitting for data, power & ECLSS systems
- 100-m-diameter landing pads, 10s km of roads, 1000s m^3 habitable pressurized volume

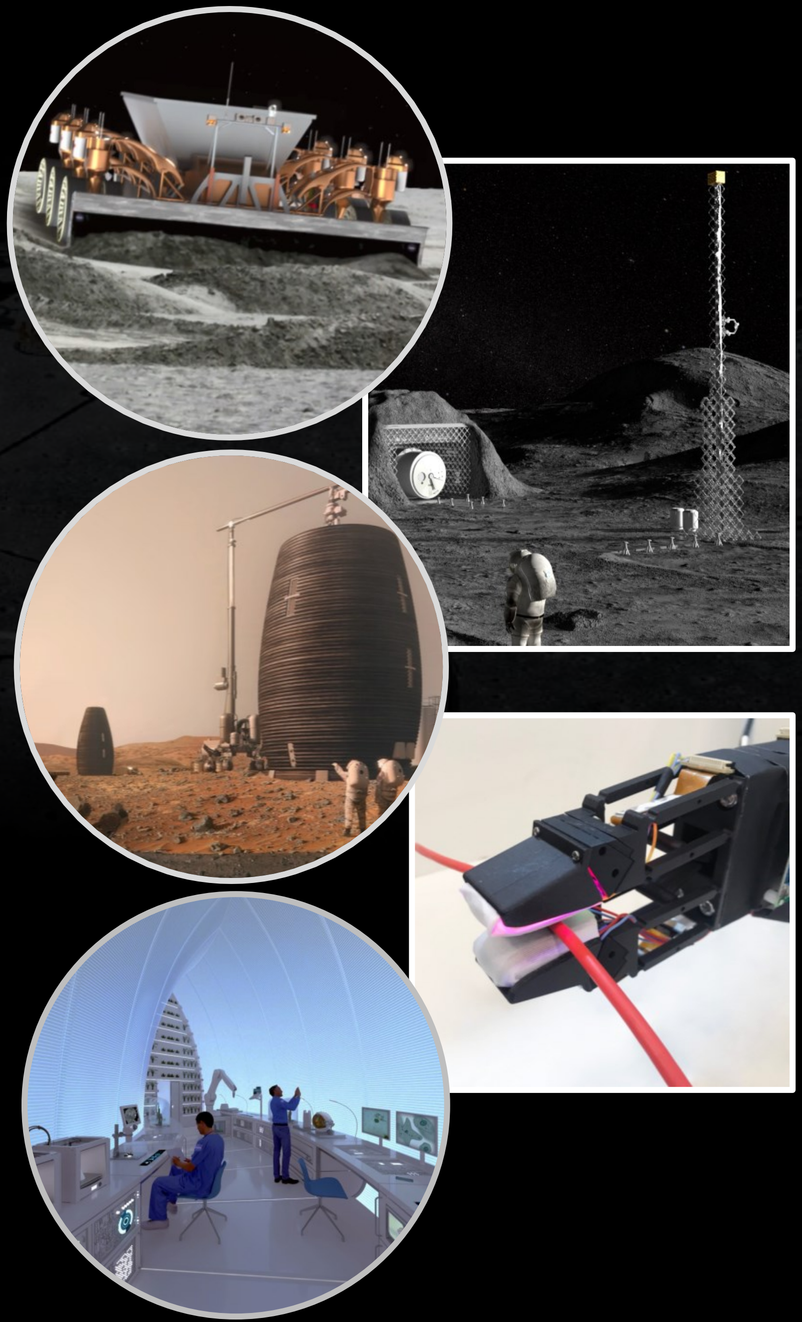
Sustainable Off-Earth Living & Working

- Commercial autonomous excavation and construction of landing pads, roads and habitable structures
- Fully outfitted buildings to support a permanent lunar settlement and vibrant space economy
- Extensible to future SMD missions and Mars settlement

Not all activities depicted are currently funded or approved. Depicts "notional future" to guide technology development vision.

Plan to Develop Excavation, Construction, and Outfitting Capabilities

- **Overall Plan**
  - Technology development roadmaps are being developed and requirements defined leading to a logical buildup of ECO capabilities and scale that culminate in a series of ground and lunar demonstrations
  - Technology investments to span entire TRL space
  - External collaboration and partnerships to leverage terrestrial civil engineering expertise
  - Leverage APL/LSIC Working Groups to perform reviews, studies, & integration
- **Next Steps**
  - Complete current technology development activities, and begin planning of next phase of developments.
  - Complete roadmap and demonstration plans - coordination with ISRU, AS&R, Power, Thermal, Dust, EE capability areas
  - Continue modest Pilot projects addressing top priorities and initiate new projects (top priorities presented herein)
  - Focus on high-priority gaps to complement current investments
  - Identify and plan ground and lunar surface demos necessary for gap closure



Excavation for ISRU

Capability Description, Outcomes, and State of the Art

Capability Description

- Autonomous resource excavation and delivery to ISRU plant –1000s t/year
- Distance traveled with repeated trafficking – 1000s km/year
- Recharging – 100s times (assuming no on-board PV charging)
- Operational Life – 5 years
- Reliability and Repair – MTBF = 10 lunar days, MTTR = <2 hrs

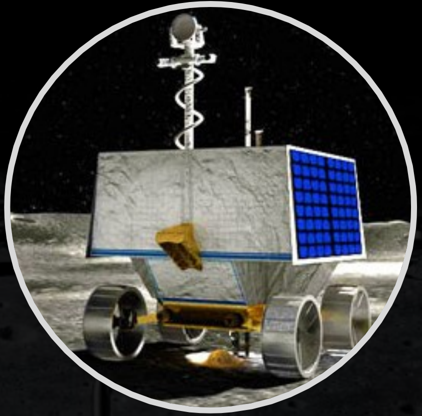
Outcomes

- Regolith for O_2
- Icy Regolith for H_2O and volatiles - hydrogen, carbon oxides, hydrocarbons, and ammonia
- Regolith for ISRU-based construction feedstocks and binders – Metals, Silicon, Slag

State of the Art: Current lunar excavation technologies can only dig into surface regolith, not deep or icy regolith.

Capability or KPP	SoA	Threshold	Goal
Excavation	Surveyor Scoop: < 10kg	100s t/year	1000s t/year
Dist. Traveled	Opportunity Rover: 46 km	100s km/year	1000s km/year
Repeated Trafficking	Apollo rover: 5X	100s X	1000s X
Operational Range between resource & delivery site	None	500 m	> 1 km
Recharge Cycles (assuming no on-board PV charging)	None	10s X	100s X
Operational Lifetime	Chinese Yutu Rover Many lunar day/night cycles	1 year	5 years
Reliability & Repair	None	MTBF: 1 lunar day MTTR: <24 hrs	MTBF: 10 lunar days MTTR: <2 hrs

ISRU resource prospecting and geotechnical characterization (ISRU dependency)



Resource excavation and delivery

MTBF = Mean Time Before Fail

MTTR = Mean Time to Repair

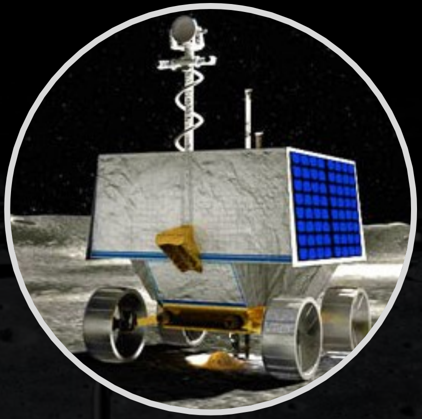
Excavation for ISRU

Current Investments and Investment Needs

- Current Investments
  - ISRU Pilot Excavator (IPE) in development for CLPS demo – high TRL
  - Regolith Scoops: COLDArm (CY24), SAMPLR (CY22) demonstrations
  - Break the Ice Lunar Challenge (Centennial Challenge Phase 2, March 2022)
  - New 2022 SBIR Topic: Lunar Surface Excavation, Construction, and Outfitting
  - Regolith simulant development
- Needed Areas with Limited* or No Investment
  - Low mass rugged robotic platforms
  - Autonomy for high throughput operations
  - Modularity and interfaces
  - Regolith flow/interaction with implements
  - Power and wireless recharging
  - Autonomous maintenance and repair
  - Wear-resistant materials and wear characterization
  - Long-life lubricants, motors, avionics
  - Dust mitigation for actuators, seals, joints, mechanisms
  - Dust-tolerant thermal control system

* Limited in scope and/or funding

ISRU resource prospecting and geotechnical characterization (ISRU dependency)



Resource excavation and delivery

Excavation for Construction

Capability Description, Outcomes, and State of the Art

Capability Description - Similar to Excavation for ISRU plus…

- Site survey – geotechnical and topography
- Load, Haul, Dump
- Bulk regolith manipulation – berms, piles, and overburden
- Level, grade, and compact
- Rock removal and gathering
- Trenching

Outcomes

- Site preparation for construction - 1000s of m^2 of prepared surface
- Provide bulk regolith berms and overburden for shielding

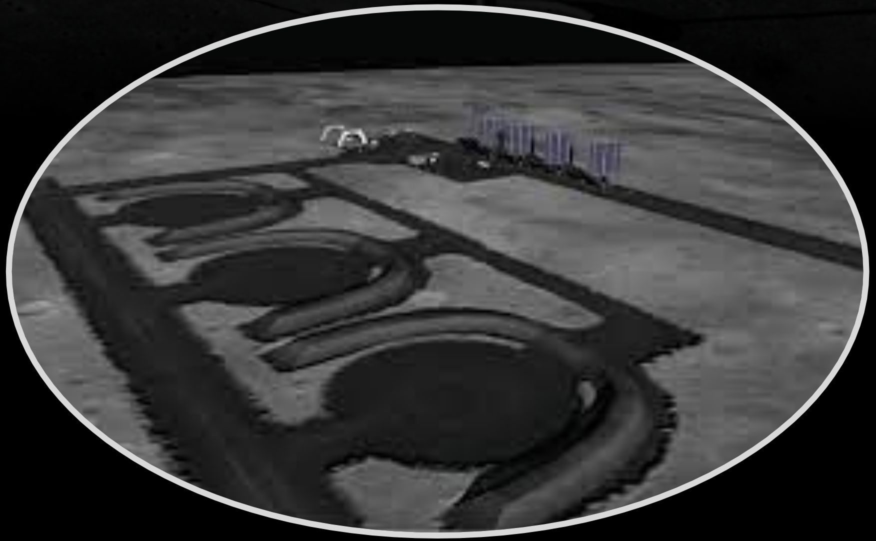
SoA: Excavation for construction has never been attempted on an extraterrestrial body. Prototypes have been built at low TRL.

Similar KPPs as Excavation for ISRU, plus the following:

Capability or KPP	SoA	Threshold	Goal
Bulk density and bearing and shear strength measurement of regolith	cone penetrometer, shear vane, coring	1 measurement per 100 m^2	10 autonomous measurements per 100 m^2
Topology characterization	LIDAR, Photogrammetry	10mm resolution	5mm resolution
Bulk Regolith Manipulation – berm building and piling	None	4 m tall	7 m tall
Site Level, Grade & Compact (1.9 g/cc)	None	25 m radius	50 m radius
Rock Removal and Gathering	Rake (Apollo): 1-10 cm	<10 cm	<50 cm
Trenching	Apollo & lunar surveyor scoop: several cm's deep	1.0 m deep	3.0 m deep

Leveling and grading

Early-phase infrastructure



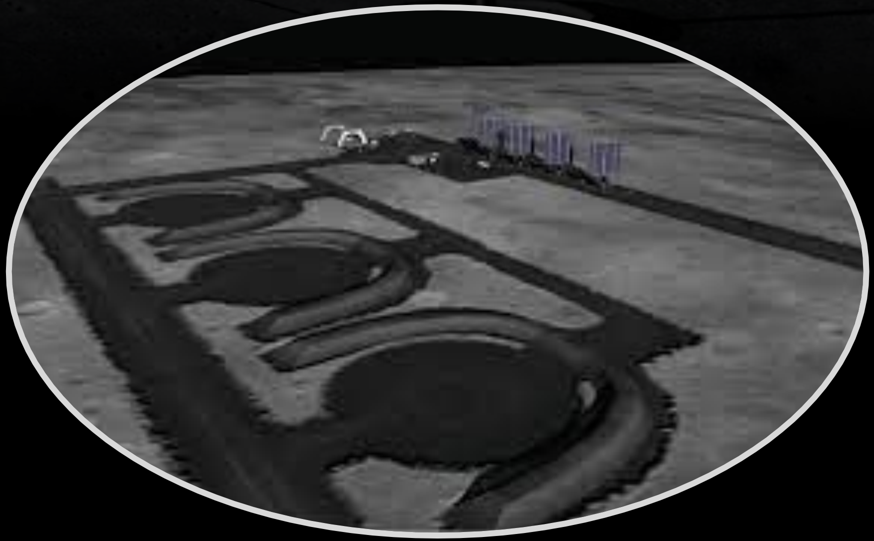
Excavation for Construction

Current Investments and Investment Needs

- **Current Areas of Investment**
  - Lunar Surface Technology Research (LuSTR) topic: **Autonomous Systems for Excavation and Site Preparation of Lunar Regolith**
    - STMD Space Technology Research Grants
    - Aligned with LSII focus areas
    - University-led with 40% industry participation allowed
    - Anticipate one award in Spring of 2022
- **Needed Areas with Limited or No Investment**
  - Similar needs as Excavation for ISRU
  - Additional needs include:
    - Site prep inspection techniques and sensor systems
    - Implements: excavation, haul, dump, rock handling, grading, leveling, compaction, berm building, trenching
    - **Need mid-TRL investments in this area**

Leveling and grading

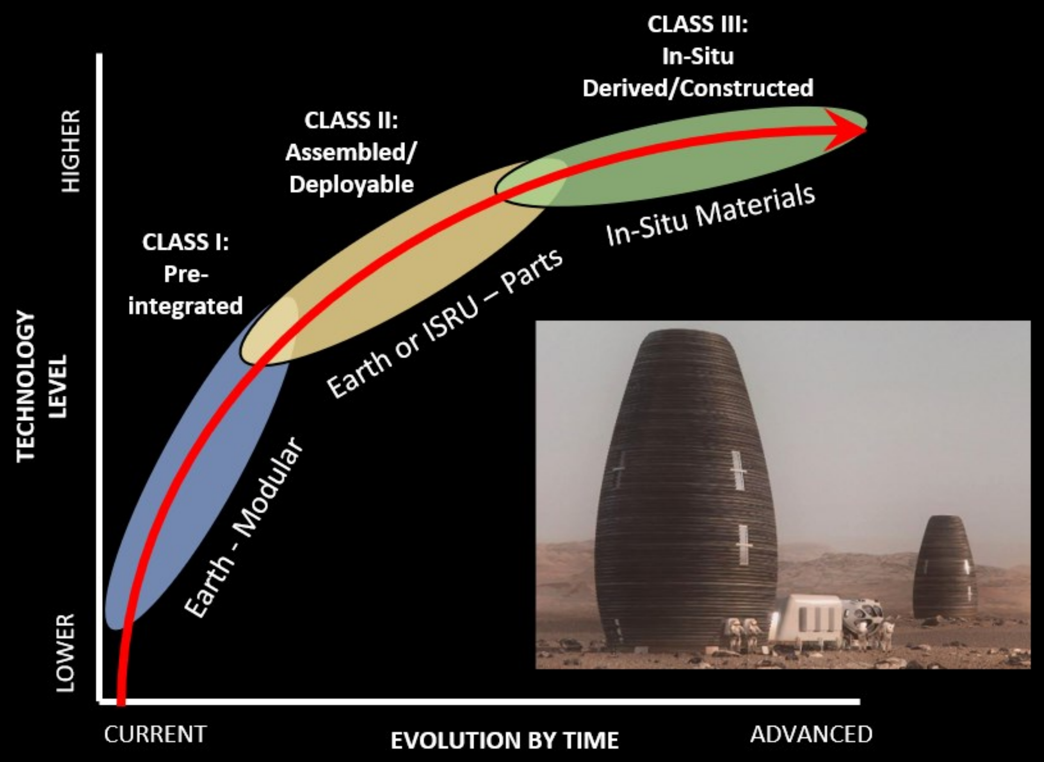
Early-phase infrastructure

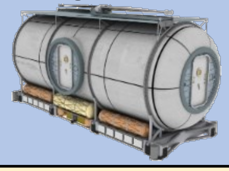


Surface Construction Classifications

Delivery of large habitable volumes will require a different approach from the "cans on landers" concepts that have been depicted for decades

- **How can we build?**



Classification	Key Characteristics
CLASS I **Pre-integrated** 	• Earth Manufactured • Pre-Integrated & Tested Prior to Launch • Space Delivered with Immediate Habitation Capability • Volume Constrained by Launch Vehicle Shroud Size • Mass Constrained by Launch Vehicle Mass Capability
CLASS II **Surface Deployed & Assembled** 	• Earth-sourced or ISRU-derived • Requires Surface Deployment, Assembly & Outfitting • May Include Partial Integration of Subsystems • Critical Subsystems are Earth Based and Tested Prior to Launch • Requires Assembly & Checkout Prior to Human Occupancy • Larger Volumes Capable (e.g., Transhab ~3X the Volume of a Standard ISS Module) • Reduced Restriction on Volume Due to Launch Vehicle Shroud Size • Restricted to Launch Mass Capability. Deliver on Multiple Vehicles
CLASS III **In-Situ Derived and Constructed** 	• Manufactured In-situ, Derived from Local Resources (Lunar or Mars) • In-space Constructed • Requires Robotic Construction Capability & Infrastructure • Requires Robotic and Human Labor During Construction • Requires Integration of Subsystems • Critical Subsystems are Earth Based and Tested Prior to Launch • Larger Volumes Capable and No Longer Constrained by Launch Vehicle (Constrained by Limitations of Construction Equipment) • Construction Equipment Constrained to Launch Vehicle Mass and Volume.

Notes:
- Class II structures can include ISRU derived components
- Shared capability areas with Servicing & Assembly, e.g., autonomous assembly, docking interfaces, outfitting, V&V

Surface Construction

Capability Description, Outcomes, and State of the Art

Capability Description:

- *Class II*: Assembly of components into built-up structures (e.g., Earth-sourced or ISRU-based truss, panel, paver, bricks); deployment of human-rated preassembled or inflatable structures
- *Class III*: In-situ construction (e.g., 3D printed construction)
- In-situ testing and inspection techniques for certification (material and structural)
- Structural enhancement and repair
- Construction System: design for lunar survivability, reliability, and maintenance

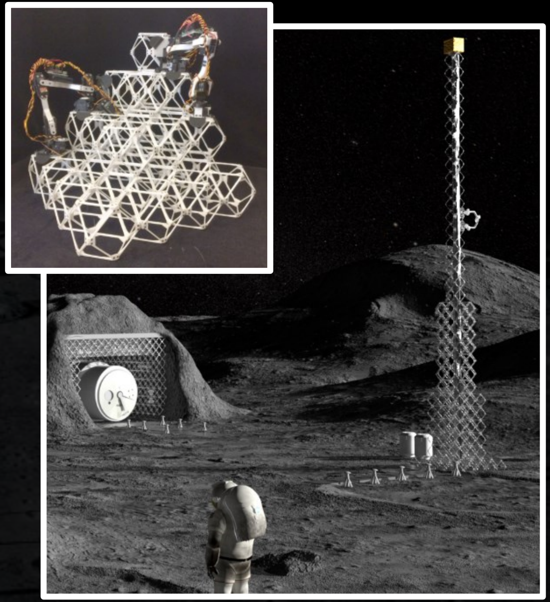
Outcomes

- 100-m-diameter launch/landing pads (LLPs)
- 10s km of roads
- Towers (100+m tall for Power and over-horizon Communication)
- Blast containment shield (BCS)– 7m-tall, 100s m long
- Shelters & habitats (1000s m^3 volume) to provide asset and crew protection (thermal, radiation, etc.)

SoA: Extraterrestrial surface construction has never been attempted. Terrestrial prototypes at low TRL.

Capability or KPP	SoA	Threshold	Goal
Class II: Deployable and assembled structures	ISS: deployable trusses for solar arrays and radiators; inflatable volumes (not human-rated).	Autonomous assembly of tower and Blast Cont. Shield with some ISRU-based components	Autonomous assembly of shelter and habitat structures with 100% ISRU based components
Class III: In-situ construction	Low TRL development work	ISRU-based LLPs, BCS, shelters and habitats with limited Earth-sourced materials	100% ISRU-based LLPs, BCS, shelters and habitats
Autonomous in-situ testing & inspection	ISS inspection: visual, thermography, eddy current, ultra-sound, strain gage, accels.	Voids & cracks, material strength and stiffness. Material degradation	full volumetric inspection of material and structural properties w/ real-time corrective actions
Structural enhancement & repair	ISS enhancement: swap-out of modular components and orbital replacement units ISS structural repair: none	Manual repair; post-construction enhancement/modification	Selected auto. repair and post-construction enhancement
System Operational Lifetime	None	2 year	10 years
Reliability & Repair	None	MTBF: 2 lunar days, MTTR: <24 hrs	MTBF: 10 lunar days, MTTR: <2 hrs

Class II: Assembly & Deployables



Class III: In-situ Construction

MTBF = Mean Time Before Failure

MTTR = Mean Time to Repair

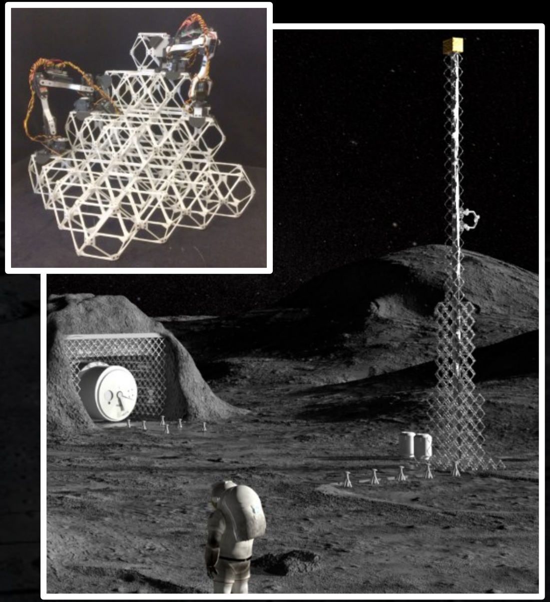
Surface Construction

Current Investments and Investment Needs

- Current Areas of Investment
  - Class II: Deployable and assembled structures
    - Precision Assembled Space Structure (PASS)
    - Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS)
    - Deployable Composite Boom (DCB)
  - Class III: In-situ construction
    - Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT)
    - Relevant Environment Additive Construction Technology (REACT/ACO)
    - NIAC/STRG/SBIR

- Needed Areas with Limited or No Investment
  - Architectural and ConOps studies (limited - MMPACT & REACT)
  - Surface characterization to inform foundation design
  - Building requirements and standards
  - Construction equipment (similar needs as Excavation)
  - Inspection methods (e.g., process, materials, structures)
  - Autonomy for complex construction and inspection tasks (very limited – MMPACT)

Class II: Assembly & Deployables



Class III: In-situ Construction

Outfitting

Capability Description, Outcomes, and State of the Art

Capability Description

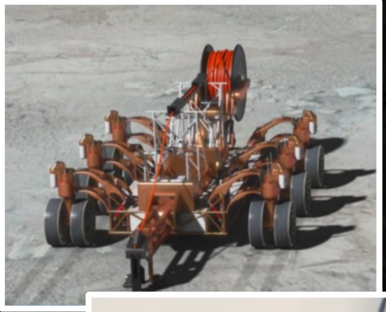
- The process by which a structure is transformed into a useable system by <u>in-situ</u> installation of subsystems.
  - Subsystem installation
  - In-situ testing/validation and inspection techniques with associated metrology
  - Structural repair and enhancement

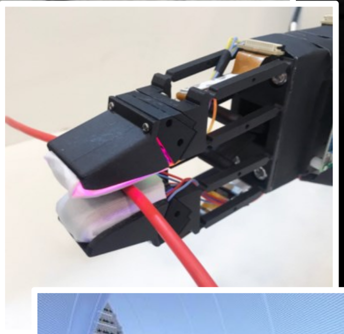
Outcomes (affects most systems that are not landed in operational self-contained state)

- Power, Lighting, Data & Communications distributed through system
- ECLSS
- Fluids & Gasses (ISRU products) managed and stored.
- Widows and Hatches
- Interior Furnishing

SoA: Preintegrated structures, with manual in-situ upgrades and repairs.

Capability or KPP	SoA	Threshold	Goal
Conductor/Cable and Piping/Tubing line management (LM)	ISS Preintegrated on ground, EVA upgrades and repairs	LM during construction using Earth-sourced harness (50% auto.). Manual repair; Post-construction manual LM for facility enhancement.	LM during construction using ISRU derived harness (100% auto.). Selected auto. repair and enhancement/expansion.
Penetration management (PM) including through pressure vessels (Habitats, tanks, shelters, blast shield etc.)	ISS Preintegrated on ground, <u>NO</u> post launch penetrations added.	PM during construction using Earth-sourced materials (50% auto.). Manual repair; Post-construction manual PM for facility enhancement.	PM during construction using ISRU derived material (100% auto.). Selected auto. repair and enhancement
Attachment of secondary systems to structures.	ISS Preintegrated some IVA and EVA rerouting.	Attachment to arbitrary surfaces and structures.	Reversible attachment to arbitrary surfaces and structures on 3D printed structures.
Metrology to verify installation and functionality.		Pressure test piping, geometry charac. for assembly verification, load test of foundations, continuity/signal strength for communications/wiring.	Continuous process monitoring, equivalency testing, structural health monitoring for 3D printed habitat by 2035.

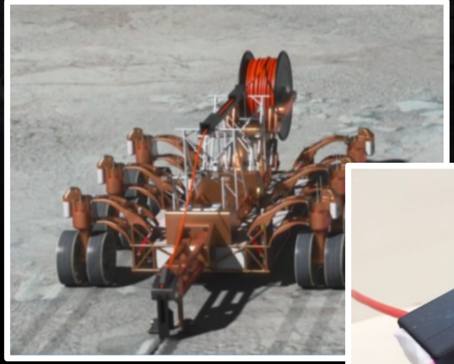


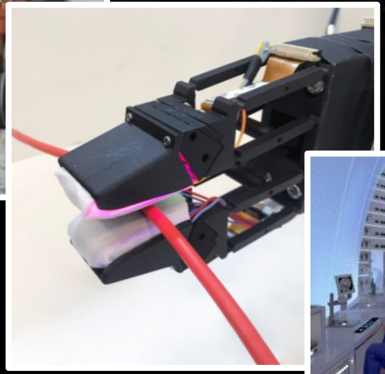


Outfitting

Current Investments and Investment Needs

- Current Areas of Investment
  - In-Space Manufacturing
    - Redwire Regolith Print (RRP): Printing parts using polymer binders with regolith filler
    - On-demand manufacturing of metals, Recycle & Reuse
  - MSFC CAN with Branch Technologies (limited scope)
    - Synthetic biology polymers (Stanford University and Ames)
    - Multi-functional, lightweight/movable partitions
- Needed Areas with Limited or No Investment
  - Architectural and ConOps studies
  - Outfitting requirements and standards
  - Outfitting technologies (e.g., lighting, harnesses, beacons, sensors, fluids, HVAC)
  - Design of pressure vessel connections/seals with penetrations
  - Common interface definition
  - Utility corridor design
  - Inspection methods & repairs
  - Autonomy for complex outfitting and inspection tasks





Autonomous Lunar Excavation, Construction, & Outfitting

targeting landing pads, structures, habitable buildings utilizing in-situ resources

Top Priority Activities

1. LSIC studies and reviews
   - What: roadmap and gap reviews for ECO, studies and working groups to help identify technology gaps and provide technical support in technology development planning, help w/ integration/collaboration with industry and DoD
   - Why: LSIC E&C WG provides a tremendous opportunity for collaboration with industry and academia in many needed technology areas

2. Modest mid-TRL Pilot projects to address known priorities (ground-based designs with path to flight, targeting operational systems and CLPS demos. Hardware development)
   - Site preparation (clearing, grading, compacting)
   - Tall Tower
   - Landing Pads (beacons, pad, blast shield, etc.)
   - Shelter construction and outfitting
   - ISRU materials production

3. Pre-formulation Studies of ECO systems and surface construction concepts
   - What: Solicit pre-formulation studies to produce ECO systems and surface construction concepts.
   - Why: Formulate new ideas for an evolvable and sustainable lunar settlement utilizing ISRU-based construction, including early infrastructure that can evolve to larger more complex construction as necessary materials and construction technologies mature. External collaboration/partnerships to leverage terrestrial expertise.
   - Outcome: Develop mission concepts, draft system-level requirements, assess performance, cost, and schedule feasibility; identify potential technology needs, and scope. Products: simulations, analysis, study reports, models, and mockups

Autonomous Lunar Excavation, Construction, & Outfitting

targeting landing pads, structures, habitable buildings utilizing in-situ resources

Top Technology Development Priorities

1. Excavation for Site Preparation and ISRU-based Commodities
   - What: Develop and demonstrate excavation capabilities needed for site preparation and construction, and regolith extraction for ISRU-based construction materials and commodities production (ground & lunar surface demonstrations)
   - Why:
     - Excavation technology needed to provide 1,000s of tons of regolith feedstock for infrastructure construction and ISRU-based commodities (ISRU Pilot Excavator 2026 demo opportunity)
     - Excavation and site preparation are required for all construction activities: **No mid-TRL funded projects currently**
     - Excavation can provide for some basic construction needs. Enables near term and achievable infrastructure emplacement using a combination of structural assembly, bulk regolith manipulation, and early in-situ manufacturing – e.g., paths and prepared surfaces, blast walls, berms, and regolith overburden for radiation, micrometeorite, and thermal protection (possible 2026 Scaled Construction Demo).

2a. ISRU-based Materials and Processes for Lunar Surface Construction
   - What: Develop/demonstrate viable ISRU-based materials and processes for the construction of horizontal and vertical extraterrestrial structures in lunar environment (sintered regolith, binder/regolith blend)
     - MMPACT, REACT/ACO
   - Why: Current SoA is to use prefabricated structures launched from Earth and is not a sustainable approach to lunar surface infrastructure development. The use of ISRU-based construction materials is expected to be the most cost-efficient methodology for development of a permanent sustainable human presence on the Moon (possible 2026 Scaled Construction Demo).

Autonomous Lunar Excavation, Construction, & Outfitting

targeting landing pads, structures, habitable buildings utilizing in-situ resources

Top Priority Activities

2b. Large-scale Class II and Class III Construction

- What: Develop a combination of robotic assembly and ISRU-based construction systems capable of repeatable, reliable, autonomous construction of
  - Horizontal structures (e.g., landing pads, roads, dust-free zones)
  - Vertical structures (e.g., towers, blast containment shields, shelters, and habitats)
- Why:
  - Assembly of 50m+ tall towers for power and comm.
  - Pads, blast walls, and roads needed to control blast ejecta, mitigate dust, and enable trafficability
  - Unpressurized shelters and pressurized habitats needed for radiation, micrometeorite, and thermal protection of surface assets and crew.
  - Class II: Assembly of towers and blast shields, evolving to shelters and habitats (currently at a higher TRL than Class III). Earth-sourced parts can be used in early phases and replaced by ISRU-derived parts.
  - Class III: Goal to provide 100% ISRU-based construction solution. Technology can be phased into lunar infrastructure architecture as it matures. Start with smaller parts for assembly, later evolving into large-scale unitized structures.
  - Possible 2026 and/or 2028 Construction Demos.

Summary Plan to Develop Excavation, Construction, and Outfitting Capabilities

- Proposed Capability-Specific Activities to Achieve the Outcomes
  - Excavation for ISRU
    - EI-1: IPE for a sub scale ISRU Oxygen production demonstration
    - EI-2: ISRU Pilot Plant excavation technology demonstration (targeting icy regolith)
    - EI-3: Excavator for full scale autonomous ISRU consumables production demonstration
  - Excavation for Construction
    - EC-1: Subscale Surface Preparation demo – site survey, basic functions, roads
    - EC-2: Subscale launch/landing pad (LLP) preparation – autonomous mobility platform
    - EC-3: Full scale autonomous site preparation for roads, LLP, and foundations
  - Surface Construction – Class II: Surface Assembly
    - SCII-1: Assembly Tech Dev. And Ground Demos
    - SCII-2: Horiz. & Vert. Truss Assembly – Landing Pad Blast Containment Shield and Power Tower
    - SCII-3: Full scale shelter (increasing complexity w/ outfitting)
    - SCII-4: Full scale habitat (CCII-3 evolved to a pressurized volume) w/ ISRU-based components
  - Surface Construction – Class III: ISRU-based Construction
    - SCIII-1: Tech Dev. And Ground Demos
    - SCIII-2: Initial lunar surface proof of concept material processing and deposition
    - SCIII-3/4: Subscale and full scale landing pad demos w/ outfitting
    - SCIII-5: Full scale autonomous vertical construction w/ outfitting
  - Outfitting
    - O-1: Horizontal harness integration for roads and LLPs (beacons, lights, cameras)
    - O-2: Tower & shelter vertical harness integration (lights, radiation sensors, cameras)
    - O-3: Habitat harness + fluid/gas integration + interior outfitting
    - O-4: ISRU plant setup and integration to storage/transportation facilities
    - O-5: Lander refueling

Acronyms

- ACO – Announcement of Collaboration Opportunity
- APL – Applied Physics Lab
- ARMADAS – Automated Reconfigurable Mission Adaptive Digital Assembly Systems
- AS&R – Autonomous Systems & Robotics
- BCS – Blast Containment Shield
- CAN – Cooperative agreement notice
- CLPS – Commercial Lunar Payload Services
- COLDArm – Cold Operable Lunar Deployable Arm
- DCB – Deployable Composite Boom
- DoD – Department of Defense
- E&C – Excavation and Construction
- ECLSS – Environmental Control and Life Support System
- ECO – Excavation, Construction, and Outfitting
- EE – Electrical Engineering
- EVA – Extravehicular Activity
- HVAC – Heating, Ventilation, and Air Conditioning
- IPE – ISRU Pilot Excavator
- ISRU – In-situ Resource Utilization
- ISS – International Space Station
- IVA – Intravehicular Activity
- KPP – Key Performance Parameter
- LIDAR – Light Detection and Ranging
- LLP – Launch/Landing Pads
- LM – Line Management
- LSIC – Lunar Surface Innovation Consortium
- LSII – Lunar Surface Innovation Initiative
- LuSTR – Lunar Surface Technology Research
- MMPACT – Moon-to-Mars Planetary Autonomous Construction Technology
- MSFC – Marshall Space Flight Center
- MTBF – Mean Time Before Failure
- MTTR – Mean Time to Repair
- NIAC – NASA Innovative Advanced Concepts
- OSAM – On-orbit Servicing, Assembly, and Manufacturing
- PASS – Precision Assembled Space Structure
- PM – Penetration Management
- PV – Photovoltaic
- REACT – Relevant Environment Additive Construction Technology
- RRP – Redwire Regolith Print
- SAMPLR - Sample Acquisition, Morphology Filtering and Probing of Lunar Regolith
- SBIR – Small Business Innovative Research
- STMD – Science Technology Mission Directorate
- SMD – Science Mission Directorate
- SoA – State of the Art
- STRG – Space Technology Research Grants
- TRL – Technology Readiness Level
- TX – Taxonomy
- V&V – Verification and Validation
- WG – Working Group

EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

EXPLORE: Advanced Avionics
NASA Space Technology Mission Directorate
August 2022

STMD welcomes feedback on this presentation
See 80HQTR22ZOA2L_EXP_LND at nspires.nasaprs.com for how to provide feedback
If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

EXPLORE: Develop next generation high performance computing, communications, and navigation

Developing flight computing architectures and advanced avionics to enable increased onboard intelligence and autonomy for future exploration missions in harsh environments

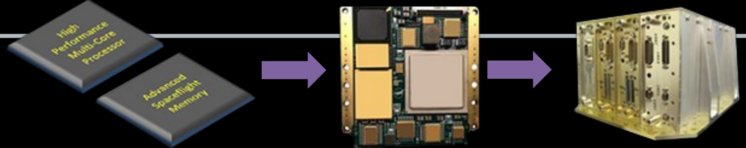
Go *Rapid, Safe, & Efficient Space Transportation*	• Develop nuclear technologies enabling fast in-space transits. • Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications. • Develop advanced propulsion technologies that enable future science/exploration missions.
Land *Expanded Access to Diverse Surface Destinations*	• Enable Lunar/Mars global access with ~20t payloads to support human missions. • Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies. • Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards.

Live *Sustainable Living and Working Farther from Earth*	• Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities
	  • Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.
	  • Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface.
	  • Technologies that enable surviving the extreme lunar and Mars environments.
	  • Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources.
	• Enable long duration human exploration missions with Advanced Life Support & Human Performance technologies.

Explore *Transformative Missions and Discoveries*	• Develop next generation high performance computing, communications, and navigation. • Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions. • Develop technologies supporting emerging space industries including: Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft technologies. • Develop vehicle platform technologies supporting new discoveries.

- Entry Descent & Landing (EDL)
  Computing for Real-Time Precision Landing Algorithms (TX 9.0)
- In Situ Resource Utilization (ISRU)
  Computing for Autonomous Robotic Systems (TX 7.2.3)
- Environmental Control and Life Support System (ECLSS)
  Computing for Autonomous Clinical Care (TX 6.3.1)
- **Avionics**
  TX 2.1 Avionics Component Technologies
  TX 2.2 Avionics Systems and Subsystems
  TX 11.1 Software Development, Engineering, and Integrity
- Autonomous Systems & Robotics
  Computing for State Estimation, Terrain Mapping and Classification, 3D Modeling, Object Recognition, Path Planning, Fault Prognosis, Anomaly Detection, Resource Planning and Scheduling, Autonomous Navigation/Obstacle Avoidance, Autonomous Management of In Situ Activities (TX 4.0)
- Rendezvous & Capture
  Computing for Rendezvous and Docking Algorithms (TX 4.5)
- Sensors and Instruments
  Computing for Instrument Control and Science Data Processing (TX 8.1, TX 8.3)

Advanced Avionics – Envisioned Future

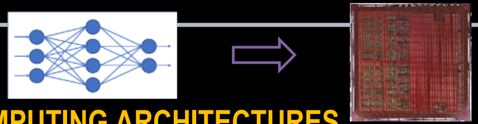


HIGH PERFORMANCE SPACEFLIGHT COMPUTING
- Radiation-hardened general-purpose processor with increased performance and flexibility to adapt to mission specific performance, power, and fault tolerance needs
- Advanced spaceflight memory with radiation tolerance and increased capacity and performance
- Intelligent, efficient, multiple output Point-Of-Load (POL) power converters
- High performance Single Board Computer (SBC) incorporating high-performance general-purpose processors, advanced memory, point-of-load converters, and real-time operating system in industry standard form factors and bus architectures
- System software tools to leverage the capabilities and manage the complexity of advanced multi-core processors

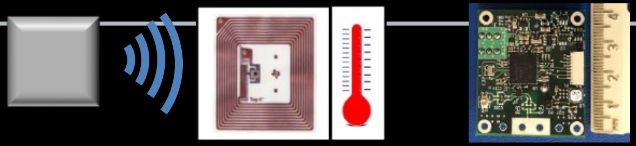

INTERCONNECT
- Radiation-tolerant interconnects to support low latency onboard video, multi-gigabit instruments, onboard science, and enhanced autonomy applications; including end points, switches, physical layer devices, and software support
- Highly reliable, high-bandwidth deterministic wireless networks



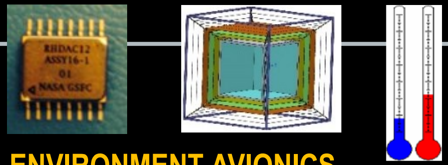
CREW INTERFACES
- Radiation-tolerant displays that can operate reliably for long durations mission beyond LEO
- Radiation-tolerant graphics processing that can operate reliably for long mission durations beyond LEO
- Heads Up Displays for Exploration EVA
- Crew voice and audio systems for deep space missions providing efficient compression of multiple streams, acoustic echo and noise cancellation, speech recognition and voice control, and wireless capabilities



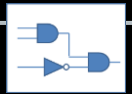
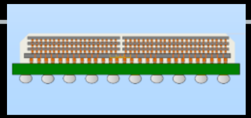
OTHER COMPUTING ARCHITECTURES
- Artificial Intelligence (AI) coprocessors to enable autonomous landing, surface navigation, robotic servicing/assembly, fault detection/mitigation, distributed systems operations, science data processing, and tip and cue for remote sensing missions
- Spaceflight quantum computers
- Low power embedded computers to support distributed robotics architectures



DATA ACQUISITION
- Wireless sensor networks to reduce harness mass and complexity, simplify integration and test, and improve system flexibility, serviceability, and expandability
- Low-cost, robust, high-accuracy data acquisition systems to enable distributed in situ monitoring of structures and subsystems on cost constrained missions

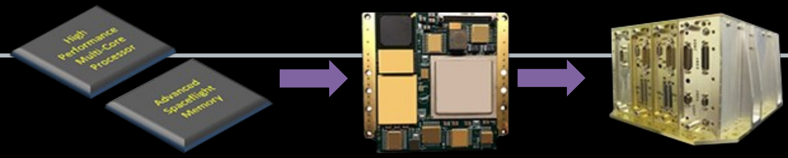


EXTREME ENVIRONMENT AVIONICS
- Extreme temperature electronics capable of operating in environments with both high radiation and wide temperature ranges, including lunar/planetary surfaces and nuclear systems
- Avionics packaging and thermal management technologies to enable avionics operation in extreme environments

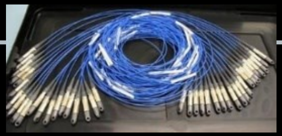
FOUNDATIONAL TECHNOLOGIES
- Advanced 2.5D/3D packaging and heterogeneous integration enabling miniaturization and improved performance
- Advanced semiconductor process nodes and libraries to enable next generation radiation hard devices
- Low-cost, radiation-hardened mixed-signal ASICs

Advanced Avionics – State of the Art



HIGH PERFORMANCE SPACEFLIGHT COMPUTING

- Processors – Current missions either using radiation-hardened processors with limited performance, or higher performance redundant COTS-based processors limiting power efficiency
  - *Target - 3-5X performance improvement over current space processors for general purpose processing (GPP), parallel processing acceleration, and flexibility to adapt performance, power, and fault tolerance to mission needs*
- Memory – Radiation-hardened memories lack capacity and/or performance, while COTS-based memories are susceptible to radiation induced upsets
  - *Target - Radiation-hardened memory with 4-8X the capacity and/or performance of existing radiation-hardened memories*
- Point-Of-Load (POL) Power Converters – Current POL converters provide a limited number of outputs and lack embedded fault tolerance
  - *Target - Radiation-hardened, high efficiency POL converters with at least 3 outputs, bus interface, and embedded fault tolerance*
- Single Board Computer (SBC) – Current SBCs using radiation-hardened processors have limited performance, and limited capability for power and performance scaling
  - *Target - Radiation-hardened SBC in industry standard form factor with 5X GPP improvement, parallel processing, and ability to scale power and performance*
- HPSC Software Tools – Current system software tools do not support the complexity of the High Performance Spaceflight Processing (HPSC) multicore processor
  - *Target - System software tools that allow developers to fully leverage the GPP and parallel processing capabilities and flexibility of the HPSC processor*



INTERCONNECT

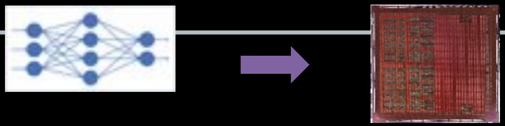
- Wired – Current onboard wired networks lack bandwidth to support increased sensor data rates of future missions
  - *Target - Wired networks with 10X bandwidth improvement*
- Wireless – Current onboard wireless networks only support low criticality needs
  - *Target - Wireless networks for critical applications in crewed and robotic missions*

CREW INTERFACES

- Crew Displays and Graphics Processors – Current spaceflight technologies offer limited visual performance and have uncharacterized radiation risks for long duration missions beyond LEO
  - *Target - Radiation-tolerant displays and graphics processors that can support displays with minimum of 1080p 30fps for Lunar and Mars mission durations (note - graphics processors are also applicable for other onboard processing functions)*
- Crew Voice and Audio Systems – Current system offer limited system performance and have uncharacterized radiation risks for long duration missions beyond LEO
  - *Target - Radiation-hardened system with efficient compression, speech recognition and voice control, and active noise control for Lunar and Mars mission durations*

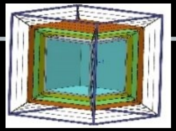
All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.

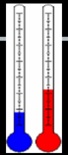
Advanced Avionics – State of the Art



OTHER COMPUTING ARCHITECTURES

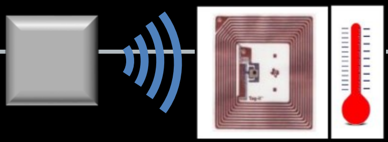
- Artificial Intelligence (AI) Coprocessors – COTS devices exist, but with unknown radiation performance and applicability to NASA onboard processing tasks
  - *Target - Radiation-tolerant AI coprocessors for NASA missions*
- Quantum Computing – Quantum computing technology is emerging, but is limited to terrestrial applications
  - *Target – Quantum computers tailored for onboard processing applications and environments*
- Low Power Embedded Computers – Current spaceflight robotics systems employ centralized architectures, which increases network bandwidth, latency, power, and system complexity
  - *Target – Low power embedded computers enabling distributed architectures*

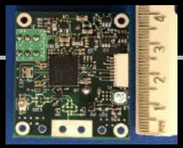




EXTREME ENVIRONMENT AVIONICS

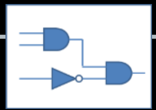
- Extreme Temperature/Radiation Electronics – Only limited functions have been implemented that can operate in environments with both high radiation and wide temperature ranges, including lunar/planetary surfaces and nuclear systems
  - *Target – Diverse set of circuit functions to enable systems that can operate in Lunar surface, planetary surface, and nuclear systems environments with both high radiation and wide ranges of operating temperatures*
- Packaging and Thermal Management Technologies – Current approaches limit the ability to operate at extreme cold and hot temperatures
  - *Target - Packaging and thermal management technologies that can be tailored to operate across wide temperature ranges for Lunar or planetary missions*

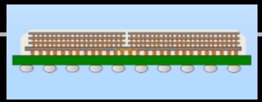




DATA ACQUISITION

- Wireless sensor networks – Current onboard sensing requires harnessing, which incurs a mass penalty
  - *Target - Readout systems and diverse onboard wireless sensor node types*
- Data Acquisition (DAQ) Systems – Current entry descent and landing DAQ systems are too costly to deploy on wide range of missions
  - *Target - 10X cost reduction for distributed in situ monitoring of structures and subsystems on cost constrained missions*





FOUNDATIONAL TECHNOLOGIES

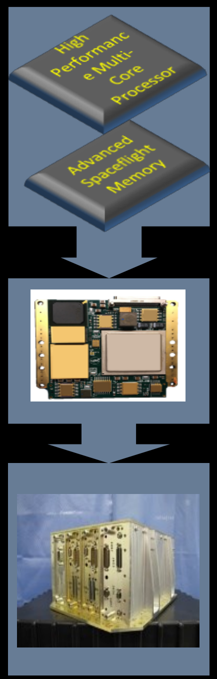
- Advanced 2.5D/3D Packaging and Heterogeneous Integration (HI) – These exist in industry, but lack spaceflight qualification
  - *Target - Qualified 2.5D/3D packaging and HI for NASA missions*
  - Advanced Semiconductor Process Nodes/Libraries – Existing 45nm RHBD libraries lack the density and performance needed for next generation of computing devices
  - *Target - Libraries with 2X/4X the performance/density existing RHBD libraries*
- Low-Cost Mixed Signal ASICs – Custom mixed-signal ASIC NRE cost limits infusion
  - *Target - Radiation-hardened structured ASIC platforms to reduce NRE cost*

All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.

Advanced Avionics Gap Closure Plans

(Green =Funded, Yellow = Partially Funded, Red = Unfunded)

HIGH PERFORMANCE SPACEFLIGHT COMPUTING	
Radiation-hardened general-purpose processor	Define a High Performance Spaceflight Computing (HPSC) processor concept that maximally leverages microelectronics technology advances for high reliability applications. Engage industry to develop and commercialize a radiation-hardened multi-core HPSC processor that addresses the computing needs of future NASA missions and broader markets. Leverage other government computing investments, as well as COTS developments, that are suitable for NASA use.
Advanced spaceflight memory	Fund the development and qualification of radiation-hardened non-volatile memory. Leverage other government agency investments in development of other radiation-hardened memory devices. Test emerging COTS memory technologies and identify devices that are suitable for NASA applications.
Point-Of-Load (POL) power converters	Leverage SBIR to develop intelligent, radiation-hardened multi-output POL converters that leverage industry smart power bus standards. Secure program funding for post Phase II commercialization.
Single Board Computer (SBC)	Define advanced avionics architectures that leverage HPSC capabilities. Develop spaceflight computer boards to demonstrate in those architectures. Engage industry to develop and commercialize spaceflight HPSC SBCs in industry standard form factors.
HPSC Software Tools	Port real-time operating systems, develop tools, and HPSC Middleware tools to support the full HPSC architecture. Assess existing libraries for image processing, signal processing, and machine learning, and augment as needed for HPSC architecture.



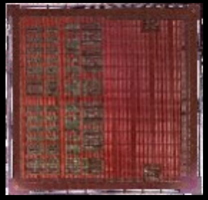
INTERCONNECT	
Radiation-tolerant interconnect	Leverage the HPSC concept studies and the NESC SpaceVPX Interoperability Study to select optimal interconnect standards for further development. Engage with standards organizations to ensure that evolution of selected standards meet future NASA mission needs. Assess availability of components required (i.e. endpoints, switches, physical-layer components) for a robust ecosystem for the selected standards, and leverage SBIR to develop needed components.
Highly reliable, high bandwidth deterministic wireless networks	Engage academic institutions to develop novel techniques that extend the capabilities of space-based wireless networks in time-sensitive and safety-critical applications. Leverage SBIR/STTR as a follow on to implement for space flight demonstration.

Advanced Avionics Gap Closure Plans

(Green =Funded, Yellow = Partially Funded, Red = Unfunded)

CREW INTERFACES	
Radiation-tolerant displays	Under ESDMD Polaris project, characterize the radiation performance of candidate display pixel technologies and support circuitry. Transfer knowledge from Polaris project to industry for development and commercialization of radiation-tolerant displays for future NASA exploration missions.
Radiation-tolerant graphics processing	Engage small business to characterize radiation performance of COTS Graphics Processor Units (GPUs) and develop system-level radiation mitigation approaches suitable for use in future NASA exploration missions. Specifically, develop system-level mitigation approaches for transient errors due to single event effect (SEE).
Heads Up Display (HUD) Optics	Advance development of Heads Up Display (HUD) optics under ESDMD Polaris project to advance xEMU displays. Continue development efforts for xEMU partnering with academia and industry.
Crew voice and audio systems	Engage, current NASA programs, industry partners, and small business to develop systems that can meet future mission environments and incorporate speech recognition capabilities.

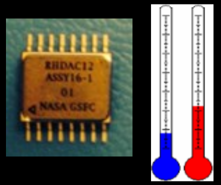
OTHER COMPUTING ARCHITECTURES	
Artificial Intelligence (AI) coprocessor	Evaluate viability of COTS coprocessor devices and foundational technologies for NASA AI applications within the RadNeuro and the NEPP programs. Devise system-level radiation mitigation approaches to address susceptibilities in COTS devices. Demonstrate coprocessors and mitigation approaches via ground radiation testing and flight demonstrations. Study the optimal mapping of onboard (AI) applications to candidate processing architectures and devices.
Quantum Computing	Explore candidate use cases for onboard quantum computing and compare performance with other computing technologies. Assess radiation susceptibilities of quantum computing and potential mitigations. Define concept for spaceflight quantum computer, and develop prototype.
Low power embedded computers	Develop distributed avionics architecture to enable modular, interoperable, and reusable robotic systems. Define low power embedded computer concepts that are consistent with that architecture and can meet SWaP and extreme environmental requirements. Perform NASA development of proof-of-concept low power embedded computer, and then engage small business for further development and commercialization.

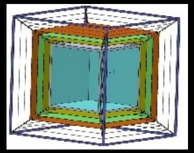


Advanced Avionics Gap Closure Plans

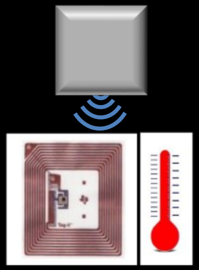
(Green =Funded, Yellow = Partially Funded, Red = Unfunded)

EXTREME ENVIRONMENT ELECTRONICS	
Extreme temperature/radiation electronics	Under the SMD ColdTech and HOTTech programs and STMD LSII and LuSTR programs, develop and characterize radiation-hardened extreme temperature design libraries in SiGe and SiC and implement digital and mixed-signal devices for infusion into NASA missions. Assess extreme temperature electronics from other industries for potential NASA use.
Avionics packaging and thermal management for extreme environments	Under the STMD PALETTE project, develop set of packaging and thermal management technologies to that avionics developers can utilize to implement passively controlled packaging for widely ranging mission environments. Infuse PALETTE technologies into lunar and planetary instruments and subsystems.

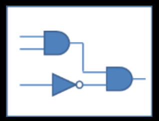


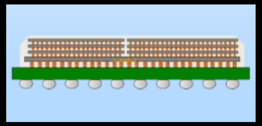


DATA ACQUISITION	
Wireless sensor networks	Develop and demonstrate enhanced wireless sensor nodes with an implementation path for hardware that can operate reliably in harsh environments and demonstration in testing, support, and flight applications as needed. Specific solutions for crewed missions may be compatible with the Radio-frequency identification (RFID) Enabled Autonomous Logistics Management (REALM) system, leveraging additive manufacturing technology to provide miniaturization.
Low-cost, robust, high-accuracy data acquisition systems	Leverage SBIR to develop a radiation-tolerant low-cost data acquisition system technology. Secure program funding for post Phase II commercialization.



FOUNDATIONAL TECHNOLOGIES	
Advanced 2.5D/3D packaging and heterogeneous integration	Develop conventional and additively manufactured 2.5D and 3D packaging technologies for low production volume devices. Engage Nextflex consortium to develop qualification methods for additively manufactured spaceflight electronics, and then demonstrate on smallsat missions. Engage industry on the development of qualification methods for 3D packaging.
Advanced Semiconductor Process Nodes/Libraries	Under NASA STMD funding, perform radiation characterization and modelling of the Global Foundries 22FDX process and automotive grade design libraries. Leverage other government and industry efforts in radiation-hardened deep submicron processes and libraries.
Low-Cost Mixed Signal ASICs	Engage industry to develop radiation-hardened mixed-signal structured ASIC platform to broadly meet NASA mission needs.





Advanced Avionics – Next Steps for Currently Unfunded Technologies

HIGH PERFORMANCE SPACEFLIGHT COMPUTING	
• Leverage SBIR to develop intelligent, radiation-hardened multi-output POL converters that leverage industry smart power bus standards.	Priority 2
CREW INTERFACES	
• Assess radiation susceptibilities and mitigations, and engage industry to develop and commercialize radiation-tolerant displays for future NASA exploration missions and crew voice and audio systems for future NASA exploration missions	Priority 1
INTERCONNECT	
• Engage with standards organizations to ensure that evolution of selected standards meet future NASA mission needs	Priority 3
• Leverage SBIR to develop technologies needed (i.e., endpoints, switches, physical components) for a robust ecosystem that supports the selected standards	Priority 7
• Engage academia to extend wireless network technology to meet the reliability and determinism needed by NASA applications for both crewed and robotic missions	Priority 8
LOW POWER EMBEDDED COMPUTER	
• Develop distributed avionics architecture to enable modular, interoperable, and reusable robotic systems	Priority 4
• Define low power embedded computer concepts that are consistent with that architecture and can meet SWaP and extreme environmental requirements	Priority 5
LOW-COST DATA ACQUISITION SYSTEMS	
• Leverage SBIR to a radiation-tolerant low-cost data acquisition system technology, then secure program funding for post Phase II commercialization	Priority 6

Conclusions

- The highest priorities for advanced avionics are:
  - Continued investment in High Performance Spaceflight Computing (HPSC), and underlying technologies
  - Continued investments in crew interfaces
- The next priority should be development of interconnect technologies to enable avionics architectures that address increasing sensor bandwidth, and can leverage the increased compute capabilities provided by HPSC
- Other priorities include development of radiation-hardened multi-output POL converters, development of low power embedded computers to support distributed robotics architectures, and development of low-cost, robust, high-accuracy data acquisition systems to enable distributed in situ monitoring of structures and subsystems on cost constrained missions
- Additionally, opportunities should be sought to leverage SBIR/STTR to address lower priority gaps

Acronyms

- AI – Artificial Intelligence
- ASIC – Application Specific Integrated Circuit
- COTS – Commercial off the shelf
- DAQ – Data Acquisition
- ECLSS – Environmental Control and Life Support System
- EDL – Entry, Descent, and Landing
- ESDMD – Exploration Systems Development Mission Directorate
- EVA – Extravehicular Activity
- GPP – General Purpose Processing
- GPU – Graphics Processor Units
- HI – Heterogeneous Integration
- HPSC – High Performance Spaceflight Computing
- HUD – Heads Up Display
- ISRU – In Situ Resource Utilization
- LEO – Low Earth Orbit
- LPEC – Low Power Embedded Computer
- LSII – Lunar Surface Innovation Initiative
- LuSTR – Lunar Surface Technology Research
- NEPP - NASA Electronics Parts and Packaging Program
- NESC – NASA Engineering & Safety Center
- NRE – Non-recurring Engineering
- PALETTE – Planetary and Lunar Environment Thermal Toolbox Elements
- POL – Point-Of-Load
- REALM – RFID Enabled Autonomous Logistics
- RFID – Radio-frequency Identification
- RHBD – Radiation-Hardened By Design
- SBC – Single Board Computer
- SBIR – Small Business Innovation Research
- SEE – Single Event Effect
- SMD – Science Mission Directorate
- STMD – Space Technology Mission Directorate
- STTR – Small Business Technology Transfer
- SWaP – Size, Weight, and Power
- TX – Taxonomy

EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

EXPLORE: Advanced Manufacturing
NASA Space Technology Mission Directorate
August 2022

STMD welcomes feedback on this presentation
See 80HQTR22ZOA2L_EXP_LND at nspires.nasaprs.com for how to provide feedback
If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

How We Explore… NASA Manufacturing

Inclusive Strategic Technology Planning

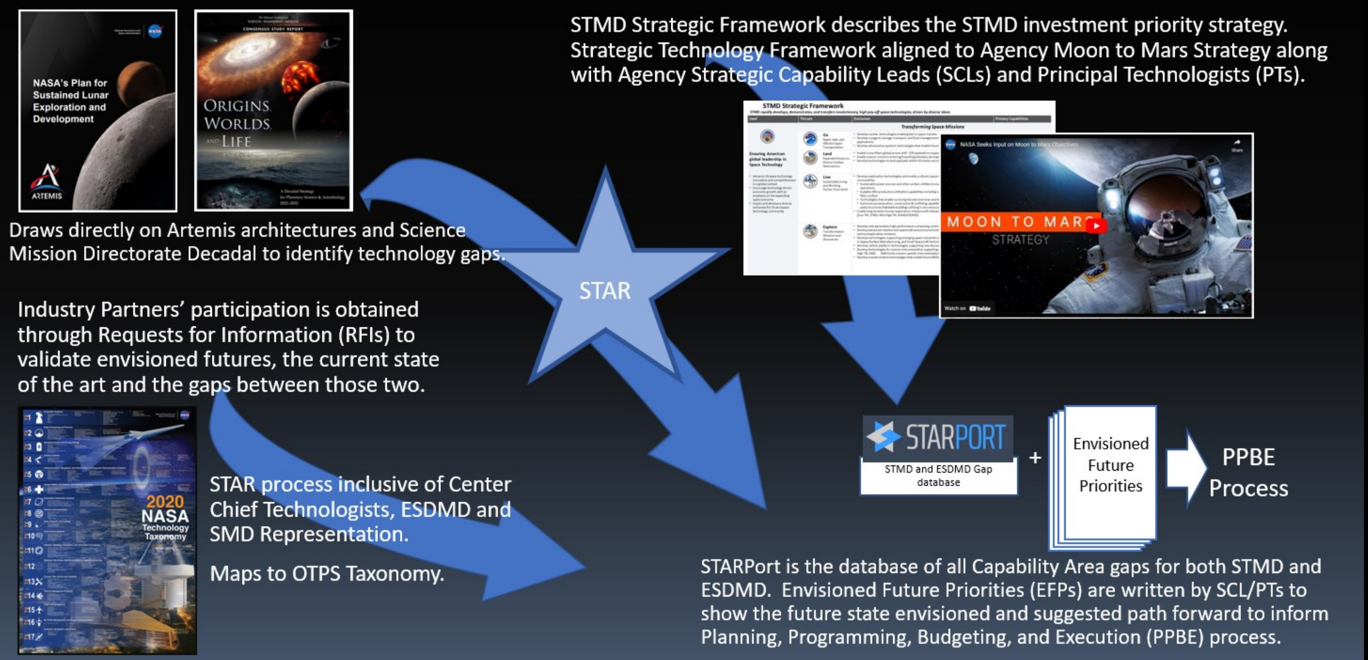
STMD utilizes STAR, the Strategic Technology Architecture Roundtable, to collect a diverse set of inputs into the strategic technology planning process.

- Draws directly on Artemis/ISS needs and SMD Science Decadal Studies: all NASA Center Chief Technologists and Mission Directorates included.
- Regular inputs directly from industry-on-industry plans and needs.
- Secure coordination and collaboration with US Space Force and DoD entities.

https://techport.nasa.gov/framework

Strategic Technology Architecture Roundtable (STAR) Process

In order to achieve the NASA Strategic Objective led by the Space Technology Mission Directorate, the STAR process was implemented to bring together the various inputs from stakeholders to produce a set of gaps that can be closed through STMD investments.



Strategic Technology Framework

STMD rapidly develops, demonstrates, and transfers revolutionary, high pay-off space technologies, driven by diverse ideas

Lead	Thrusts	Outcomes	Primary Capabilities
Ensuring American global leadership in Space Technology • Advance US space technology innovation and competitiveness in a global context • Encourage technology driven economic growth with an emphasis on the expanding space economy • Inspire and develop a diverse and powerful US aerospace technology community	**Go** Rapid, Safe, and Efficient Space Transportation	• Develop nuclear technologies enabling fast in-space transits. • Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications. • Develop advanced propulsion technologies that enable future science/exploration missions.	• Nuclear Systems* • Cryogenic Fluid Management* • Advanced Propulsion*
	Land Expanded Access to Diverse Surface Destinations	• Enable Lunar/Mars global access with ~20t payloads to support human missions. • Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies. • Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards.	• Entry, Descent, Landing, & Precision Landing*

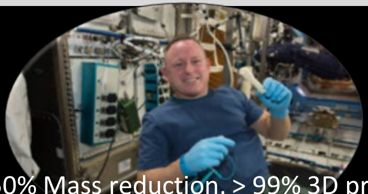
	Live
	Sustainable Living and Working Farther from Earth
		• Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities
		  • Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.
		  • Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface.
		  • Technologies that enable surviving the extreme lunar and Mars environments.
		  • Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources.
		• Enable long duration human exploration missions with Advanced Habitation System technologies. [Low TRL STMD; Mid-High TRL SOMD/ESDMD]
			• Advanced Power*
			• In-Situ Resource Utilization*
			• Advanced Thermal*
			• Advanced Materials, Structures, & Construction*
			• Advanced Habitation Systems*

* represents contributing crosscutting technologies	**Explore** Transformative Missions and Discoveries	• Develop next generation high performance computing, communications, and navigation. • Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions. • Develop technologies supporting emerging space industries including: Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft technologies. • Develop vehicle platform technologies supporting new discoveries. • Develop technologies for science instrumentation supporting new discoveries. [Low TRL STMD/Mid-High TRL SMD. SMD funds mission specific instrumentation (TRL 1-9)] • Develop transformative technologies that enable future NASA or commercial missions and discoveries	• Advanced Avionics Systems • Advanced Communications & Navigation • Advanced Robotics • Autonomous Systems • Satellite Servicing & Assembly* • Advanced Manufacturing • Small Spacecraft* • Rendezvous, Proximity Operations & Capture • Sensor & Instrumentation

EXPLORE: Develop technologies supporting emerging space industries

Priorities - Targeted advanced manufacturing outcomes aligned with space industry trends that will shape the course of research and development over many years

In-Space Manufacturing and Space Infrastructure



> 50% Mass reduction, > 99% 3D printer readiness. A catalyst for space infrastructure and economic opportunities

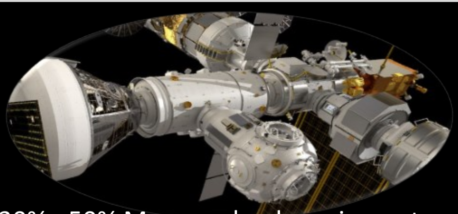
3D Printing/Additive Manufacturing

> 50% Cost reduction, 12 months instead of five years, Parts reduction >100 to 1

Digital Transformation - Digital Twins and Artificial Intelligence

More intelligent and more accurate predictions and capabilities, > 50% of physical resources replaced with virtual

Lightweight Composites Spacecraft

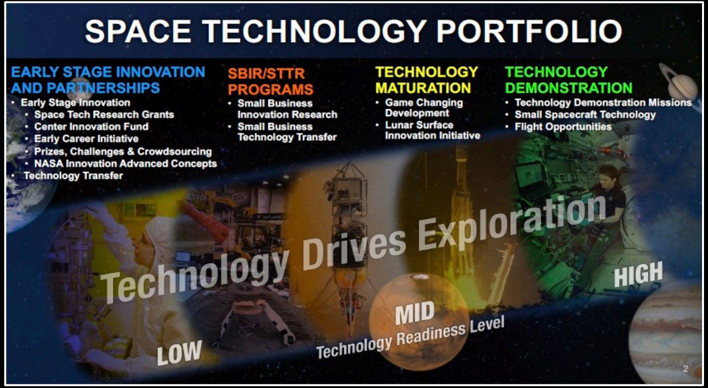


30% - 50% More payload, equipment, and experiments

Advanced Manufacturing technologies make NASA's missions more capable and affordable by bringing together industry, academia, and government

Plan to close gaps and achieve outcomes

- Integrated plan across Mission Directorates and Centers; Across TRLs (e.g., leverage STRG), programs and projects pipeline; Industry/Academia alignment, Workshops/TIMs
- Increase collaboration and public private partnerships. Leverage National Strategic Plans: Office of Science and Technology Policy Subcommittee on Advanced Manufacturing; In-Space Servicing, Assembly, and Manufacturing; Materials Genome Initiative; National Nanotechnology Initiative; others
- Outcome based - Innovative advanced manufacturing technologies targeted at commercial drivers for performance, affordability, and sustainability. "Bridge the Valley of Death"

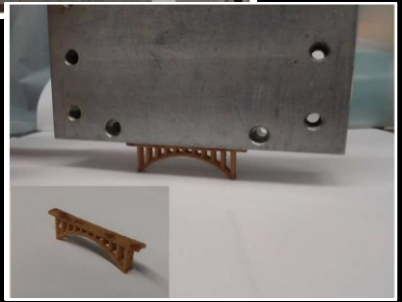


In Space Manufacturing and Space Infrastructure

Motivation/State of the Art

- Aligned with Lunar Utilization infrastructure priorities “industrialization of the Moon”
- The Post-ISS Plan: Commercial demand for in-space manufacturing
- The current logistics model is unsustainable for long duration space missions
- 3D Printer GCD tech demo on-board ISS in 2014
- 20 years of ISS microgravity materials science research (SMD BPS)
- STMD GCD ISM project (FabLab prototype testing)
- ISS commercial In Space Production Applications (InSPA)
- ISS National Lab/CASIS In-orbit materials/manufacturing
- NASA OSAM-1 and OSAM-2

Next Steps, Future Focus Areas and Investments



- Announcement of Collaboration Opportunity & Partnership Proposals to Advance Tipping Point Technologies
- On-demand manufacturing of metals, electronic components, recycling and reuse
- ISRU-derived materials for feedstocks (e.g., Al, Si) for lunar surface manufacturing
- Certification is a top challenge - Physics-based models to predict processing and material properties
- ISAM - welding in space, recycling and reuse, large scale additive manufacturing
- Maximize use of ISS for demonstration

3D Printing/Additive Manufacturing

Motivation/State of the Art

- Administration Launch of AM Forward Initiative
- Revolutionary design flexibility and dramatic reductions in cost/schedule
- Ideal applications for complex components (e.g., liquid rocket engines)
- Large-scale additive technologies are just being demonstrated
- Available materials are limited and not optimized for AM
- All empirical certification approaches
- Variability is the achilles heel

Next Steps, Future Focus Areas and Investments

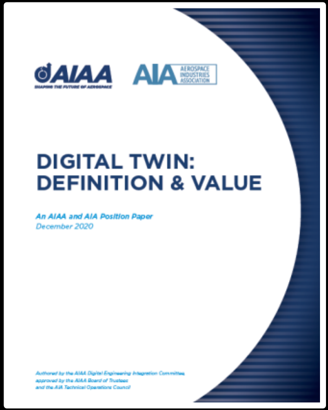
- Accelerate additive manufacturing certification (computational tools in concert with experimentation)
- Materials for extreme environments (e.g., refractories for nuclear)
- New processes (e.g., additive friction stir, directed energy)
- Large scale freeform applications
- NDE/Inspection, In situ monitoring, and closed-loop control
- Technologies for non-propulsion structures (e.g., common bulkheads, tanks, domes, optical structures etc.)
- Advance modeling and simulation for optimal parameters, property predictions and material designs

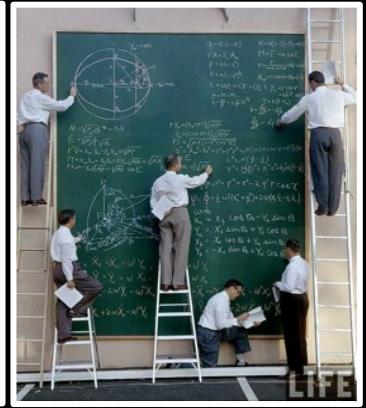
Extensive National Collaborations - Industry Driven Focus

Manufacturing Digital Transformation
Digital Twins and Artificial Intelligence

Motivation/State of the Art

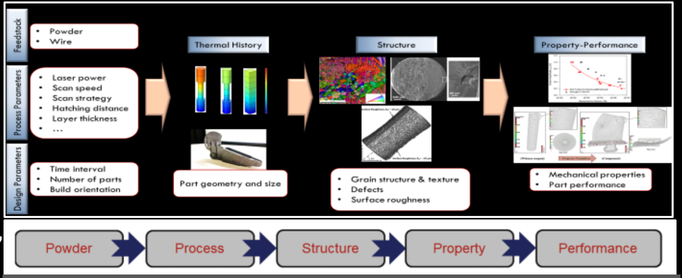
- Complexity of aerospace systems has significantly outpaced conventional development approaches – Inflection point!
- Global competition to achieve economic leadership through the development and application digital transformation
- Industry 4.0 EU strategic initiative for digital transformations in design, manufacture, and operations
- Air Force to develop F-16 "digital twin"
- Limited physics-based computational materials, design and manufacturing capabilities in use today (e.g., ICME, MGI initiatives)


AIAA AIA
DIGITAL TWIN:
DEFINITION & VALUE
An AIAA and AIA Position Paper
December 2020



Next Steps, Future Focus Areas and Investments

- Interdisciplinary modeling across the building block levels of "R&D to certification" (major agency/industry problem)
- Digital twin physics-based modeling and simulation of predictive relationships between processing parameters, material microstructure, material properties, and hardware performance
- Artificial intelligence, machine learning, and digital twin technologies for manufacturing processes

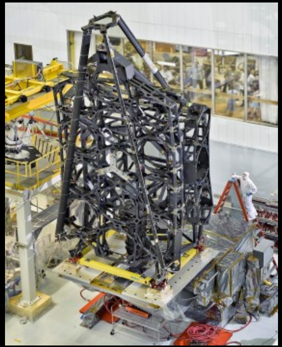


Modeling Process-Structure-Property Relationships for Additive Manufacturing

Lightweight Composite Spacecraft

Motivation/State of the Art

- Decadal Survey (Astro2020) - "Composite Material Process Development and Optimization"
- Immediate 30% weight savings and 25% cost savings compared to SOA
- Aluminum is most widely used in space vehicle structures
- Composites usage in space applications lags aviation and military
- Thermoplastic composites development is rapidly advancing
- Thermoset composites are de facto baseline and mechanical fastening is still primarily used (joints are the achilles heel)



Next Steps, Future Focus Areas and Investments

- Dimensional stability - Topic 3 ECF22
- Early Stage Innovations Solicitation
- Thermoplastic composites for space applications
- Adhesive bonding thermosets and welding thermoplastics
- Tailorable properties offer new design possibilities
- Digital/model-based discovery, characterization, and maturation
- High temperature materials & structures
- New materials and space environmental effects on materials
- Accelerated analytical certification and failure mode approaches

Current Investments

Additive Manufacturing

- On-orbit servicing, assembly, and manufacturing
- Rapid analysis and manufacturing propulsion technology
- Additive manufacturing of thermal protection systems
- Refractory alloys processing by additive manufacturing
- Additively manufacturing for tribological and radiation resistance improvement
- Metal digital direct manufacturing for combustion chambers and nozzles
- Moon to Mars oxygen and steel technology
- Computational design of functionally graded materials
- Design of metastable high entropy alloys for additive manufacturing
- Additive manufacturing for rotating detonation rocket propulsion
- Predicting the integrity of additively manufactured nickel alloys

In-Space Manufacturing

- On-orbit servicing, assembly, and manufacturing
- In-space manufacturing: on-demand manufacturing electronics
- In-space manufacturing: on-demand manufacturing metals
- In-space manufacturing: recycling and reuse
- Commercial feasibility of in-space manufacturing applications
- In-space assembly of perovskite solar cells for very large arrays
- In-space production applications (InSPA) ISS Implementation strategy
- Microgravity materials science program
- Materials International Space Station Experiment
- On-surface 3D printing of sodium-ion batteries using ISRU materials
- In-space coating development utilizing atomic layer deposition

Composites

- Institute for ultra-strong composites by computational design
- Superlightweight aerospace composites
- Deployable composite booms
- RAMPT carbon-carbon nozzle
- Composite technology for exploration
- Thermoplastics development for exploration applications
- 3D printing for low mass, multifunctional polymer composites
- Multifunctional composite textile materials for advanced spacesuits
- Manufacturing variation in multiscale analysis of composite structures
- Advanced composite solar sail
- OOA process or manufacture of large thin gauge composites
- Lightweight radiation shielding composites for small spacecraft
- ARMD hi-rate composite aircraft manufacturing

Manufacturing Digital Transformation

- Multiscale framework for material systems
- Modeling of additive manufacturing processes
- Process simulation for thin-ply composites
- Tool material design for friction stir welding
- Computational design of polymeric materials
- Digital twins for controlled environment plant production in space
- Computational design of graded alloys made with additive manufacturing
- Microstructure and defect informed predictions of damage tolerance
- Computational modeling of residual stresses in additive parts
- Digital twin certification for additive manufacturing
- Multiphysics integrated modeling of self-reading friction stir welding

(*representative project activities, not a comprehensive list)

Summary

- Advanced manufacturing technologies are critical to NASA, the Nation's aerospace industry, and almost every sector of the U.S. economy
- White House Critical Emerging Technology List - Advanced Manufacturing (Additive Manufacturing), Space Technologies and Systems (In-Space servicing, assembly, and manufacturing), Advanced Engineering Materials (Materials Genome), Artificial Intelligence
- Better collaboration between government, industry, and academia will accelerate realization of innovative technologies
- An integrated/focused plan of investment strategies across the full TRL pipeline and across Mission Directorates
  - Linked to Agency missions, other national needs, and commercial strategies
  - Deep understanding of SOA, key challenges, and emerging innovations
  - Bridge the "valley of death" for translational technologies from science to manufacturing

Acronyms

- ARMD: Aeronautics Research Mission Directorate
- BPS: Biological and Physical Sciences
- GCD: Game Changing Development
- ICME: Integrated Computational Materials Engineering
- InSPA: In-Space Production Applications
- ISAM: In-space Servicing, Assembly, and Manufacturing
- ISRU: In-Situ Resource Utilization
- MGI: Materials Genome Initiative
- NASA: National Aeronautics and Space Administration
- OCT: Office of the Chief Technologist
- OOA: Out Of Autoclave
- R&D: Research and Development
- SMD: Science Mission Directorate
- SOA: State of the Art
- STAR: Strategic Technology Architecture Roundtable
- STMD: Space Technology Mission Directorate
- STRG: Space Technology Research Grants
- TIM: Technical Interchange Meeting
- TRL: Technology Readiness Level

EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

EXPLORE: Autonomous Systems & Robotics (ASR)
NASA Space Technology Mission Directorate
August 2022

STMD welcomes feedback on this presentation
See 80HQTR22ZOA2L_EXP_LND at nspires.nasaprs.com for how to provide feedback
If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

What is Autonomous Systems and Robotics (ASR)?

Autonomous Systems and Robotics

- … is a broad, multi-disciplinary technology domain
- … enables high priority outcomes across NASA's entire Strategic Framework
- … is foundational for establishing lunar infrastructure (survey, construction, deployment, outfitting, servicing, etc.)
- … is foundational for ISRU (prospecting, excavation, transport, handling, etc.)
- … is foundational for both in-space and planetary surface missions

Self- and Situational Awareness
- Sensing and Perception
- State Estimation and Monitoring
- Object, Event, Trend, & Activity Recognition
- Force and Tactile Sensing
- Remote Sensing
- Onboard Science Data Analysis
- Knowledge and Model Building
- Hazard Assessment
- Anomaly Detection

Mobility
- Extreme Terrain Mobility
- Below-Surface Mobility
- Above-Surface Mobility
- Small-Body and Microgravity Mobility
- Surface Mobility
- Robot Navigation
- Mobility Components
- GN&C Algorithms

Manipulation
- Manipulator Components
- Dexterous Manipulation
- Control of Contact Dynamics
- Mobile Manipulation
- Sample Acquisition and Handling
- Grappling

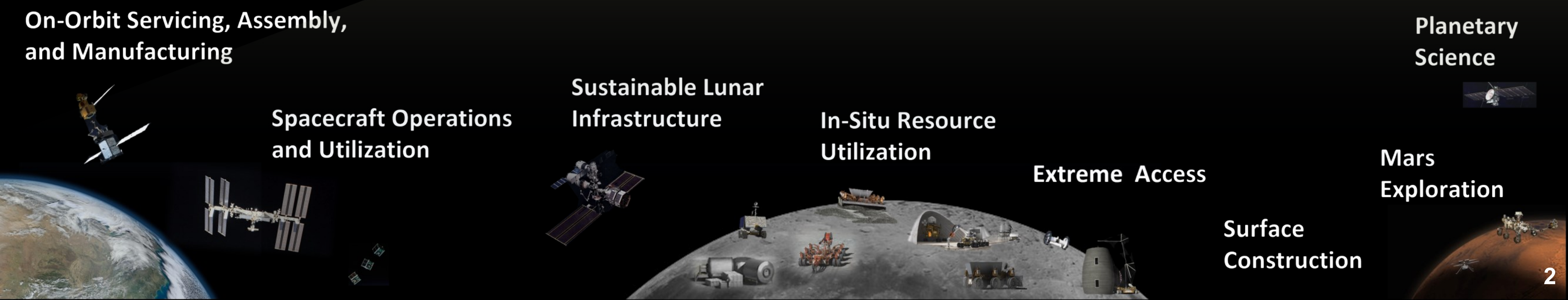
Multi-Agent Cognition and Operations
- Collaborative Mobility
- Collaborative Manipulation
- Distributed Cooperation and Collaboration
- Agent Coordination
- Joint Knowledge and Understanding
- Behavior and Intent Prediction
- Goal and Task Negotiation
- Operational Trust Building

Human System Interaction
- Multi-Modal Interaction
- Supervisory Control
- Proximate Interaction
- Intent Recognition and Reaction
- Common and Standard HSI
- Remote Interaction

Reasoning and Acting
- Mission Planning
- Activity and Resource Planning and Scheduling
- Motion Planning
- Execution and Control
- Fault Diagnosis and Prognosis
- Fault Response
- Learning and Adapting

Systems Engineering and Integrity
- Modularity, Commonality, and Interfaces
- Verification and Validation
- Modeling and Simulation
- Architecture and Frameworks
- Safety and Trust
- Test and Evaluation
- Operational Assurance
- Design Tools

"Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions"



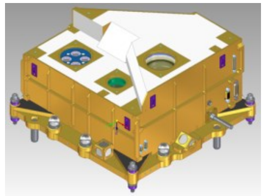
Key Points

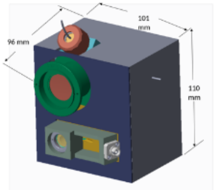
Goals

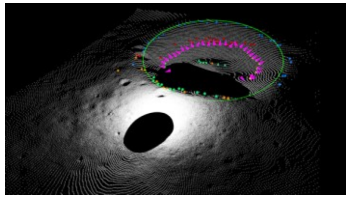
- Enable space missions that cannot currently be performed
- Increase space mission effectiveness, productivity, and safety
- Respond to the needs of commercial missions, human exploration missions, and science missions
- Establish a self-sustaining community of academia, government, and industry to develop ASR technology and expand workforce
- Reduce barriers (cost, schedule, risk, etc.) to collaboration, deployment, and reuse of new technology

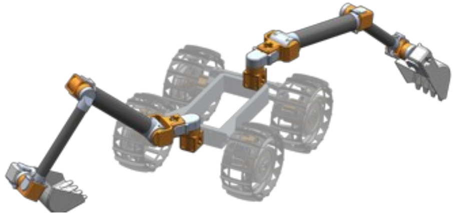
Approach

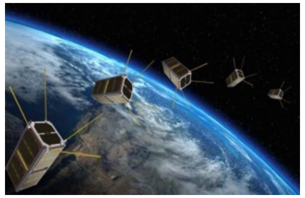
- Target cross-cutting (multi-mission) and STMD demo needs – not mission-specific autonomy and robotics technology
- Focus on six “envisioned future” technology objectives
- NASA helps break barriers and reduce tech risk for industry
- Adopt an Open Framework to enable incremental development of modular, interoperable, and reusable tech by many parties
- Leverage the Lunar Surface Innovation Consortium to engage the non-NASA space community

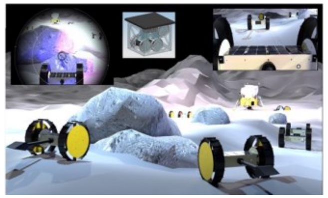






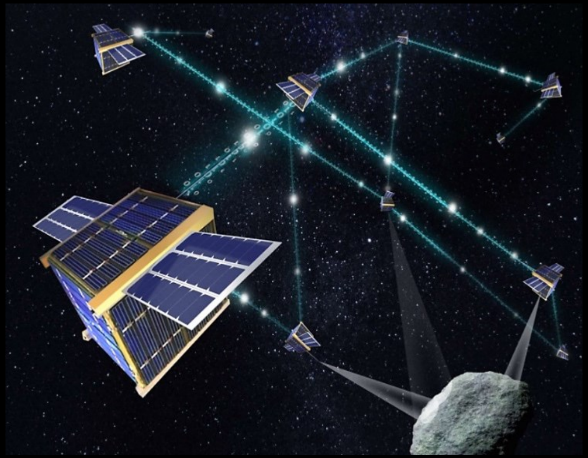






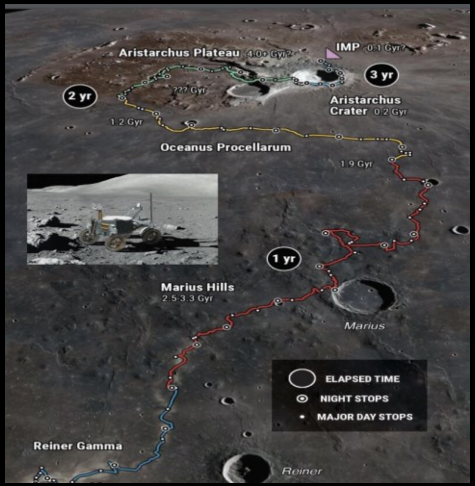
EXPLORE: Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions.

Autonomous Multi-Spacecraft System for Distributed Science Measurements



Autonomous Fail-Active, High-Tempo Science Missions

Autonomous High Progress Rate Science Rover



Autonomous Continuous Lunar Surface Operations

Technology Objectives

- **Cooperative multi-spacecraft system with efficient human teaming** for cost-effective interdependent and distributed work (system operable as a single "entity" for satellite and planetary science missions)
- **Self-adaptive and fail-active autonomy for high-tempo missions** in high-risk, dynamic, and uncertain environments (example: guaranteed sampling from one-time events during short duration mission)
- **Efficient on-board autonomy for continuous surface operations** with cost-effective mission control (1/10 cost of current practice) and increased performance (10x productivity / time) for long range (450 km/yr) or worksite operations (750 km/yr)

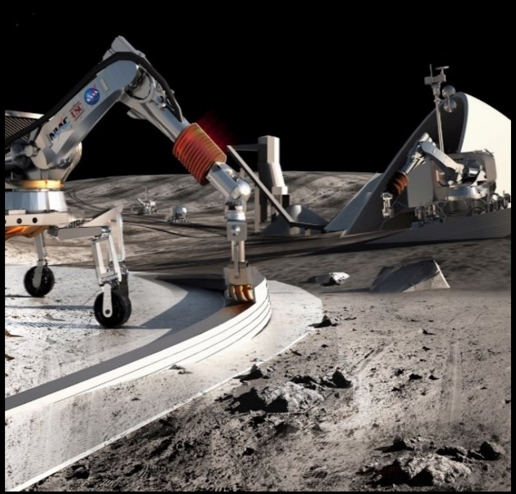
Examples shown depict "envisioned futures" to guide technology development vision and are not currently approved or funded.

EXPLORE: Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions.

Robotic Caretaking Inside Habitats and Spacecraft

Robotic Exploration of Extreme Environments

Robotic Construction of Surface Infrastructure



Robotic Resource Extraction and Transport

Technology Objectives

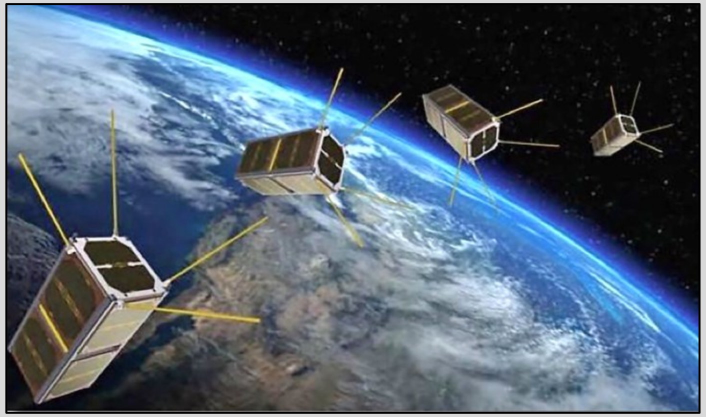
- **Remotely operated intra-vehicular robotics for maintenance and utilization:** 4,000+ hr/yr of high duty-cycle exploration spacecraft and surface habitat activities (uncrewed up to 90% of time)
- **Robust robot mobility for extreme access:** surfaces (up to 5,000 km life-cycle drive), deep interiors through rock (up to 10 km) and cryogenic ice (up to 25 km), and handling of dangerous topography (up to 90° slopes)
- **Durable, self-maintainable robotics for heavy-duty surface work:** bulk excavation (up to 400 metric tons), material transport (up to 600 km/yr), and surface construction (up to 15,000 kg carrying capacity)

Examples shown depict "envisioned futures" to guide technology development vision and are not currently approved or funded.

State of the Art: Spacecraft Autonomy Technologies

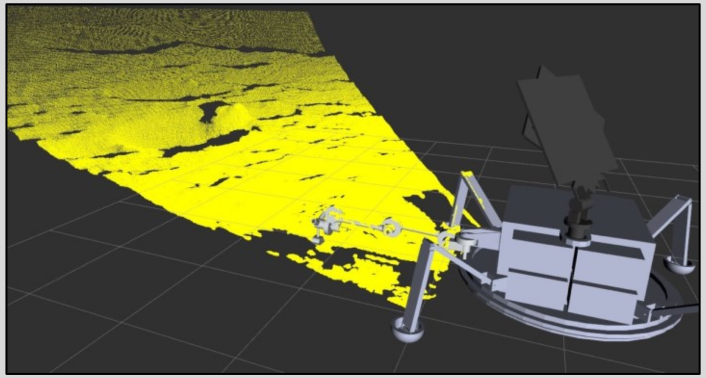
Cooperative multi-spacecraft system with efficient human teaming

Multi-robot autonomy and commanding for distributed measurements (JPL, 2021) ***TRL 5***

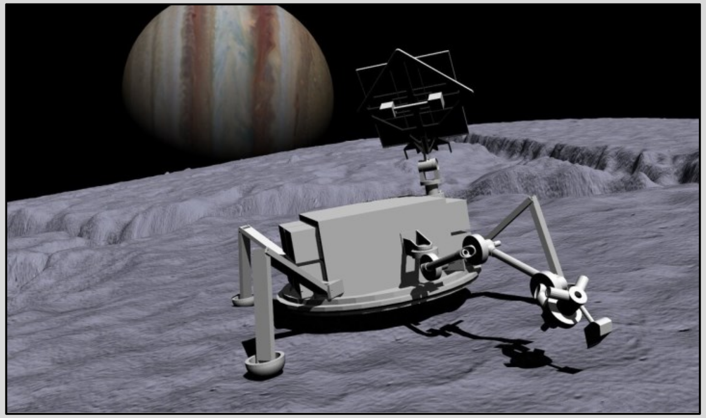


Distributed spacecraft autonomy and human-swarm control tech demo (ARC, 2022) ***TRL 6***

Self-adaptive and fail-active autonomy for high-tempo missions



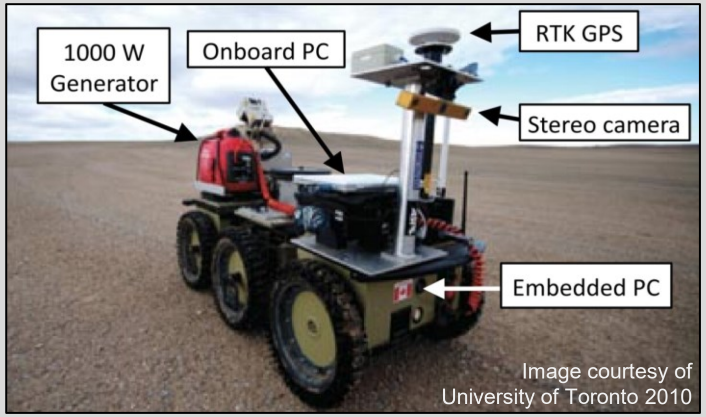
On-board recalibration for adaptation to faults for Europa (Caltech, 2021) ***TRL 3***



Stochastic fail-active robotic task planning for Europa (Honeybee Robotics, 2021) ***TRL 4***

Efficient on-board autonomy for continuous surface operations

Autonomous rover traverse (26 km in 10 days) across the Atacama (CMU, 2015) ***TRL 5***



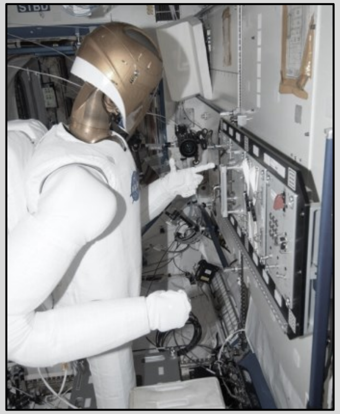
"Visual Teach and Repeat" achieving 99.6% repeatable traverse (U Toronto, 2010) ***TRL 5***

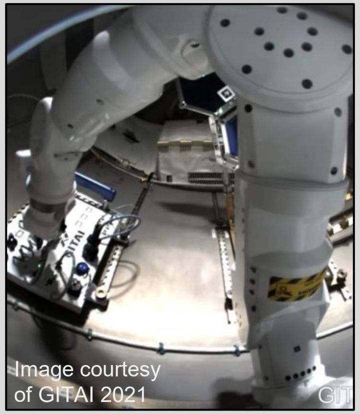
Examples shown are not intended to be comprehensive, an endorsement, or representative of all aspects of each technology objective.

State of the Art: Advanced Robotics

Remotely operated intra-vehicular robotics for maintenance and utilization

Astrobee, an operational ISS facility supporting IVA robotics R&D (ARC, 2019) ***TRL 7***

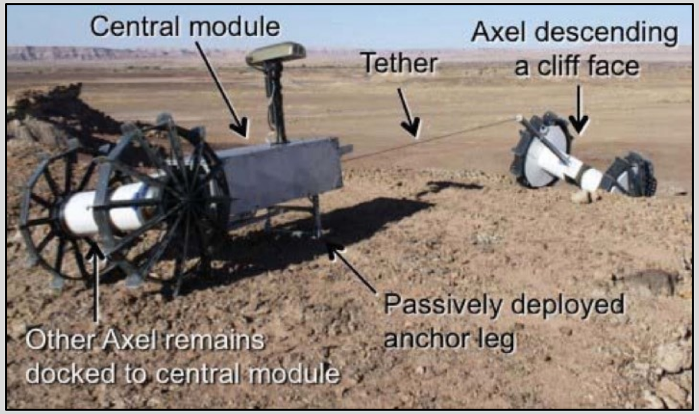




Dexterous manipulation demonstrations on ISS (Robonaut 2, JSC, 2014) (GITAI, 2021) ***TRL 6***

Robust robot mobility for extreme access

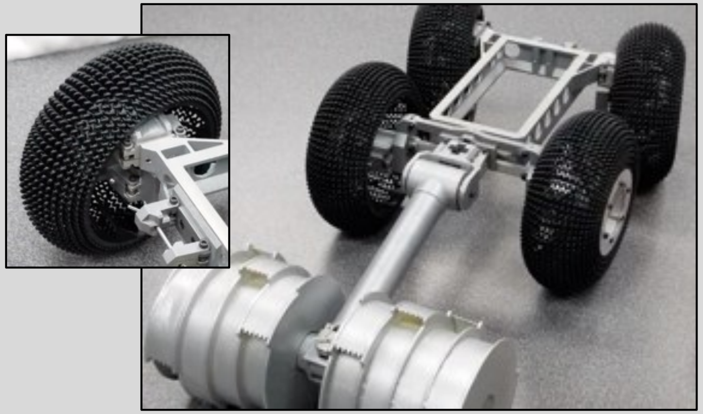
Traversing obstacles with 3x wheel radius with RoboSimian (JPL, 2020) ***TRL 5***



Dual tethered robots for handling steep terrain and cliffs (DuAxel, JPL, 2013) ***TRL 5***

Durable, self-maintainable robotics for heavy-duty surface work

Prototype robot for excavation of lunar regolith (RASSOR, KSC, 2021) ***TRL 5***



Field-serviceable, modular vehicle concept for the lunar surface (NASA, 2018) ***TRL 3***

Examples shown are not intended to be comprehensive, an endorsement, or representative of all aspects of each technology objective.

Demand for Autonomous Systems & Robotics (ASR)

2022 NASA Strategic Plan: STMD – Innovate and advance transformational space technologies. Develop revolutionary, high-payoff space technologies driven by diverse ideas to transform NASA missions and ensure American leadership in the space economy

Commercial Space

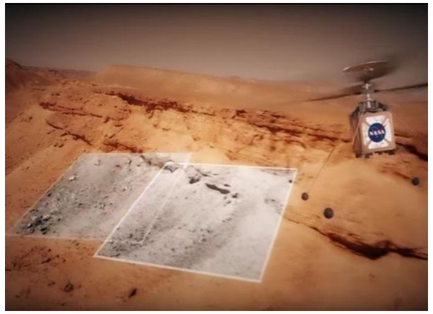
- Sustainable infrastructure and common, interoperable technologies would facilitate broader industry integration and infusion of new technical capabilities
- Industry needs data sets, operational models, and testbeds to support rapid, cost-effective development of autonomy and robotic products

Human Exploration

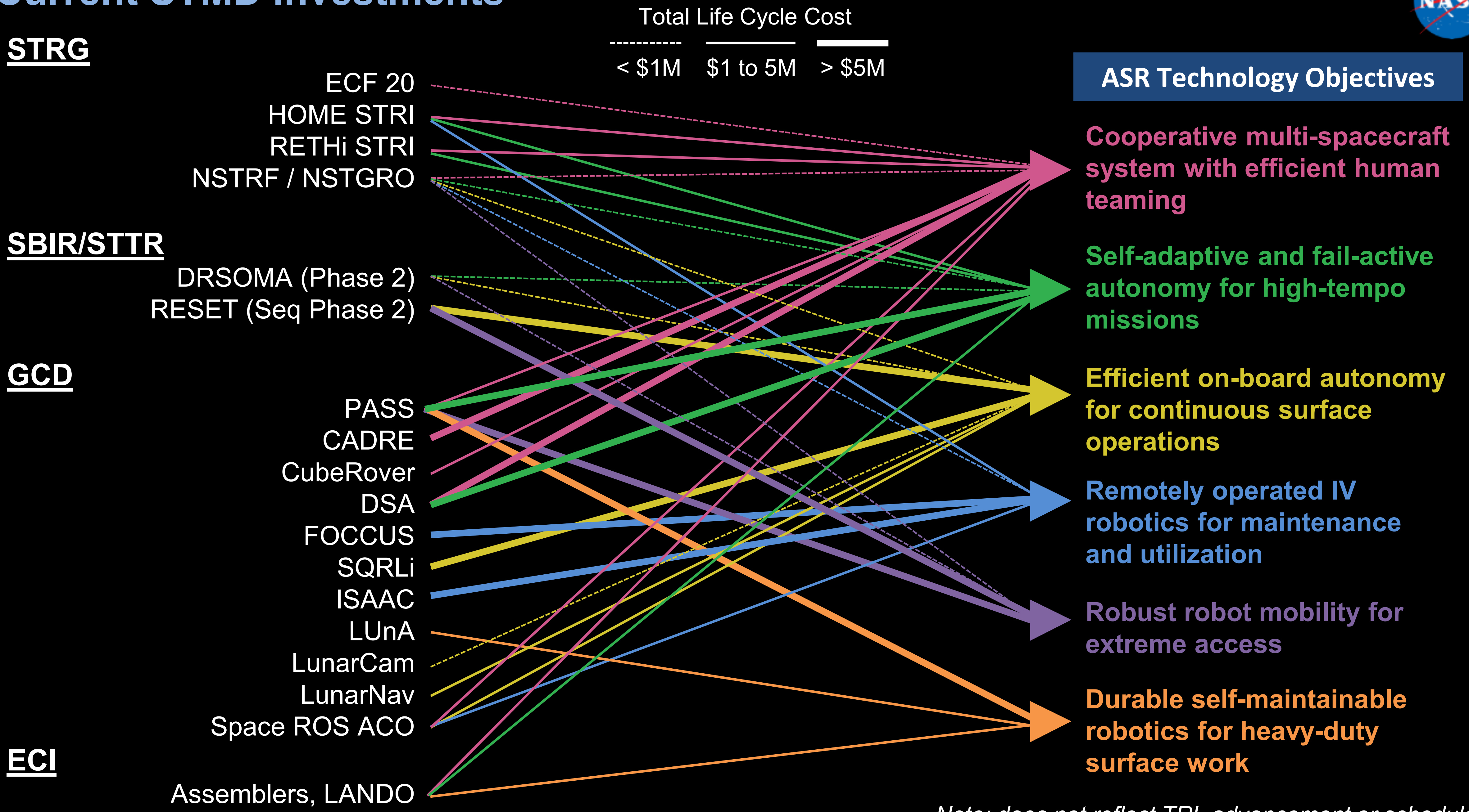
- All future human spacecraft need to be monitored and maintained during uncrewed periods to protect the vehicle and increase utilization
- Artemis architecture includes robotic deployment, surface mobility, and ISRU
- Autonomous systems and robots capable of efficient human interaction preserve valuable crew time for high-priority exploration and science activities

Science

- New missions to challenging destinations are made possible with technology advances, particularly in cooperative multi-spacecraft systems and self-reliant autonomy
- Large-scale observatories would benefit from autonomous in-space assembly, inspection, and/or maintenance



Current STMD Investments



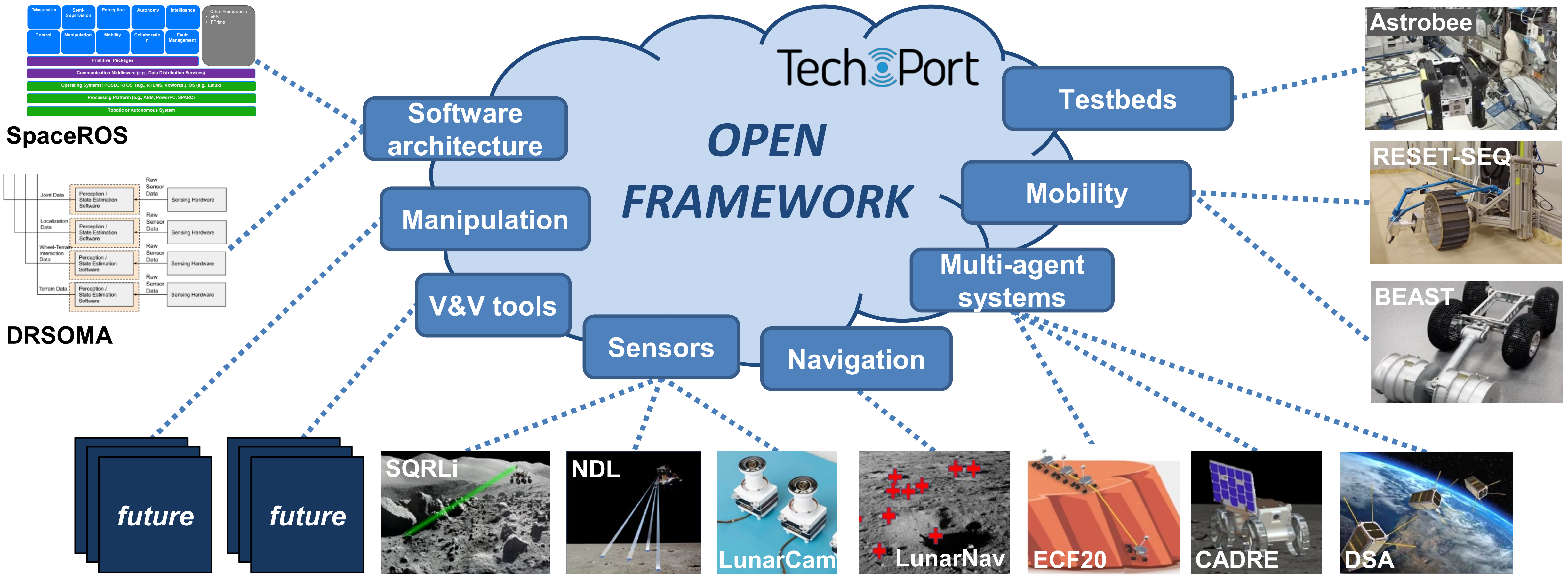
Note: does not reflect TRL advancement or schedule

ASR Strategy: Grow the Space Economy and Workforce

1. **Open framework approach to create sustainable, industry-driven hardware and software**
   - Modular, interoperable, and reusable components (open-source & proprietary) developed by many parties
   - Lower barriers to entry for infusion and adaptation of industry/terrestrial ASR technologies into spaceflight applications
   - Facilitate transfer/licensing/release of NASA investments to US entities (academic, government, and industry) with appropriate export control
2. **NASA develops prototypes to break barriers and reduce risk as needed (not constant level of effort)**
   - Demonstrate new technology and development processes/tools (V&V, etc.) as needed
   - Examples: DSA autonomy software, CADRE rover, SQRLi rover lidar, RASSOR excavator, etc.
3. **Encourage and support testbeds to accelerate development**
   - Leverage ESDMD investments (e.g., ISS Astrobee Facility) to support STMD development
   - Leverage SMD investments (e.g., COLDTech autonomy testbed) to support STMD development
   - Identify and support release of software simulators (LaRC AEON BEAM, ARC VIPER RSIM, etc.)
4. **Industry and NASA collaborate to integrate technologies for flight missions**
   - ASR technology drawn from both industry and NASA, tailored for mission need in partnership with relevant parties
   - Benefits not limited to STMD tech demos, but also human exploration and science missions
5. **Use LSIC to engage non-NASA space autonomy & robotics community**
   - TIMs and RFIs to support open framework approach
   - Industry site visits and targeted technology assessments

Open Framework: Modular, Interoperable, and Reusable Technology

- **Objective**: sustainable **technology** that is **modular**, **interoperable**, and **reusable**
- Create a public **catalog** for ASR technology – build off of **TechPort v3.8** to create a tool for the ASR community (not just NASA!) and to motivate continuous tech transfer and reuse to/from all parties (NASA and industry)
- STMD projects will seed the clearinghouse and lead **licensing/release** of NASA developed technology

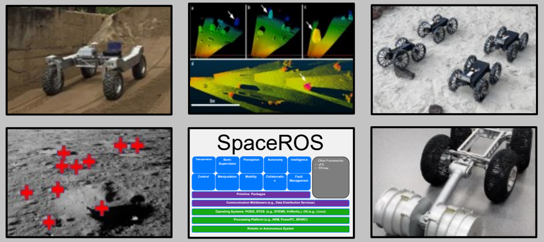


Example: Lunar Surface Infrastructure

Autonomous, cooperative, and durable robotic systems for deployment and long-term surface operations

- Requires extended duration robotic excavation, construction, outfitting, and maintenance capabilities in the lunar environment
- Builds on current STMD investments (e.g. COLDArm, ECF20, LSII Seq., PASS, SQRLi) toward mission infusion

Current NASA / STMD Investments



External Partnerships, Tech Transfer, and Infusion

Industry ⟷ NASA ⟷ Academia

Open Framework

- Modular, Interoperable Software
- Common Hardware Interfaces and Standards
- Datasets and Testbeds

Synergistic Efforts Across Technical Domains

(ISRU, Power, Structures, Thermal, . . .)

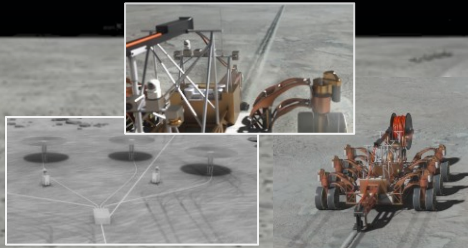
New Subsystem Technology Development

- Long range and duration lunar drive systems
- On board localization, planning, and execution
- Explainable autonomy/AI
- Extreme terrain mobility
- Multi-agent coordination
- Self-maintenance/repair
- Adaptive ops for long term degradation
- Low-mass rugged mechanisms
- Modular implements
- High progress rate autonomous navigation
- And more . . .

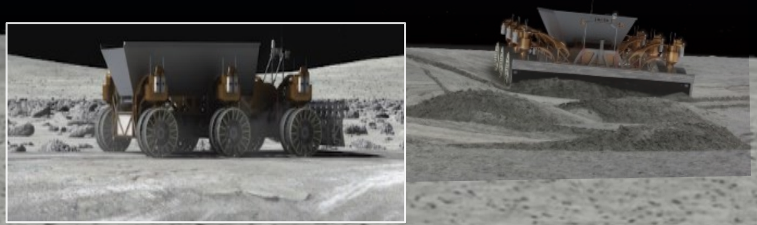
Interoperability and reusable technology enable rapid integration and collaborative operations across multiple vendors and systems

Production-scale ISRU prospecting and transport

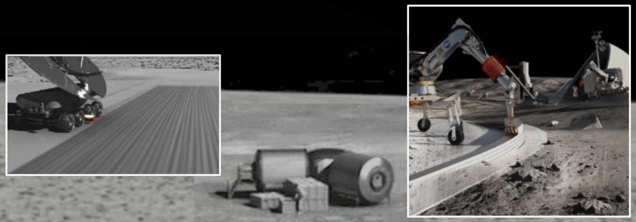
Trenching, laying and connecting cables, etc. for long-distance power distribution



Full-scale excavation, transport, and construction for sustained surface activities



Autonomous surface operations over multiple lunar day/night cycles

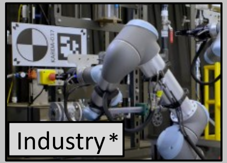


Example: Human Spacecraft Support

Autonomous robotic systems that enable remote and uncrewed IVA maintenance and utilization

- Addresses key Artemis architecture capability gaps and needs in autonomy and robotics
- Builds on current STMD investments (e.g. FOCCUS, ISAAC, SpaceROS, STRI SmartHabs) toward mission infusion

Technology Infusion from Multiple Sources



* Image courtesy of Woodside Energy 2020
† Image courtesy of GITAI 2021

Open Framework

Modular, Interoperable Software

Common Hardware Interfaces and Standards

Datasets and Testbeds

New Subsystem Technology Development

- Affordance recognition
- Object detection
- Pose estimation
- Fault-tolerant actuation
- Self-adaptive and fail-active autonomy
- Adaptable end effectors
- Multi-mission robot control interfaces
- Robust manipulation
- Grasp planning
- Semantic SLAM
- IVA mobility and navigation planning
- Standardized docking and grasping interfaces
- Coordinated task planning & execution
- And more . . .

Open Framework approach enables cooperation across different vendor systems

Multi-mission reuse extensible from IVA to EVA surface ops and astronaut assistance (e.g. LTV manipulator)

Versatile robotic capabilities facilitate in-space commercial activity and lay the foundation for humans on Mars

Next Steps (Near-term)

	Subsystem Tech (Gaps)	Rationale
Autonomy	• Develop on-board planning for extreme terrain traversal (STMD-ASR-002, STMD-ASR-003) • Develop on-board rover terrain embedding & entrapment recovery methods (STMD-ASR-014, SMD-PESTO) • Develop reusable autonomous manipulation behaviors and task planning (STMD-ASR-003, STMD-ASR-008)	• Site preparation and regolith collection robotics must be capable of reliable continuous operations to handle surface operations at scales beyond proof-of-concept demos. • Reliable autonomous navigation over unmodified terrain is required for all lunar surface operations. • Robust dexterous manipulation for assembly work in unimproved environments is a key technology for deploying and maintaining surface power distribution infrastructure and other lunar assets.
Robotics	• Develop long-range and rugged drive systems (STMD-ASR-002, STMD-ASR-010) • Develop field-swappable repair units (STMD-ASR-013) • Develop fault-tolerant robotic actuators and end-effectors (STMD-ASR-020, STMD-ASR-021)	• Site preparation and regolith collection robotics must be able to traverse long-distances over their lifetime to handle surface operations at scales beyond proof-of-concept demos. • Resilient robotics technology is needed to support IVA utilization, inspection, maintenance, and contingency response inside habitable volumes (in-space and surface).
R&D Infrastructure	• Open Framework: Establish clearinghouse and implement incentivization strategy • Extend ISS Astrobee facility to support IVA robotics technology development	• Open Framework approach will help industry, NASA, & other organizations move away from custom, one-off development • STMD can leverage on-going ESDMD investment to support and accelerate ASR development

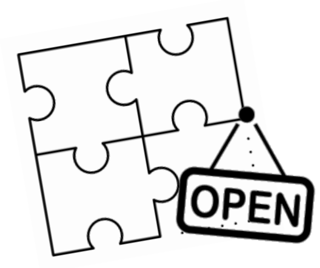
Next Steps (Mid-term)

	Subsystem Tech (Gaps)	Rationale
Autonomy	• Develop adaptive ops for long-term degradation (STMD-ASR-008, HEOMD-2021-3449-TX10) • Develop auto recovery from loss of data comm (HEOMD-2021-3052-TX10.1) • Develop efficient robot perception systems suitable for space computing (STMD-ASR-018)	• Establishing a long-distance power transmission/distribution network requires autonomous navigation and reliable handling of communications. • STMD tech demos and multiple stakeholder missions require on-board autonomy to operate at high cadence and be able to fail-active (i.e. continue to accomplish goals in spite of faults).
Robotics	• Develop low-mass rugged mechanisms (STMD-ASR-012, STMD-ASR-022) • Develop very low-temperature mechatronics (STMD-ASR-0012) • Develop steep slope climb/descent systems (STMD-ASR-010)	• Site preparation and regolith collection robotics must be low mass, yet capable of high force and payload capabilities, as well as able to tolerate multiple lunar day/night cycles and operate in permanently shadowed regions. • Long-lived robotic work systems must be repairable or serviceable in order to maintain nominal operation and recover from component failures and degradation.
R&D Infrastructure	• Open Framework: Connect ASR community to other government agencies • Adapt SMD OceanWaters simulator to support STMD solicitations (ACO/TP, SBIR, or STRG)	• Open Framework approach can increase ASR workforce and speed system development in support of government activities beyond NASA • STMD can leverage on-going SMD investment to support and accelerate ASR development

Next Steps (Long-term)

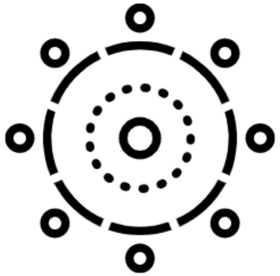
	Subsystem Tech (Gaps)	Rationale
Autonomy	• Develop explainable autonomy / AI operator interfaces for use by ground control and crew (STMD-ASR-005, STMD-ASR-015) • Develop methods and tools for V&V of autonomous systems used for critical functions	• Increased use of on-board autonomy requires effective supervisory control interfaces. This requires capabilities for efficient notification, summarization, and detailing of task execution (particularly autonomous fault management) • Reliance on autonomy for safety-critical and mission-critical functions requires new V&V capabilities.
Robotics	• Develop interchangeable implements & tools (STMD-ASR-012, STMD-ASR-013) • Develop mission-rated multi-robot tethering (STMD-ASR-013) • Develop low-mass thermal control modules for lunar robotics (STMD-ASR-012)	• Planetary robotic work systems will greatly benefit from modular end-effectors and devices in terms of flexibility, maintainability, and task performance. • Tethered multi-robot systems have significant potential for increasing access to extreme locations, improving rescue capabilities, and force multiplication.
R&D Infrastructure	• Develop ASR standards • Release NASA curated datasets for ASR development	• Based on 6+ years of experience with the Open Framework, NASA should lead an effort to establish open standards for ASR interoperability. This could involve partnerships with CCSDS, ISO, and/or technical societies (IEEE, SAE, etc). • Curated reference datasets can speed R&D by providing key information for benchmarking and testing.

Conclusion: ASR Strategy for Interoperability and Tech Transfer



Develop ASR open framework implementation
- Explore relevant existing standards for and develop licensing and controlled release models for hardware and software
- Determine baseline(s) for software interoperability (e.g., SpaceROS, cFS, DDS, etc.)
- Determine need(s) for creating and enhancing NASA testbeds
- Work with STRG, SBIR, GCD, LSIC, and tech partnership

Focus current ASR portfolio towards "envisioned future" tech objectives
- Revise gaps from ASR, ESDMD/SOMD, and SMD (including Decadal Survey) based on open framework approach
- Work with current STMD projects and programs to include tech transfer as deliverable (may require scope increase)
- Establish new starts (focus on ACO/TP, GCD, and SBIR)



Build ASR community
- Use LSIC to conduct TIMs and open framework engagement strategy
- Identify and support creation of testbeds to accelerate tech development

Acronyms

- ACO – Announcement of Collaboration Opportunity
- ARC – Ames Research Center
- AEON – Autonomous Entity Operations Network
- AI – Artificial Intelligence
- ASR - Autonomous Systems and Robotics
- BEAM – Baseline Environment for Autonomous Modeling
- BEAST – Build and Excavation Autonomous System with Transportation
- CADRE – Cooperative Autonomous Distributed Robotic Exploration
- CCSDS – Consultative Committee for Space Data Systems
- cFS – core Flight System
- CMU – Carnegie Mellon University
- COLDArm – Cold Operable Lunar Deployable Arm
- COLDTech – Concepts for Ocean worlds Life Detection Technology
- DDS – Data Distribution Service
- DRSOMA - Dynamically Reconfigurable Software and Mobility Architecture
- DSA – Distributed Spacecraft Autonomy
- ECF – Early Career Faculty
- ECF20 – Early Career Faculty 2020
- ECI – Early Career Initiative
- ESDMD – Exploration Systems Development Mission Directorate
- EVA – Extravehicular Activity
- FOCCUS – Fail Operational Capabilities for Caretaking and Utilization Scenarios
- GCD – Game Changing Development
- GN&C – Guidance, Navigation, and Control
- HEOMD – Human Exploration and Operations Mission Directorate
- HOME – Habitats Optimized for Missions of Exploration
- HSI – Human-Systems Integration
- IEEE – Institute of Electrical and Electronics Engineers
- ISAAC – Integrated System for Autonomous and Adaptive Caretaking
- ISO – International Organization for Standards
- ISRU – In-situ Resource Utilization
- ISS – International Space Station
- IVA – Intravehicular Activity
- JPL – Jet Propulsion Laboratory
- JSC – Johnson Space Center
- KSC – Kennedy Space Center
- LANDO - Lightweight Surface Manipulation System (LSMS) AutoNomy capabilities Development for surface Operations and construction
- LaRC – Langley Research Center
- LSIC – Lunar Surface Innovation Consortium
- LSII – Lunar Surface Innovation Initiative
- LTV – Lunar Terrain Vehicle
- LUnA – Lunar Underactuated Robotic Arm
- NASA – National Aeronautics and Space Administration
- NDL – Navigation Doppler LiDAR
- NSTRF – NASA Space Technology Research Fellowships
- NSTGRO – NASA Space Technology Graduate Research Opportunities
- PASS – Precision Assembled Space Structure
- PESTO – Planetary Exploration Science Technology Office
- R&D – Research and Development
- RASSOR – Regolith Advanced Surface Systems Operations Robot
- RESET – Rover Slip Estimation and Traction Control in Lunar Environments
- RETHi – Resilient Extra-Terrestrial Habitats Institute
- RFI – Request for Information
- ROS – Robot Operating System
- RSIM – Rover Simulation Software
- SAE – Society of Automotive Engineers
- SBIR – Small Business Innovative Research
- SLAM – Simultaneous Localization and Mapping
- SMD – Science Mission Directorate
- SOMD – Space Operations Mission Directorate
- SQRLi – Space Qualified Rover LiDAR
- STMD – Space Technology Mission Directorate
- STRG – Space Technology Research Grants
- STRI – Space Technology Research Institute
- STTR – Small Business Technology Transfer
- TIM – Technical Interchange Meeting
- TP – Tipping Point
- TRL – Technology Readiness Level
- US – United States
- V&V – Verification and Validation
- VIPER – Volatiles Investigating Polar Exploration Rover

EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

EXPLORE: Communications and Navigation
NASA Space Technology Mission Directorate
August 2022

STMD welcomes feedback on this presentation
See 80HQTR22ZOA2L_EXP_LND at nspires.nasaprs.com for how to provide feedback
If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

EXPLORE: Develop Next Generation Communications and Navigation Technologies

Develop communications, navigation, and sensing infrastructure capable of handling high data volumes with near real-time communication (cislunar), and increased onboard navigation and time-keeping autonomy

QUANTUM COMMUNICATIONS

- High-quality, high-rate entangled photon sources
- Entanglement swapping
- Quantum memory
- Nondemolition measurement
- Networking: repeater, error correction, etc.

CISLUNAR AND MOON

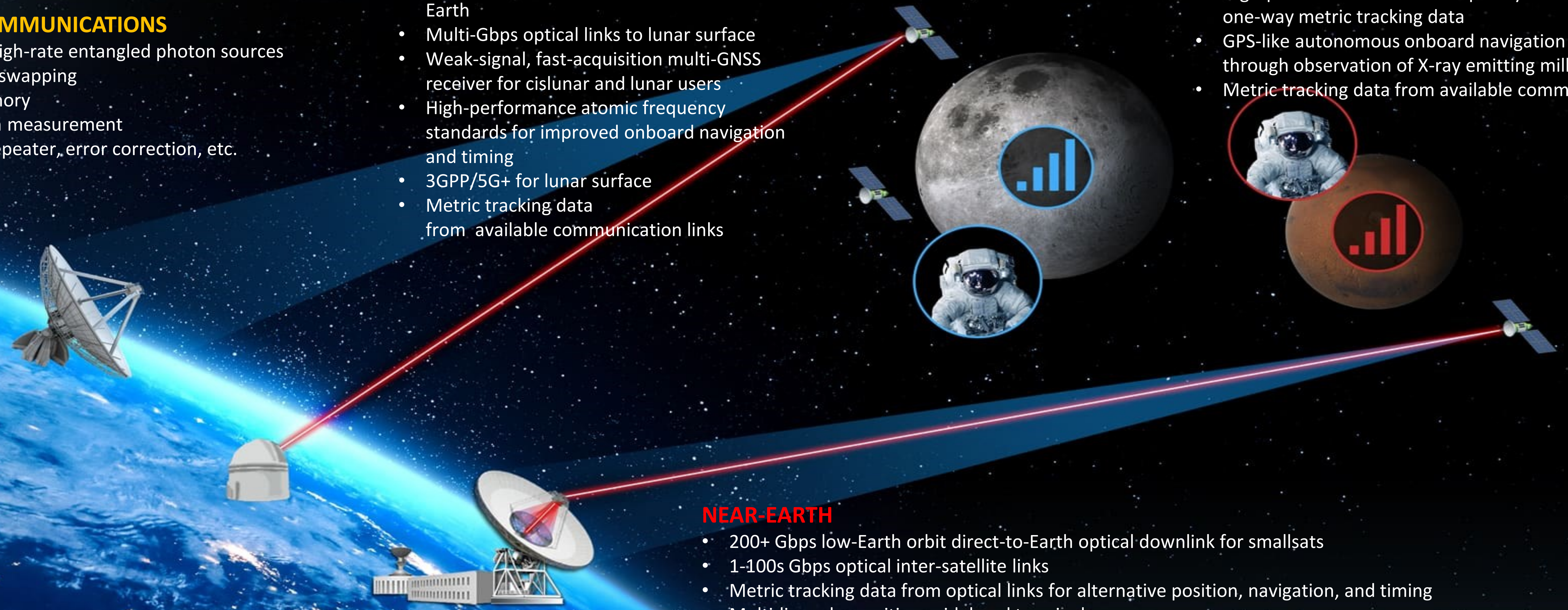
- LunaNet framework for interoperable and resilient communication and navigation
- 1-10+ Gbps coherent optical links direct-to-Earth
- Multi-Gbps optical links to lunar surface
- Weak-signal, fast-acquisition multi-GNSS receiver for cislunar and lunar users
- High-performance atomic frequency standards for improved onboard navigation and timing
- 3GPP/5G+ for lunar surface
- Metric tracking data from available communication links

OTHER CELESTIAL BODIES AND DEEP SPACE

- Extension of LunaNet framework beyond Earth-Moon for interplanetary and deep space network
- High Photon Efficiency optical links for 100s Mbps direct-to-Earth downlink
- High-performance atomic frequency standards enabling one-way metric tracking data
- GPS-like autonomous onboard navigation and timing through observation of X-ray emitting millisecond pulsars
- Metric tracking data from available communication links

NEAR-EARTH

- 200+ Gbps low-Earth orbit direct-to-Earth optical downlink for smallsats
- 1-100s Gbps optical inter-satellite links
- Metric tracking data from optical links for alternative position, navigation, and timing
- Multi-lingual, cognitive, wideband terminals
- Weak-signal, fast-acquisition multi-GNSS smallsat compatible receiver for above GNSS constellation users
- Metric tracking data from available communication links



Communications & Navigation Envisioned Future

- Envisioning the 2030 + timeframe
- Presented in 3 Separate Regimes:
  - ✓ Near Earth Regime
  - ✓ Lunar Regime
  - ✓ Deep Space Regime
- Technology Needs:
  - ✓ Optical Communications
  - ✓ Networking Technology
  - ✓ Planetary Surface Communications and Navigation
  - ✓ Position, Navigation, and Timing (PNT)
  - ✓ Radio Frequency Communications
  - ✓ Quantum Communications (***)

Range from Earth*	***Regime***	***Notation***
Deep Space > 2M km Mars 54.6M-400M km 	Deep Space	>2M km from Earth is considered **Deep Space****
Sun-Earth L1/L2 1.5 M km Cislunar 455,000 km  Earth-Moon L1/L2 61,000km from center of Moon Lunar Proximity 70,000km from center of Moon	Lunar	**Near Space** is considered from 80km to 2 million km from the Earth **
Earth Proximity Below 36,000 km	Near Earth	

*Unless otherwise noted

** Per the Space Communications and Navigation System Requirements Document

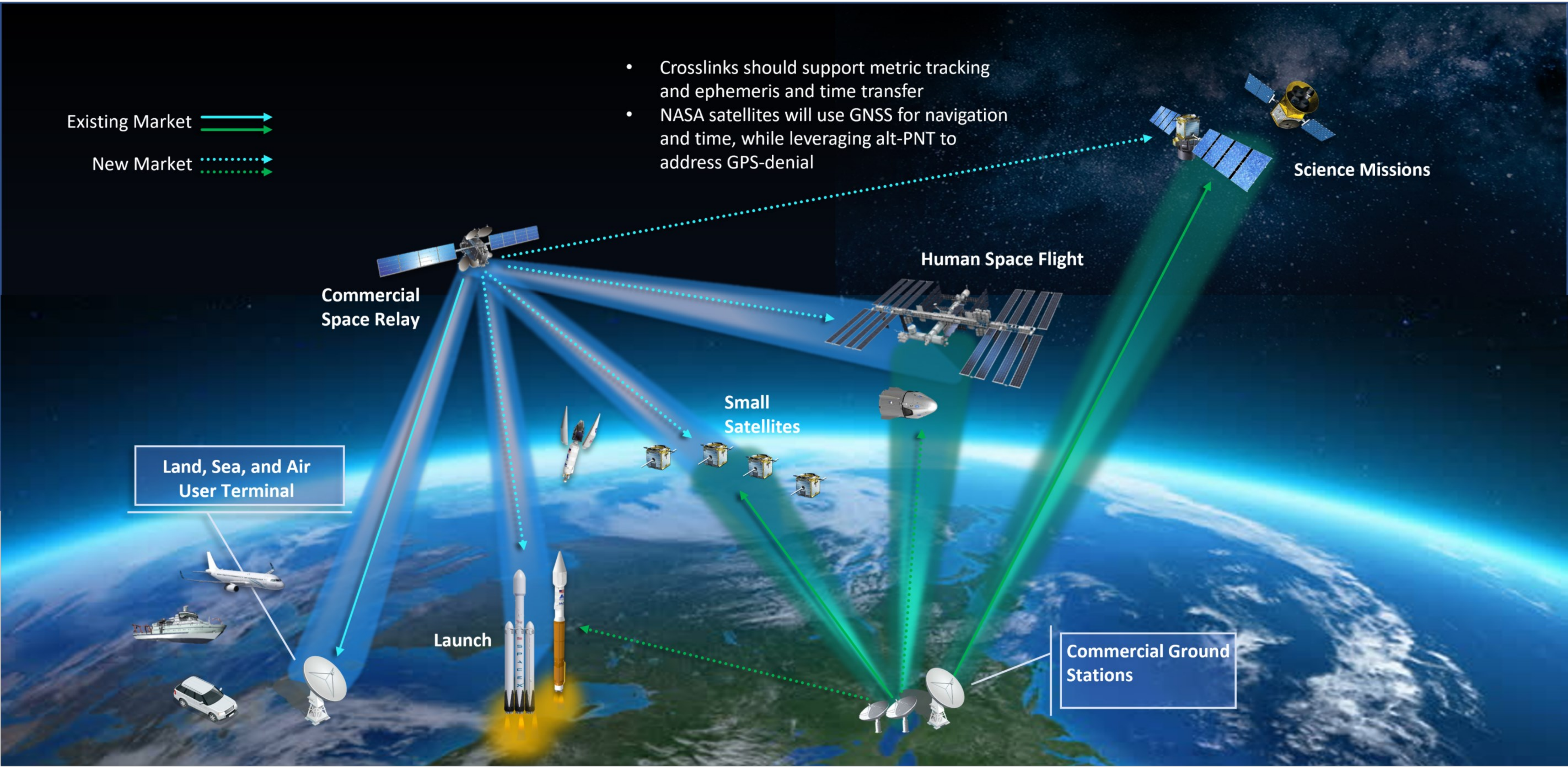
*** Quantum communications doesn't appear in the near-term Envisioned Future because of its current low TRL. However, NASA is supporting the development of the fundamental technology.

Near Earth Regime

Near Earth: NASA Commercial Communications Services Efforts and Impacts

Trends	Current NASA activities	Impact on 2030+ Near Earth communications
Transition to commercial SATCOM	End-to-end commercial services demonstrations using various technologies, orbits, and data pathways are taking place through 2030.	Users will transition from the NASA Tracking and Data Relay Satellite System to commercial SATCOM services.
Growing direct-to-Earth market	NASA is establishing a broader direct-to-Earth commercial market and is transitioning from service provider to commercial user.	Users will be able to access and seamlessly switch between a variety of service provider options based on real-time mission needs.
Adoption of standards and technologies	NASA is increasing engagement with standards bodies such as 3GPP (3rd Generation Partnership Project) Cellular Standards Group and investing in critical technologies like wideband terminals.	Adoption of commercial standards will provide operational efficiencies and interoperability benefits to NASA missions.

Near Earth: Extending Commercial Capabilities to Space



Near Earth: 2030+ NASA Comm & Nav Needs

Capability needs for interoperability

Application and network layer needs
NASA users will need shared standards and protocols to reliably and securely transfer data across and obtain navigation and timing information from multiple service provider networks.

Physical layer needs
Wideband and multilingual terminals, along with phased arrays, integrated optical systems, and cognitive radios will allow users to access the full suite of service provider options.

Capability needs for autonomous operations

Information needs for autonomous decision making
Users will need access to service provider's estimated cost, waveform configurations, availability, and other key information to support decision making.

Autonomous decision making for routine operations
Users will need technologies to sense and provide awareness of the communication environment, along with a decision making process to schedule services, select waveform and protocol configurations, and identify available networks among other routine tasks.

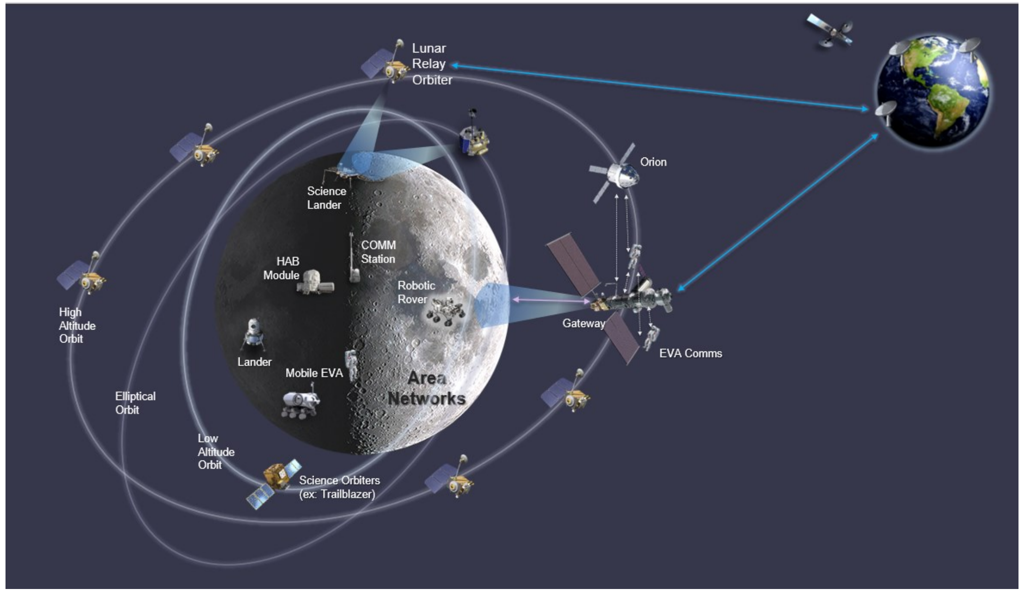
Autonomous decision making for non-routine operations
Artificial intelligence, machine learning, and similar techniques will be needed for user spacecraft to learn appropriate responses to a variety of quality of service impairments including spectral interference, weather, and network configuration or topology changes.

Lunar Regime

Lunar: 2030+ NASA Comm & Nav Needs

Future state beyond 2030 is anticipated to include:

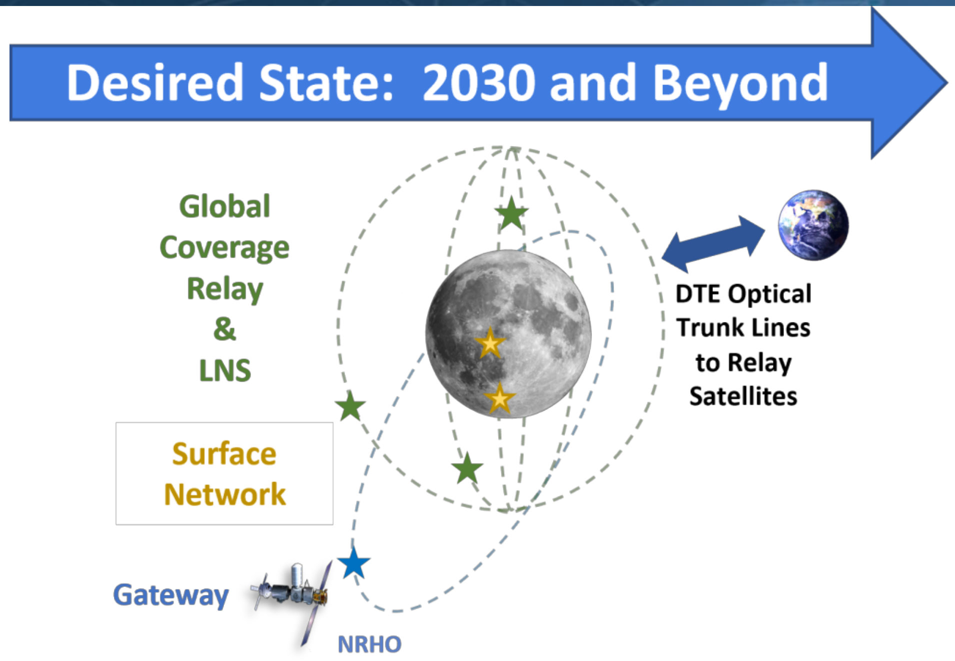
- Commercial industry (at least on the near side) needing precise location and timing services and communications relay services to/from Earth
- Human exploration and science experiments on both the near and far-side of the moon, with longer durations
- Sustained Artemis basecamp operations with high data volumes even when crew are not present
- More frequent, longer, and more complex human and robotic mobility operations needing precise location services on demand
- Increased connectivity between surface elements, including crew – surface-to-surface high-rate traffic a significant portion of all communications
- Greater diversity of missions in general – including international and commercial participants
- Commercial service providers meeting the needs of NASA and other participants



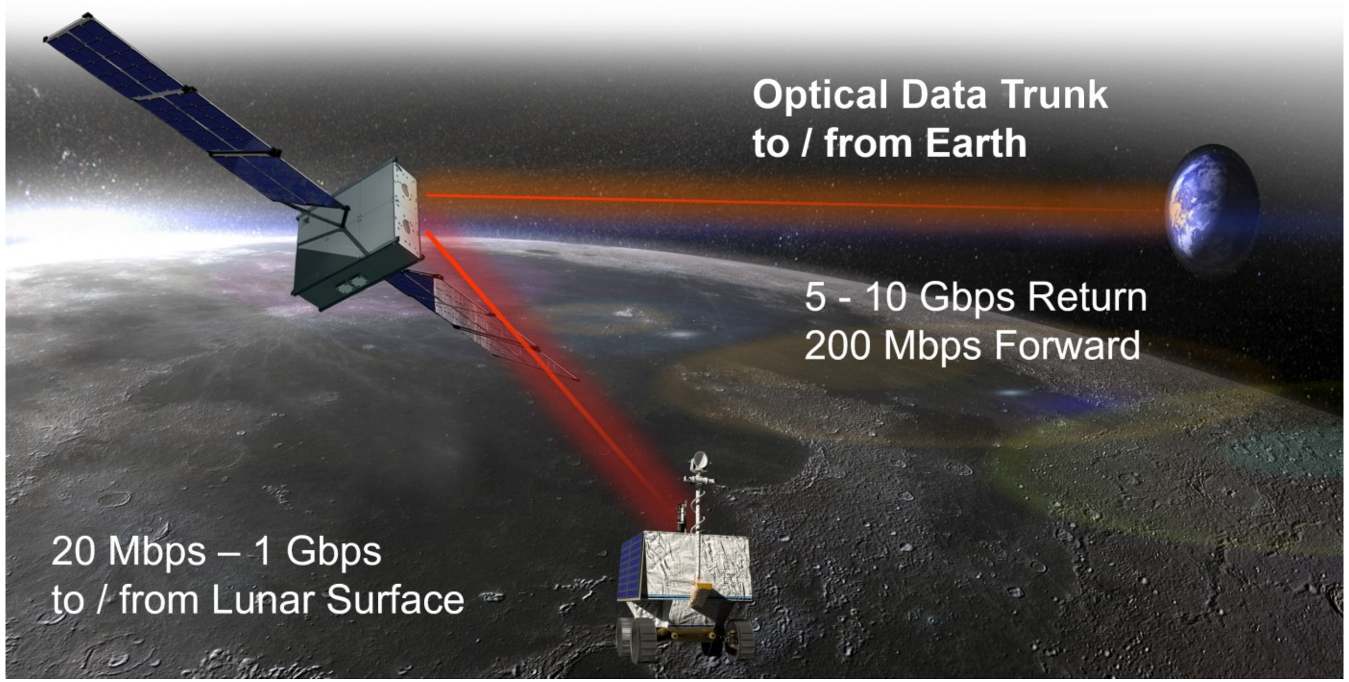
Extending the Internet to the Moon:

Crew, robotic science, and commercial surface operations mimic Earth terrestrial ops – service-based wireless connectivity with seamless support

Lunar: 2030+ Lunar Comm & Nav Architecture



- ❑ **S, X, and Ka-Band Radio Frequency links** in the lunar vicinity
  - Between lunar elements in orbit and on the surface
  - S, X, and Ka-Band RF link to and from the Earth
- ❑ **Coherent Optical links** for trunk lines between lunar relays and Earth stations
  - Provide 5 to 10 Gbps from the Moon to the Earth in the near term (coherent signaling can support 10's to 100's of Gbps)
  - Future relays could also support optical intersatellite links between relays and surface users
  - 1-Meter class optical ground stations on Earth
- ❑ **Metric tracking** on RF and optical links



❑ Lunar Navigation Service

- Provides the necessary geometric diversity, local dynamics, and simultaneous observations for rapid navigation knowledge
- More relays improve real-time accuracy, enabling mission ops flexibility and meeting user requirements
- Designed for incremental growth to extend service beyond south pole to global coverage as demand warrants

Lunar: 2030+ Surface Communications via 3GPP

Initial Artemis missions can be supported with One Base Station

- Could be integrated on the HLS
- 3GPP Cellular signals at the hardware level can support improved PNT if protocols pass required measurements from the physical layer

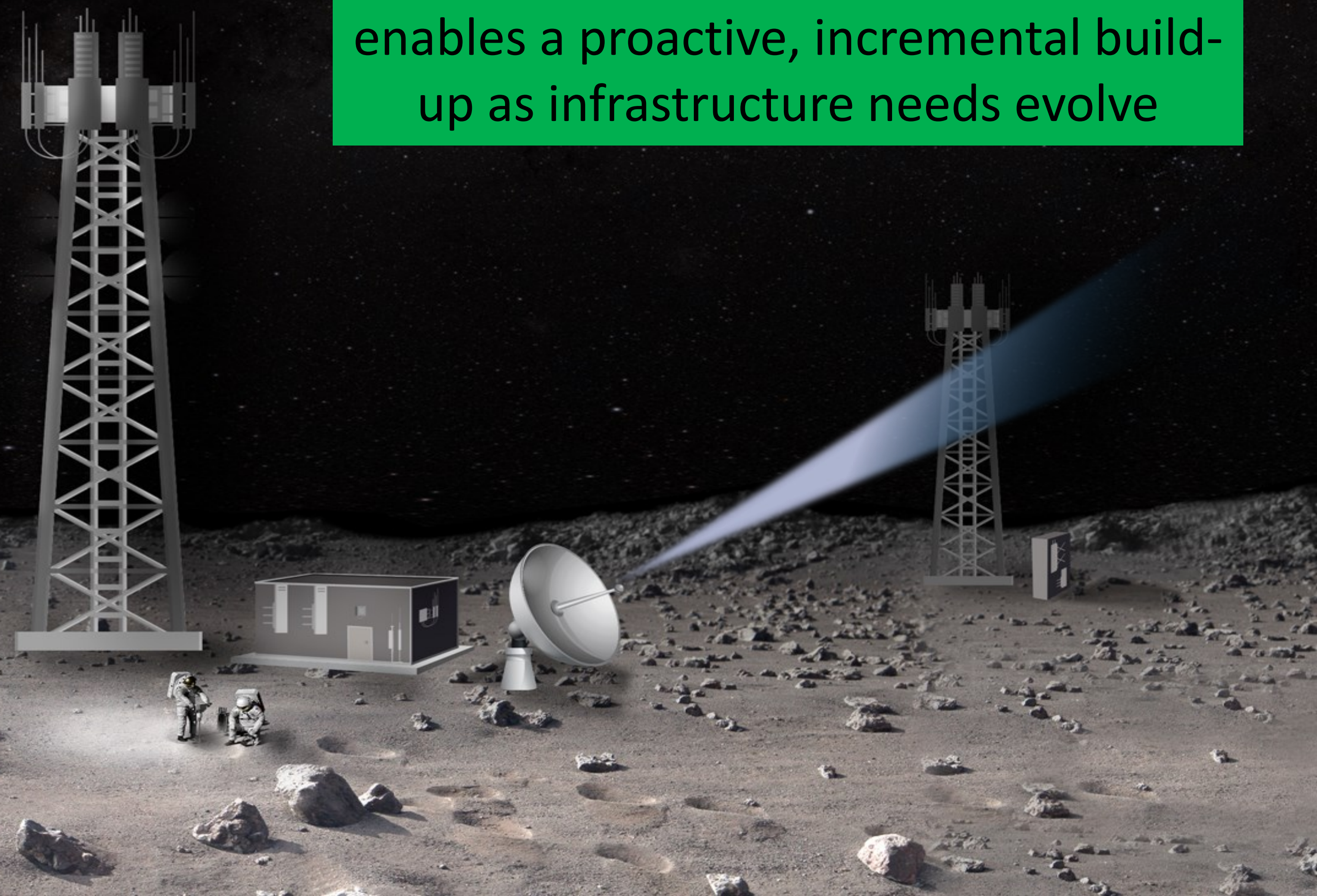
Multiple Base Stations:

- Cross-links connect base stations to *central hub*
  - Surface links via point-to-point, fiber, lunar relay satellite system, or other connectivity
- Base stations beacons enhance surface PNT
- Evolving standards could provide enhanced PNT

3GPP Cellular Non-Terrestrial Networking (NTN) lunar relay augmentation:

- Seamlessly tie to the surface network
- Surface User Equipment routes via relay satellite or base station

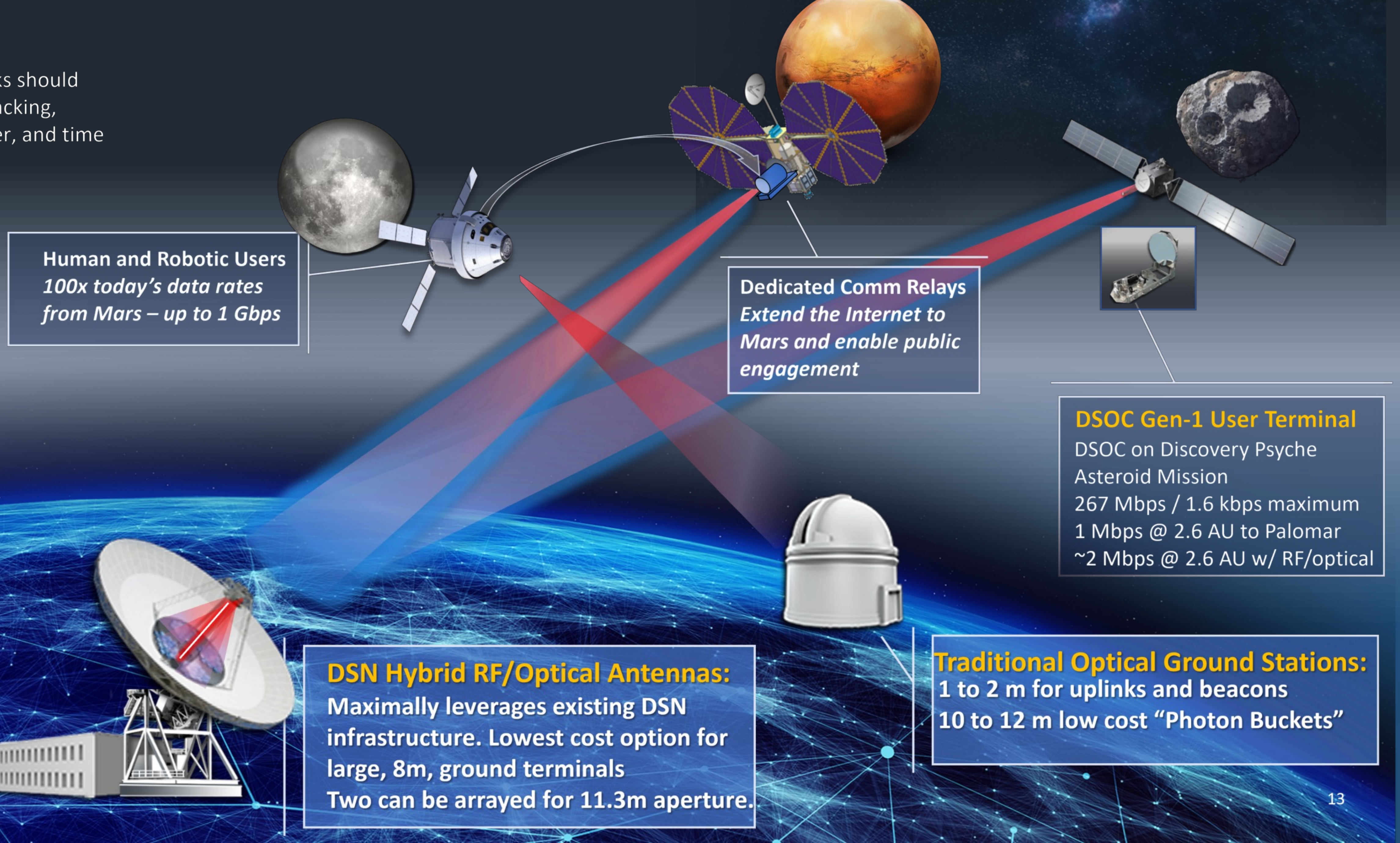
A 3GPP Cellular Lunar Surface Network enables a proactive, incremental build-up as infrastructure needs evolve



Deep Space Regime

Deep Space: 2030+ RF and Optical Communications

- RF and optical links should support metric tracking, ephemeris transfer, and time transfer

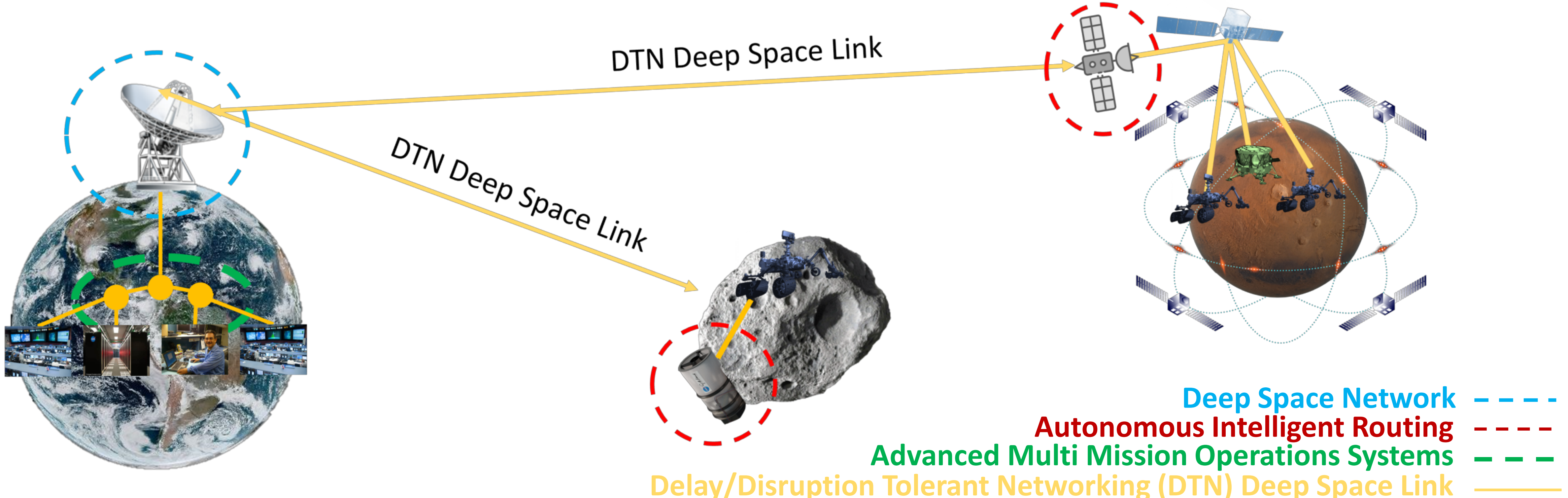


Deep Space: 2030+ DTN, Operations, and Navigation

Space-based Disruption / Delay Tolerant Network (DTN) links will be RF and optical. DTN nodes need to have an onboard capability to process trajectories, telecom capabilities, and schedules for all active assets, then be able to decide the most appropriate path for communications. Also, they will need to ensure time coordination. They must also be able to point antennas and optical communications telescopes. Enables:

- Fewer ground antennas and optical communications telescopes for more spacecraft
- Elimination of manual scheduling & contact graph routing.
- More responsive communications & navigation.

Deep Space Network (DSN) continues to provide ranging, Doppler, and Delta-DOR (Differential One Way Ranging) to support navigation



Recent RFIs and Interoperability Activities

- Lunar Communications Relay and Navigation Services
  - *[Seeking]* information from potential providers of space communications relay and navigation services in support of the Artemis program and its planned missions to the Moon; closed 2020-10-30
- Communications Services Project (CSP)
  - *[Seeking]* commercial TDRSS replacement for Earth-based relay services through staged sequence of capability demonstrations via Funded Space Act Agreements (FSAAs); closed 2021-09-03
- Near Space Network Services (NSN)
  - Sources Sought Notice (SSN) for capabilities, ideas and information that will lead to commercialization of the Near Space Network (NSN) Communications and Tracking services to support multiple missions across the full NASA portfolio to include LEO, MEO, GEO, Sun/Earth L1, L2 and Lunar orbital regimes; closed 2021-10-22
- Draft LunaNet Interoperability Specifications
  - *Living* document meant for technical industry members to provide feedback on NASA's plan for communications and navigation interoperability at the Moon
- Primary Reference Oscillator for Onboard Navigation
  - Industry poll for mid/high performance local spacecraft oscillators (clocks) for cis-lunar and lunar applications; closed 2021-12-08
- Near Space Network Services (NSN) solitication (draft)
  - *[Seeking comments on]* acquisition of Communications and Navigation services to support multiple customer missions across the full Near Space Network portfolio to include Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geostationary Orbit (GEO), and Lunar orbital regimes; closed 2022-07-29.
- Continuing Involvement with the Inter-Agency Operations Advisory Group (IOAG) and the Consultative Committee for Space Data Systems (CCSDS)
- NASA is an official member of the 3rd Generation Partnership Project (3GPP)

Technology Needs

Top 3 Overall Priorities That Are Not Funded (1 of 2)

- ❑ 5 to 10 Gbps Coherent Optical Communications Transceiver (GCD)

- ❑ Lunar PNT
  - Precision clocks, network synchronization via simple entanglement (GCD/ECI/ESI)
  - DSACv2+* (TDM)
  - Flight opportunity for cislunar multi-GNSS receiver (NavCube3-mini) prior to lunar communications support

- ❑ Space Qualified 3GPP (5G) Cellular Technology* (GCD/LSII)

Top Priorities That Are Not Funded – by TRL (2 of 2)

High-TRL

1. Flight opportunity for cislunar multi-GNSS receiver (NavCube3-mini) prior to lunar communications support (SST/TDM)
2. DSACv2+ (TDM)
3. Operational Large Aperture Optical Ground Stations (Deep Space)* (GCD)

Mid-TRL

1. 5 to 10 Gbps Coherent Optical Communications Transceiver (GCD)
2. Low-Cost Operational Optical Ground Stations (GCD)
3. Efficient High Power Optical Amplifiers (SBIR/GCD)
4. High-Efficiency Solid-State Power Amplifiers (SBIR/GCD)
5. 20 W Laser Transmitter for > 100 Mb/s from Mars farthest range (GCD/ECI/ESI)
6. Large aperture space terminal (GCD/ECI/ESI)
7. Precision clocks, network synchronization via simple entanglement (GCD/ECI/ESI)

Low-TRL

1. Storage and Network Processing Nodes to support 10 to 100 Gbps Communication Links (GCD/SST)
2. Cognitive radios networking with DTN (GCD/SST)
3. Space Qualified WiFi Technology* (GCD/LSII)
4. Space Qualified 3GPP (5G) Cellular Technology (GCD/LSII)
5. Absorption-Based Quantum Memories (GCD)
6. High Fidelity Entangled and Single Photon Sources (GCD)
7. Low-Cost Space Compatible Cryocoolers (GCD)

Optical Communications

- Space Terminal Technologies
  1. Flexible, power-efficient, coherent transceivers – 5 Mbps to 20 Gbps transmit and receive
  2. Power-efficient optical amplifiers – 20 to 50 W, coherent or low-duty-cycle PPM
  3. Low-mass, low-cost, telescopes with sub-beam-width pointing actuation– 1 mm to 50 cm aperture
  4. Vibration isolation systems for large apertures
  5. Space-compatible photon counters for spatial acquisition (wide field of view) and/or communications (high count rate)
  6. Processing-efficient, power-efficient forward-error correction codes (e.g. 5G codes)
  7. High-bandwidth mass memories for store-and-burst data architectures
  8. Wide-field-of-view multi-access optical communications terminals
  9. Enhanced capability spatial acquisition systems– e.g. beaconless pointing, acquisition without external coordination, utilize optimetrics for navigation
  10. Autonomous onboard observations / measurements from optical links and onboard sensors for onboard navigation
  11. Low-cost lunar surface based optical terminals

- Ground Terminal Technologies
  1. Operational large aperture optical ground stations– 1 m to >5 m, able to operate within ~3 deg of Sun
  2. High-power optical transmitters– 100W to >10 kW
  3. Wide field-of-view narrow band optical filters
  4. Low-cost operational ground stations for mission-specific applications
     - Low-cost 20-70 cm telescopes
     - Efficient multi-spatial-mode receivers
     - Low-cost adaptive optics
  5. Superconducting nanowire single photon detectors
     - Spatially-resolved cameras for spatial acquisition, and adaptive optics
     - High operating temperature for low-cost ground terminals

Networking Technology

1. Storage and Network Processing Nodes to Support 10 to 100 Gbps Links
   - Including DTN processing, and high speed secure DTN bundle protocol
2. Space Qualified Network Implementations to Support High Speed Optical and RF
   - Leverage early work on hardware acceleration via FPGA
3. Interoperable Network Management across Multiple Nodes from Different Providers
   - Security for management interfaces and protocols
4. High Speed Multi-Terabit Radiation Tolerant Mass Memory for Store and Forward
5. Standard Protocols for Dynamic Storage and Bandwidth Allocation for Emergency Communication

Planetary Surface Communications and Navigation

1. Space Qualified WiFi Technology
   - Rad-hard Wi-Fi 6 chipsets for mission-critical local networking (access points and end users)
2. Space Qualified 3GPP (4G and 5G) Cellular Technology
   - Rad-Hard 3GPP eNodeBs/gNodeDs, cores, and user equipment for mission-critical, multi-km class mobile networking
   - Spectrum allocation for multi-band (carrier aggregated) 3GPP lunar surface networking
   - Advanced lunar surface 3GPP propagation models to plan deployments
   - Backhaul solutions for interlinking multiple 3GPP cores to enable lunar surface roaming
   - Self-erecting lunar communication towers to enable 50m-class elevation
3. Through-ice communications
   - Need wireless methods to enable exploration of subsurface oceans away from Earth
   - Magneto-Inductive Antenna Concepts
4. Harsh Environment Communications
   - Need communication systems capable of withstand extreme environments such as those on the surface of Venus
   - All Metal, Multi-beam Steerable Antennas for Harsh Environments Communications and for RF Communications through Hypersonic Plasma
5. Wireless links need to support metric tracking and time transfer wherever possible

Position, Navigation, and Timing

Sensors

1. Lunar capable reduced SWaP-C multi-GNSS receivers
2. Multi-function cameras supporting full 6-DOF
3. Reduced SWaP-C high and extreme stability clocks
4. X-ray pulsar detector
5. Improved and modular LiDAR systems
6. POSE cameras w/ adjustable visible magnitude and near/far-field
7. Reduced SWaP-C accelerometers, and other relevant GNC sensors (*OSAM overlap)*
8. Quantum sensing for nav observables (accelerometers, gyros, combined to IMUs, magnetometers, and gravimeters).
9. Improved clocks capable of extreme stability over both long and short time intervals.

Onboard Processing

1. Advanced filtering & data fusion
2. 6-DOF path planning & closed-loop real-time controllers
3. Multi-spectrum vision-based optical navigation (OpNav)
4. Improved space and surface location algorithms
5. Improved fault detection for autonomous systems

Knowledge

1. Improved time keeping and dissemination systems
2. Improved Cartography and Digital Elevation Map (DEM) generation (*EDL overlap)*

Radio Frequency Communications

1. Multi-Band Radios
2. Multi-Band Antennas:
   - Tri-Band Antennas (S-, X-, and Ka-Band) and tri-band frequency selective surfaces
   - Dual-Band High-Gain Antennas (X- and Ka- or S- and Ka-Band, covering lunar up- and downlinks (full duplex) in both frequency schemes)
3. Ka-band wideband terminal able to communicate with NASA, commercial and DoD nodes (for of support roaming users across multiple systems)
4. Electronically Steerable Phased Arrays for crosslinks and orbit to ground links
5. Flight Receivers for the proposed 22 GHz band and the proposed 27 GHz band
6. Flight Transmitter developments in the proposed 22 GHz band
7. Simultaneous Transmit and Receive (STAR) / In-Band Full Duplex (IBFD) technology (enabling support for more users per frequency band)
8. Low SWAP-C space-qualified rake receiver for CDMA applications to address near/far issues
9. Ultra-High Efficiency Solid-State Power Amplifiers using GaN (>50% would render them competitive with TWTAs)
10. High-bandwidth radio transmitters (>100 MHz to support advanced positioning (Pseudo Noise Delta-DOR) transmissions at Ka-band)
11. Multiple Uplinks per Antenna (MUPA) for DSN ground antennas
12. Compact optical reference cavities for space laser/frequency comb stabilization
    - 10^{-14} stability at 1 s averaging time with <1 l volume, <2 W of power consumption and 10^{-10}/g acceleration sensitivity
13. Spectrally pure oscillators (-120 dBc/Hz or better at 10 kHz offset at 100GHz) for W- and G-band radars & VLBI applications
14. High stability low SWaP W- and G-band clocks for radio occultation
15. High-stability, compact space clock (DSAC v2: order of magnitude smaller SWaP, with performance similar to masers)
16. Opportunistic Multiple Spacecraft Per Antenna (OMSPA) for DSN ground antennas (using post-processing of digitized Ifs)
17. Autonomous onboard observations / measurements from radio links and onboard sensors for onboard navigation
18. Demand Access Communications (spacecraft-initiated, including inter-spacecraft links)
19. Low-cost, reliable, High power-DSN transmitters (based on tubes or solid-state, up to 1 MW at up to 34 GHz)
20. Cognitive and Smart Software Defined Radios (capable of ad hoc networking and cross-platform communications for spacecraft constellations)

Quantum Communications

1. Large aperture space terminal
   - 30-cm considered for LEO TDM and 80-cm considered for MEO M2.0 system. Required for long-haul trunk lines.
2. Large aperture ground terminals
   - Greater than 1 meter apertures and high-performance AO systems that mitigate uplink turbulence via cubesat beacons.
3. Demonstrate the feasibility of using simple entanglement sources to achieve precision clock network synchronization that mitigates the requirement for a wideband mode locked laser comb source
   - Supports GPS-denied PNT
4. Absorption-Based Quantum Memories
5. Low-Loss Optical Switching to Support Multiplexing of Quantum Signals
6. High Fidelity Entangled and Single Photon Sources
7. Flight-qualified SNSPDs for space-to-ground quantum communication demonstrations
8. Low-Cost Space Compatible Cryocoolers
9. Radiation-tolerant time-to-digital converter ASICs for space-to-ground quantum communication demonstrations
10. Ultra-low jitter waveguide SNSPDs for quantum communication at clock rates >20 GHz
11. Integrated photonic circuits for quantum – high efficiency transceivers
12. Doppler shift and synchronization compensators

Acronyms

- 3GPP: 3rd Generation Partnership Project
- AO: Adaptive Optics
- ASIC: Application-Specific Integrated Circuit
- CDMA: Code-Division Multiple Access
- CSP: Communications Services Project
- DoD: Department of Defense
- DSAC: Deep Space Atomic Clock
- DSOC: Deep Space Optical Communications
- DSN: Deep Space Network
- EDL: Entry, Descent, and Landing
- FPGA: Field-Programmable Gate Array
- GaN: Gallium-Nitride
- GCD: Game Changing Development
- GEO: Geostationary Network
- GPS: Global Positioning System
- IBFD: In-Band Full Duplex
- LEO: Low Earth Orbit
- LNS: Lunar Network Satellite
- LSII: Lunar Surface Innovation Initiative
- MEO: Medium Earth Orbit
- MUPA: Multiple Uplinks Per Antenna
- NASA: National Aeronautics and Space Administration
- NSN: Near-Space Network
- NTN: Non-Terrestrial Networking
- NRHO: Near-Rectilinear Halo Orbit
- OMSPA: Opportunistic Multiple Spacecraft Per Antenna
- PNT: Position, Navigation, and Timing
- RF: Radio Frequency
- SATCOM: Satellite Communications
- SBIR: Small Business Innovation Research
- SNSPD: Superconducting Nanowire Single-Photon Detector
- SST: Small Spacecraft Technology
- STAR: Simultaneous Transmit and Receive
- STMD: Space Technology Mission Directorate
- SWaP: Size, Weight, and Power
- TDM: Technology Demonstration Missions
- TRL: Technology Readiness Level
- TWTA: Traveling-Wave-Tube amplifiers
- VLBI: Very-Long-Baseline Interferometry

EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

EXPLORE: In-space Servicing, Assembly, and Manufacturing (ISAM) and Rendezvous, Proximity Operations and Capture (RPOC)

NASA Space Technology Mission Directorate
August 2022

STMD welcomes feedback on this presentation
See 80HQTR22ZOA2L_EXP_LND at nspires.nasaprs.com for how to provide feedback
If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

Develop technologies supporting emerging space industries including Satellite Servicing & Assembly


Seeker Test Flight, 2019


Gateway Deep Space Logistics


Roman Space Telescope


Rotating Space Station

Enabling in-space…

Close Inspection

Small inspectors diagnose anomalies, enabling corrective action and in-space repair operations. Small satellite inspectors launch "on need."

Free-Flyer Capture and Relocation

Commercial servicers perform autonomous capture of active spacecraft and uncontrolled debris, relocating them to new operational, disposal or salvage orbits.

Delivery and Aggregation

Commercial launch and high-efficiency in-space transportation systems deliver commodities and cargo to assets in multiple orbits, enabling frequent and lower-cost resupply and client relocation.

Maintenance & Repair

US Spacecraft launch with standard interfaces enabling frequent upgrades. Commercial servicers conduct planned and on-demand manufacturing, repair and maintenance. Human exploration spacecraft refurbished and recertified in space.

Refueling and Fluid Transfer

Spacecraft launch with standard in-space fueling (and other) accommodations. Commercial servicers provide fueling on-demand in multiple orbits and planetary surfaces.

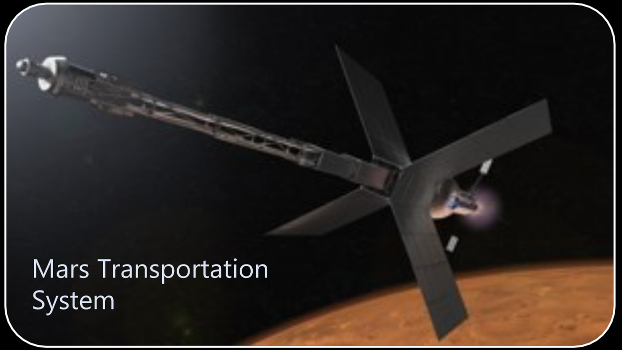
Installation and Upgrade

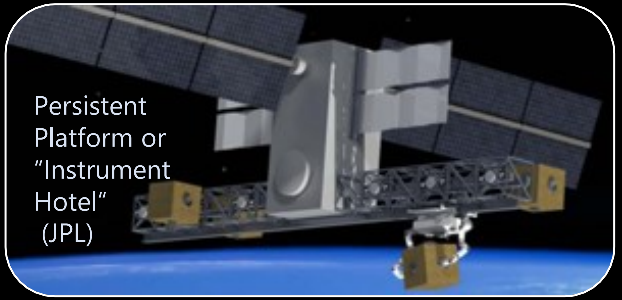
Great Observatories and platforms in multiple orbits enable hosting of operational and experimental instruments and payloads. Commercial servicers provide delivery, installation and hosting services.

Manufacturing and Assembly

Purpose-built in-space systems enable audacious new science, exploration, and commercial-ization of space: a 20-meter space telescope discovers signs of life on extrasolar planets; an outer planets human exploration mission departs aboard an in-space assembled craft; manufacturing products for use in space and on Earth provide a stimulus to the U.S. economy.


OSAM-1

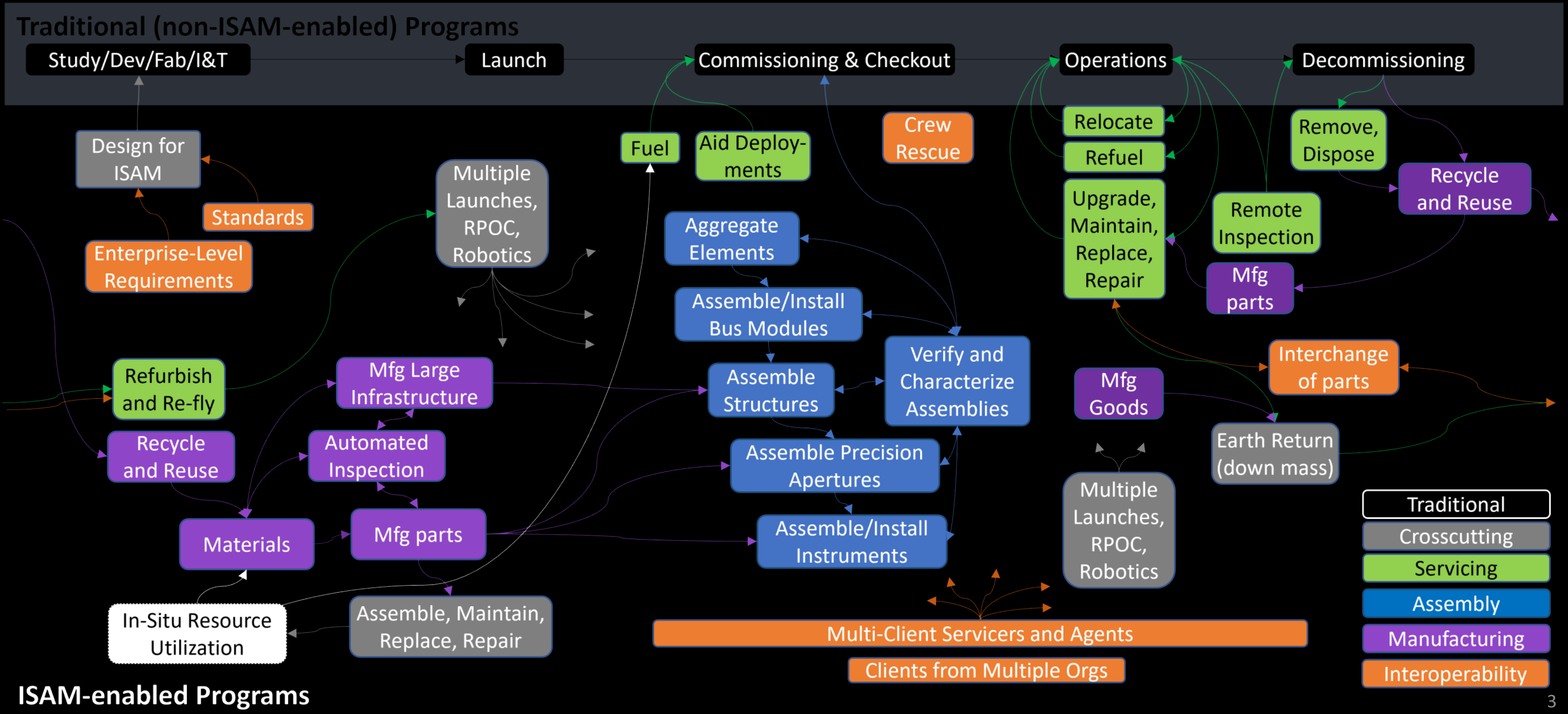

Mars Transportation System


Persistent Platform or "Instrument Hotel" (JPL)


Great Observatories

<u>All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.</u>

What is In-Space Servicing Assembly & Manufacturing?



RPOC- & ISAM-Enabled or Enhanced Architectures

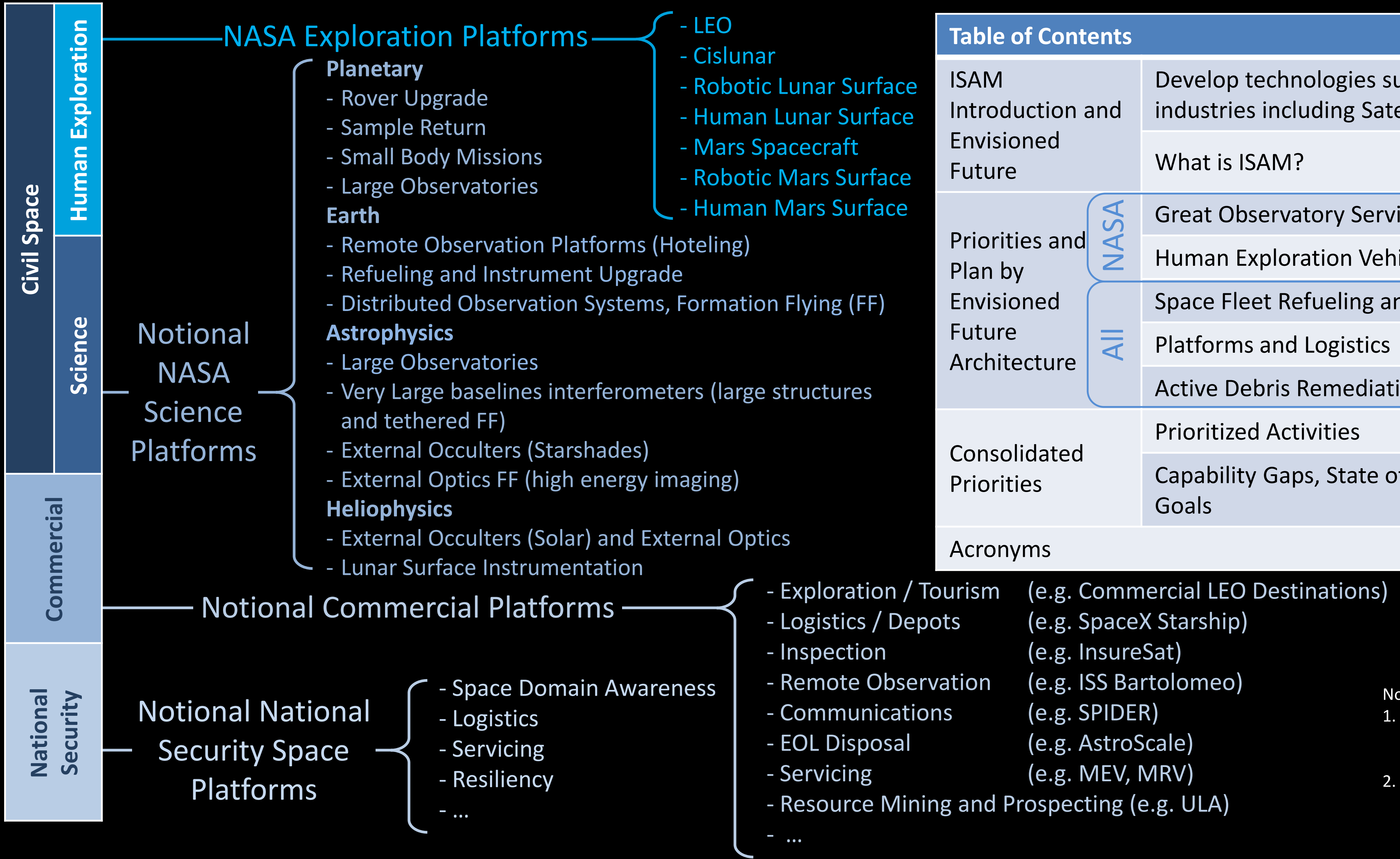
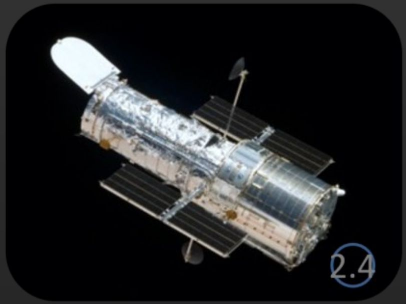


Table of Contents

Notes:
1. For surface assembly applications, see "Excavation, Construction, and Outfitting" EFP, Hilburger et al
2. For in-space manufacturing details, see "Advanced Manufacturing" EFP, Vickers et al

Great Observatory Servicing & Assembly

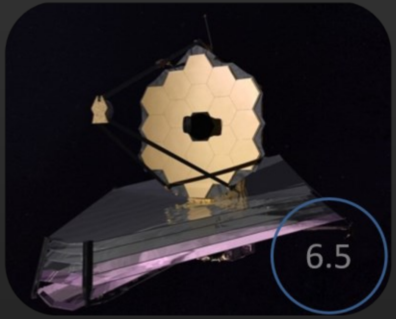
Hubble Space Telescope (1990, LEO)



Extensive servicing (Space Shuttle, crew + robotic)

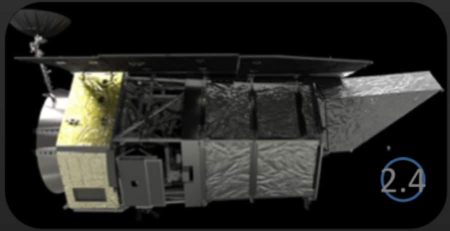
3+ decades of world class science

James Webb Space Telescope (2021, SE-L2)



No servicing or assembly planned

Roman Space Telescope (2025, SE-L2)



Refuelable (no servicer planned)

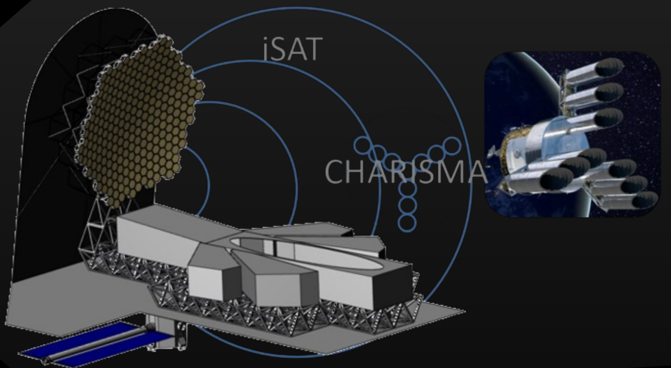
Increased science operations if refueled; potential to upgrade other systems

Sun-Earth L2 Servicer (mid 2030s, SE-L2)

PROPOSED Astrophysics and Planetary Assembled Observatories

Robotic servicing and assembly of large SE-L2 telescopes and starshades;

"BIG" SCIENCE; Risk, cost, and mass distribution across multiple launches

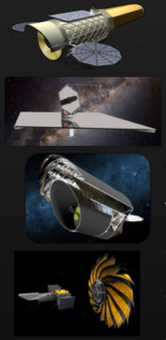


Assembled Great Observatories

Refuelable / Assembled Starshades

Astro2020 Great Observatory (2040s, SE-L2)

6m off-axis



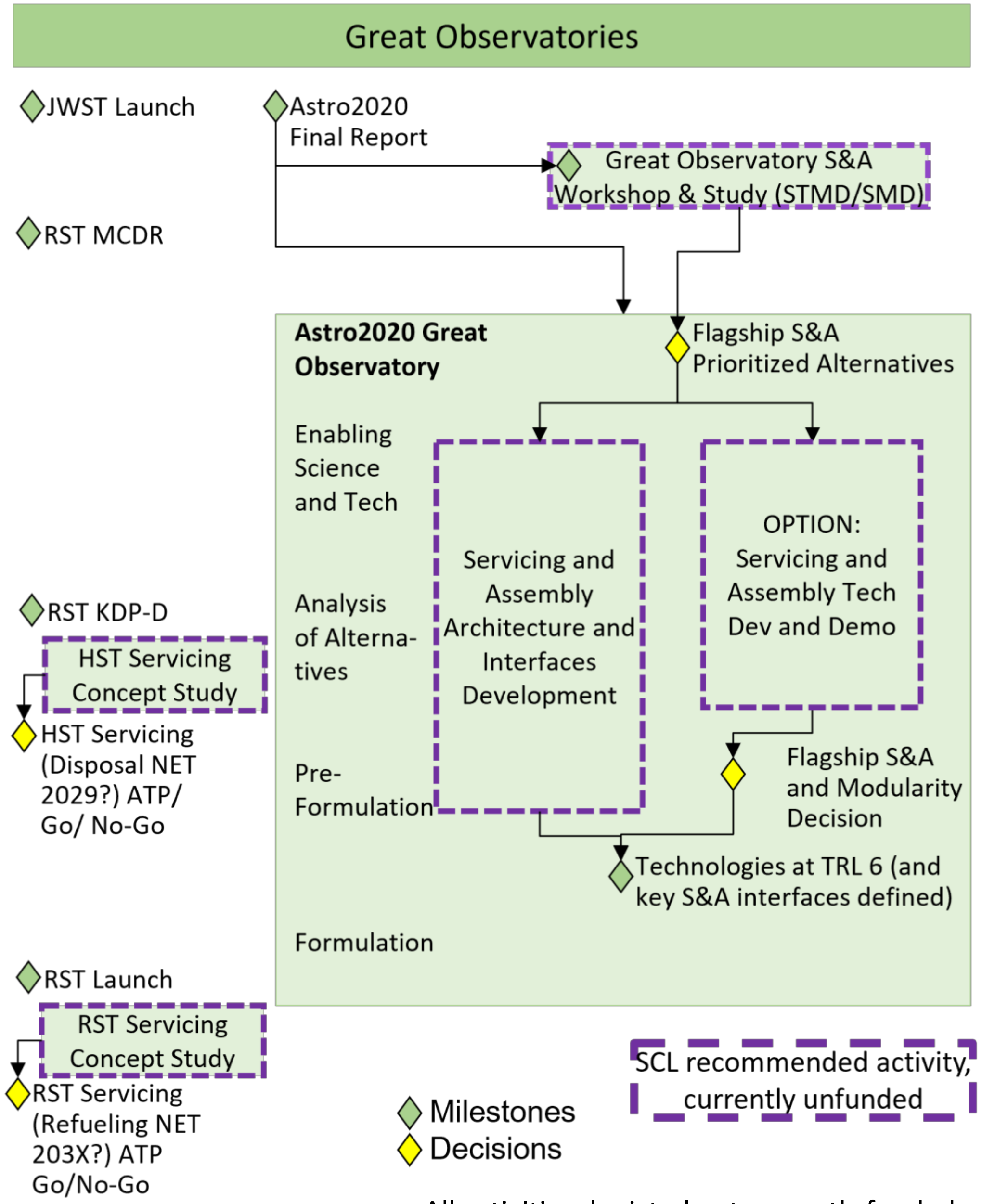
Refuelable, modular, and upgradeable

Multi-decade, world-class science via planned instrument upgrade, refueling, and maintenance

○ Primary mirror diameter (m)

All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.

Gaps, Priorities, Investments, and Plans for Great Observatory S&A



Priority Gap: Astro2020 Great Observatory Servicing & Assembly (S&A)

Architecture: telescope and spacecraft modularity; Sun-Earth L2 (SE-L2) logistics, servicing, and assembly concept of operations (conops) and agents; use of deployment and assembly techniques;

Closure Plan: Great Observatory Servicing and Assembly Workshop and Study

- Multi-org activity to mature architectural options and ConOps, and identify and prioritize technology gaps for a serviceable and/or assembled Astro2020 flagship

Other Priority Gaps

- Instrument installation and upgrade – telescope and instrument design features to accommodate in-space servicing
- Sun-Earth L2 Robotics – especially mobile systems for manipulation of very large and sensitive instruments
- Standards – define ISAM cooperative interfaces, aids, and interoperability
- Lifecycle Cost Benefit Analysis (Value Proposition) – utility gained vs. cost incurred by mission phase to incorporate cooperative ISAM features, extend mission life, assemble in space
- Optical telescope modular assembly, metrology, and V&V

Selected Relevant Investments

- Servicing and Assembly robotics – OSAM-1, SPIDER, OSAM-2, Canadarm3 (CSA)
- Assembly interfaces – SPIDER RF reflector assembly (STMD/Maxar), Precision Assembled Space Structure (PASS, STMD)
- Deep Space Delivery Logistics – Gateway Logistics Services

All activities depicted not currently funded or approved. Depicts “notional future” to guide technology vision.

Human Exploration Vehicle Servicing and Assembly

Skylab (1973, LEO)

Crew and Logistics Delivery (Apollo docking), EVA Repair

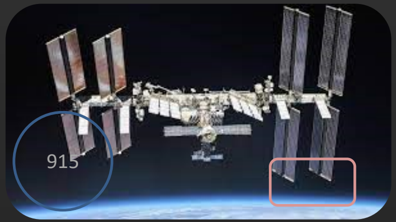
3 crewed periods totaling 172 days over 9 months

Space Shuttle Orbiter (1981-2011, LEO)

Crew and Cargo Del., Spacecraft Reloc., Earth Return, Servicing, and Assembly

133 total missions; serviced dozens of spacecraft (including HST), assembled ISS

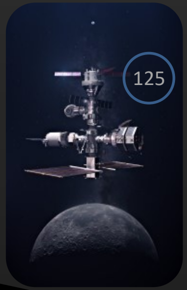
International Space Station (2000, LEO)



Assembly, bi-prop refueling, module replacement, payload hosting and deployment, tele-operated robotics, EVA repair

Humans and robots living and working in LEO for 20 years and counting

Gateway (2024, Cislunar)



Assembly of Elements (docking), Crew and Cargo Delivery, Chem/ Xenon Refueling, Robotics

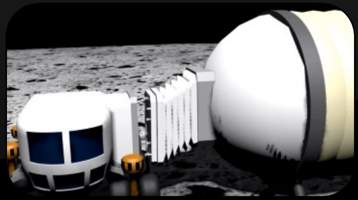
Sustainable lunar and solar system exploration via cislunar operations

Commercial LEO Destinations Program (202X, LEO)

Private, crewed, orbiting platforms supporting human research, technology demonstrations, biological and physical science, and the National Lab

Lunar Landing and Surface Systems (202X)

In-space and surface docking for Fueling and Crew Transfer



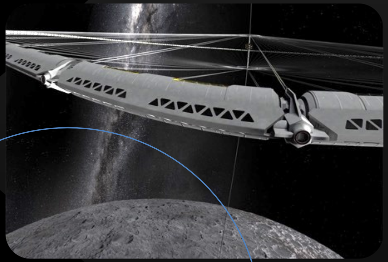
Sustained return to the lunar surface

Mars Exploration (20XX)

Mars Transportation System cislunar assembly, (re)fueling, refurb, recert; Maintenance *en route* to and on surface of Mars; Mars Ascent Vehicle surface fueling

First humans on Mars

Where to Next?



Very large-scale space manufacturing assembly, and servicing

Space Factories? Human exploration beyond Mars?

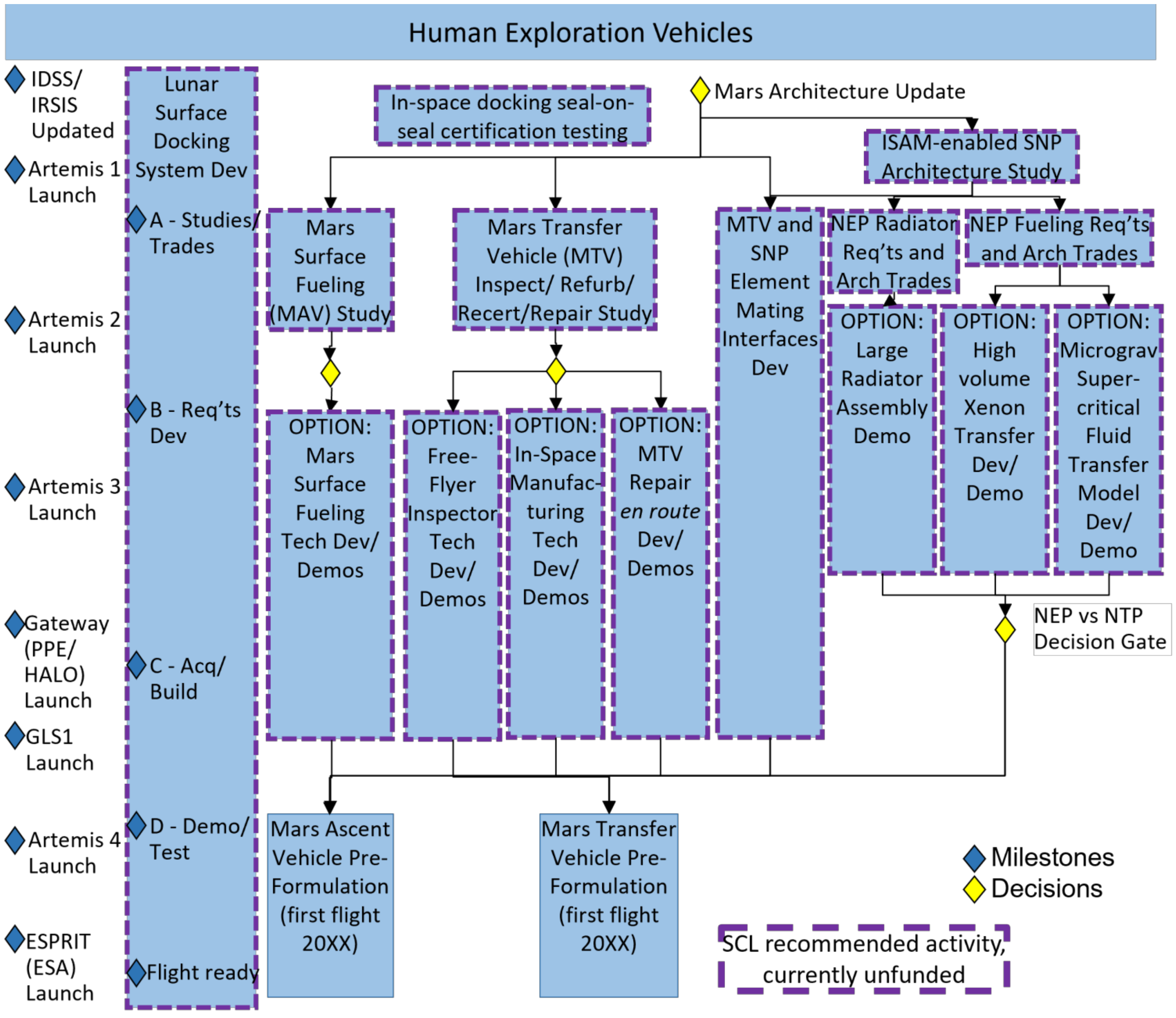
Future

Pressurized Volume (m^3)

Radiator Area

All activities depicted not currently funded or approved. Depicts “notional future” to guide technology vision.

Gaps, Priorities, Investments, and Plans for Human Exploration



All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.

Priority Gap: Space Nuclear Propulsion Servicing and Assembly Architectures – Large in-space transportation systems require unprecedented scale of fueling operations and heat rejection systems likely to benefit from in-space assembly techniques

Closure Plan: SNP Technology Maturation Planning – Ongoing activities including assembly, autonomy, and fluid transfer subject matter experts to develop NEP fueling and radiator assembly concepts and identify critical technology development activities

Other Priority Gaps – pending Mars architecture updates

- **Lunar and Mars surface pressurized crew transfer interfaces** – includes suitport and surface docking and tunnels
- **In-space docking system seal-on-seal certification** – supports active-to-active docking system mating (androgyny)
- **Mars surface storable fueling systems** – supports Mars Ascent Vehicle (propellant landed separately from vehicle)
- **Free-flyer inspection, and robotic repair, maintenance, refurbishment and recertification requirements and architecture** – support Mars Transportation Vehicle *en route* to Mars and between trips

Relevant Current Investments

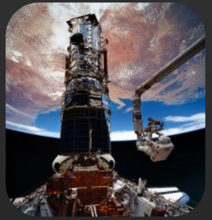
- **In-space Manufacturing** – investment (funding source)
- **In-Space Assembly** – PASS, ARMADAS (STMD)
- **In-Space Robotics** – OSAM-1, OSAM-2 (STMD), Canadarm3 (CSA)
- **In-Space Fluid Transfer (non-cryo)** – Gateway (SOMD), OSAM-1 (STMD), ESPRIT (ESA)

Space Fleet Servicing and Upgrade

JP-8 (1990)

USG specifies JP-8 as the common fuel for US military aircraft

Hubble Servicing Missions (1993-2009, LEO)



Five servicing missions installed corrective optics, new instruments, and modular bus H/W

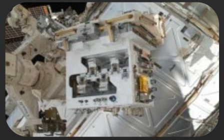
USB (1996)

First USB standard released with specs for cables, connectors, and protocols for computers

Orbital Express (2007, LEO)

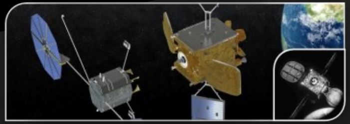
Demo of fully autonomous coop-erative rendezvous and docking, re-fueling, and compo-nent replacement

ISS & RRM (2011-21, LEO)



Dozens of robotic and EVA ORU installations; Coop. Bi-prop refueling (Russian), Robotic fluid transfer demos including cryo and storable fluids (high pressure Xe demo pending) to legacy and cooperative interfaces

MEV (2020-21, GEO)

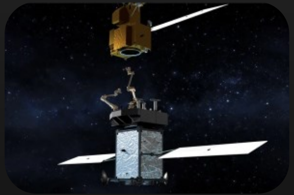


1st commercial satellite servicing via life extension

RSGS/MRV (2024, GEO)

Public-private partnership develops a robotic servicer including module delivery and installation

OSAM-1 (2026, LEO)



Refuels a legacy satellite and demonstrates assembly and manufacturing ops

Refuelable Spacecraft

All spacecraft launched with interfaces enabling autonomous robotic refueling of standard fuels

Upgradeable Spacecraft

All spacecraft launched with "USB for Space" interfaces to enable upgrade

Paradigm Change

Routine refueling and on-orbit upgrade

In-space logistics support Space Fleet

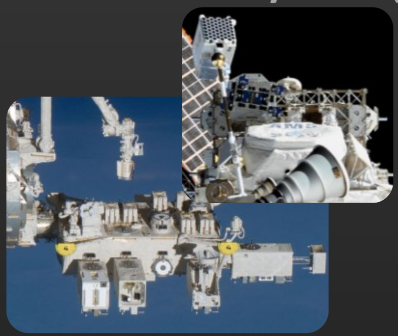
PROPOSED Responsive and Resilient Space Fleet

Cooperative servicing features and modular designs; Commercial services for routine planned, and on demand robotic servicing

Modular designs, and In-space logistics enable on-demand, responsive spacecraft for planned and unplanned operations.

Platforms and Logistics

ISS Hosted Payloads (2000, LEO)



Internal and external payload delivery, installation, and hosting

Dozens of internal and external payloads delivered and hosted

Commercial ISS Platforms

Commercial payload hosting services in 51.6deg inclined LEO

Commercial LEO Destinations

Commercial payload hosting and crew destinations

Gateway (202X, Cislunar)

Internal and external payload delivery, installation, and hosting

Cislunar hub for lunar and solar system exploration

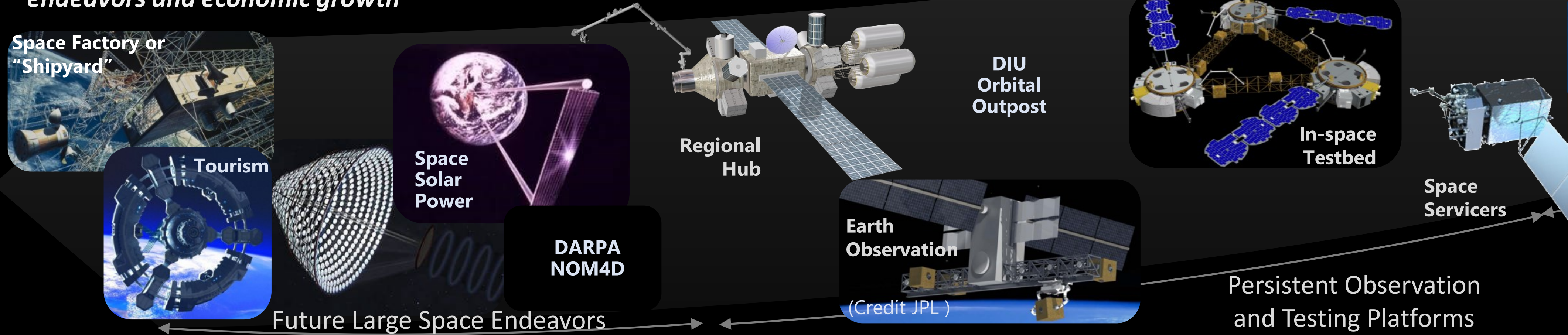
PROPOSED creation of long duration evolvable platforms

Robotic Servicing, Assembly and Manufacturing of advanced space infrastructure;
Interoperable, cooperative, modular interfaces on all USG spacecraft

"Space Superhighway", logistics, vehicles and platforms in multiple orbit regimes host science, weather, and in-space test payloads, and provide transportation and fueling, enabling increased flexibility, reduced cost and risk, enabling ambitious space endeavors and economic growth

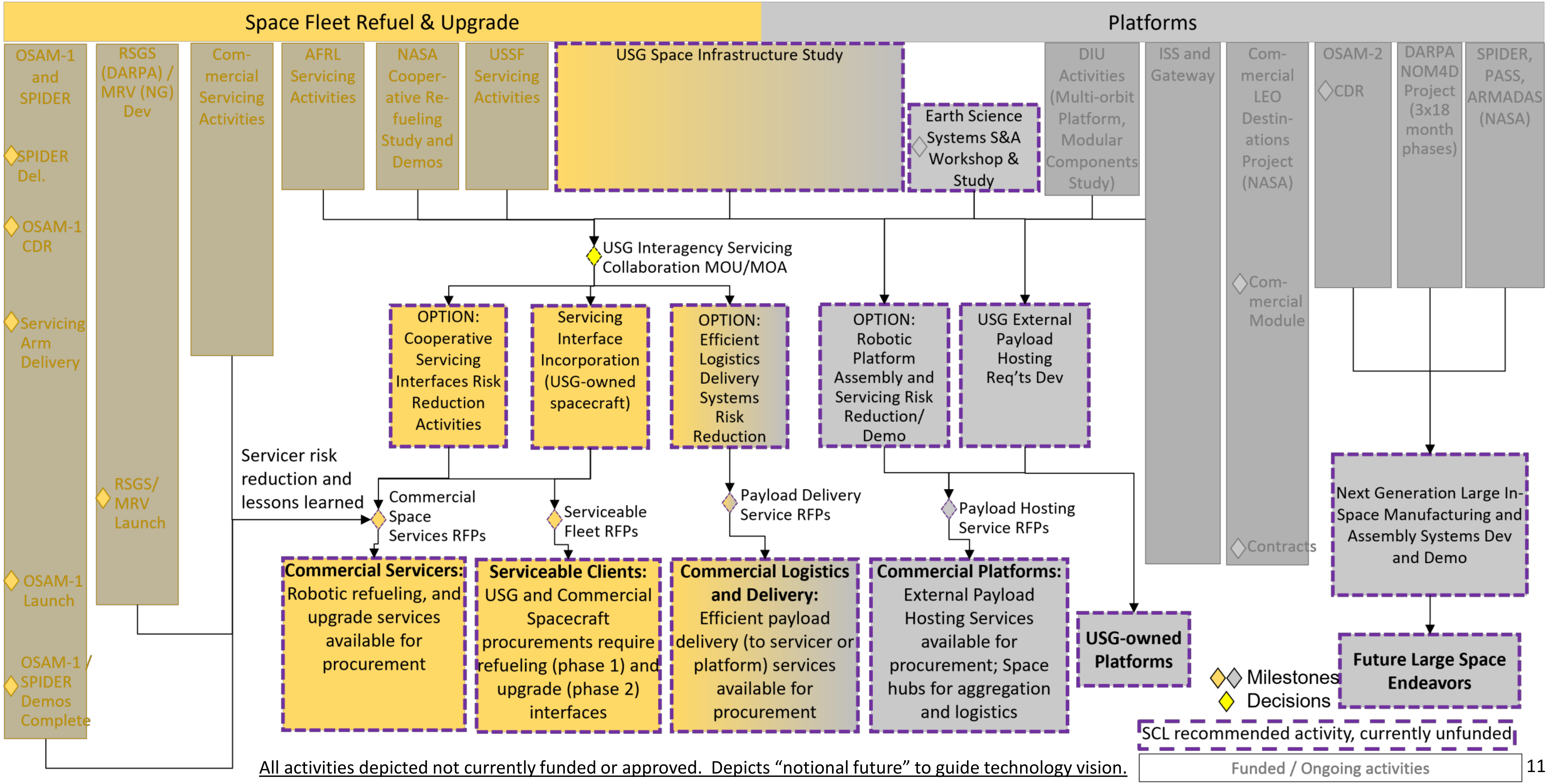
Space Tugs

Fuel Depots



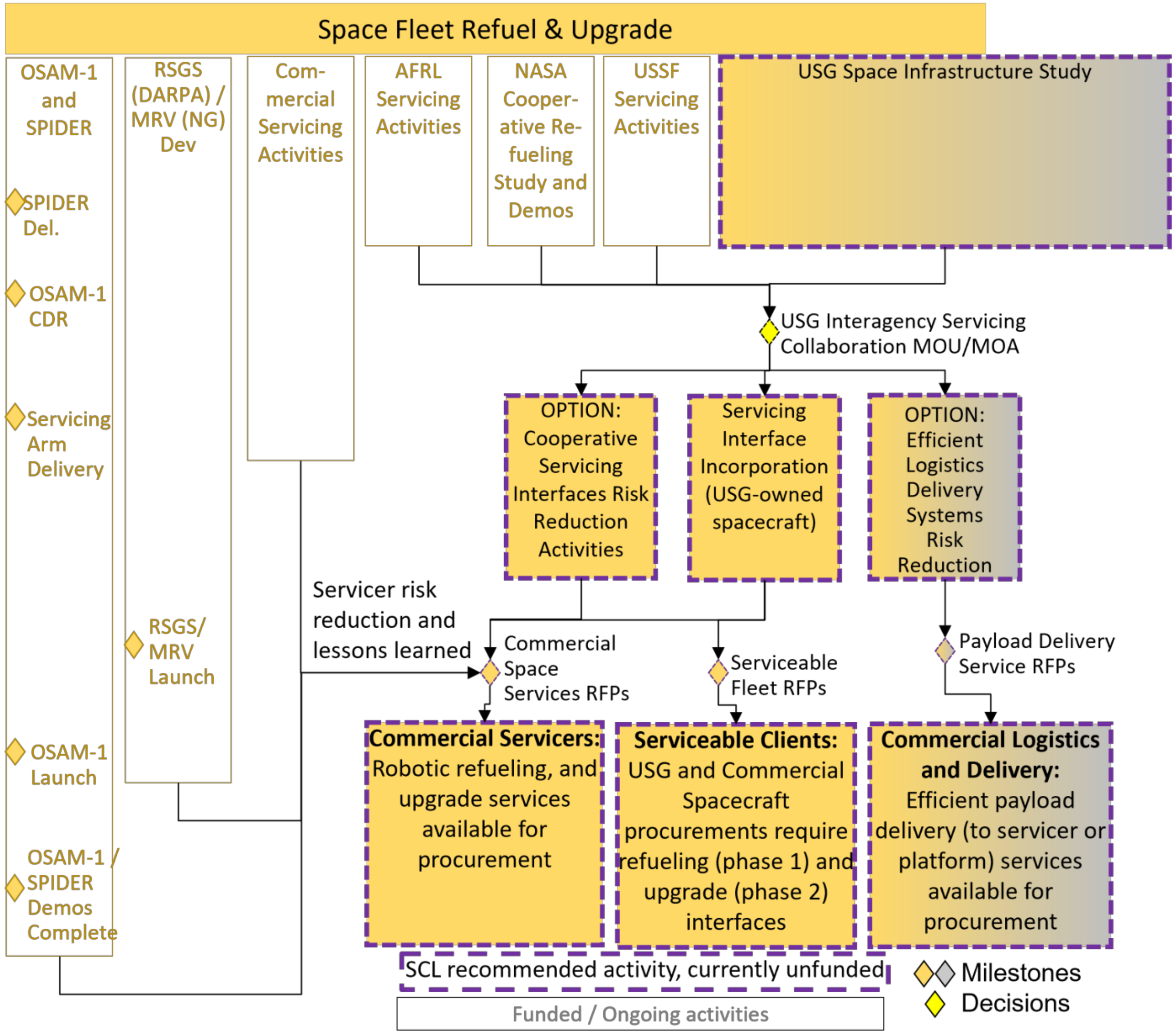
<u>All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.</u>

Cross-Cutting Space Infrastructure and Logistics



<u>All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.</u>

Gaps, Priorities, Investments, and Plans for Space Fleet Refueling and Upgrade



Priority Gap: Refuelable and upgradable space fleet and servicers - interoperable ecosystem of serviceable client spacecraft, servicers, and delivery vehicles

Closure Plan: Space Infrastructure Study & Workshops

- Coordination USG space infrastructure plans
- Collaborate with industry on standardization of propellant commodities, common interfaces for capture, refueling, and upgrade of components
- Goal is infrastructure of commercial services providing refueling, component upgrade, on-demand, in multiple orbit locations

Other Priority Gaps

- Incorporation of common interfaces for RPO, capture, refueling, and upgrades across the fleet
- Key fluid transfer challenges: liquid-free venting of PMD tanks in microgravity; flight pneumatic compressor for GHe/GN2 transfer and refill; propellant accounting (high accuracy and multi-phase fluid flow metering)
- In-space demonstration of suite of high priority gaps needed for future systems

Selected Relevant Current Investments

- RPOC – ISS VV (commercial), GLS, Gateway, Orion (ESDMD), OSAM-1 (STMD), Others
- Servicing – OSAM-1 (STMD), RSGS (DARPA), Others
- Refueling – OSAM-1, Gateway (ESDMD), USSF, Others

All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.

Gaps, Priorities, Investments, and Plans for Platforms and Logistics

Priority Gap: In-Space Logistics Infrastructure – Commercial logistics, delivery, and payload hosting platforms

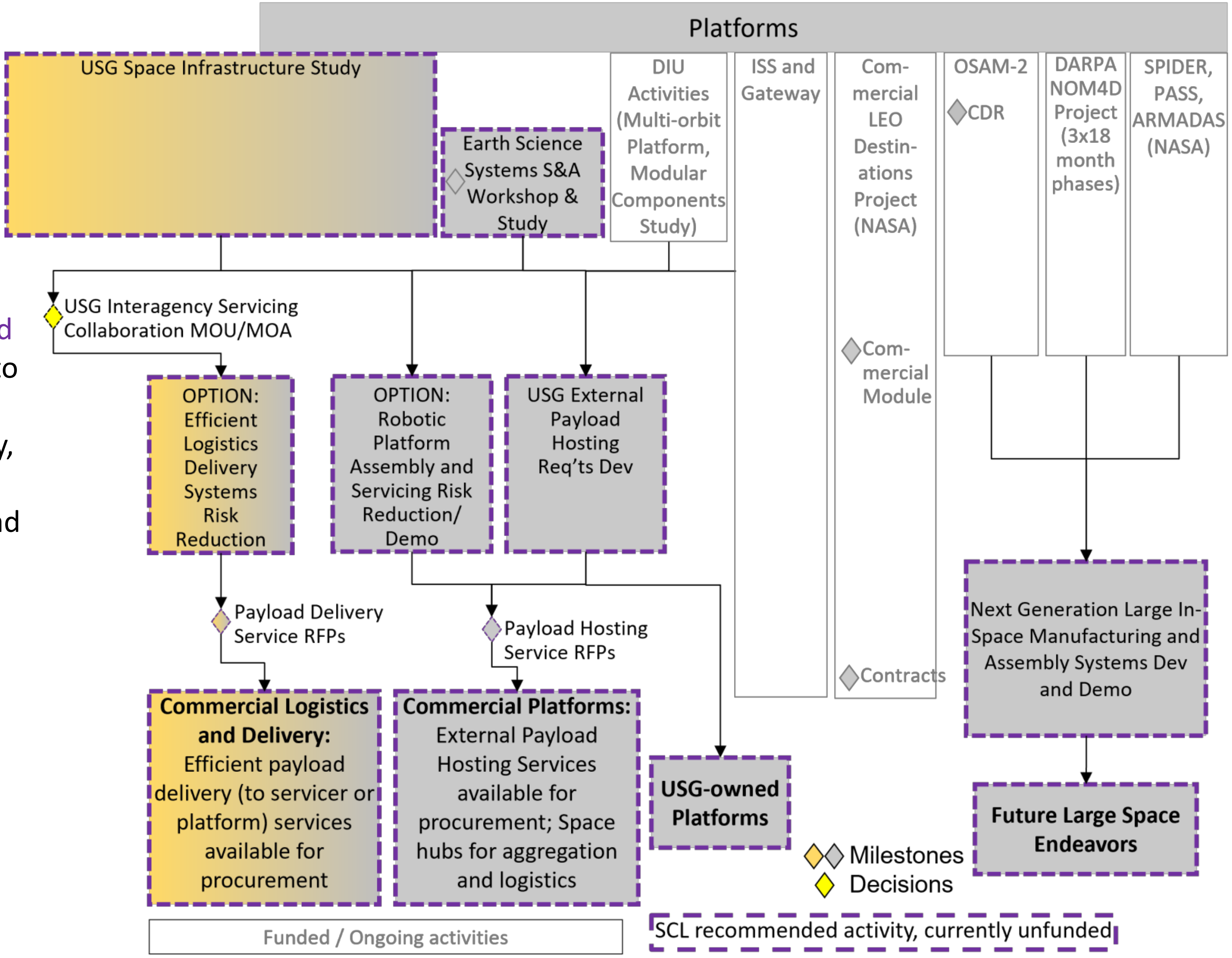
Closure Plan: Space Infrastructure and Logistics Study - Study to define future architectures to leverage future envisioned capabilities leading to selected end states

Other Gaps

- Efficient servicing and assembly payload delivery and logistics – in-space systems to deliver commodities to servicers and platforms
- Modular elements and interfaces for initial assembly, in-situ exchange, expansion/adaption/evolution (extend power, heat control, communication, payload rotations, etc.) with associated design guides
- Systems for "next generation" in-space manufacturing and assembly of very large space platforms

Relevant Investments

- Automated Assembly Architectures – Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS) (STMD), PASS (STMD)
- Human/Autonomy Trust – ISS, CLD, Orion, Gateway (ESDMD/SOMD)

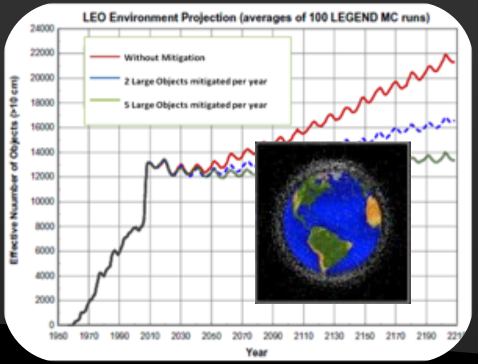


<u>All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.</u>

Active Debris Remediation

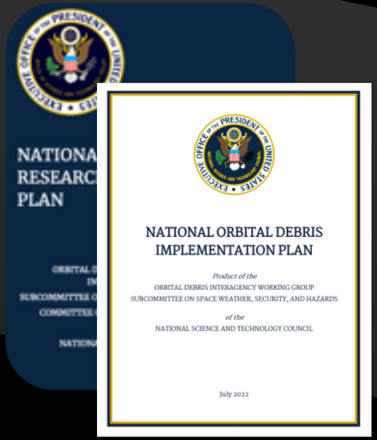
1984 – STS-51-A mission retrieves and de-orbits the defunct Westar 6 satellite after failed deployment

2010 - Pivotal work by NASA ODPO and others recommends mitigation and remediation action



2018 - European RemoveDEBRIS mission tests a variety of remediation technologies

National Orbit Debris R&D Plan (2021) and Implementation plan (2022)



ELSA-d (LEO, 2021)

PROPOSED Ability to move, remove, and reuse debris

Large and small debris is manipulated to avoid collisions just-in-time; Bulk debris removal services are commercially available; Defunct satellites are sold to private companies for refurbishment or scrap

The ability to avoid debris-on-debris collisions, rapidly clean up orbits after debris generating events, and de-orbit dangerous debris reverses Kessler Syndrome and reduces costs to space operators

ESA ClearSpace-1 Launch (2025) Credit Clear Space

JAXA Commercial Removal of Debris Demonstration (CRD2)

Phase II: Debris deorbit (by 2026)

Phase I: Debris Inspection (by 2023)

NASA OTPS ADR Cost Benefit Study (2022)

X Prize ADR Challenge Study (2022)

SpaceWERX (USSF) Orbital Prime STTR Awards (2022)

NASA STMD Ignite SBIR Solicitation ADR Topic Released (2022)

International ADR missions

All activities depicted not currently funded or approved. Depicts “notional future” to guide technology vision.

Gaps, Priorities, Investments, and Plans for Active Debris Remediation

Priority Gap: Active Debris Remediation Approach – Identify prioritized ADR approaches that reduce operational risks and minimize cost in order to focus near term technology investment

Closure Plan:

- **Step 1 – NASA OTPS Cost Benefit Analysis Study** – in progress, to be completed November 2022

Other Priority Gaps – pending CBA final report

- **Capture of large space debris** – capture of various types of uncontrolled large space debris, including spent upper stages and derelict spacecraft. RPO and capture systems to perform pose estimation and capture of uncontrolled, non-prepared objects at order of magnitude higher relative attitude rates as compared to existing state of the art.
- **Capture and remediation of small space debris** – Capture and remediation of small space debris (<10cm)
- **Non-traditional ADR mission concepts and capabilities** – just in time collision avoidance (JCA), responsive post-fragmentation cleanup, and other concepts could be more scalable than traditional approaches that physically capture debris. Additional study is required to determine feasibility and scalability.

Relevant Gaps captured in other EFPs

- ESPA-Class High-ΔV SEP (Propulsion Gap)
- Laser ranging for unprepared spacecraft and debris
- Small Spacecraft Propellentless Deorbit Devices (EDL Gap)
- In-space recycling and re-use (Advanced Manufacturing Gap)

Selected Relevant Current Investments

- **SBIR Ignite** – 2023 solicitation is progress
- **Small Satellite Propulsion Systems** – Several ongoing investments
- **Studies and Analyses** – Cost benefit, risk assessments, tech evaluations
- **OSAM-1** – Rendezvous, proximity operations, and capture of a (controlled) non-prepared (legacy) spacecraft, including sensors, computer vision, robotics and tools

All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.

A more simplified view – Where should USG ISAM stakeholders focus?

ISAM Clients
(The Customer)

Priority: Support USG customer

- Focus on USG ***enterprise-level*** cost and risk
- Educate USG spacecraft buyer
  - Quantify alternatives/benefits (studies and trades)
  - Include ISAM capabilities in early mission architecture trade space
- Help USG spacecraft buyers and operators:
  - Specify and procure serviceable and assembled spacecraft
  - Procure in-orbit services

ISAM Agents
(Servicers, Inspectors, Robotics, Tools, Manufacturers, EVA)

Priority: Enable commercial providers

- Purchase services and fund infrastructure / destinations
- Break down regulatory hurdles
- Assist the providers: publish and share guidelines, best practices, lessons learned, support standards development efforts
- Fund high risk, high return enabling technology development and demos

(Cargo launch, transport, "last mile" delivery)
ISAM Logistics

RPOC and Sat S&A Gaps by Roadmap Team (1/2)

Team	Gap Title	Currently Investing
In-orbit and Surface Docking and Berthing Systems	In-space Docking and Berthing Systems	
	Pressurized In-Space IDSS System Technologies	✓
	Unpressurized In-Space Docking and Berthing	✓
	Pressurized In-Space Next Generation Docking for Crew and Cargo	✗
	Surface Mating Systems	
	Pressurized Surface Mating between Vehicles and Elements for Crew and Cargo	✓
	Unpressurized Surface Mating and Berthing Systems	✗
	Mating port for transfer of crew and cargo (Suit port)	✓
	Dust Tolerant Sealing Surfaces and Mechanisms	✓
Instrument Servicing and Installation	Future Great Observatory Servicing and Assembly architecture and agents	✗
	Upgrade or install instruments on large space observatories	✗
	Precision instrument latches	✗
	Modular thermal design for on-orbit Instrument Installation	✗
	Address contamination concerns associated with on-orbit instrument servicing & installation	✗
	Thermal safekeeping approach for unpowered on-orbit or on-surface installation	✗
Storable and EP Propellant Refueling	Storable Propellant Mass Accounting	✓
	Pressurant accommodation and ullage venting for in-space fluid transfer	
	Venting of PMD Tanks in Microgravity	✗
	Efficient Pneumatic Compressor/Pump for In-Space Gas Transfer	✓
	In-Space Xenon Transfer Technologies	✗
	Filling of PMD Tanks in Microgravity	✗
Design for ISAM	Modular design for on-orbit installation	✓
	ISAM cooperative interfaces, aids, and standards	✓
	ISAM Value Proposition and Acquisition Strategy	✓

RPOC and Sat S&A Gaps by Roadmap Team (2/2)

Team	Gap Title	Currently Investing
In Space Manufacturing	In-space structural joining and welding	✓
	In-space salvage and recycling	✓
On-Orbit and On-Surface Validation and Verification	Integrated modeling and digital twin for space-based V&V	✗
	V&V of in-space assembled modular structures using metrology	✗
	V&V of a precision assembled telescope using metrology	✗
ISAM Robotics Systems and Hardware	Affordable servicing and assembly robotics (supply chain)	✓
	Deploy, install, manipulate soft goods (umbilicals and shades)	✗
	Proximity and vision sensors for increased robotic autonomy	✓
	Contact sensors for robotic manipulation	✓
	Robotic manipulation system architectures enabling large and dispersed workspaces	✓
Small Sat and ISAM Delivery Logistics RPOD	Consolidated advanced sensors for relative navigation	✓
	Small satellite RPOC with close free-flying inspection of a high-value asset	✓
	Affordable on-demand unpressurized cargo module delivery to in-space assets	✓
	Small satellite docking systems	✓
	SmallSat RPO Propulsion Capability	✓
ISAM Materials	Dimensionally Stable High Stiffness Structural Materials for In-Space Assembled Telescopes	✓
Assembly of Structures	Assembly of modular structures	
	Assembly of efficient, modular, stable structures	✓
	Assembly of Nuclear Propulsion Vehicle backbone structure with utility connections	✗
	Robotically Assemble In-Space Platform	✓
Active Debris Remediation	Capture of large space debris	✗
	Capture and remediation of small space debris	✗
	Non-traditional ADR mission concepts and capabilities	✗

Acronyms

- ADR = Active Debris Removal
- AFRL = Air Force Research Laboratory
- ARMADAS = Automated Reconfigurable Mission Adaptive Digital Assembly Systems
- APD = Astrophysics Division
- ATP = Authority to Proceed
- cc = cubic centimeter
- CDR = Critical Design Review
- CHARISMA = Caroline Herschel high-Angular Resolution In-Space assembled Multi-Aperture
- CIF = Center Innovation Fund
- ConOps = Concept of Operations
- COTS = Commercial Off The Shelf
- CPOD = Cubesat Proximity Operations Demo
- CSA = Canadian Space Agency
- DARPA = Defense Advanced Research Projects Agency
- DIU = Defense Innovation Unit
- DSNE = Design Specification for Natural Environments
- ECI = Early Career initiative
- EFP = Envisioned Future Priorities
- ESA = European Space Agency
- ESDMD = Exploration Systems Development Mission Directorate
- ESPRIT = European System Providing Refueling, Infrastructure and Telecommunications
- EVA = Extra Vehicular Activity
- ExPA = Express Pallet Adapter
- FF = Formation Flying
- FTS = Force-Torque Sensor
- GCD = Game Changing Development
- GEO = Geosynchronous Orbit
- GHe = Gaseous Helium
- GLS = Gateway Logistics Services
- GN2 = Gaseous Nitrogen
- GO = Great Observatory
- GW = Gateway
- HABEX = Habitable Exoplanet Observatory
- HALO = Habitation and Logistics Outpost
- HEV = Human Exploration Vehicle
- HST = Hubble Space Telescope
- H/W = Hardware
- I&T = Integration & Test
- IDA = International Docking Adaptor
- IDSS = International Docking System Standard
- IRSIS = International Rendezvous System Interoperability Standards
- ISAM = In-Space Servicing, Assembly, and Manufacturing
- iSAT = in-Space Assembled Telescope
- ISM = In-Space Manufacturing
- ISS = International Space Station
- JP-8 = Jet Propellant-8
- JWST = James Webb Space Telescope
- KDP = Key Decision Point
- LEO = Low Earth Orbit
- LST = Large Space Telescope
- LUVOIR = Large UV/Optical/IR Surveyor
- MAV = Mars Ascent Vehicle
- MCDR = Mission Critical Design Review
- MEV = Mission Extension Vehicle
- Mfg = Manufacturing
- MOA = Memorandum of Agreement
- MOU = Memorandum of Understanding
- MRV = Mission Robotic Vehicle
- MSS = Mobile Servicing System
- MTV = Mars Transfer Vehicle
- MUSES = Multi-User System for Earth Sensing
- NDS = NASA Docking System
- NEP = Nuclear Electric Propulsion
- NET = No Earlier Than
- NG = Northrop Grumman
- NICER = Neutron Star Interior Composition Explorer
- NOM4D = Novel Orbital and Moon Manufacturing, Materials and Mass-efficient Design (pronounced “NOMAD”)
- NTO = Nitrogen Tetraoxide
- NTP = Nuclear Thermal Propulsion
- ORU = On-orbit Replaceable Unit
- OSAM = On-Orbit Servicing, Assembly, and Manufacturing
- PASS = Precision Assembled Space Structure
- PM = Primary Mirror
- POD = Payload Orbital Delivery
- PPE = Power & Propulsion Element
- ProxOps = Proximity Operations
- RF = Radio Frequency
- RFP = Request for Proposals
- RPOC = Rendezvous, Proximity Operations, and Capture
- RSGS = Robotic Servicing of Geostationary Spacecraft
- RST = Roman Space Telescope
- S&A = Servicing & Assembly
- SCL = System Capability Lead
- SE-L2 = Sun-Earth L2 (Lagrange Point)
- SF = Space Fleet
- SIL = Servicing Infrastructure & Logistics
- SLSTD = System Level Segmented Telescope Design
- SMD = Science Mission Directorate
- SNP = Space Nuclear Propulsion
- SOMD = Space Operations Mission Directorate
- SPIDER = Space Infrastructure Dexterous Robot
- STMD = Space Technology Mission Directorate
- TBD = To Be Determined
- TRL = Technology Readiness Level
- TDM = Technology Demonstration Missions
- ULA = United Launch Alliance
- ULTRA = Ultra Stable Telescope Research & Analysis
- USB = Universal Series Bus
- USG = United States Government
- USSF = United States Space Force
- V&V = Validation & Verification
- VV = Visiting Vehicle (at ISS)
- WFE = Wavefront Error

EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

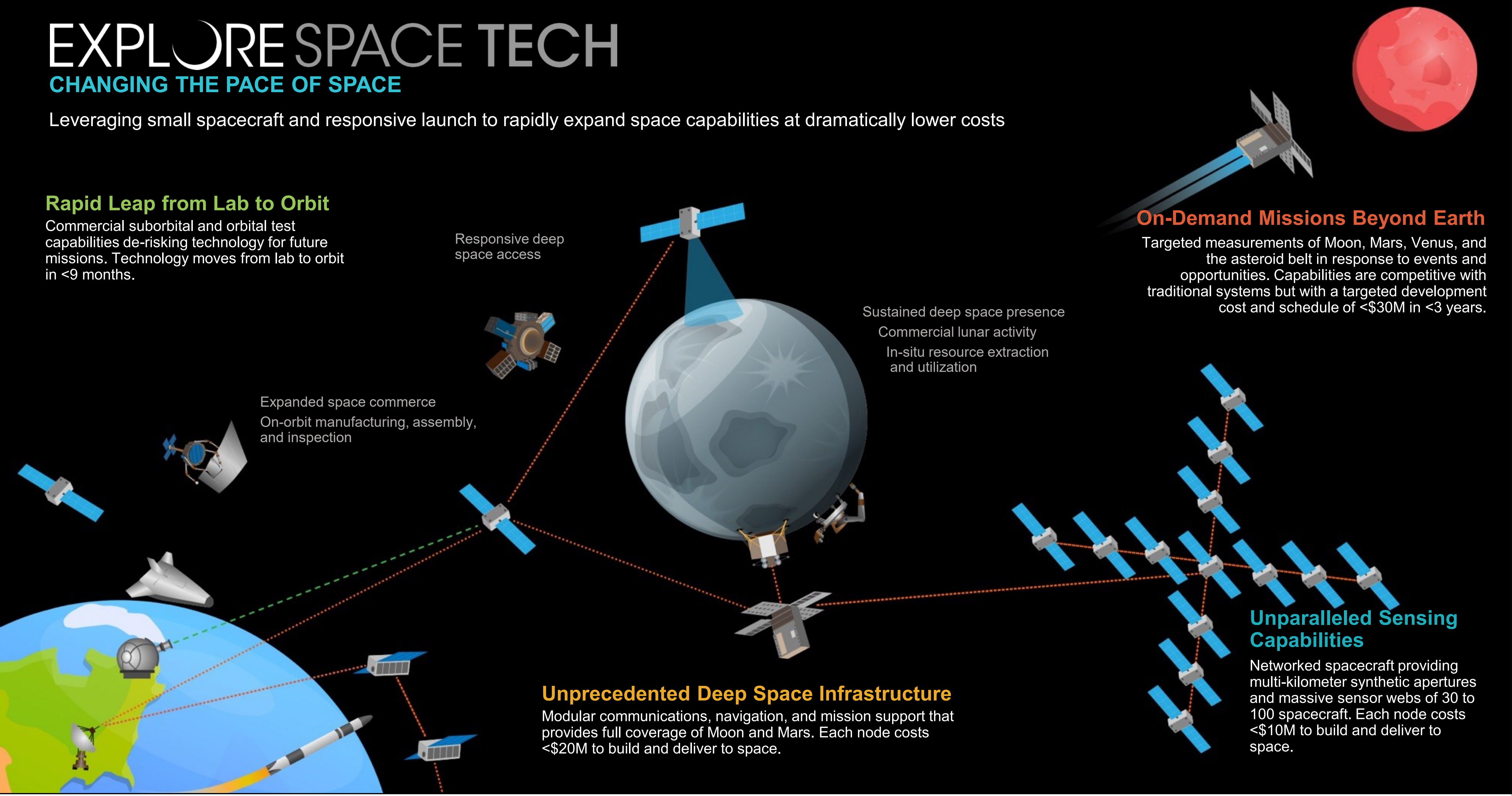
EXPLORE: Small Spacecraft Technologies
NASA Space Technology Mission Directorate
August 2022

STMD welcomes feedback on this presentation
See 80HQTR22ZOA2L_EXP_LND at nspires.nasaprs.com for how to provide feedback
If there are any questions, contact HQ-STMD-STAR-RFI@nasaprs.com

EXPLORE SPACE TECH

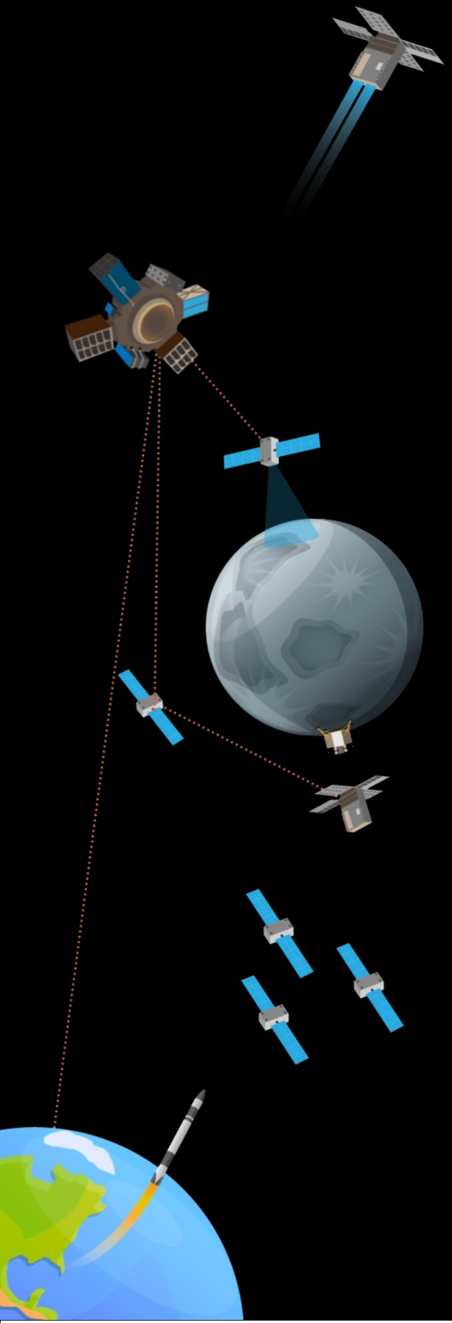
CHANGING THE PACE OF SPACE

Leveraging small spacecraft and responsive launch to rapidly expand space capabilities at dramatically lower costs



NOT ALL ACTIVITIES DEPICTED ARE CURRENTLY FUNDED OR APPROVED. DEPICTS "NOTIONAL FUTURE" TO GUIDE TECHNOLOGY VISION

CHANGING THE PACE OF SPACE: Envisioned Future For Small Spacecraft Technology



High dV Small Spacecraft Propulsion Systems

Low size, weight, power, and cost (SWaP-C) systems capable of imparting 2-5+ km/s change in velocity (dV) to microsatellites. Highly manufacturable and compatible with the deep space environment. ► Small missions to the Moon, Lagrange Points, NEOs and beyond as well as plane changes and more responsive missions in Earth orbit.

Deep Space Orbital Maneuvering Vehicles (OMVs)

OMVs capable of 10+ km/s dV and providing position, navigation, and timing (PNT) services and communications relay to deployed spacecraft or hosted payloads. Affordable and demonstrated in the deep space environment. ► Expansion of small risk-tolerant missions further beyond Earth and the ability to reach multiple destinations from a single launch.

In-Space Autonomy for Small Spacecraft and Distributed Systems

Significant (~75%) reduction in ground station aperture time for single small spacecraft missions. Increased in-space autonomy that allows 10's of small spacecraft to operate as a single unit beyond Earth. ► Large distributed missions (e.g., heliophysics) and missions in Earth-orbiting or beyond that can react without ground stations in the loop.

Small Spacecraft Communications and PNT Services

Small spacecraft that can be deployed to the Moon and other deep space destinations to provide global PNT and communications relay infrastructure. ► Addresses future strain on terrestrially-based capabilities (e.g., tracking) caused by concurrent cislunar missions and global surface missions where direct communications with Earth is not feasible.

Interoperable Networking for Small Missions

Increased interoperability between government and commercial space networks. Operational interoperability protocols that help pair the NASA Delay Tolerant Networking (DTN) and LunaNet with the Hybrid Space Architecture. ► Ubiquitous communication between in-space assets, airborne systems, in-situ sensors, and ground assets as well as networking in cislunar space.

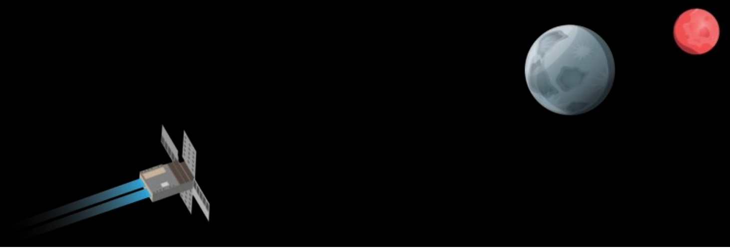
Small Spacecraft Proximity Operations and Abort Systems

De-risked low size, weight, power and cost (SWaP-C) proximity sensors and reliable proximity abort systems. ► Reduced risk in use of small satellites in close proximity to high value assets (e.g., for servicing / inspection) and for small missions to natural targets like NEOs.

Responsive Access to Suborbital and Orbital Space

Additional suborbital vehicle performance and payload accommodations for technology testing (e.g., payloads hosted on recoverable orbital launch vehicle stages and hosted orbital payloads). ► Rapid advancement of capabilities requires frequent risk-tolerant opportunities to test and evaluate in an operational environment.

High dV Small Spacecraft Propulsion Systems



Current State of the Art (2021)

Current demonstrated systems are typically able to provide 100's of m/s of dV with experimental systems nearing 2 km/s dV at the nanosatellite scale.

Yost, B. and Weston, S. (ed.), "State-of-the-Art Small Spacecraft Technology", NASA/TP-20210021263, October 2021

Envisioned Future

Low-SWaP-C systems capable of imparting 2-5+ km/s dV at the microsatellite scale. Highly manufacturable with repeatable performance and compatible with the deep space environment.

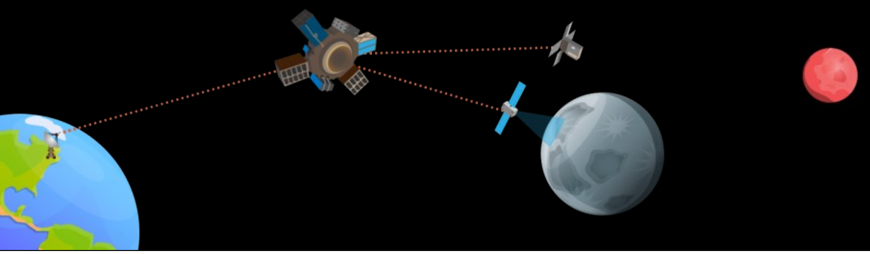
Enables small spacecraft missions to the Moon, Lagrange Points, Mars, Venus, and near-Earth objects (NEOs) as well as longer duration and more responsive missions in Earth orbit, including those at lower-altitude or requiring plane changes.

Small spacecraft represent cost-efficient mission options, but high dV implementation within SWaP-C constraints of small spacecraft is non-trivial.

- To achieve 5+ km/s dV, the propellant throughput / system life of nano- and microsatellite propulsion systems must be increased.
- Highly efficient propulsion (e.g., electric or dual mode) will be essential to meet volume and size constraints.
- Non-traditional propellants (e.g., "green", metallic, water) may provide greater compatibility with lower cost launch opportunities
- Will require sufficient modification, testing, and analysis to ensure radiation tolerance and reliability for multiyear missions and deep space operation.
- Manufacturability and commonality between systems for different missions / applications will keep costs low and increase reliability.

NOT ALL ACTIVITIES DESCRIBED ARE CURRENTLY FUNDED OR APPROVED. DEPICTS "NOTIONAL FUTURE" TO GUIDE TECHNOLOGY VISION

Deep Space Orbital Maneuvering Vehicles (OMVs)



Current State of the Art (2021)

Orbital Maneuvering Vehicles (OMVs) have been demonstrated and used operationally in Earth orbit. Higher performance 5+ km/s dV capabilities in development with demonstrations anticipated in the near future.

Yost, B. and Weston, S. (ed.), “State-of-the-Art Small Spacecraft Technology”, NASA/TP-20210021263, October 2021

Tan, F. et al (ed), “NASA Access 2 Space Workshop: Summary Report: Increased Science Return through Rideshare”, NASA Doc. 20205006748, Laurel, MD, 31 August 2020

Envisioned Future

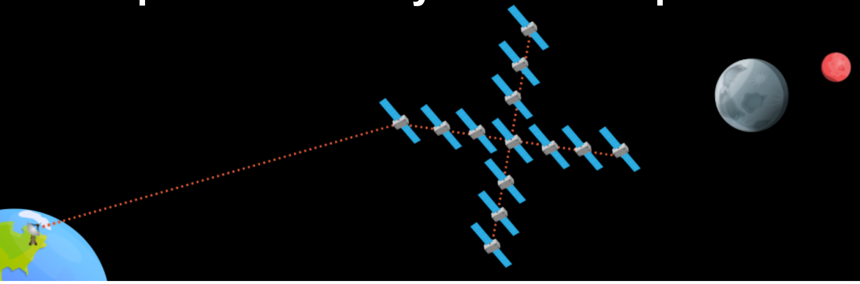
OMVs capable of 10+ km/s dV and that can provide position, navigation, and timing (PNT), communications relay, and other services to deployed spacecraft or hosted payloads. Affordable and demonstrated in the deep space environment.

Enables expansion of small risk-tolerant missions further beyond Earth. Enables small missions to reach multiple destinations from a single launch, achieve multiple orbital plane changes or nontraditional orbits, and reach beyond the Moon, Mars, and Venus to asteroids in the main belt or other deep space objects.

OMVs allow small spacecraft to reach orbits less achievable with on-board propulsion, higher dV capability and PNT / communications relay can make OMVs uniquely enabling for cost-efficient missions.

- Emerging systems (e.g., small launch interplanetary transfer stages and GEO life extension systems) may require increased capabilities to achieve 10+ km/s dV
- Systems being demonstrated for Earth orbit applications (e.g., propulsive ESPA rings and other space tugs) may require modification and testing to de-risk them for multiyear missions and deep space operation.
- Adding PNT / communications relay to OMVs can significantly increase the operational capabilities of low-SWaP-C spacecraft for distributed (e.g., heliophysics) and multiple individual missions at deep space destinations.
- Interfaces for hosted scientific instruments and payloads can allow the OMV to also act as the primary spacecraft bus for a mission, reducing mission-specific developmental costs.

In-Space Autonomy for Small Spacecraft and Distributed Systems



Current State of the Art (2021)

Most current constellations use ground-based, semi-autonomous scheduling and orbital maintenance to decrease human-in-the-loop operations but still upload commands to each spacecraft individually. Newer systems move more autonomy onboard but still rely on updates from ground-based systems. DARPA's Blackjack and SDA's architecture seek to increase in-space autonomy.

Yost, B. and Weston, S. (ed.), "State-of-the-Art Small Spacecraft Technology", NASA/TP-20210021263, October 2021

Envisioned Future

Significant (circa 75%) reduction in ground station aperture time for single small spacecraft missions. Increased in-space autonomy that allows 10's of small spacecraft to operate as a single unit beyond Earth.

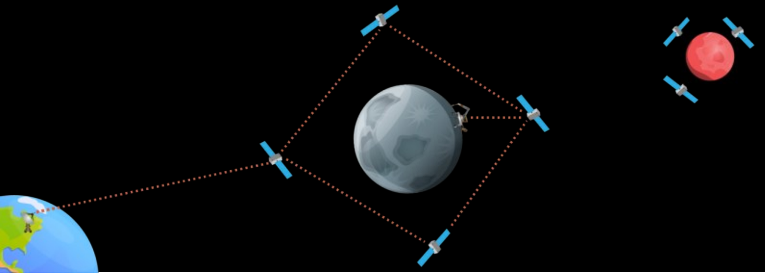
Enables large distributed missions such as sensor webs for heliophysics and advanced Earth-orbiting missions that can react without ground stations in the loop. Single-spacecraft autonomy can enable near-"lights out" operations for missions beyond Earth.

Small spacecraft are uniquely suited for large distributed missions, but operations are prohibitive without autonomy. In-space autonomy can also assist missions with communications limitations or that need to react to sensor data.

- Commercial software architectures and modules that are part of other USG / non-NASA distributed missions can be adapted for use by NASA missions and in environments operationally relevant for NASA.
- To enable multipoint measurements beyond Earth (e.g., heliophysics), 10s of spacecraft must be operated without saturating cross-link or ground-link bandwidth.
- Autonomous coordination allows small spacecraft to be configured in space as virtual telescopes and distributed apertures for investigation of Earth and the universe.
- Single-spacecraft autonomy can help addresses communications limitations and enable more robust situational awareness, fault recovery, and science data collection.
- Autonomous spacecraft can help enable responsible utilization of popular / congested orbits, providing benefits to commercial and USG users.
- Autonomy can also enable dynamic reconfiguration of assets for Earth observations

NOT ALL ACTIVITIES DESCRIBED ARE CURRENTLY FUNDED OR APPROVED. DEPICTS "NOTIONAL FUTURE" TO GUIDE TECHNOLOGY VISION

Small Spacecraft Communications and Position, Navigation, and Timing (PNT) Services



Current State of the Art (2021)

Space-based assets in Earth orbit currently provide global PNT and communications services for terrestrial activity and many small spacecraft in LEO. For lunar missions, PNT and communications are currently provided through large, terrestrially-based dishes such as those employed by NASA's Deep Space Network (DSN).

Envisioned Future

Small spacecraft that can be deployed to the Moon and deep space destinations to provide global lunar / comprehensive PNT and communications relay infrastructure.

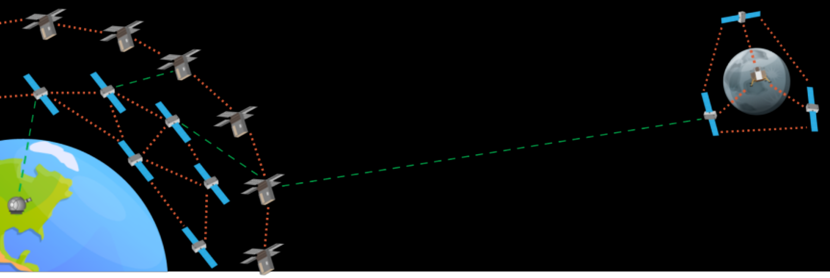
Can help address the strain on current terrestrially-based capabilities - particularly tracking - from future cislunar and deep space missions. Offers options for cislunar and lunar surface missions where direct communications with Earth-based systems will not be available.

Low-SWaP-C deep space communications, navigation, and timing synchronization will be critical for missions beyond Earth. While use of Multiple Spacecraft Per Aperture (MSPA) capabilities will help DSN service a growing number of concurrent missions, peer-to-peer navigation (e.g., CAPSTONE) paired with DSN tracking or emerging capabilities for use of weak-signal multi-GNSS at the Moon (e.g., NavCube3-mini) can play a role.

- Low-SWaP-C solutions can allow multiple communications and PNT satellites to be deployed around the Moon or Mars from a single launch vehicle or OMV. Lunar relay architecture studies for global coverage have used a minimum of 3 to 5 satellites (some as many as 15). Studies on ideal Mars networks show a minimum of 5 or 6 satellites.
- Rapid and cost-effective deployment of infrastructure may be possible through adaptation of small spacecraft-based LEO/MEO commercial communications spacecraft and terrestrial telecom technology (e.g., 4G/5G cellular) to the cislunar environment.
- Optical cross-links and downlinks may provide very high-bandwidth alternatives to RF for in space elements and fixed ground stations.
- Low-SWaP-C PNT sources for deep space will also be needed for use on small spacecraft or on OMVs that can relay PNT information to small spacecraft.

NOT ALL ACTIVITIES DESCRIBED ARE CURRENTLY FUNDED OR APPROVED. DEPICTS "NOTIONAL FUTURE" TO GUIDE TECHNOLOGY VISION

Interoperable Networking for Small Missions



Current State of the Art (2021)

Delay Tolerant Networking (DTN) in use by NASA missions. Hybrid Space Architecture concept adopted by DoD and commercial companies as a "variable trust" network framework for rapid and secure data exchange across USG, international, and commercial space systems. NASA's Space Communications and Navigation Office developed draft operational interoperability standards for LunaNet.

Yost, B. and Weston, S. (ed.), "State-of-the-Art Small Spacecraft Technology", NASA/TP-20210021263, October 2021

NASA, "Draft LunaNet Interoperability Specification, LN-IS Baseline V001, 2 September 2021

Burleigh, S., "Interplanetary Overlay Network: An Implementation of the DTN Bundle Protocol", 4th IEEE Consumer Communications and Networking Conference, 11-13 January 2007

Moigne, J. and Cole, M., "Advanced Information Systems Technology (AIST) New Observing Strategies (NOS) Workshop Summary Report", NASA Doc. 20210010318, 26 February 2021

Envisioned Future

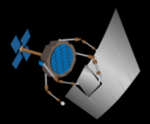
Increased interoperability between government and commercial space networks. Operational interoperability protocols that help pair the NASA LunaNet concept with the Hybrid Space Architecture and existing capabilities like DTN.

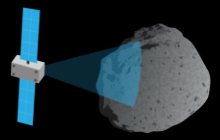
Enables ubiquitous communication between in-space assets, airborne systems, in-situ sensors, and ground assets. In cislunar space, will enable a network of surface and orbital nodes, low-SWaP-C relays, and more capable assets that can serve as hubs connecting to Earth-based communication networks.

Unification of interoperability approaches from NASA and the DoD can further ubiquitous networking and coordination across NASA, other USG, commercial, and international space assets.

- The Hybrid Space Architecture may help realize the dynamic coordination of assets from NASA and other organizations to optimize measurement acquisition for Earth observation across diverse capabilities.
- The LunaNet architecture resulted from efforts to leverage advances in small spacecraft technologies to update envisioned lunar communications architectures. NASA's SCaN Office has developed draft operational interoperability standards for LunaNet (https://go.nasa.gov/3ljMacw).

Small Spacecraft Proximity Operations and Abort Systems





Current State of the Art (2021)

Technology demonstrations at small spacecraft relevant scales have been conducted for on-orbit servicing and inspection with several more demonstrations upcoming.

Yost, B. and Weston, S. (ed.), “State-of-the-Art Small Spacecraft Technology”, NASA/TP-20210021263, October 2021

Envisioned Future

De-risked low-SWaP-C proximity sensors, software, and reliable proximity abort systems.

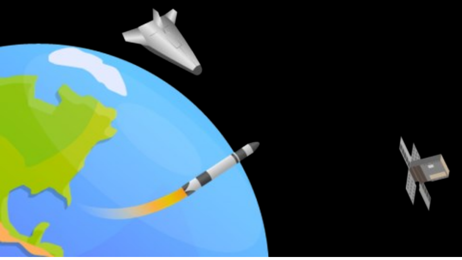
Needed to reduce risk in use of small satellites in close proximity to high value assets. These systems can also enable small missions to natural targets like NEOs or other missions requiring persistent formation flight.

Small spacecraft can be well suited to play roles in inspection, servicing, and other proximity operations with inhabited or high value assets as well as asteroids or other small bodies.

- Use of lower-cost risk-tolerant spacecraft in proximity to risk-intolerant assets is possible if the small spacecraft is equipped with a sufficiently robust proximity operations abort system that will reliably prevent a collision in the event of a fault or error.
- Low-SWaP-C onboard relative navigation systems for safe, autonomous, and persistent proximity / formation flight will be needed.
- Relative navigation sensors and proximity operations abort systems will need to be sufficiently demonstrated in operational relevant conditions.
- OMVs equipped with relative navigation / proximity operations abort systems can act as delivery (especially “last mile”) agents to high-value assets for servicing and resupply.

NOT ALL ACTIVITIES DESCRIBED ARE CURRENTLY FUNDED OR APPROVED. DEPICTS “NOTIONAL FUTURE” TO GUIDE TECHNOLOGY VISION

Responsive Access to Suborbital and Orbital Space



Current State of the Art (2021)

Commercial suborbital vehicles are currently providing valuable flight test capabilities for technologies relevant to exploration, discovery, and space commerce.

Envisioned Future

Additional vehicle performance and payload accommodations, including payloads hosted on recoverable orbital launch vehicle stages and greater access to orbital platforms for hosted technology testing.

Rapid advancement of capabilities requires frequent opportunities to test and evaluate new technology in an operational environment. Embracing "fly-fix-fly" and agile aerospace practices allows technologists to iterate through flights, and failures, to innovate at a pace impossible in a less risk-tolerant environment.

Advancement and additional access to commercial suborbital and LEO capabilities can further expand NASA use of rapid and lower cost commercial spaceflight for technology development and demonstration.

- Higher altitude suborbital flights, or the ability to host payloads on recoverable orbital rocket stages, could provide longer duration microgravity as well as access to speeds and heating conditions more relevant to planetary entry/reentry testing
- Routine and affordable hosting of small LEO payloads on orbital platforms can provide NASA-sponsored research rapid access to longer duration testing in relevant space environments.
- Through frequent low-cost access and increased capabilities – such as variable reduced gravity testing, high altitude balloon station keeping, and enhanced closed-loop EDL testing – commercial suborbital vehicles can continue to expand their role as a critical tool in the continuum of space technology flight testing.

Acronyms and Abbreviations

DTN	**Delay Tolerant Networking**
dV	**Delta-v**
EDL	**Entry, Descent, and Landing**
EELV	**Evolved Expendable Launch Vehicle**
ESPA	**EELV Secondary Payload Adapter**
GEO	**Geosynchronous Equatorial Orbit**
LEO	**Low Earth Orbit**
MEO	**Medium Earth Orbit**
MSPA	**Multiple Spacecraft Per Aperture**
NASA	**National Aeronautics and Space Administration**
NEO	**Near Earth Object**
OMV	**Orbital Maneuvering Vehicle**
PNT	**Position, Navigation, and Timing**
RF	**Radio Frequency**
SWaP-C	**Size, Weight, Power, and Cost**

NOT ALL ACTIVITIES DESCRIBED ARE CURRENTLY FUNDED OR APPROVED. DEPICTS "NOTIONAL FUTURE" TO GUIDE TECHNOLOGY VISION