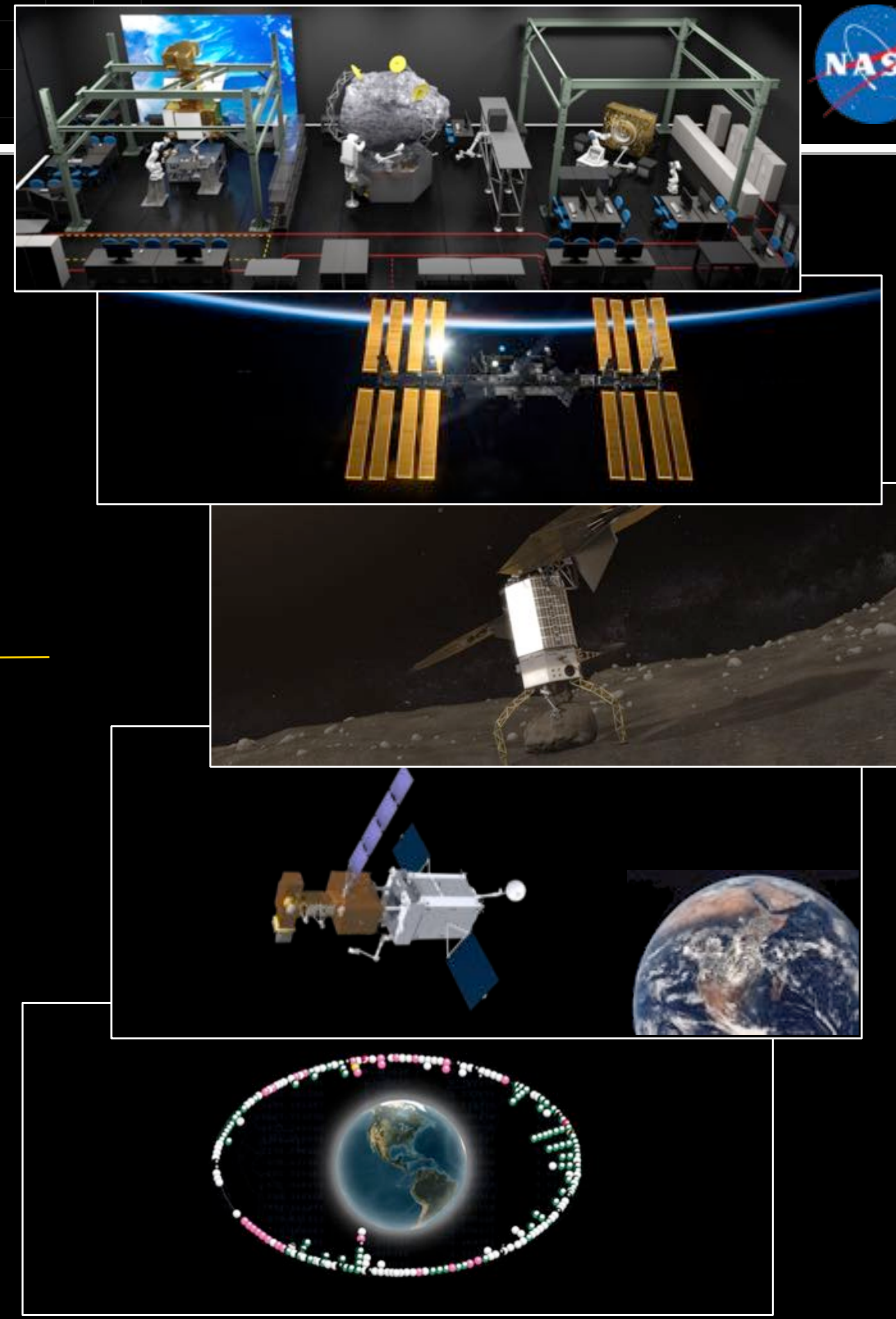
On-orbit Servicing and Refueling Concepts



June 17, 2015

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Deputy Project Manager
Satellite Servicing Capabilities Office
http://ssco.gsfc.nasa.gov

Introduction

- **Over the past five years, NASA has:**
  - **Invested in satellite-servicing technologies and tested them on the ground and in orbit**
  - **Examined several different “design reference missions”**
    - Non-Shuttle-based Hubble Space Telescope
    - Propellant depot
    - 30-m telescope assembly
    - GOES-12 refueling (GEO)
    - Landsat 7 refueling (LEO)

Growing momentum towards robotic satellite servicing capability.

In Space Robotic Servicing

- The Satellite Servicing Capabilities Office is responsible for the overall management, coordination, and implementation of satellite servicing technologies and capabilities for NASA. To meet these objectives it:
  - Conducts studies
  - Conducts demonstration experiments in orbit and on the ground
  - Manages technology development and satellite servicing missions
  - Advises and designs cooperative servicing elements and subsystems

In Space Robotic Servicing Team and Partners

Canadian Space Agency

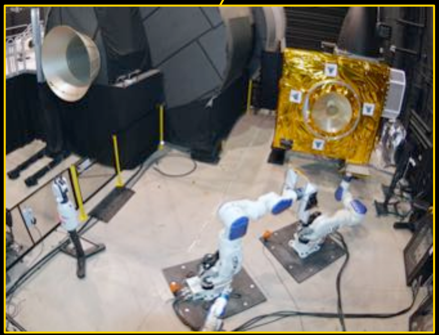
Johnson Space Center

Goddard Space Flight Center

Department of Defense Space Test Program

Glenn Research Center

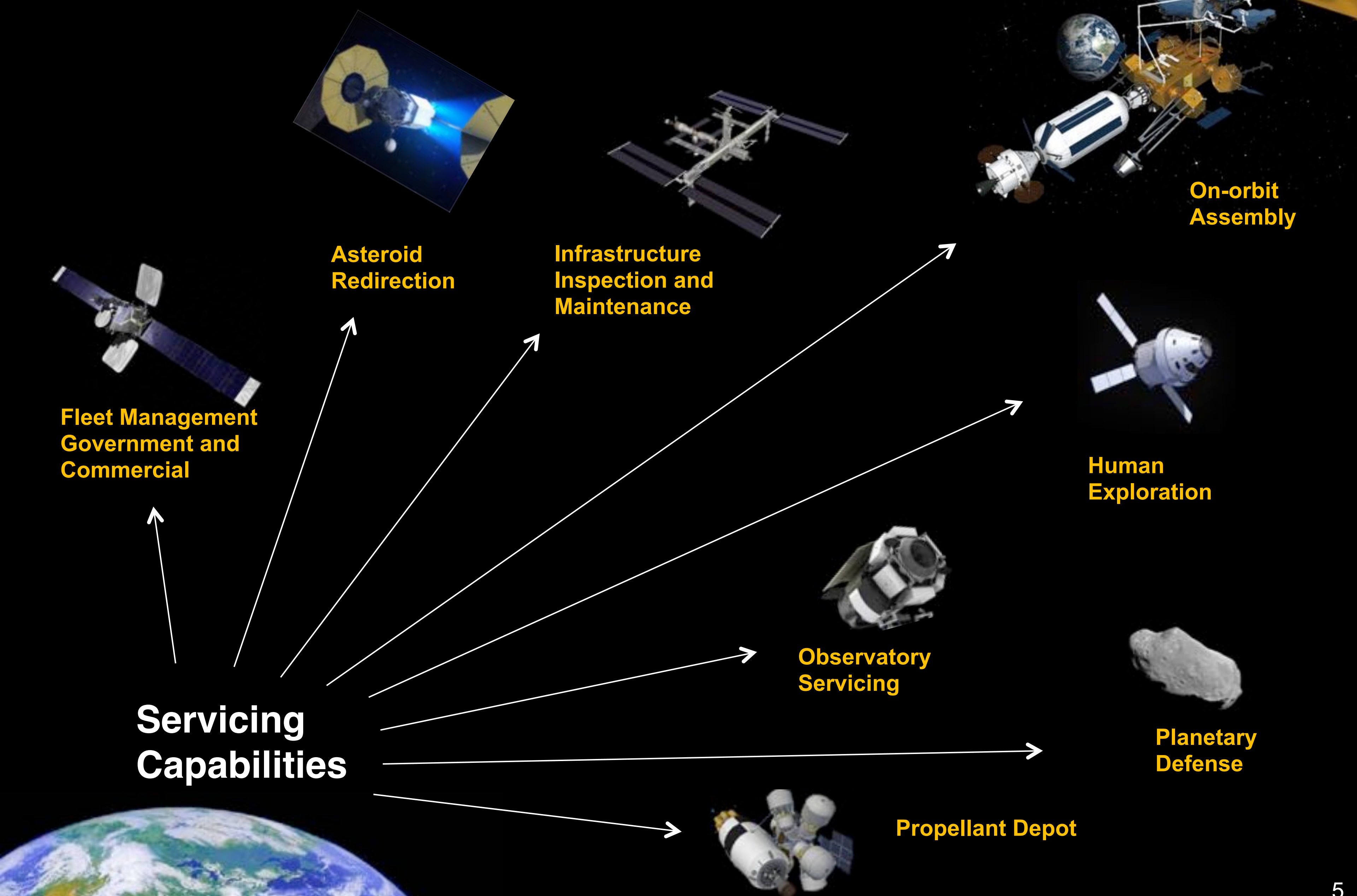
Naval Research Laboratory



WVU
RPI
JHU
UMD

Kennedy Space Center

Servicing Supports Multiple Objectives



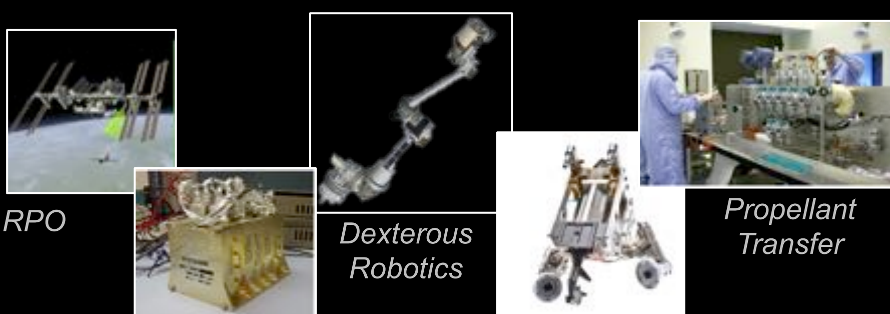
Scope of SSCO Efforts

Concept/Tech Development

Point Design Mission Studies

Restore-G *Restore-L* *ARM* *ROSE*

Technology Development Campaign



RPO
High-speed Computing
Dexterous Robotics
Advanced Tools
Propellant Transfer

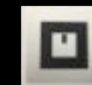
Reviews

Systems Engineering 2012

Payload Systems Requirements 2013

Community Engagement & Research

Cooperative Servicing Aids



Features that could be incorporated into <u>any</u> phase of satellite production to facilitate servicing.

Request for Information
2013
2011
2009

International Workshops 2010 & 2012

Request for Quote
2014
2014

Ongoing engagement with:

- Legal community
- Investment bankers
- Commercial bus manufacturers
- Fleet owners/operators

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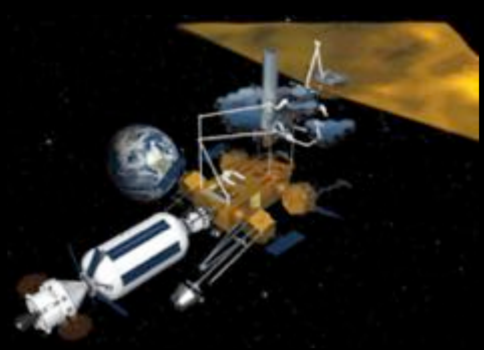
Servicing Capabilities
Benefits to Fleets

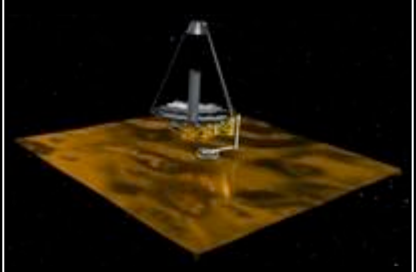
Fleet Management

On-orbit imagery and repair capabilities to support anomaly resolution ↓ Corrective action, mission continuance	Life extension of existing assets ↓ More value from initial investment, gap mitigation	Greenfield testing using extended assets ↓ Low-cost technique to evaluate unexplored market	Flexibility to launch half-empty with on-orbit cooperative fueling ↓ Cheaper access to space from smaller launch vehicles

Servicing Capabilities Enable Novel Architectures



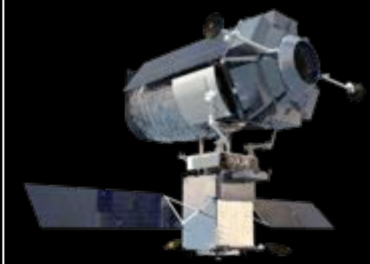
On-orbit Assembly



Construction of large-aperture observatories

↓

Discovery and characterization of exo-Earths



Modular, upgradable spacecraft

↓

Flexibility to react to new discoveries and changes in new satellite technologies

Construction of commercial space-based solar power satellites

↓

Transmit vast quantities of solar energy to ground

Servicing capabilities facilitate more complex and capable structures to unlock the secrets of the universe.

What SSCO Encompasses

Servicer Designs, Capabilities, Technologies, and Beneficiaries

Legacy Servicing

Developing robotic servicer to extend the life of existing spacecraft already in orbit.

Servicer	Capabilities	Technologies Being Matured	Notional Clients
Restore-G	Remote Survey	RPO sensors, avionics, algorithms	Landsat 7
Restore-L	Relocation	Dexterous robotics	Asteroid
ARM	Refueling	High-speed, fault tolerant computing	Terra
	Repair	Advanced robotic tools	Aqua
	Replacement (component)	Propellant Transfer System	

Cooperative Servicing

Developing modular, serviceable spacecraft to facilitate swift, upgradable science to orbit.

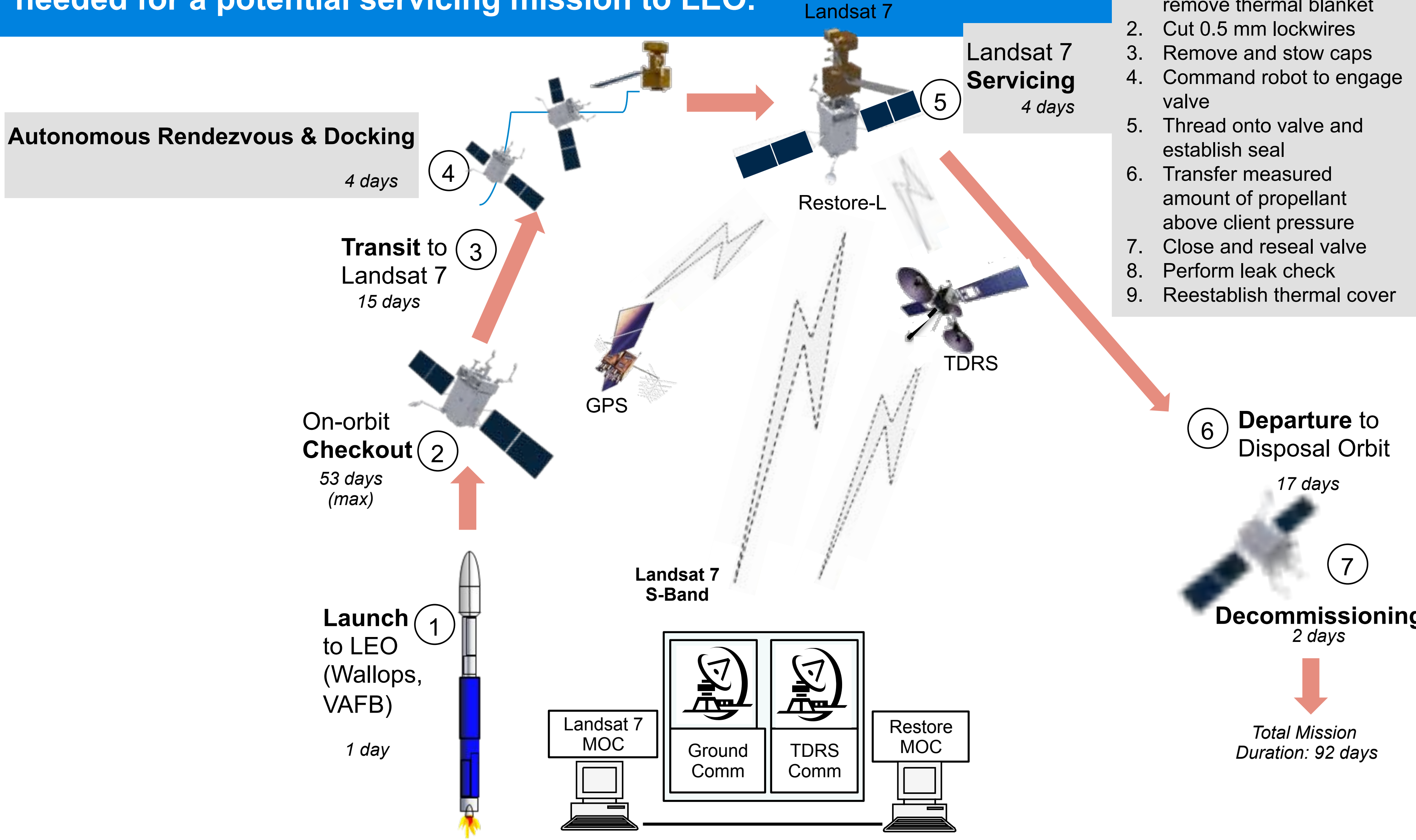
Servicer	Capabilities	Technologies Being Matured	Notional Clients
TBD	Bus subsystem replacement	*See above, plus:*	ROSE
	Instrument upgrade	Cooperative latches and fixtures	MMS, JWST, GOES-R
	Refueling	Cooperative Propellant Transfer System	ARM
		Xenon transfer	WFIRST
			ATLAST
			30-m

Overview of Notional Restore-L Mission

NASA is building and maturing the technologies needed for a potential servicing mission to LEO.

Refueling Task

1. Cut, manipulate and remove thermal blanket
2. Cut 0.5 mm lockwires
3. Remove and stow caps
4. Command robot to engage valve
5. Thread onto valve and establish seal
6. Transfer measured amount of propellant above client pressure
7. Close and reseal valve
8. Perform leak check
9. Reestablish thermal cover



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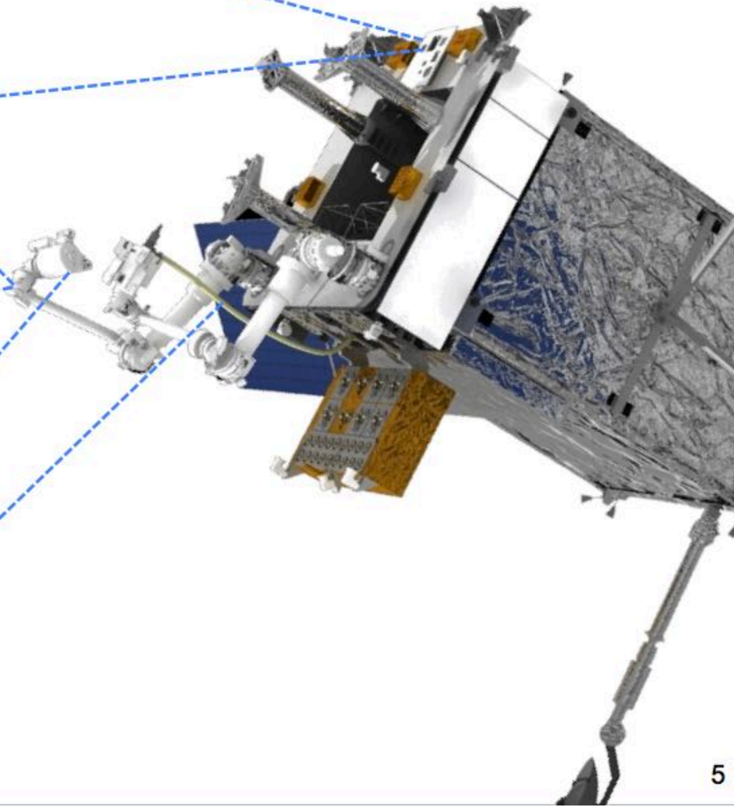
Critical Technologies Under Development

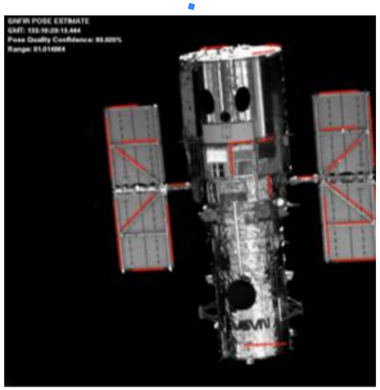
- Rendezvous & Prox Ops System
- High-speed, Fault-Tolerant Computing
- Dexterous Robotics
- Robotic Tools and Tool Drive
- Fluid Transfer



Rendezvous and Proximity Operations
Technology Maturation and Test Campaign

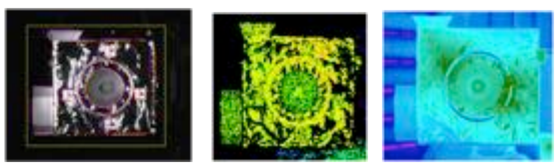
2005-2009 2010 2011 2012 2013 2014 2015 2016 2017

Real-time 6-DOF pose of HST



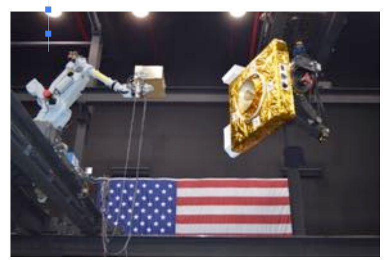
GNFIR and SpaceCube (within RNS) on STS-125: non-cooperative tracking using visible camera

Proximity Sensors & Algorithms



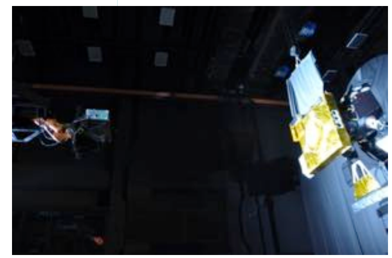
EDU (Argon) test suite demonstrated multi-wavelength (visible, flash lidar, and long-wave infrared) sensor fusion on flight avionics

Closed Loop Testing



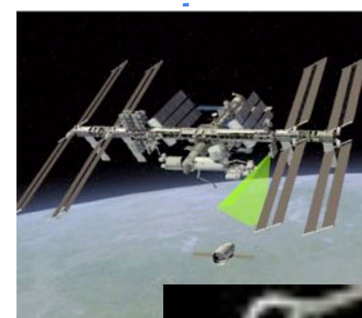
Final approach and capture box closed-loop demonstration

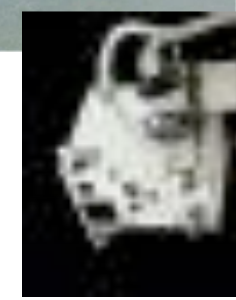
Closed Loop Testing 2



Midrange, closed-loop demonstration and high-fidelity characterization of pose algorithms and sensors

Autonomous tracking of spacecraft (Raven)





Raven demo to fly to ISS as part of DoD's STP-H5 payload

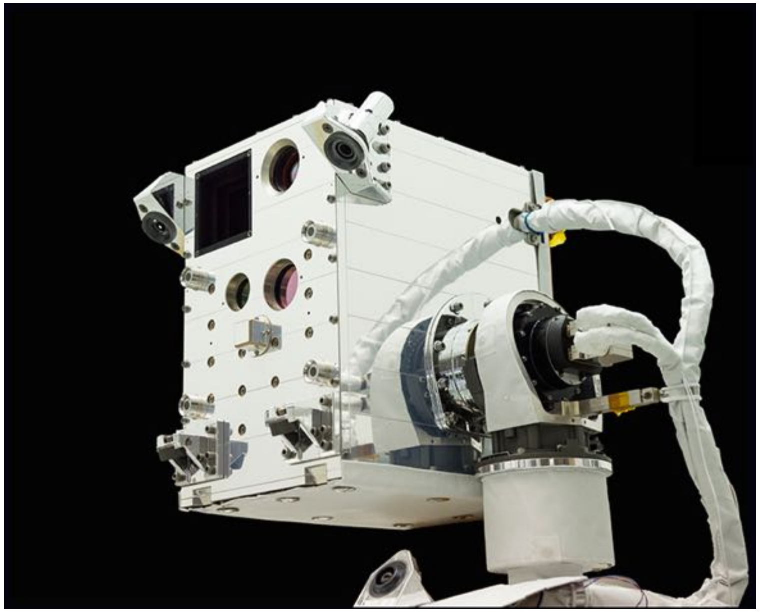
Rendezvous and Proximity Operations
Raven: Technology Demonstration on ISS

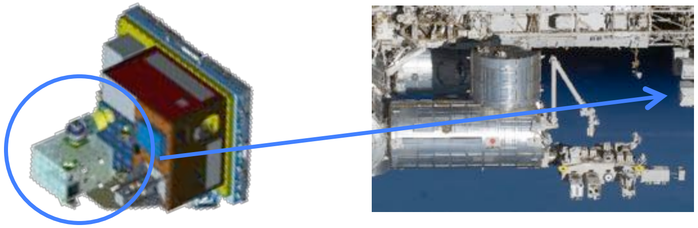
Raven is an ISS technology demonstration of system-level technologies applicable to accomplish cooperative and non-cooperative relative navigation.

Complex, but compact, hardware complement

- Two-axis gimbal provides sensor pointing
- Relative navigation sensors provide tracking in three bands – visible, long-wave IR, and short-wave lidar
- State-of-the-art pose algorithms provide relative position and attitude measurement of the visiting vehicle relative to each sensor
- High-performance avionics provide efficient, reliable, and reconfigurable computing environment
- Navigation algorithms provide an optimal estimate of the relative state – position, velocity, attitude, and rate – based on data from all the sensors

Two-year mission provides upwards of 60 relative navigation tracking events (rendezvous and departures).





High-speed, Fault Tolerant Computing

Technology Maturation and Test Campaign

2005-2009 — Real-time 6-DOF pose of HST

2010 — SpaceCube 1.0 (MISSE-7)

2011

2012 — SpaceCube 2.0 STP-H4

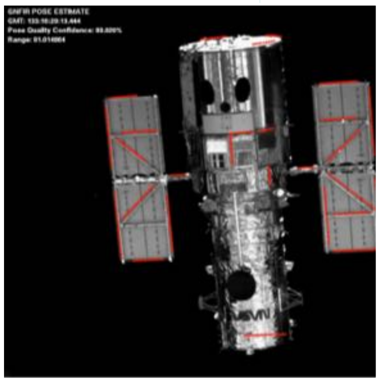
2013 — RPO, Real-time, Closed-Loop Testing

2014 — Flight processor executing robot control algorithms

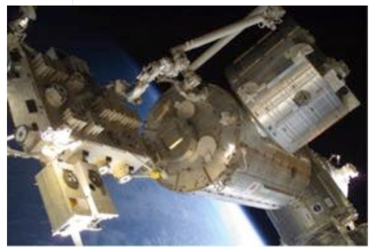
2015 — *Comprehensive Refueling Tasks*

2016 — *SpaceCube driving Eng. Arm*

2017 — *Raven*

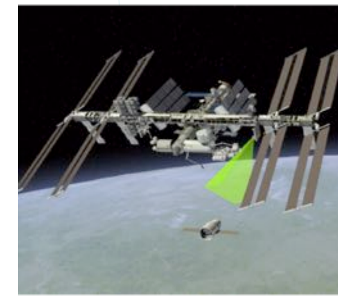


First flight of SpaceCube 1.0, demonstrated non-coop, vision-based nav



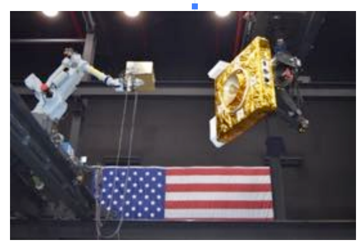
First flight of Virtex 5 FPGA as part of SpaceCube platform

SpaceCube emulator used for joint control

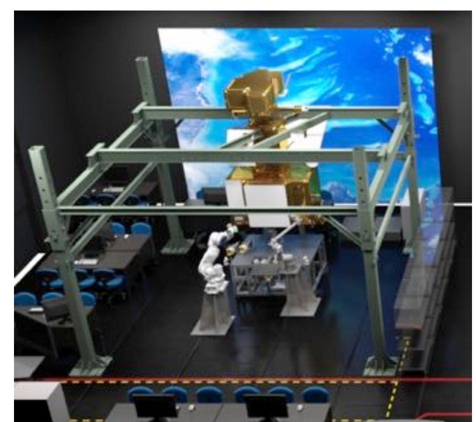


SpaceCube 2.0 EM integrated for Raven – real-time processing of natural feature vision algorithms

First operational use of SpaceCube 1.0



SpaceCube used for closed-loop RPO demos

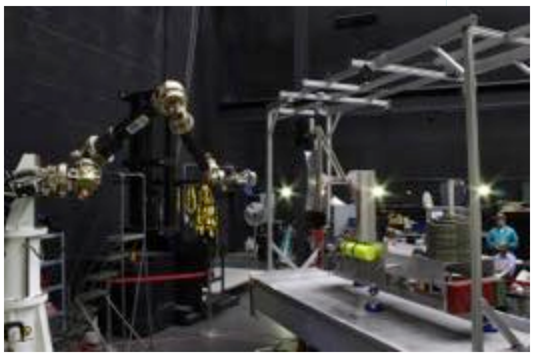


SpaceCube used for teleop control of EDU conducting servicing tasks

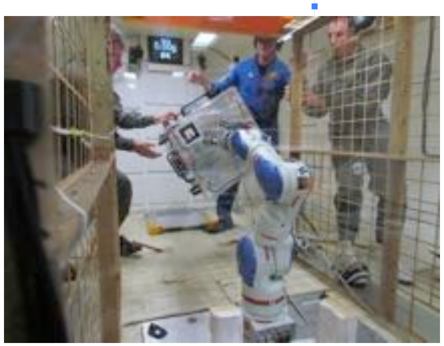
Dexterous Robotics
Technology Maturation and Test Campaign

2005-2009 | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** | **2017**

- 2011: 3-DOF Capture
- 2012:  Zero-G 6-DOF auto tracking
- 2013:  Contact Dynamics Validation
- 2013:  Refueling Procedure Validation
- 2014: Remote control w/ oxidizer
- 2015: *Receipt of 7-DoF Eng Arm*
- **Comprehensive Refueling Tasks**
- 2016: *Engineering arm w/ flight-like algorithms*
- 2017: *Receipt of 7-DoF –space qualified Arm*



3-DOF Capture tool evaluation at NRL



Autonomous Tracking in zero-G – tracking algorithms and closed loop control

Remote teleop with time delay during hazardous operations

EDU arm received

Qual arm for flight

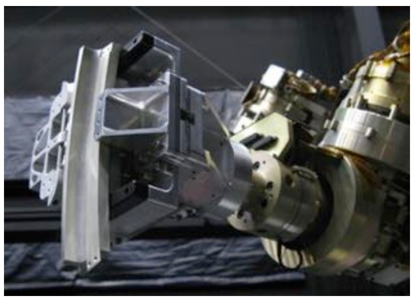
Dexterous Robotics

- **The Challenge**
  - Building on FREND and Mars robotic arm programs to meet new objectives
    - Autonomous capture of non-cooperative clients
    - Teleoperated servicing of non-prepared worksites at LEO, GEO or interplanetary
- **Robot Arm Subsystem in Development**
  - 7 DOF; 2-meter class
  - Force-torque sensor & payload accommodation: tailored for servicing tools
  - Centralized electronics; external flex harness
- **Robot Control Electronics and Software in Development**
  - Flight motor controller based on JPL-developed Joint Controller Board used for Mars Science Laboratory actuator acceptance
  - Software automatically handles control of tool tip and control of shoulder-elbow-wrist angle; and avoids singularities, and workspace and joint limits
- **Achievements**
  - Closed the loop around fused RPO and end-of-arm-camera data to execute capture
  - Have conducted joint motion with flight processor emulator
  - All candidate flight algorithms are in ground development industrial robots and poseable
  - EDU arm delivered to Goddard June 2015

Advanced Robotic Tools and Tool Drive
Technology Maturation and Test Campaign

2005-2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017

- 2010: Gripper Tool
- 2013: Four RRM tool on-orbit validatior
- 2014: Oxidizer Tool validation
- 2015: Leak Locator shipped
- 2015: Inspection tool ops
- 2016: *Next-gen refueling tools*



Early prototype Gripper Tool

Wire Cutter Tool

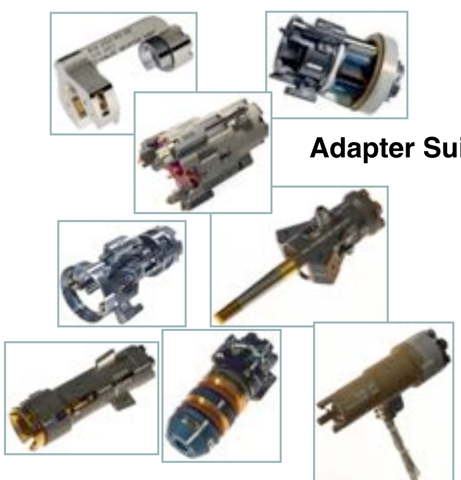
Safety Cap Tool

Multifunction Tool

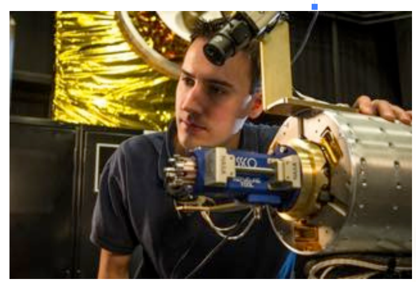
EVR Nozzle Tool

Ammonia Leak Locator, awaiting launch

MLI Gripper Tool



Adapter Suite



Oxidizer Nozzle Tool with ATDS visible (right)

VIPIR (Visual Inspection Poseable Invertebrate Robot)

Advanced Robotic Tools and Tool Drive

- **The Challenge**
  - Create low-mass, multi-drive tool drive system with analog-to-digital conversion that enables low-mass, no-motor smart tools
  - Develop fault-tolerant tool capable of grasping non-cooperative satellite, while accommodating off-angle approach
  - Produce suite of low-mass robotic tools capable of fault-tolerant operations on unprepared worksites (inspection, refueling, and repair)

- **Hardware in Development**
  - Advanced Tool Drive System (ATDS): third-generation prototype in fabrication; EDU in fabrication
  - Capture Tool: early-stage prototype; two-fault tolerant EDU
  - Refueling tools: five tools, one adapter
  - Cryo disassembly: seven adapters
  - Repair: three adapters
  - Inspection: one tool

- **Achievements**
  - Successful use of first two ATDS prototypes
  - Disassembled non-cooperative fueling hardware, attached and provided fluid to legacy spacecraft interface (on orbit)
  - Validated oxidizer transfer tool (on ground)

Fluid Transfer

Technology Maturation and Test Campaign

2005-2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017

Oxidizer seal-less pump evaluation

Ethanol refueling on orbit

Hose tests in zero-g, NBL

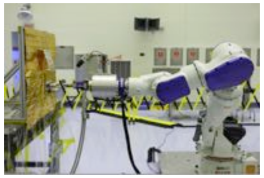
Oxidizer Transfer

Comprehensive Refueling Tasks

Propellant Transfer system

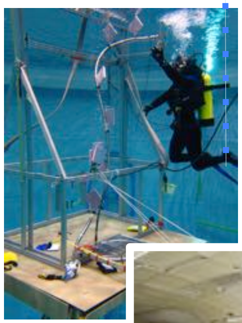
Cryo and Xenon transfer (RRM-3)

Robotic Refueling Mission demo of tools and procedures and transfer of ethanol

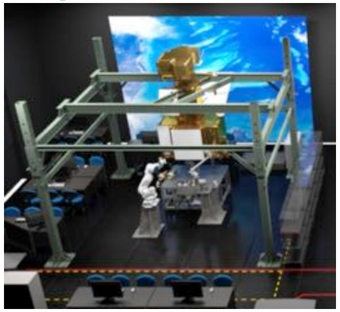


Oxidizer transfer at flight pressures, flow rates and quantities

Demo of xenon recharge & cryogen transfer



Neutral buoyancy and zero-g evaluations of flexible hose characteristics



Propellant Transfer System integrated into system-level test of refueling

Fluid Transfer

- **The Challenge**
  - Provide fluid on orbit to spacecraft not designed for servicing
  - Wide variation in properties of various commodities (cryo, corrosive, high-pressure)

- **Subsystem in Development**

Fluids to Transfer

- Chemical Propellants
  - Hydrazine
  - Monomethyl hydrazine
  - Nitrogen tetroxide
- Pressurant
  - GHe
- Cryogenic Fluids
  - Liquid Methane
- Electric Propulsion
  - Xenon

Tested Hardware

- Delivery Methods
  - Pumps
  - Bellows
  - Pressure
  - Pistons
- Flow Meters
  - Ultrasonic
  - Coriolis
  - Balanced orifice
  - Positive displacement
  - Turbine
- Valves, latches and regulators

- **Achievements**
  - Pumped ethanol on orbit (Robotic Refueling Mission)
  - Developed Propellant Transfer System and successfully transferred oxidizer on ground (Remote Robotic Oxidizer Transfer Test)
  - Delivered Xenon to cooperative interface via piston transfer
  - Transferred cryogen on the ground pump-free

Fluid Transfer
Robotic Refueling Mission Demonstrations

RRM is a multi-phased ISS investigation of tools, technologies and techniques for robotic refueling, cryogen replenishment and xenon recharge.

RRM Phase 1

- Storable propellants: steps required to refuel in legacy spacecraft
  1. Take apart components (cut wire, manipulate thermal blankets & fasteners, remove caps)
  2. Connect refueling hardware and transfer fluid
  3. Reseal fuel port
- Cryogen fluid: steps required to replenish cryogens in legacy satellites
  1. Take apart components

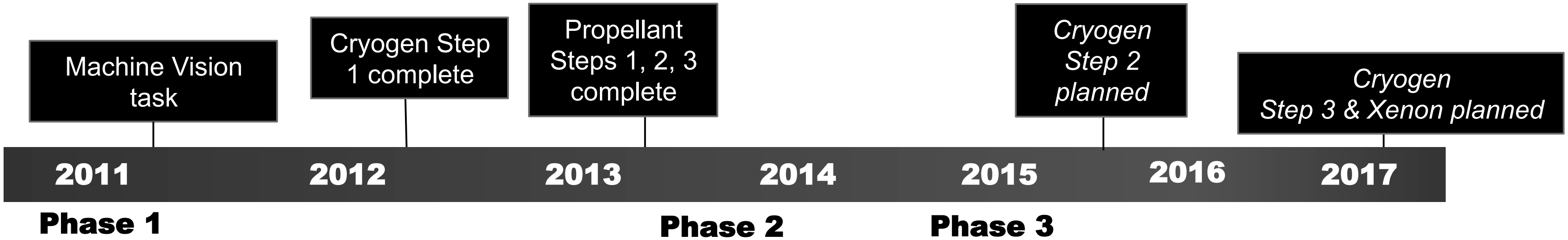
RRM Phase 2

- Cryogen fluid: intermediate steps required to replenish cryogens
  2. Connect replenishment hardware

RRM Phase 3

- Cryogen fluid: final steps required to replenish cryogens
  3. Transfer ~50 L
- Cooperative recharge of xenon

Phase 3 data to be shared with:
- *Cryo depot community*
- *ISRU*
- *Advanced ECLLS*



Cooperative Servicing Aids (CoSA) Options

CoSA: features that could be incorporated into new satellites to facilitate servicing in the future.

Rendezvous and Proximity Operations

- Features and techniques to increase the reliable and robust rendezvous sequence

Capture

- Features and markings on client tailored to the capture technique going to be employed by servicer

Refueling / Replace

- Design external and internal propellant system to be accommodating of refueling

Placing servicing aids on new spacecraft is an inexpensive way to hedge for a future servicing mission.

Cooperative Service Aids (CoSA)

Six Months to Launch (or less)

Low Level of Spacecraft Modification (examples)

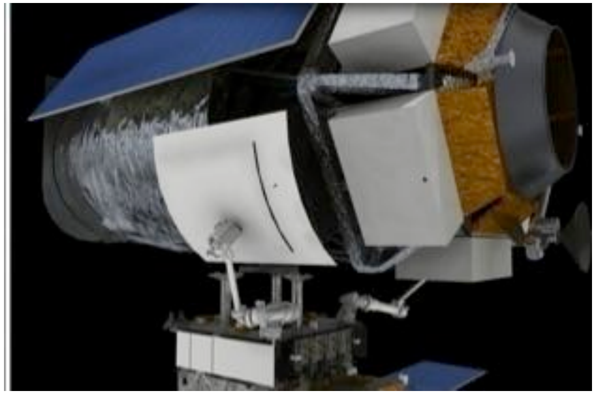
- Addition of optical / reflective targets on docking / capture axis (adhesive decals)
- Add reference markings around Marman ring (clock-face tic marks)
- Standardize loop size and color (to maximize contrast) of Fill / Drain Valve safety wires

Between PDR and CDR

Medium Level of Spacecraft Modification (examples)

- Install hemispherical retro reflectors for long-range targeting
- Establish spacecraft servicing mode in flight software
- Install robotically compatible "quick disconnect" on Fill / Drain Valve prior to launch

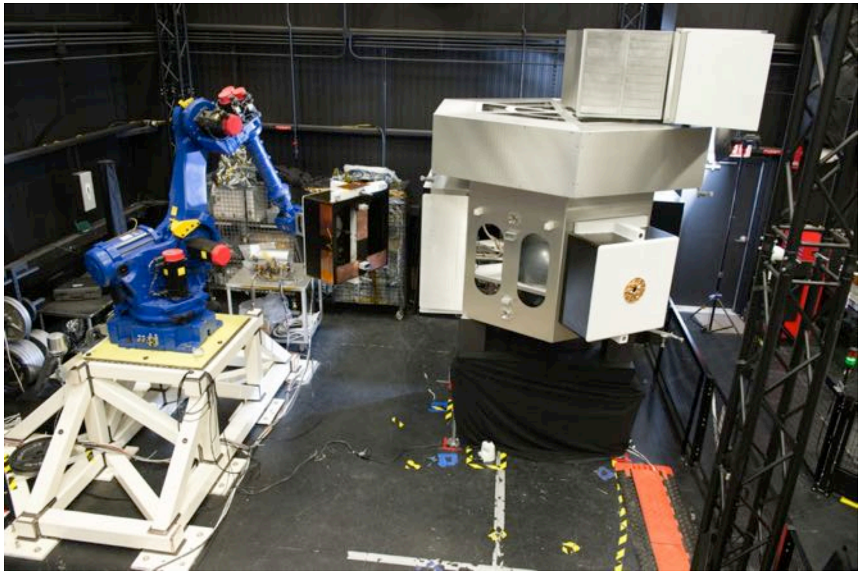
Phase A to PDR

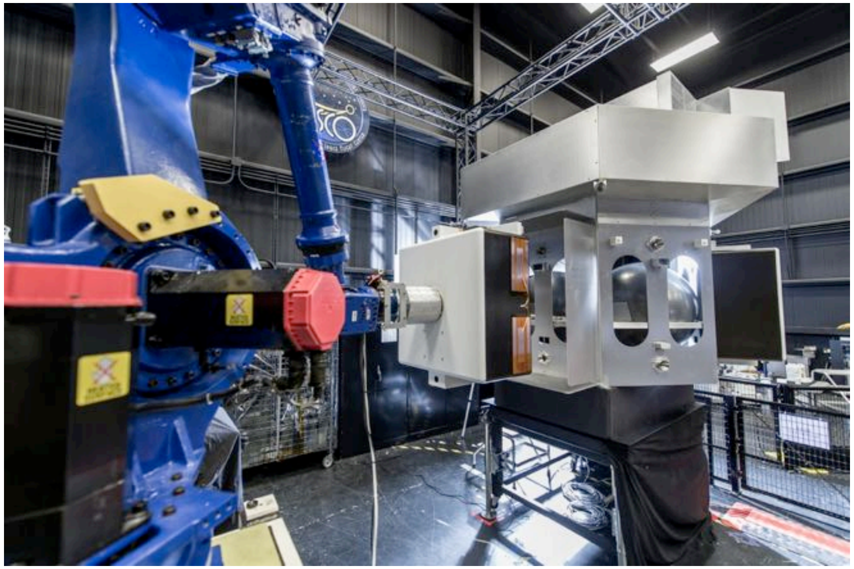


High Level of Spacecraft Modification (examples)

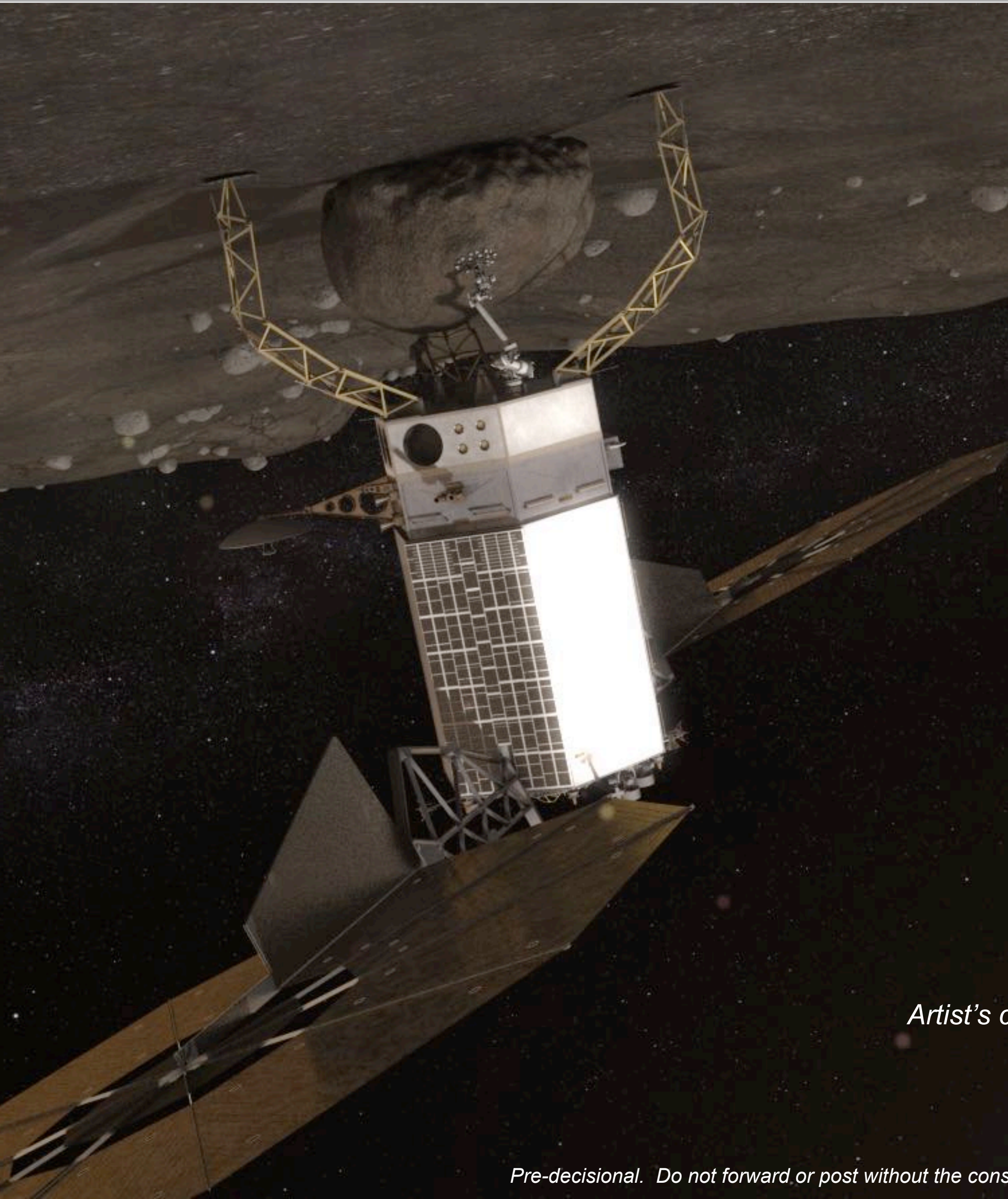
- Add omnidirectional, low power radio frequency beacons
- Redesign Fill / Drain Valve to be compatible with robotic interface
- Incorporate module design for unit replacement

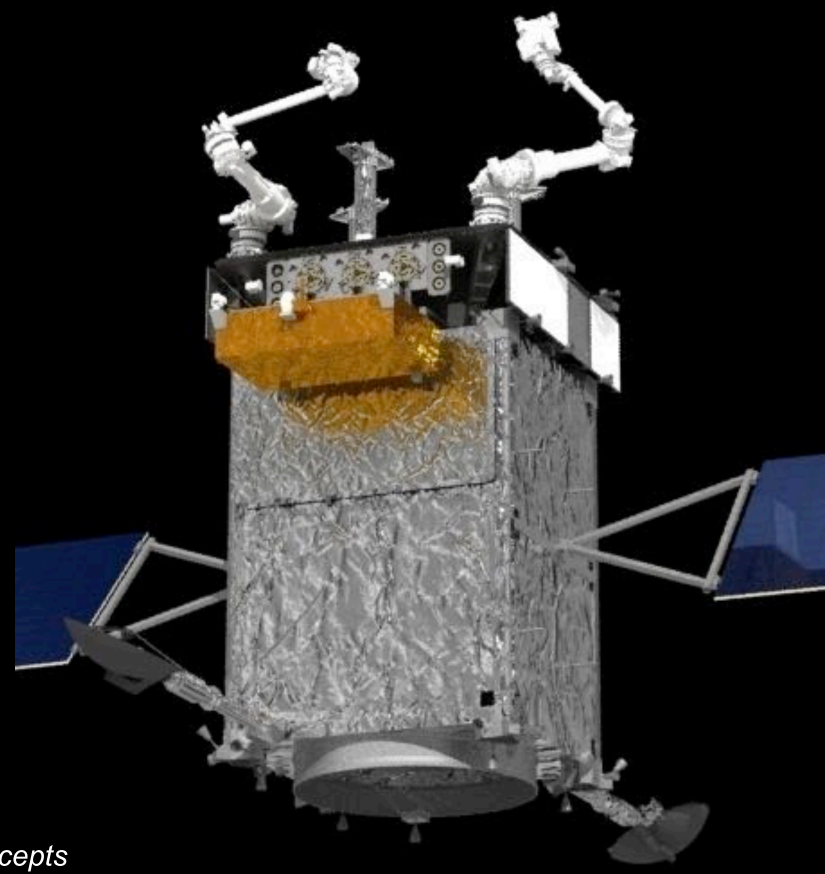
Early Prototype Module Removal and Replacement





Asteroid Redirect Robotic Mission (ARRM) and Restore-L





Artist's concepts

Looking Forward

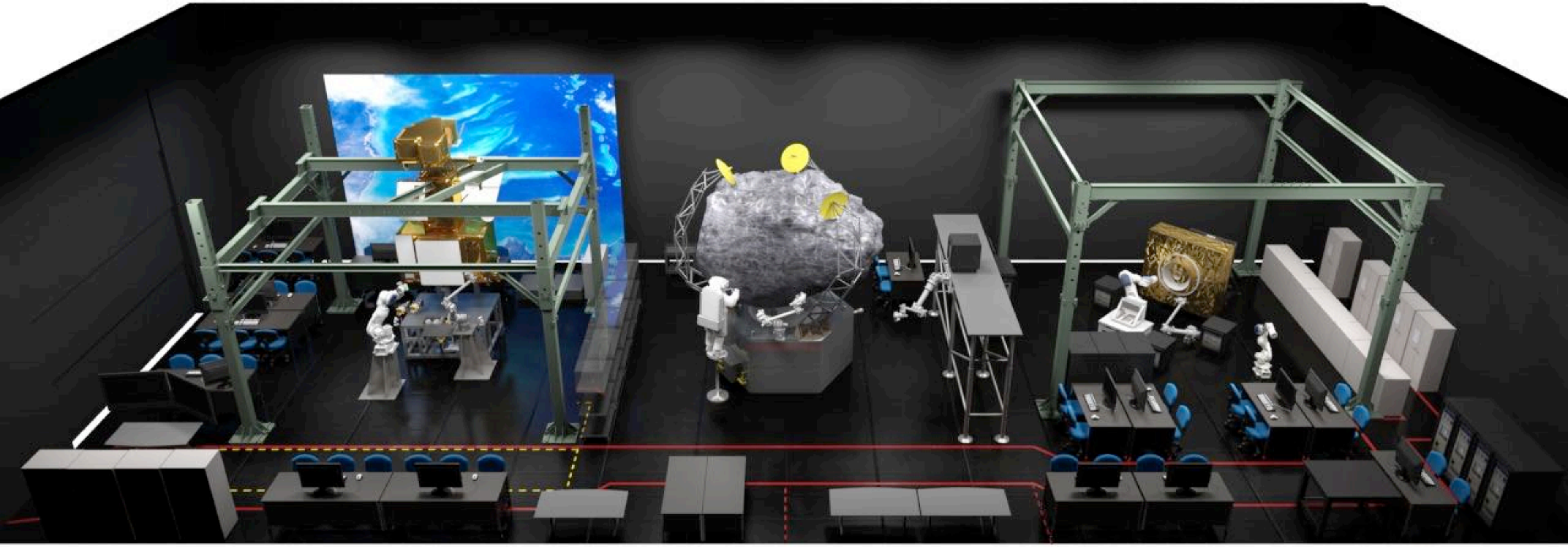
- NASA is taking the long view to foster an enduring, expanding domestic industry and stimulate the U.S. economy by extension

- NASA's servicing technology efforts have yielded a return on investment of 16 patents and growing. NASA brings this IP and more to the table to foster and nurture a robust new industry.

- NASA's in-space robotic servicing efforts deliver a portfolio of advanced, flight-tested technologies that directly benefits NASA missions

NASA's In Space Robotic Servicing portfolio is enabling new NASA missions, is fostering a new satellite servicing industry, and is poised to transition new capabilities to other stakeholders.

The Cauldron



- Facility opens summer 2015: we invite you to visit
- Integrated environment for the development of technologies, capabilities and operations for multiple missions
- Investing in infrastructure for the future