

Designing for On-Orbit Servicing Capability

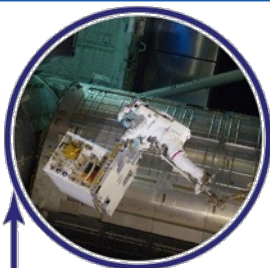
Maintenance Availability and Maintainability

October 11, 2019

Benjamin Reed, Deputy Director
Satellite Servicing Projects Division
NASA's Goddard Space Flight Center



NASA's Rich Heritage of In-Orbit Satellite Servicing



Robotic Refueling Mission
2011 - 2017



Remote Robotic Oxidizer
Transfer Test
2014



Robotic External Leak Locator
2015



Raven
2017 - 2019



Restore-L
2022 (planned)



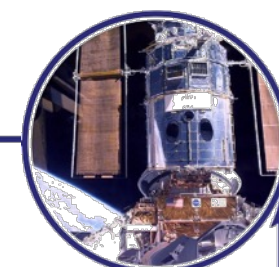
Hubble Servicing Mission 4
2009



Hubble Robotic Servicing and
Deorbit Mission (HRSDM)
2005



Hubble Servicing Mission 3B
2002



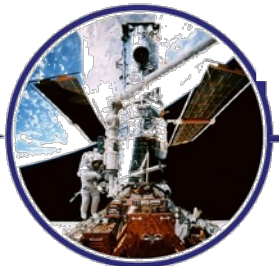
Hubble Servicing Mission 3A
1999



Solar Max
1984



Hubble Servicing Mission 1
1993



Hubble Servicing Mission 2
1997



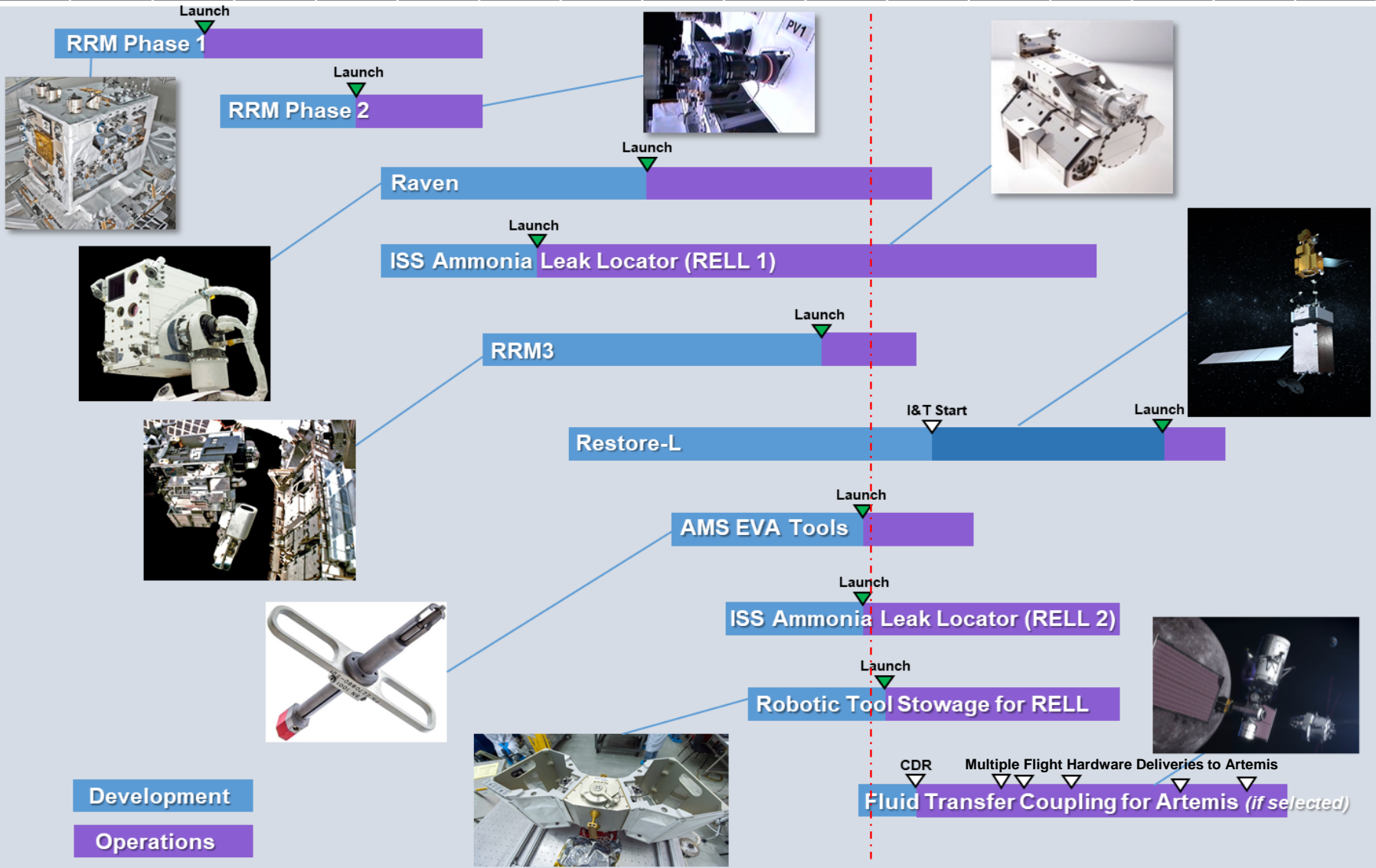
HST Orbiting Systems Test (HOST)
1998



SSPD Portfolio Overview



2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
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Technology Transfer Enables Robust Servicing Market

FIRST GENERATION (~2018)

SECOND GENERATION (~2020)

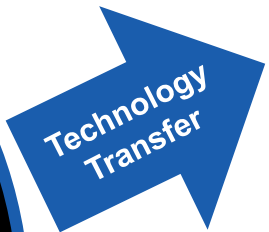
Rendezvous and Proximity Operations

High Speed Computing

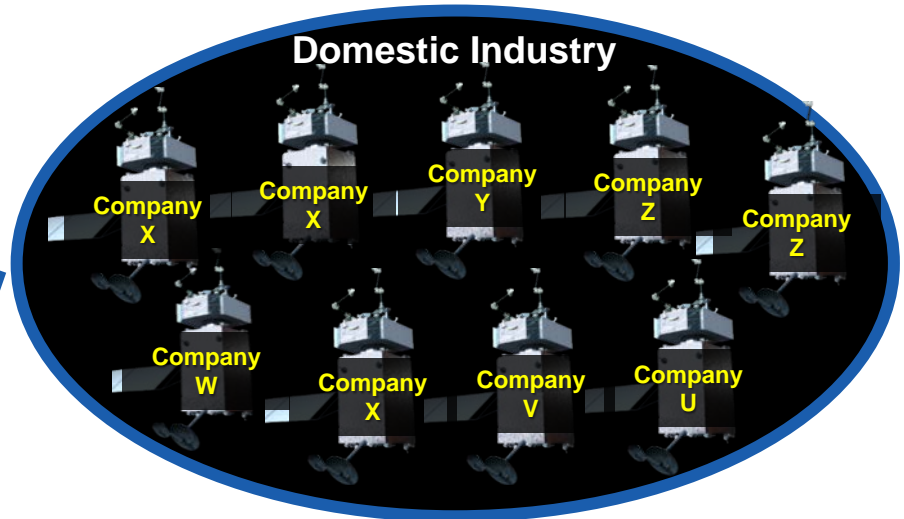
Dexterous Robotics

Fluid Transfer

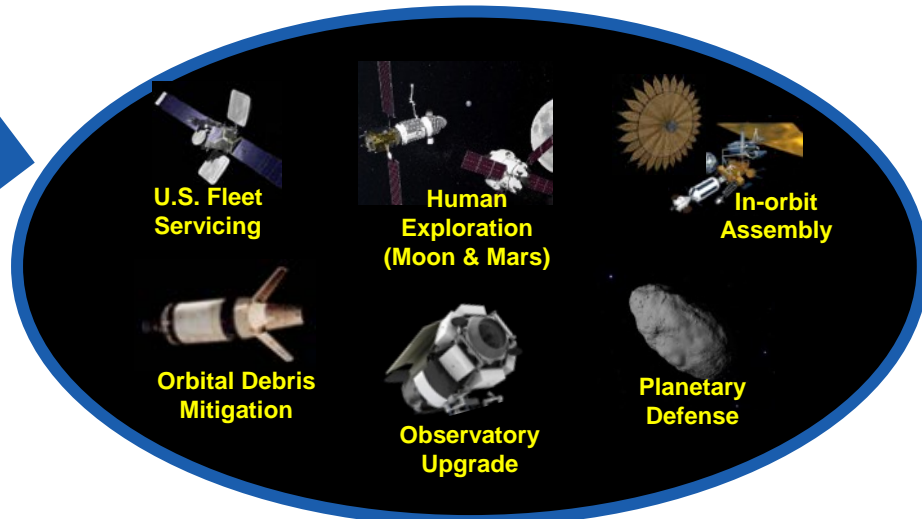
Specialized Tools



Domestic Industry



Competitive Market



Non-recurring Engineering Standards Development

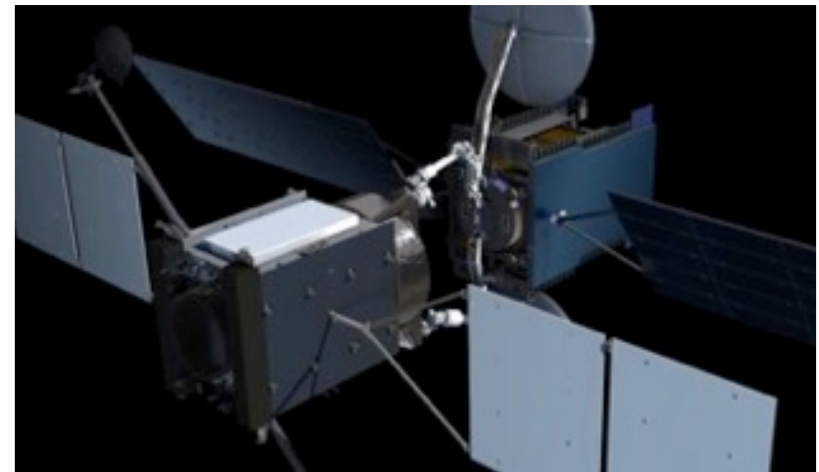
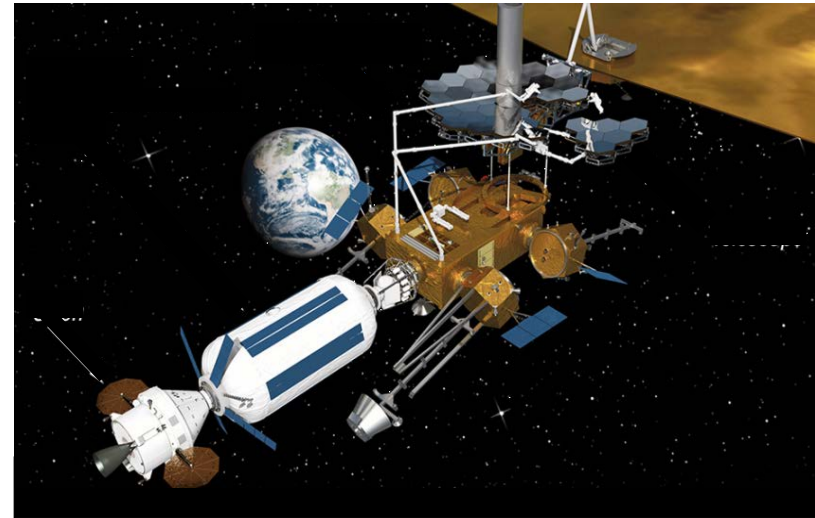
Application of Developed Technology



Cooperative Servicing Overview



- **What is Cooperative Servicing?**
 - *Cooperative Servicing is the implementation of design features that enable in-space servicing, assembly, and manufacturing*
 - There are many degrees and options of Cooperative Servicing implementation
- **What are some examples of Cooperative Servicing applications?**
 - Closeout photos
 - Rendezvous aids
 - Refueling valves
 - Grapple/Grasp fixtures
- **Why is Cooperative Servicing important?**
 - In-space servicing, assembly, and manufacturing are rapidly developing through multiple government and commercial efforts
 - Cooperative Servicing can simplify these missions as well as reduce risk and cost

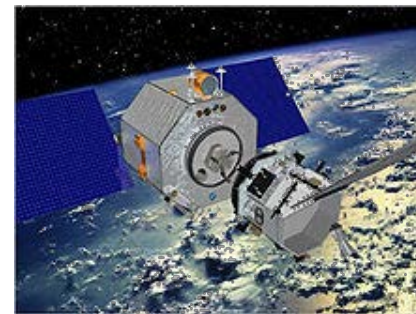
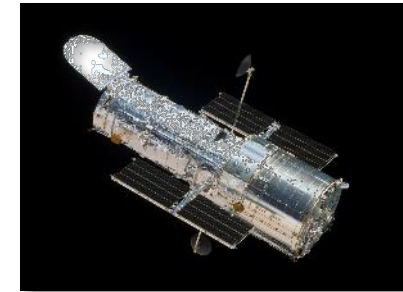




History of Cooperative Servicing



- **SolarMax:** Successfully repaired in 1984 through the cooperative features incorporated into the MMS spacecraft design that added five years to its life
- **HST:** Five different servicing missions took advantage of the cooperative interfaces for ORUs, built-in EVA aids, and interfaces for the SSRMS to keep HST running far longer than envisioned
- **ISS:** The showcase example of the success of in-space assembly, the ISS continues to utilize cooperative human and robotic servicing aids today for payload changeout, upgrades and repairs, and visiting vehicles
- **Orbital Express:** Technology demonstration mission in 2007 that used cooperative servicing aids to perform rendezvous, docking, refueling, ORU changeout.
- **MMS:** Launched in 2015 with cooperative decals to aid in autonomous rendezvous, if required, which were provided by SSPD

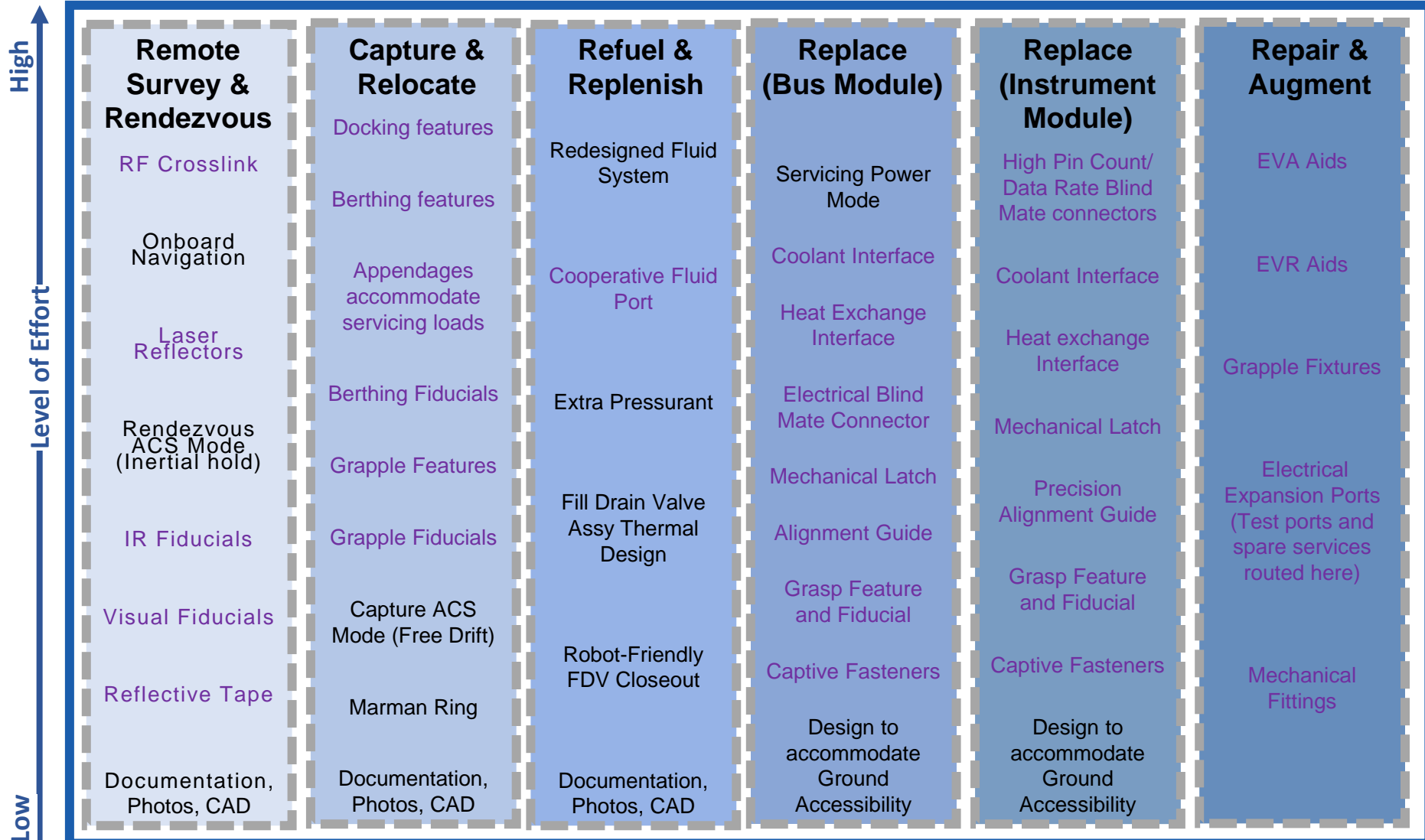




Serviceability Is a Spectrum



Potential crossover with Assembly and Manufacturing

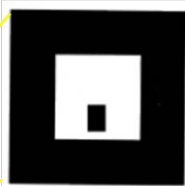
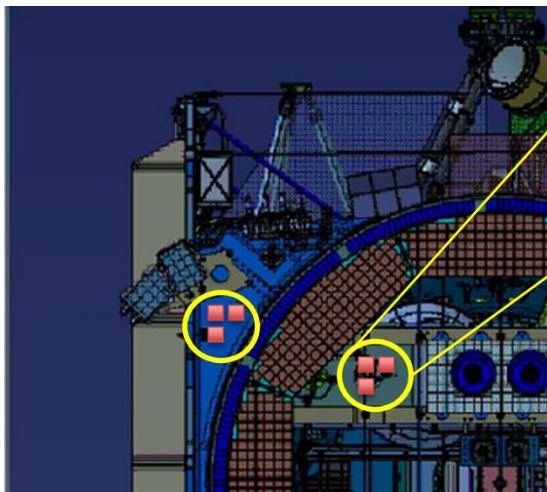




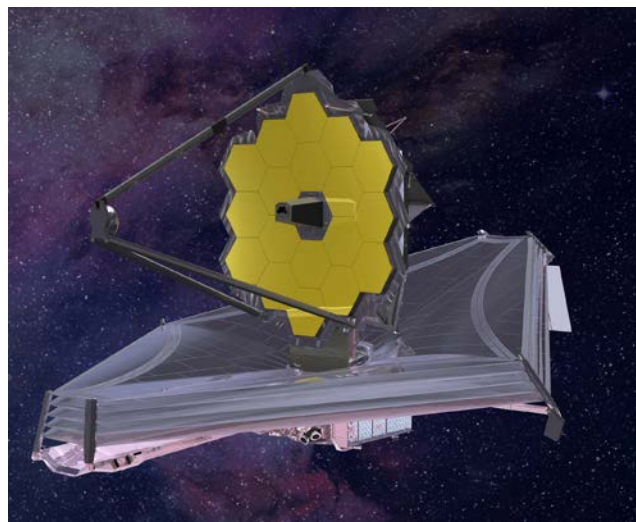
James Webb Space Telescope RPO Decals



- SSPD collaborated with JWST to develop a plan for installing rendezvous decals on the JWST spacecraft bus
- The plan included requirements for installation, placement, spacing of the decals as well as detailed photographic documentation of the closeout

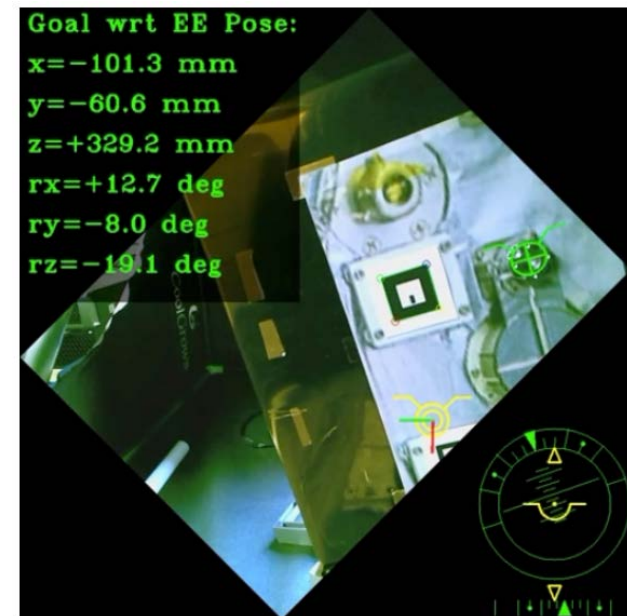
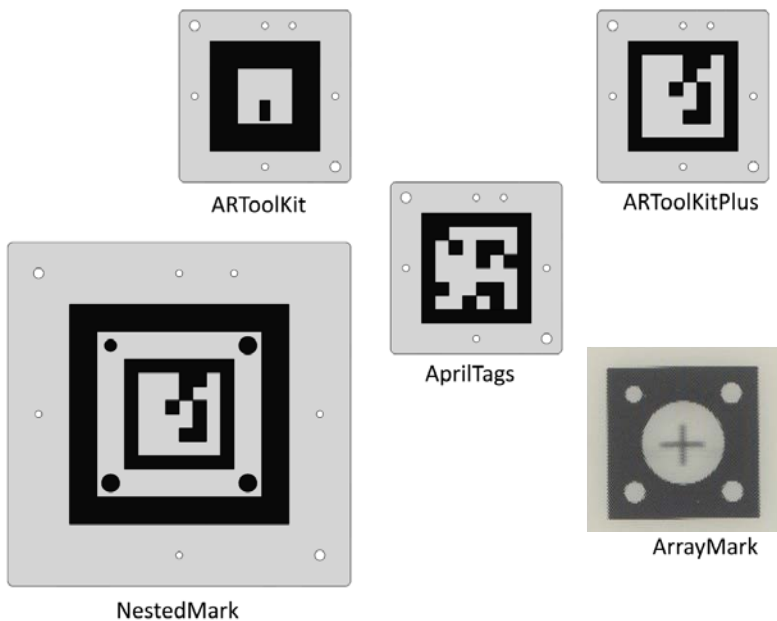


- Different sets of decals for aid in RPO and Grapple
- Decal installation and as-built photography to be completed in 2020
- Delays in the JWST schedule have presented opportunities for additional efforts that are currently being evaluated



Cooperative Target Evaluations

- Work ongoing on the ground and on-orbit (RRM3) to evaluate different target designs and derive quantitative data on how effective they are
- Data taken on RRM3 is still being analyzed

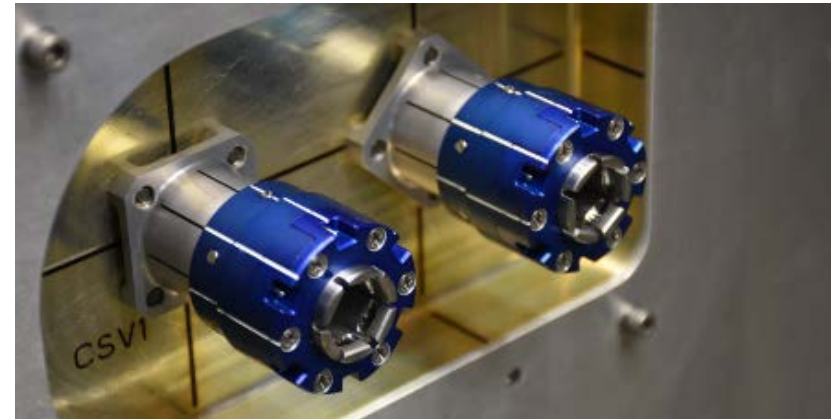




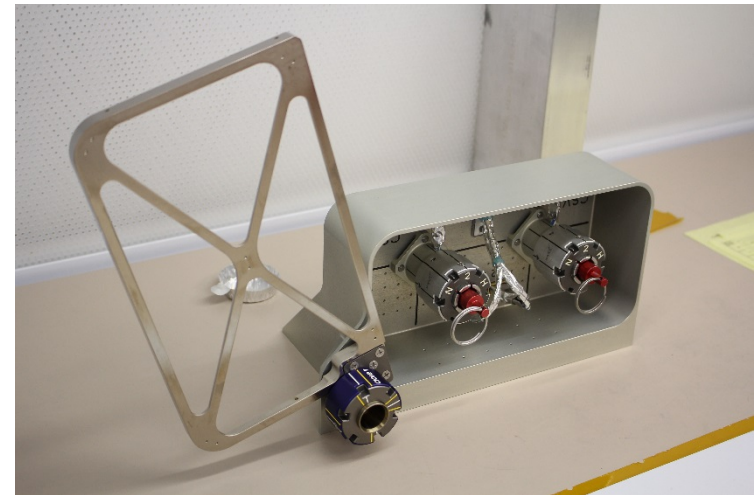
Cooperative Service Valve – Overview



- Documentation:
 - Performance specification
 - Interface Control Drawings
- Flight Acceptance testing of the CSV is complete
- Final qualification tests planned for this Fall
- CSVs/CASA will be installed on the Restore-L Spacecraft in 2020

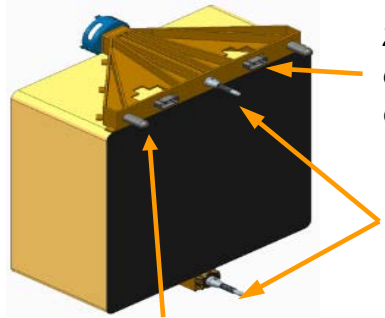


CSV EDUs in test configuration



*Flight CSVs and CASA
MLI not shown*

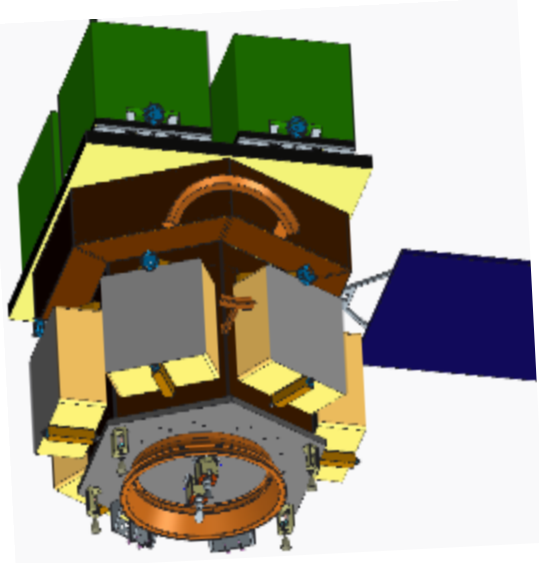
Replacement (Bus Module)



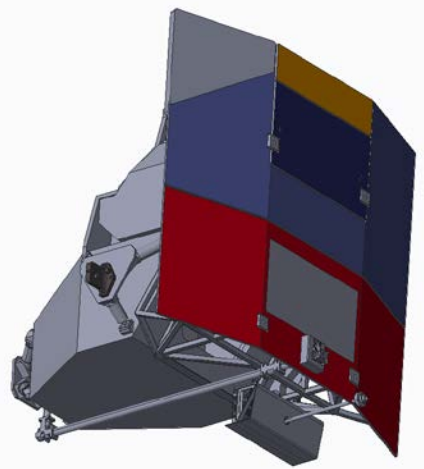
2X blind mate electrical connectors

2x threaded bolt s/c bus attachment points

kinematic interface



The ROSE study conceived of a modular bus design with On-orbit Replaceable Units (ORUs)



WFIRST:

Co-designing, leveraging on lessons learned from HST, to create replaceable instruments on WFIRST

Reconfigurable Operational spacecraft for Science and Exploration (ROSE):

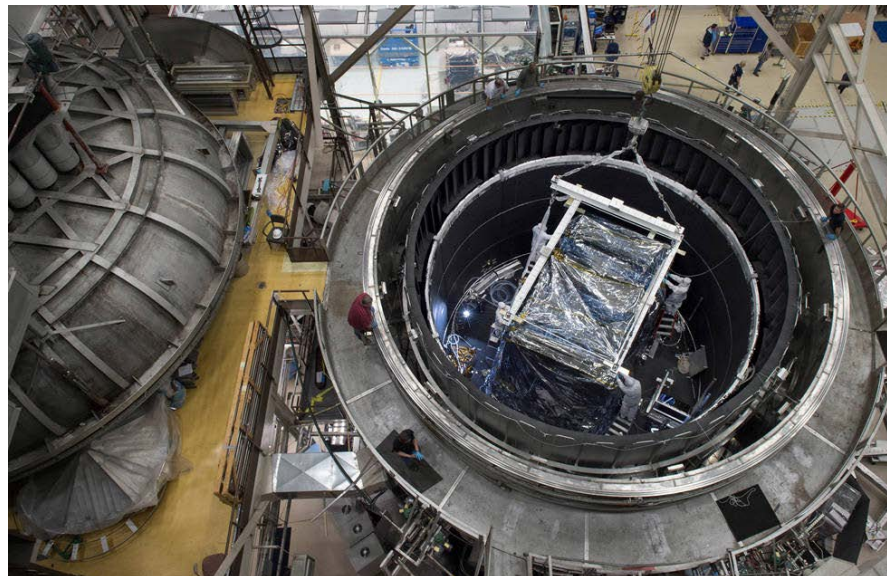
Study to develop a notional design for a spacecraft that could be assembled on-orbit



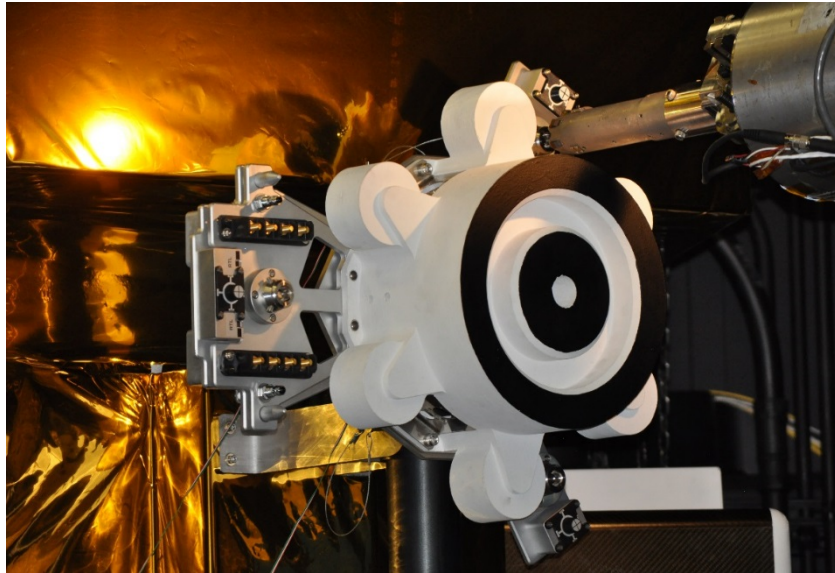
I&T Facilitation Through Modularity



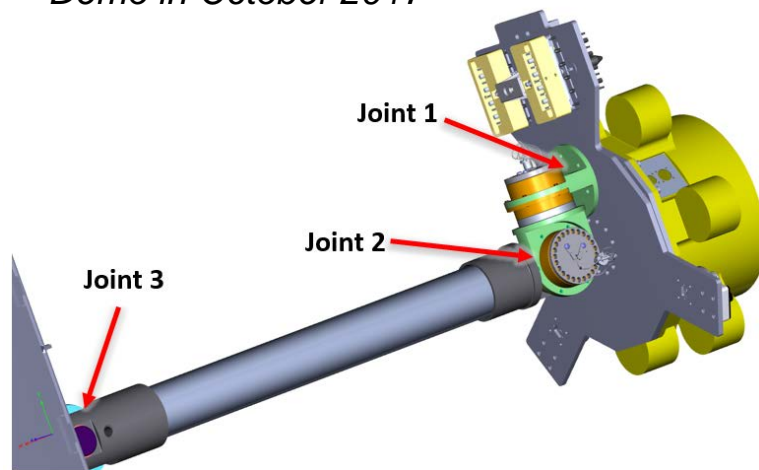
- Modular spacecraft bus modules and modular instruments facilitate I&T
- Expedited removal of modules that failed during TVAC reduces I&T time
- How to quantify the net effect on project lifecycle cost?



Replacement (Bus Module) *Solar Electric Propulsion Thruster*



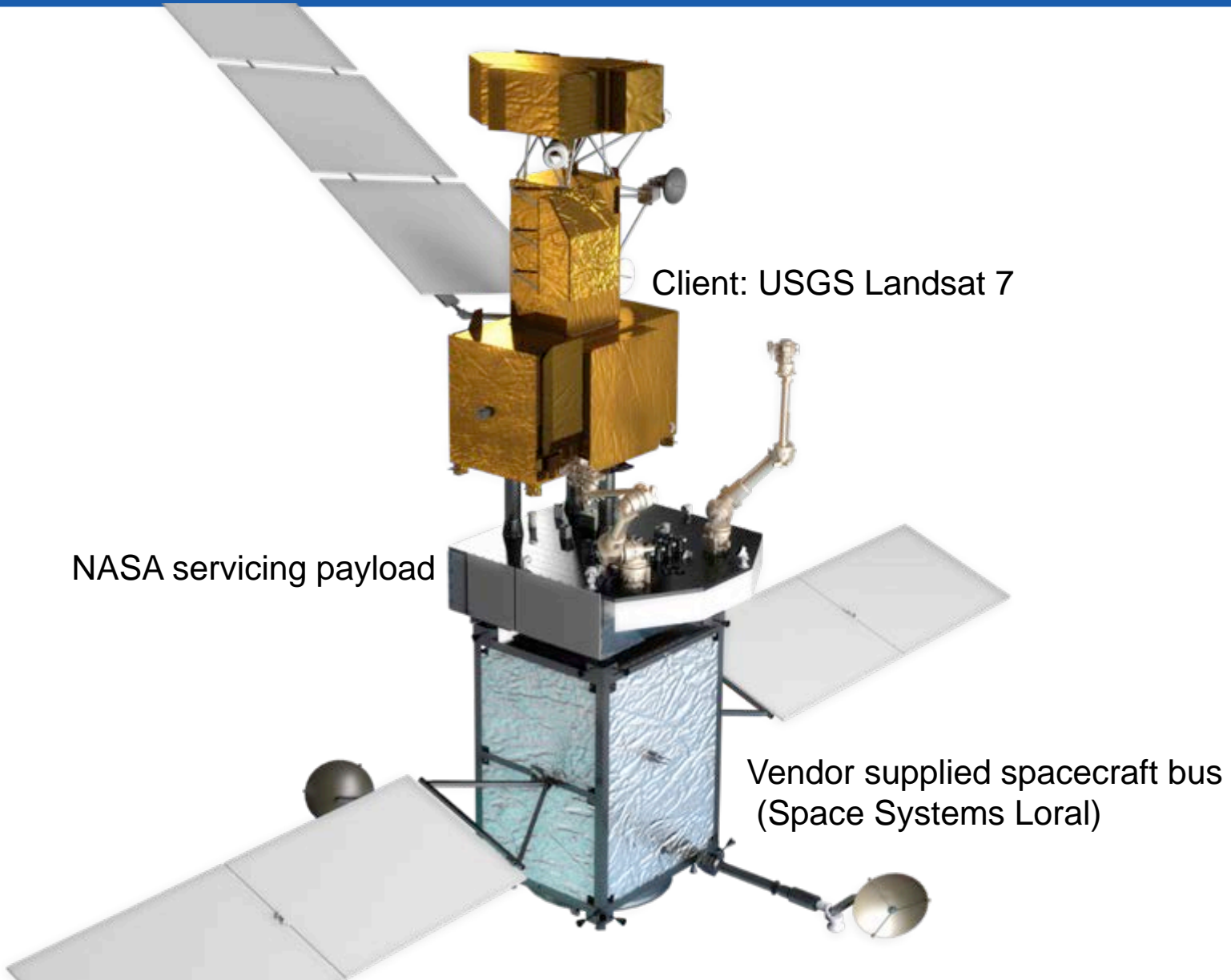
Demo in October 2017



- SSPD collaborated with a team at the Glenn Research Center to demonstrate changeout of a modular xenon thruster
- Objective of the demonstration was to show feasibility as well as begin to characterize the forces and torques resulting from the operation
- This data can be used to influence the design of the mechanisms in future designs
- More data published in AIAA Space 2018 paper *"In-Space Robotic Replacement of Solar Electric Propulsion Thrusters"*



Legacy Refueling Overview: Restore-L



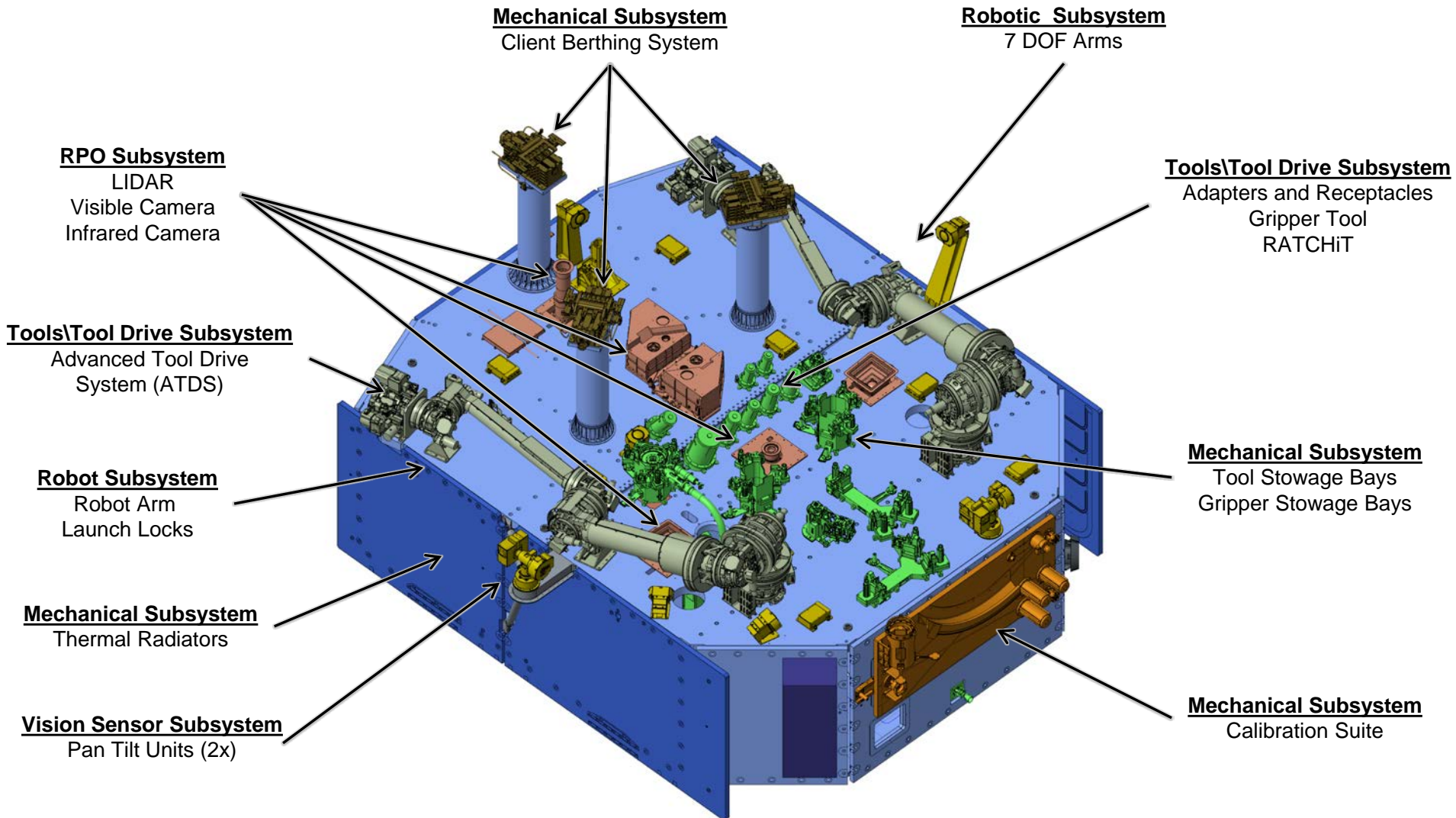
Client: USGS Landsat 7

NASA servicing payload

Vendor supplied spacecraft bus
(Space Systems Loral)

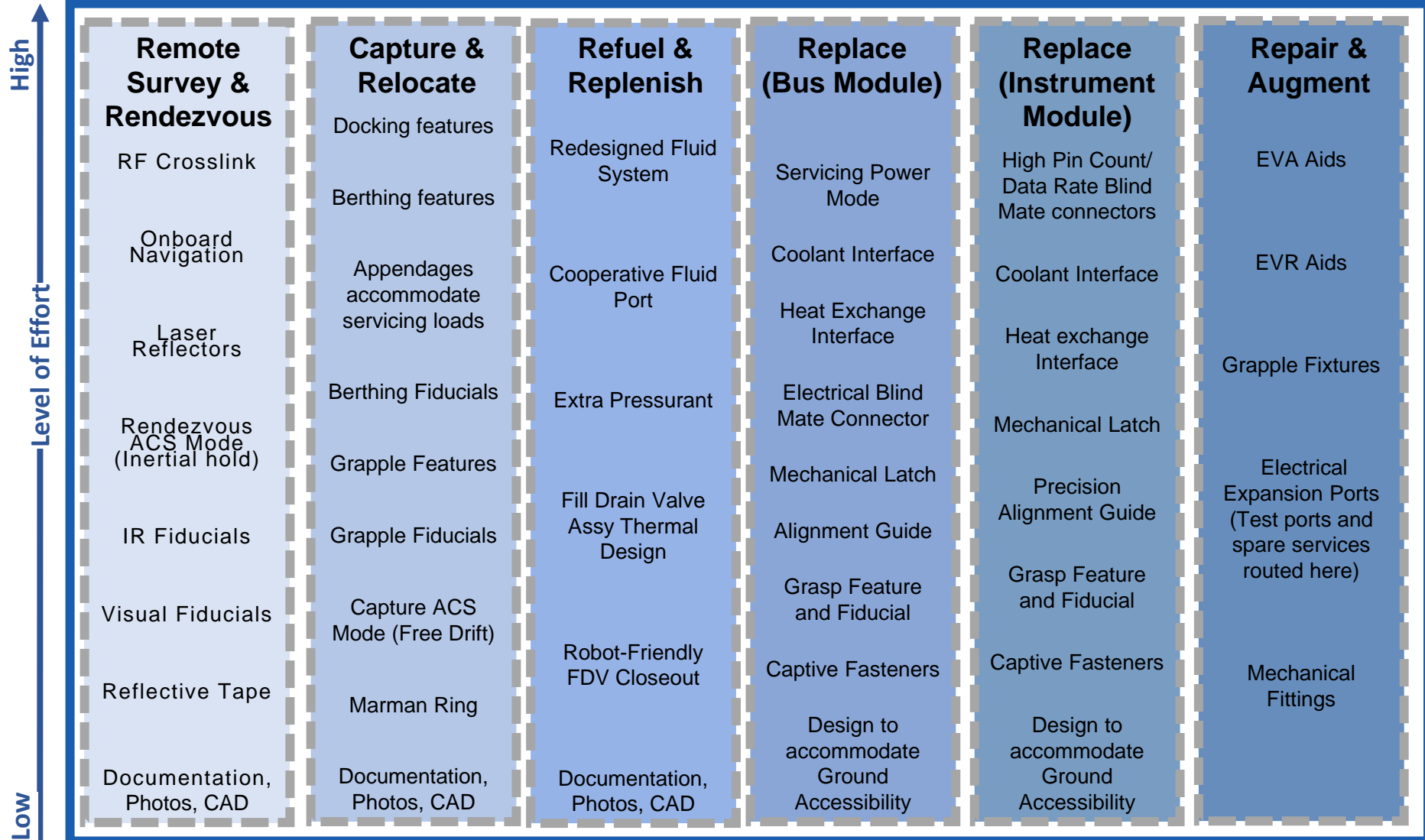


Restore-L Payload Overview





Serviceability Is a Spectrum





Servicing Spectrum Landsat 7



Increasing Complexity

	Remote Survey & Rendezvous	Capture & Relocate	Refuel & Replenish	Replace (Bus Module)	Replace (Instrument Module)	Repair & Augment
	RF Crosslink	Docking features	Redesigned Fluid System	Servicing Power Mode	High Pin Count/Data Rate Blind Mate connectors	EVA Aids
	Onboard Navigation	Berthing features	Cooperative Fluid Port	Coolant Interface	Coolant Interface	EVR Aids
	Laser Reflectors	Appendages accommodate servicing loads	Extra Pressurant	Heat Exchange Interface	Heat exchange Interface	Grapple Fixtures
	Rendezvous ACS Mode (Inertial hold)	Berthing Fiducials	Fill Drain Valve Assy Thermal Design	Electrical Blind Mate Connector	Mechanical Latch	Electrical Expansion Ports (Test ports and spare services routed here)
	IR Fiducials	Grapple Features	Robot-Friendly FDV Closeout	Mechanical Latch	Precision Alignment Guide	
	Visual Fiducials	Grapple Fiducials		Alignment Guide	Grasp Feature and Fiducial	
	Documentation, Photos, CAD	Capture ACS Mode (Free Drift)		Grasp Feature and Fiducial	Captive Fasteners	Mechanical Fittings
		Marman Ring		Captive Fasteners		
		Documentation, Photos, CAD	Documentation, Photos, CAD	Design to accommodate Ground Accessibility	Design to accommodate Ground Accessibility	



Servicing Spectrum

Hubble



↑ Increasing Complexity

Remote Survey & Rendezvous	Capture & Relocate	Refuel & Replenish	Replace (Bus Module)	Replace (Instrument Module)	Repair & Augment
RF Crosslink	Docking features	Redesigned Fluid System	Servicing Power Mode	High Pin Count/Data Rate Blind Mate connectors	EVA Aids
Onboard Navigation	Berthing features	Cooperative Fluid Port	Coolant Interface	Coolant Interface	EVR Aids
Laser Reflectors	Appendages accommodate servicing loads	Extra Pressurant	Heat Exchange Interface	Heat exchange Interface	Grapple Fixtures
Rendezvous ACS Mode (Inertial hold)	Berthing Fiducials	Fill Drain Valve Assy Thermal Design	Electrical Blind Mate Connector	Mechanical Latch	Electrical Expansion Ports (Test ports and spare services routed here)
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Visual Fiducials	Grapple Fiducials	Documentation, Photos, CAD	Alignment Guide	Grasp Feature and Fiducial	
Documentation, Photos, CAD	Capture ACS Mode (Free Drift)		Grasp Feature and Fiducial	Captive Fasteners	Mechanical Fittings
	Marman Ring		Captive Fasteners	Design to accommodate Ground Accessibility	
	Documentation, Photos, CAD		Design to accommodate Ground Accessibility		



Servicing Spectrum ISS



↑ Increasing Complexity

Remote Survey & Rendezvous

RF Crosslink

Onboard Navigation

Laser Reflectors

Rendezvous ACS Mode (Inertial hold)

IR Fiducials

Visual Fiducials

Documentation, Photos, CAD

Capture & Relocate

Docking features

Berthing features

Appendages accommodate servicing loads

Berthing Fiducials

Grapple Features

Grapple Fiducials

Capture ACS Mode (Free Drift)

Marman Ring

Documentation, Photos, CAD

Refuel & Replenish

Redesigned Fluid System

Cooperative Fluid Port

Extra Pressurant

Fill Drain Valve Assy Thermal Design

Robot-Friendly FDV Closeout

Documentation, Photos, CAD

Replace (Bus Module)

Servicing Power Mode

Coolant Interface

Heat Exchange Interface

Electrical Blind Mate Connector

Mechanical Latch

Alignment Guide

Grasp Feature and Fiducial

Captive Fasteners

Design to accommodate Ground Accessibility

Replace (Instrument Module)

High Pin Count/Data Rate Blind Mate connectors

Coolant Interface

Heat exchange Interface

Mechanical Latch

Precision Alignment Guide

Grasp Feature and Fiducial

Captive Fasteners

Design to accommodate Ground Accessibility

Repair & Augment

EVA Aids

EVR Aids

Grapple Fixtures

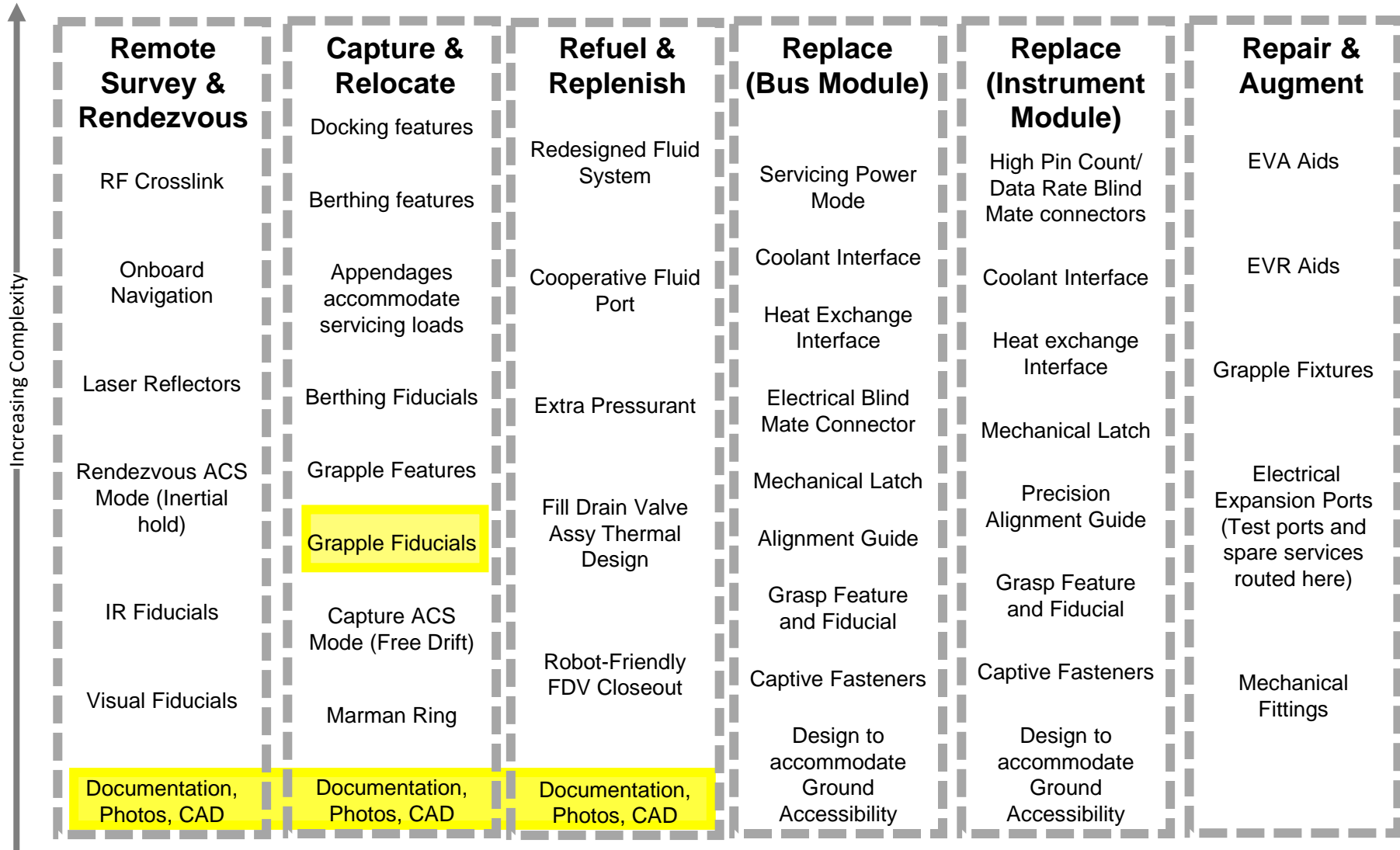
Electrical Expansion Ports (Test ports and spare services routed here)

Mechanical Fittings



Servicing Spectrum

JWST





Near Term Priorities for Serviceability

Grapple Features and Fiducials



Orbital Express Probe Fixture Assembly (MDA)



Retrieved from <http://arc.aiaa.org/doi/pdf/10.2514/6.2013-5484>

Availability: Commercially Available

Cost: Low

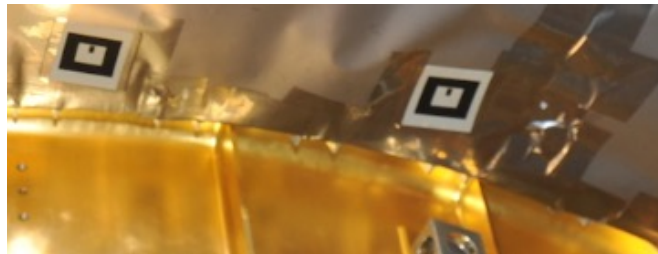
Mass: < 1kg

Benefit: Improves capture machine vision accuracy, simplifying servicer GNC and robotics

Other commercial sources:

- Altius Space Machines
- Oceaneering
- Honeybee Robotics

Visual Fiducials on NASA MMS Spacecraft (SSPD)



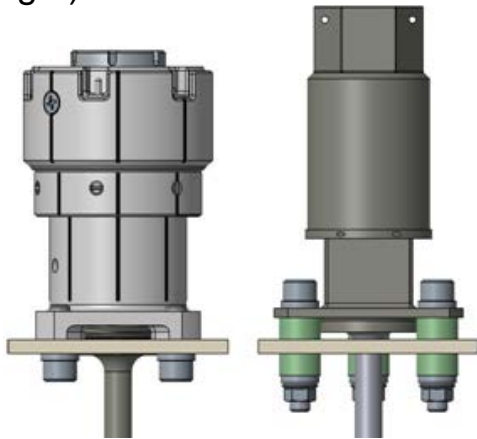
Remote Survey & Rendezvous	Capture & Relocate	Refuel & Replenish	Replace (Bus Module)	Replace (Instrument Module)	Repair & Augment
RF Crosslink	Docking features	Redesigned Fluid System	Servicing Power Mode	High Pin Count/ Data Rate Blind Mate connectors	EVA Aids
Onboard Navigation	Berthing features	Cooperative Fluid Port	Coolant Interface	Coolant Interface	EVR Aids
Laser Reflectors	Appendages accommodate servicing loads	Extra Pressurant	Heat Exchange Interface	Heat exchange Interface	Grapple Fixtures
Rendezvous ACS Mode (Inertial hold)	Berthing Fiducials	Fill Drain Valve Assy Thermal Design	Electrical Blind Mate Connector	Mechanical Latch	Electrical Expansion Ports (Test ports and spare services routed here)
IR Fiducials	Grapple Features	Robot-Friendly FDV Closeout	Mechanical Latch	Precision Alignment Guide	Mechanical Fittings
Visual Fiducials	Grapple Fiducials		Alignment Guide	Grasp Feature and Fiducial	
Documentation, Photos, CAD	Capture ACS Mode (Free Drift)		Grasp Feature and Fiducial	Grasp Feature and Fiducial	
	Marman Ring		Captive Fasteners	Captive Fasteners	
			Design to accommodate Ground Accessibility	Design to accommodate Ground Accessibility	



Near Term Priorities for Serviceability

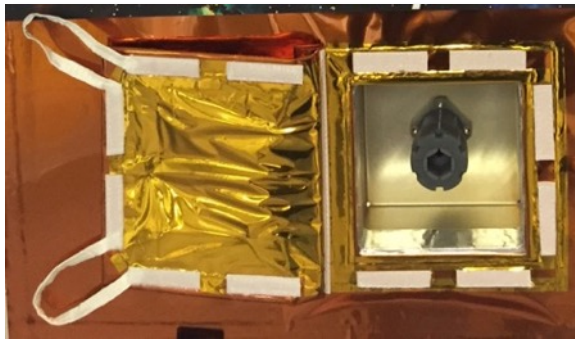
Cooperative Refueling

NASA GSFC Cooperative Servicing Valve (CSV) (left) compared to a typical Fill/Drain Valve closed out for flight (right)



Availability: License via NASA Tech Transfer
Cost: Comparable with standard FDV
Mass: < 0.5 kg
Benefit: Provides improved reliability on orbit, reduces servicer tool count and complexity, reduces refueling timeline

Restore-L CSV Closeout Concept
 – No tape!



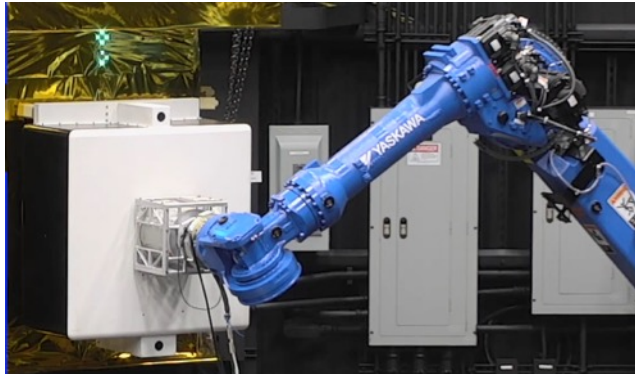
Remove Survey & Rendezvous	Capture & Relocate	Refuel & Replenish	Replace (Bus Module)	Replace (Instrument Module)	Repair & Augment
RF Crosslink	Docking features Berthing features	Redesigned Fluid System	Servicing Power Mode	High Pin Count/ Data Rate Blind Mate connectors	EVA Aids
Onboard Navigation	Appendages accommodate servicing loads	Cooperative Fluid Port	Coolant Interface	Coolant Interface	EVR Aids
Laser Reflectors	Berthing Fiducials	Extra Pressurant	Heat Exchange Interface	Heat exchange Interface	Grapple Fixtures
Rendezvous ACS Mode (Inertial hold)	Grapple Features Grapple Fiducials	Fill Drain Valve Assy Thermal Design	Electrical Blind Mate Connector	Mechanical Latch	Electrical Expansion Ports (Test ports and spare services routed here)
IR Fiducials	Capture ACS Mode (Free Drift)	Robot-Friendly FDV Closeout	Mechanical Latch	Precision Alignment Guide	
Visual Fiducials	Marman Ring		Alignment Guide	Grasp Feature and Fiducial	
Documentation, Photos, CAD	Documentation, Photos, CAD	Documentation, Photos, CAD	Grasp Feature and Fiducial	Grasp Feature and Fiducial	Mechanical Fittings
			Captive Fasteners	Captive Fasteners	
			Design to accommodate Ground Accessibility	Design to accommodate Ground Accessibility	



Near Term Priorities for Serviceability Module Replacement

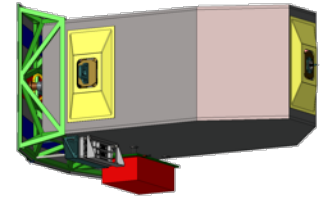


ROSE demonstration, *Bus Module*
(NASA GSFC)



Availability: License via TT
Cost: Much less than full vehicle replacement
 (if servicer is available)
Mass: Varies, can be low
Benefit: Allows replacement or upgrade of
 failed or degraded components

HST and WFIRST
Instruments



HST, Orbital Express, and ISS Orbital
Replacement Units (ORUs)

“Robotic Transfer and Interfaces for External
ISS Payloads”

P. Callen, 3rd Annual ISS Research and Development Conference,
June, 2014



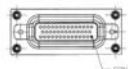
H-Fixture



Micro-fixture



Micro-Conical Fitting (MCF)



User Umbilical Connector



Modified Truncated Cone (MTC) Target

Remote Survey & Rendezvous	Capture & Release	Refuel & Replenish	Replace (Bus Module)	Replace (Instrument Module)	Repair & Augment
RF Crosslink	Docking features	Redesigned Fluid System	Servicing Power Mode	High Pin Count/ Data Rate Blind Mate connectors	EVA Aids
Onboard Navigation	Berthing features	Cooperative Fluid Port	Coolant Interface	Coolant Interface	EVR Aids
Laser Reflectors	Appendages accommodate servicing loads	External Reservoir	Heat Exchange Interface	Heat exchange Interface	Grapple Fixtures
Rendezvous ACS Mode (Inertial hold)	Berthing Fiducials	Fill Drain Valve Assy Thermal Design	Electrical Blind Mate Connector	Mechanical Latch	Electrical Expansion Ports (Test ports and spare services routed here)
IR Fiducials	Grapple Features	Robot-Friendly FDV Closeout	Mechanical Latch	Precision Alignment Guide	Mechanical Fittings
Visual Fiducials	Grapple Fiducials		Alignment Guide	Grasp Feature and Fiducial	
Documentation, Photos, CAD	Custom ACS Mode (Free Drift)		Grasp Feature and Fiducial	Captive Fasteners	
	Marman Ring		Captive Fasteners	Captive Fasteners	
			Design to accommodate Ground Accessibility	Design to accommodate Ground Accessibility	



Near Term Priorities for Serviceability

On-Orbit Augmentation

Availability: Commercially Available

Cost: Comparable to standard

Mass: Comparable to standard

Benefit: Add functionality or replace failed components not planned for modular replacement, extending mission life and utility

Restore-L spare services and ground test ports routed to accessible, external, robotically compatible connector

Numerous commercial blind mate connector sources



RMM TB4 was delivered to ISS separately from RRM and robotically installed (NASA GSFC)

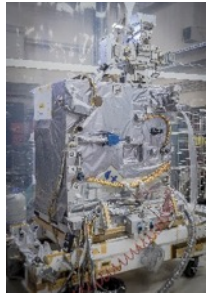
Remote Survey & Rendezvous	Capture & Relocate	Refuel & Replenish	Replace (Bus Module)	Replace (Instrument Module)	Repair & Augment
RF Crosslink	Docking Features Berthing features	Redesigned Fluid System	Servicing Power Mode	High Pin Count/ Data Rate Blind Mate connectors	EVA Aids
Onboard Navigation	Appendages accommodate servicing loads	Cooperative Blind Port	Coolant Interface	Coolant Interface	EVR Aids
Laser Reflectors	Berthing Fiducials	Extra Pressure	Heat Exchange Interface	Heat exchange Interface	Grapple Fixtures
Rendezvous ACS Mode (Inertial hold)	Grapple Features Grapple Fiducials	Fill Drain Valve Assy Thermal Design	Electrical Blind Mate Connectors Mechanical Latch	Mechanical Latch	Electrical Expansion Ports (Test ports and spare services routed here)
IR Fiducials	Capture ACS Mode (Free Drift)	Robot-Friendly FDV Closeout	Alignment Guide	Alignment Guide	
Visual Fiducials	Marman Ring		Grasp Feature and Fiducial	Grasp Feature and Fiducial	
Documentation, Photos, CAD	Documentation, Photos, CAD	Documentation, Photos, CAD	Captive Fasteners	Captive Fasteners	Mechanical Fittings
			Design to accommodate Ground Accessibility	Design to accommodate Ground Accessibility	



NASA Activities



Technology



Robotic Refueling Mission 3



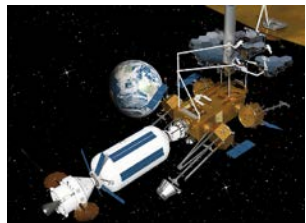
Restore-L



In-Space Manufacturing and Assembly Tipping Point



Science



Large Telescope Assembly (iSAT, FASST)



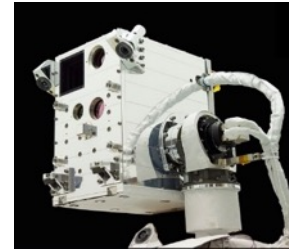
Astrophysics Decadal Studies



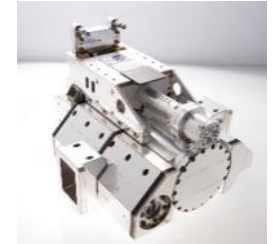
Planetary/NEO/Lunar



Human Exploration



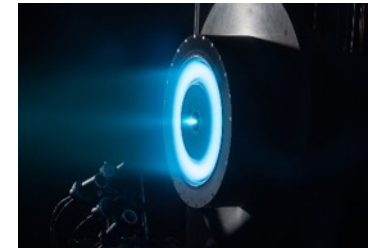
ISS - Raven



ISS - Robotic External Leak Locator / Robotic Stowage



Lunar Gateway



Power Propulsion Element



Reusable Lunar Lander



Journey to Mars





<https://ssp.gsfc.nasa.gov/>



@NASA.Satellite.Servicing



@NASA_SatServ