Robotic Servicing of Geosynchronous Satellites (RSGS) Proposers Day

Dr. Gordon Roesler, Program Manager

DARPA Tactical Technology Office

Briefing prepared for Robotic Servicing of Geosynchronous Satellites (RSGS) Proposers Day

May 25, 2016

DARPA

DARPA Perspective on Space

Ms. Pamela A. Melroy, Deputy Director
DARPA Tactical Technology Office

May 25, 2016

Mission

The Defense Advanced Research Projects Agency (DARPA) was established in 1958 to **prevent strategic surprise** from negatively affecting U.S. national security and **create strategic surprise** for U.S. adversaries by maintaining the technological superiority of the U.S. military.

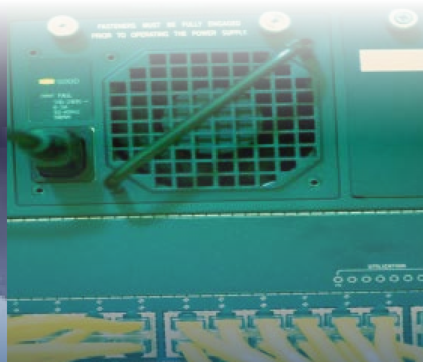
To fulfill its mission, the Agency relies on **diverse performers** to apply multi-disciplinary approaches to both advance knowledge through basic research and **create innovative technologies** that address current practical problems through applied research.

As the DoD's **primary innovation engine**, DARPA undertakes projects that are finite in duration but that create **lasting revolutionary change**.

DARPA History

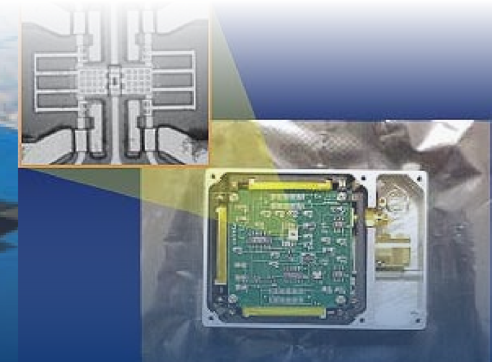
SATURN F1
Rocket Engine
1960

Speech Recognition
1971



Stealth Fighter
1983

Microelectromechanical Systems
(MEMS)
1991

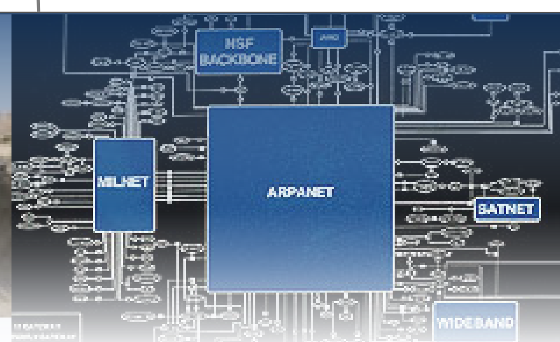


1960 1970 1980 1990 2000

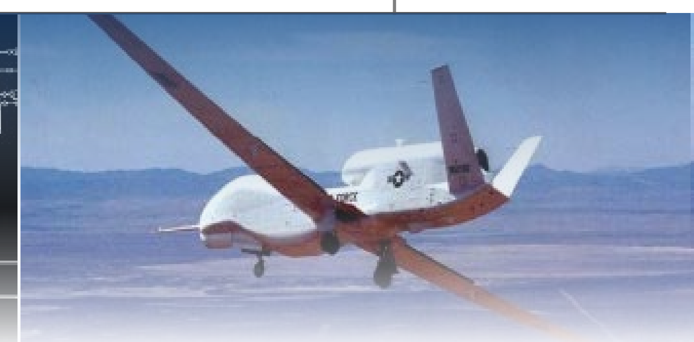
ARPA Established
1958

M16 Assault Rifle
1965

ARPANET
1969



Global Hawk
1998



DARPA Technical Offices

BTO – Biological Technologies Office

- Neurotechnologies
- Biological Complexity at Scale
- Engineering Biology
- Restore and Maintain Warfighter Capabilities

DSO – Defense Sciences Office

- Math, Modeling & Design
- Physical Systems
- Human-Machine Interaction

I2O – Information Innovation Office

- Empower the Human within the Information Ecosystem
- Guarantee Trustworthy Computing and Information

MTO – Microsystems Technology Office

- EM Spectrum
- Tactical Information Extraction
- Globalization

STO – Strategic Technology Office

- System of Systems (SoS)
- Battle Management, Command & Control (BMC2)
- Communications and Networks
- Electronic Warfare (EW)
- Intelligence, Surveillance, and Recon
- (ISR)
- Positioning, Navigation, & Timing (PNT)

TTO – Tactical Technology Office

- Ground, Maritime and Undersea, Air, & Space Systems
- Agile Development
- Cooperative Autonomy
- Unmanned Systems
- Power and Propulsion

Challenges in Space

Launch Flexibility

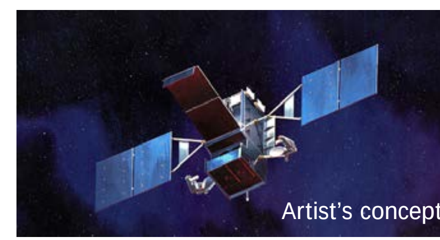
- Current launch has no surge capability and long call-up times
  - 2+ years to get "into the queue"
  - Custom-built production line of a few (Maserati model) vs. assembly line of thousands (Ford model)
- Fixed launch sites are vulnerable

Architectures

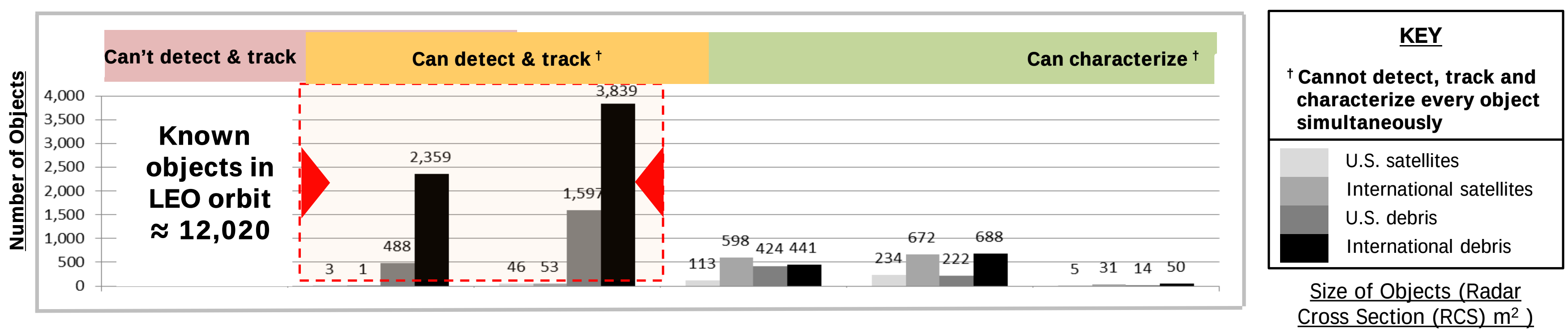
- DoD payloads launched on Evolved ELV at >$3B/year & growing
- Small payloads launched at $50M+ on few remaining Minotaurs

Space Domain Awareness

- There are approximately 16,000+ objects in 10^{14} km^3 (240,000 oceans)
  - Approximately 12,020 in low Earth orbit (LEO), 1,890 in medium Earth orbit (MEO), and 1,890 in geosynchronous Earth orbit (GEO)



LEO

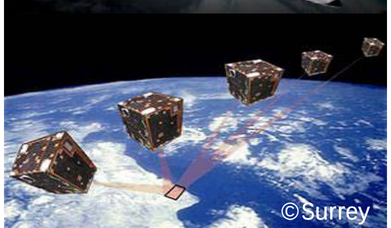


What’s Changing and What’s Happening

Commercial access easier than ever

Ever-growing and lucrative commercial satcom markets

Wealthy visionaries are investing in space tourism and transportation



Commercial startups and international entrants are expanding microsat and smallsat capabilities

NASA investments are buoying new entrants for orbital and suborbital markets

DARPA Vision for Robust Space

Launch:

- Experimental Spaceplane (XS-1): Aircraft-like space access to lower cost and increase capabilities

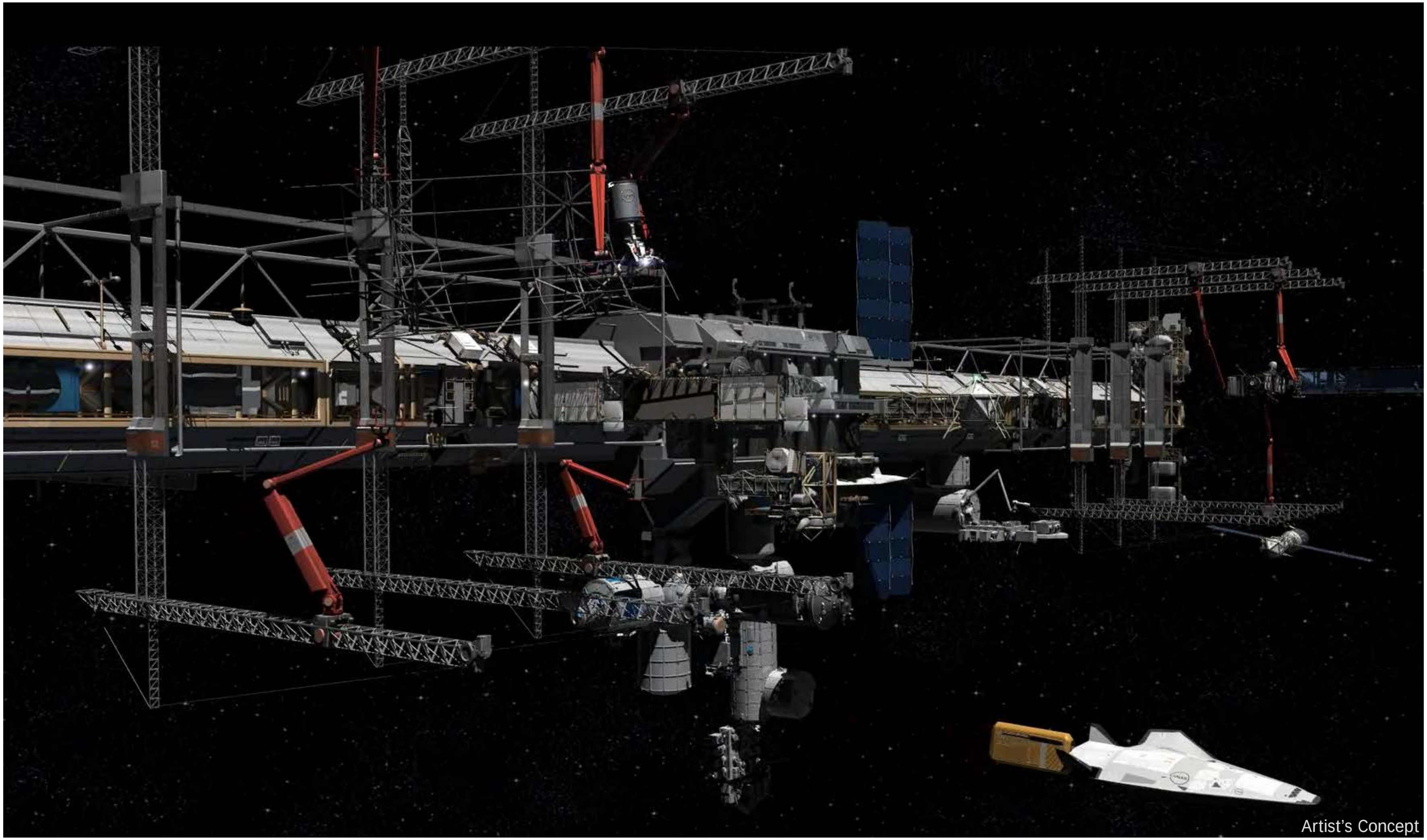
Satellite:

- Robotic Servicing of Geosynchronous Satellites (RSGS): Dexterous space robotics that could provide improve satellite resilience and create significant opportunities for U.S. Government and commercial satellite partners

Space Domain Awareness (SDA):

- OrbitOutlook: Real-time detection and tracking versus catalog maintenance and days to weeks of forensics
- Hallmark: Integrated real-time space domain command and control (C2) capabilities for the U.S. space enterprise

Port of Call at 36,000 Kilometers



www.darpa.mil

Program Overview

Dr. Gordon Roesler

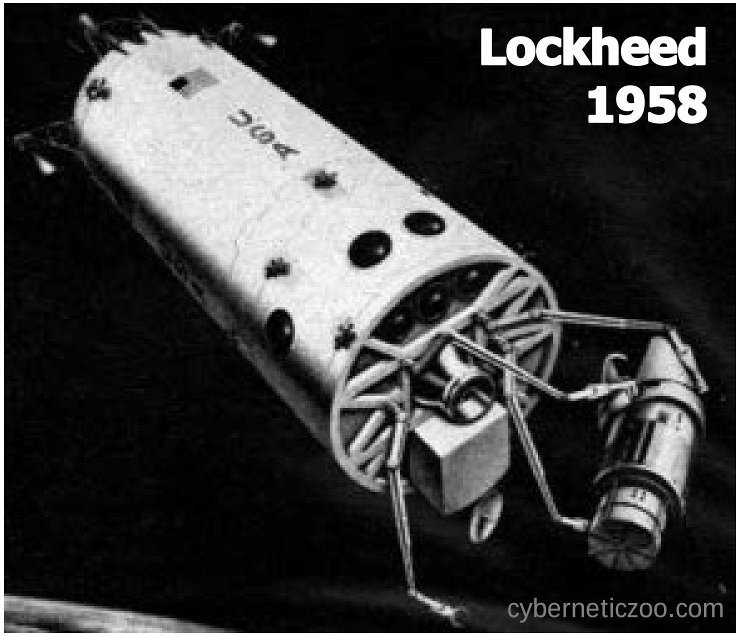
RSGS Program Manager

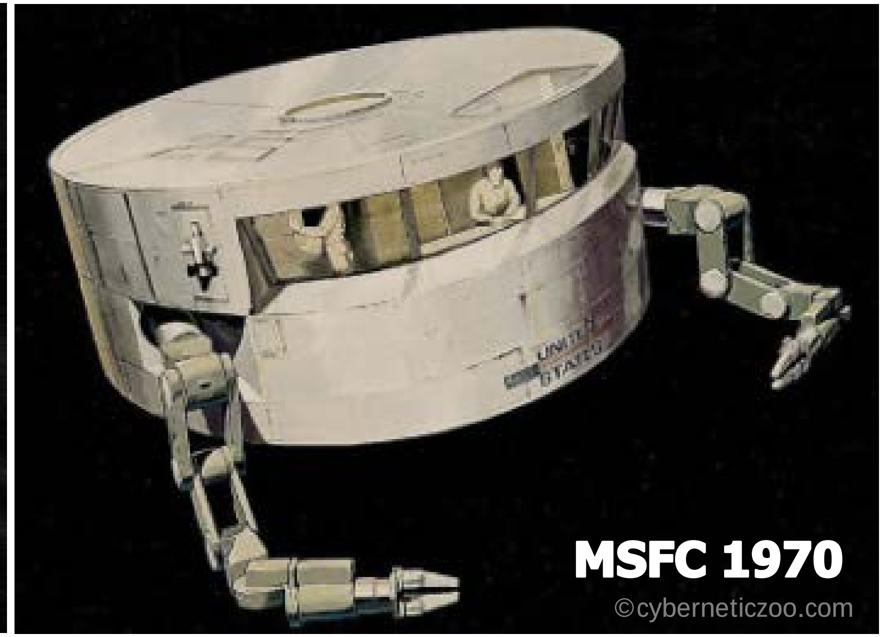
May 25, 2016

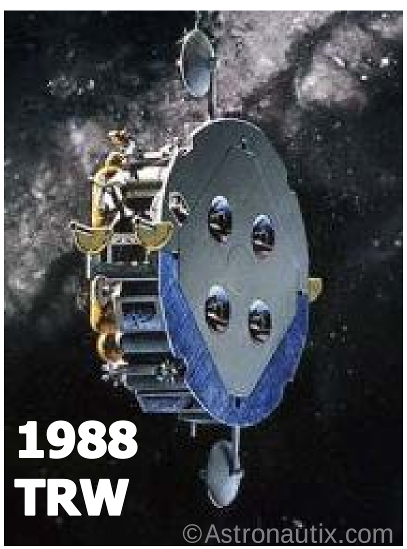
DARPA

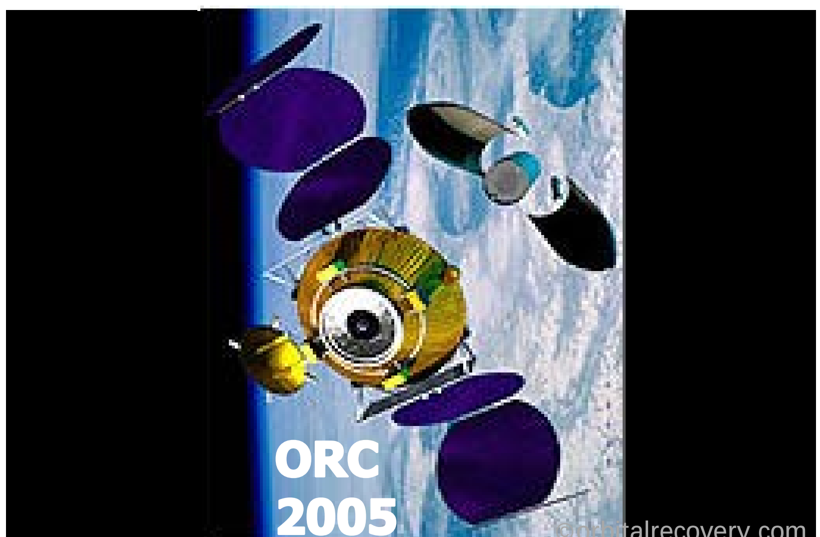
We’ve been talking about this for a long time...

An idea whose time has come

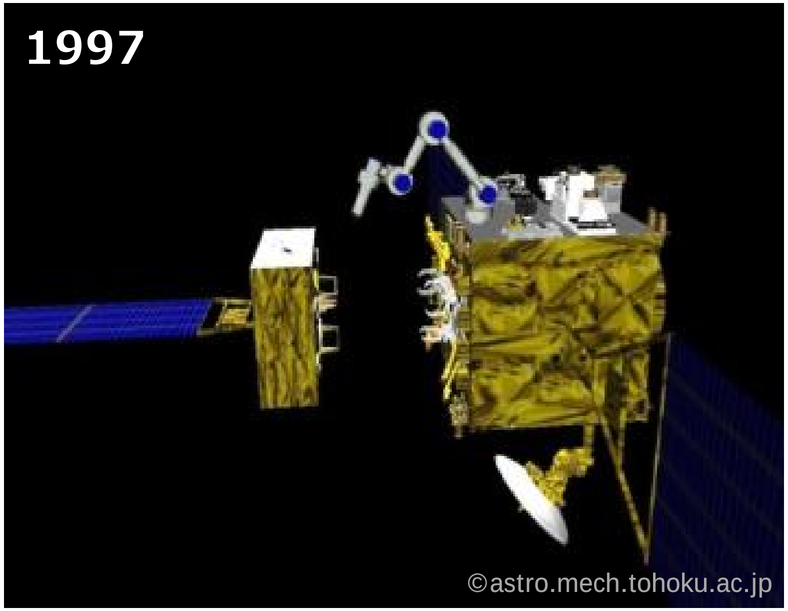








Automated robotics on orbit

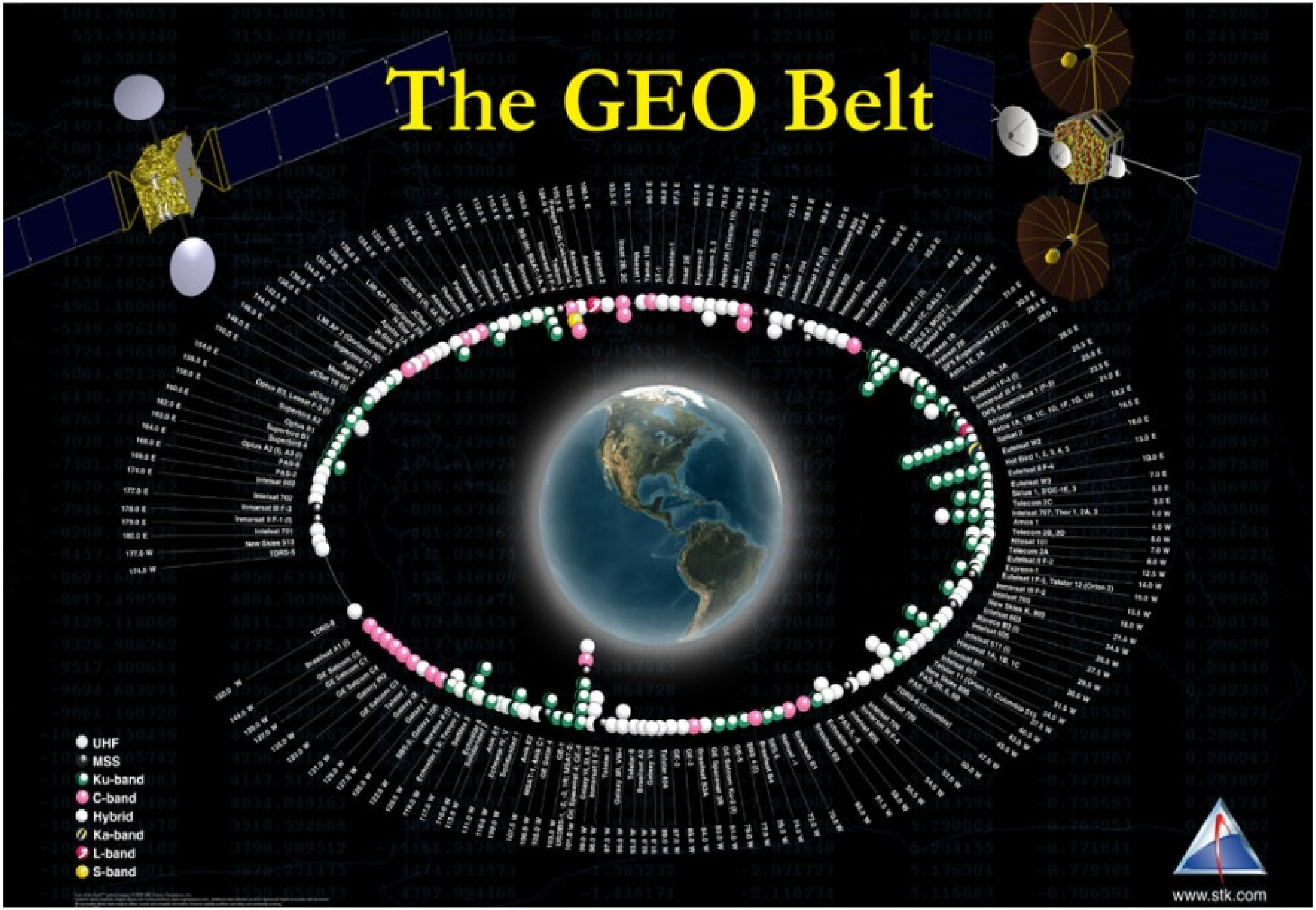


JAXA ETS-VII

DARPA Orbital Express

Why GEO?

More potential customers



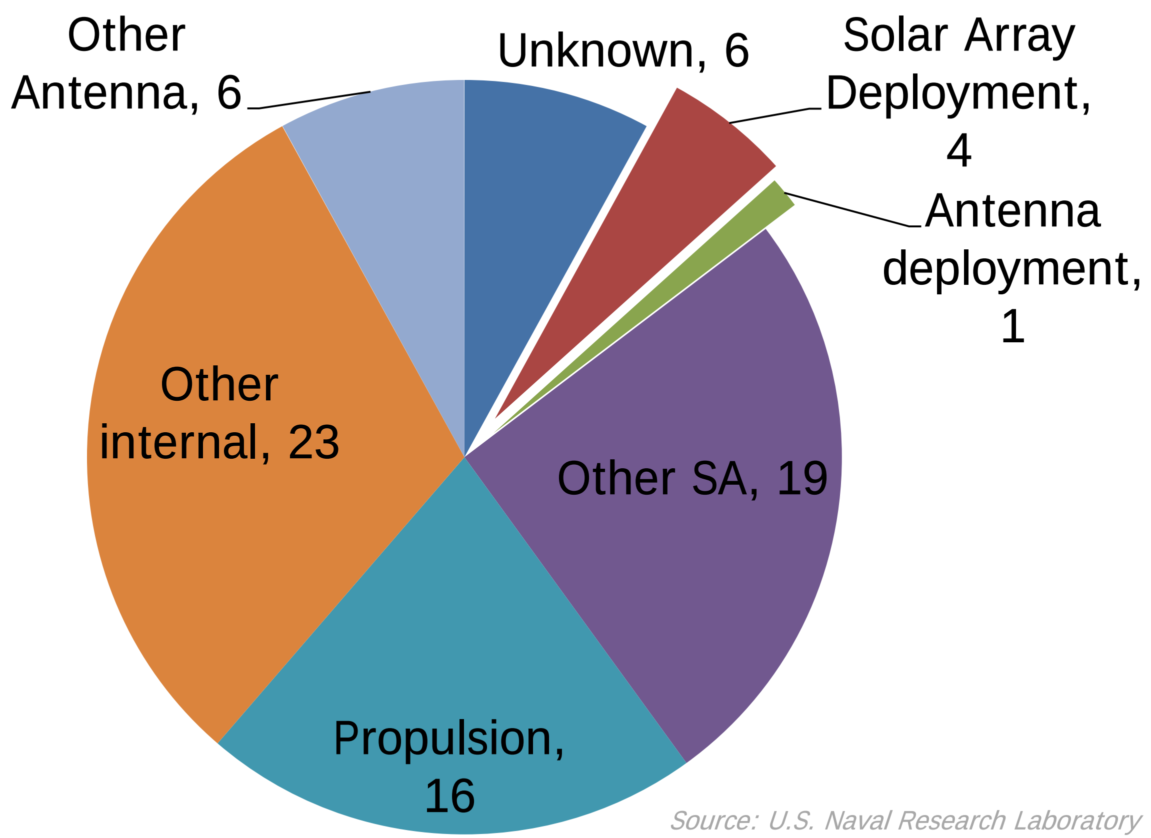
~5:1 commercial to government

Things go wrong

AEHF-1

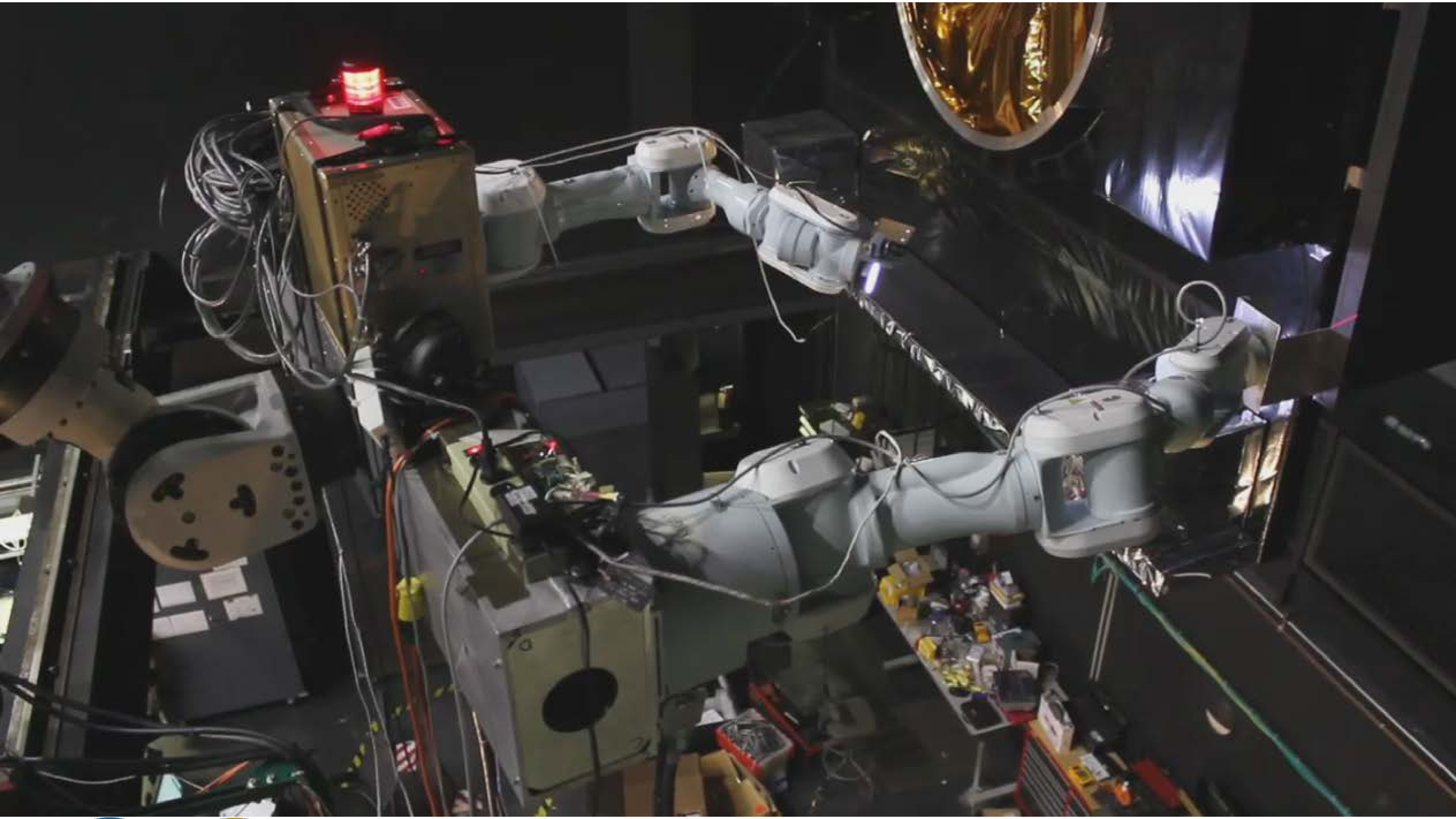
New Dawn

Ten years' worth of GEO anomalies



Source: U.S. Naval Research Laboratory

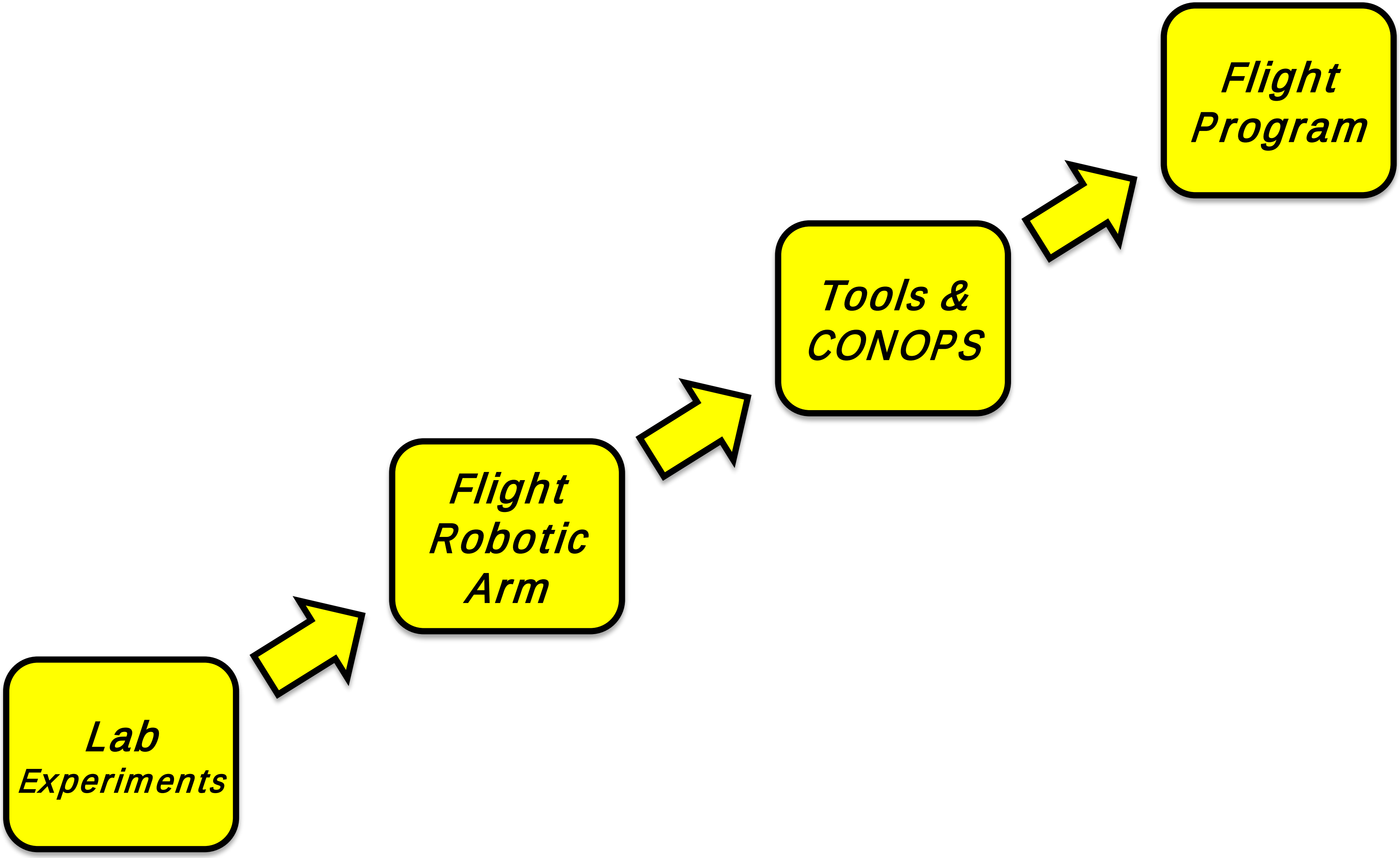
Repair is feasible



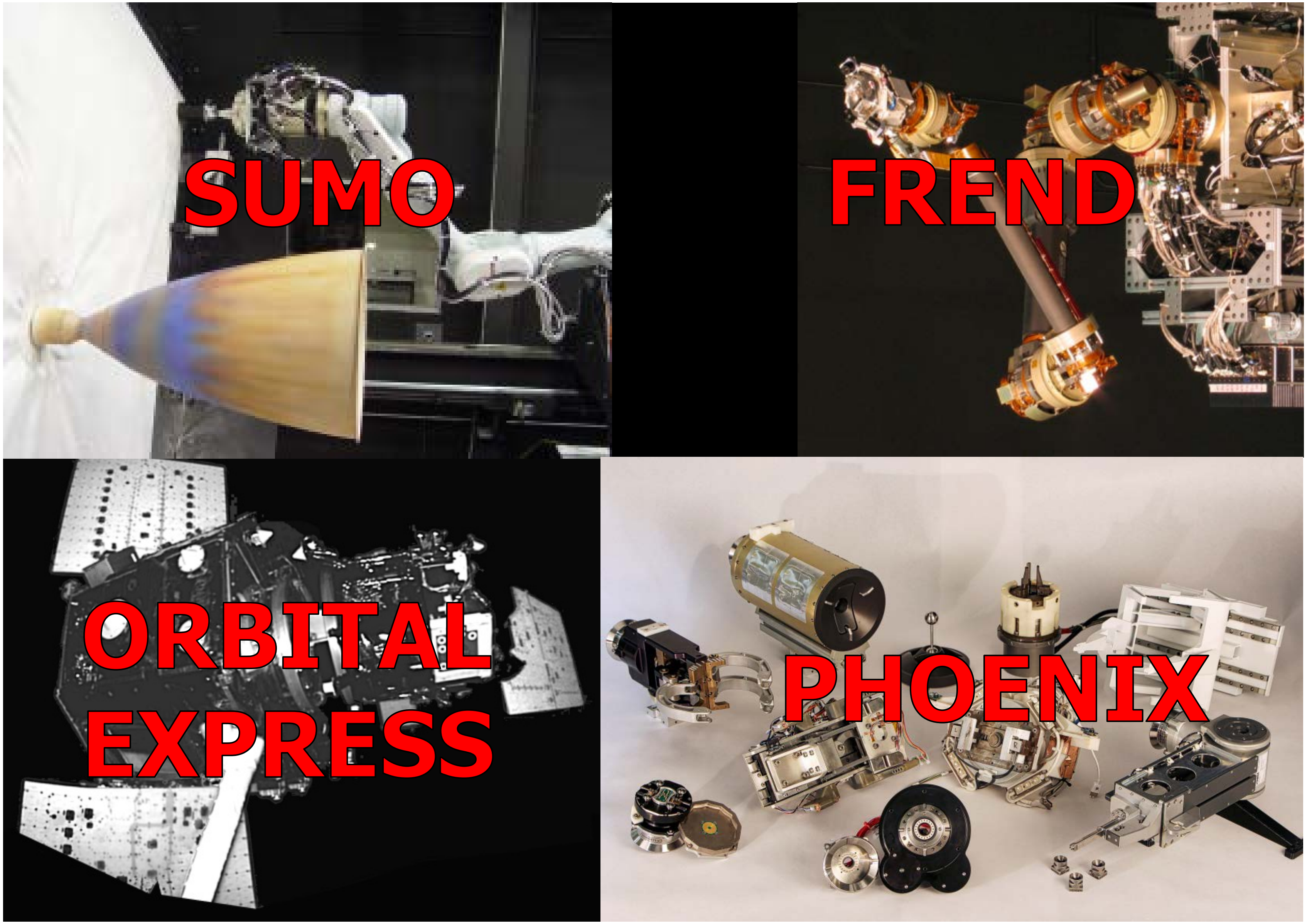
U.S. Naval Research Laboratory BICEP test 2010

Preparation

From concept to flight

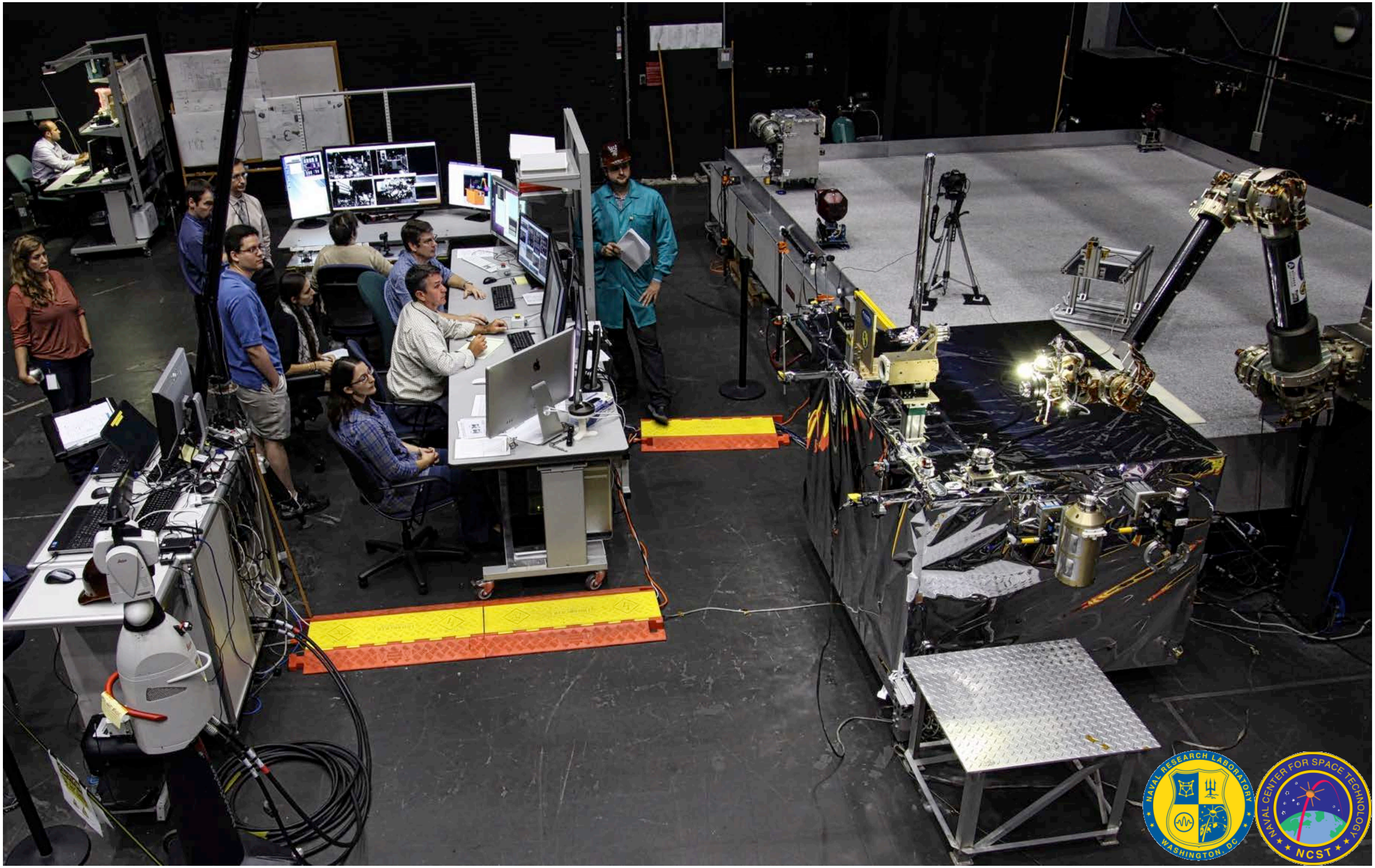


Pulling together technologies



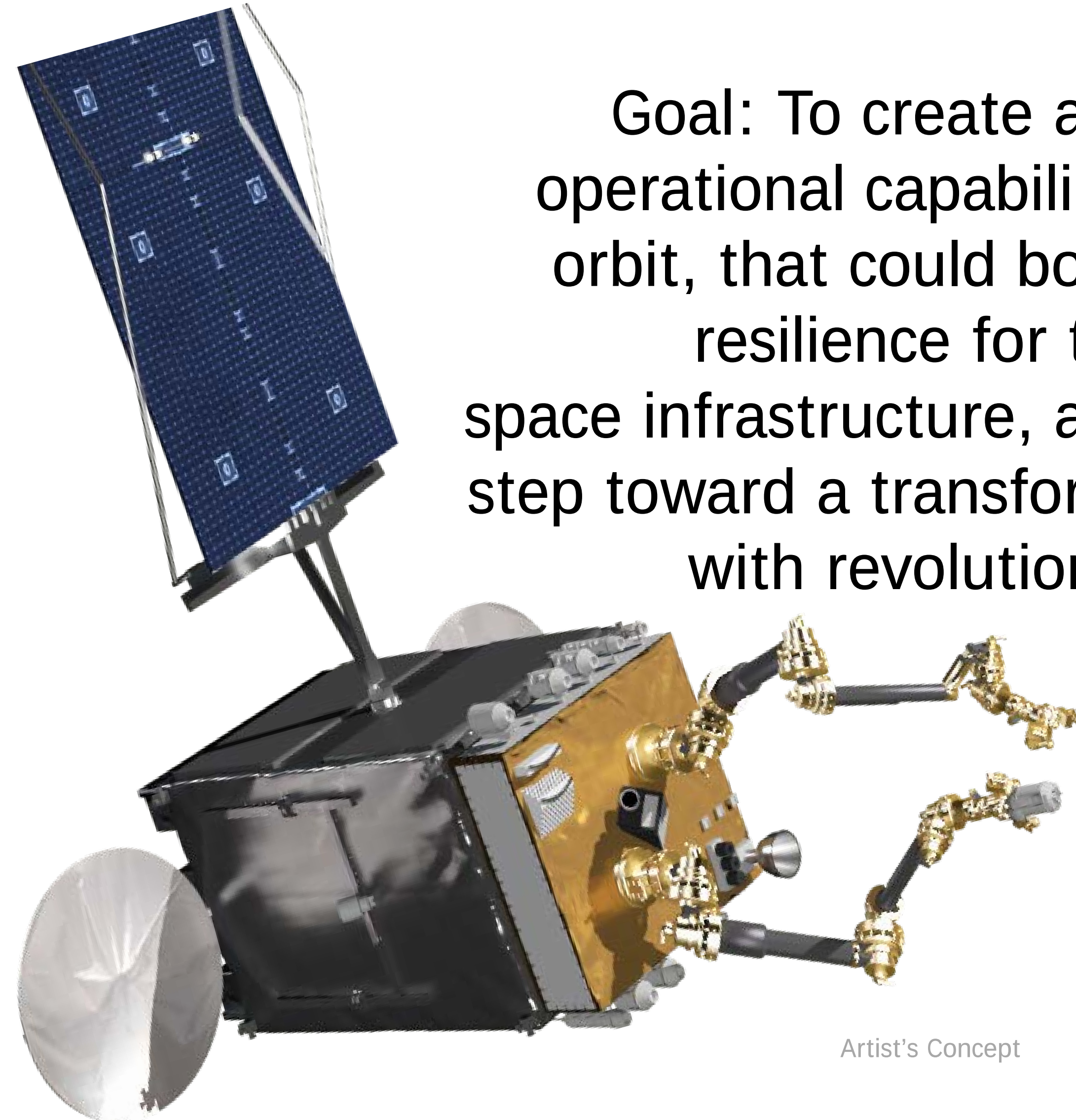
DARPA

Increasing levels of integrated testing



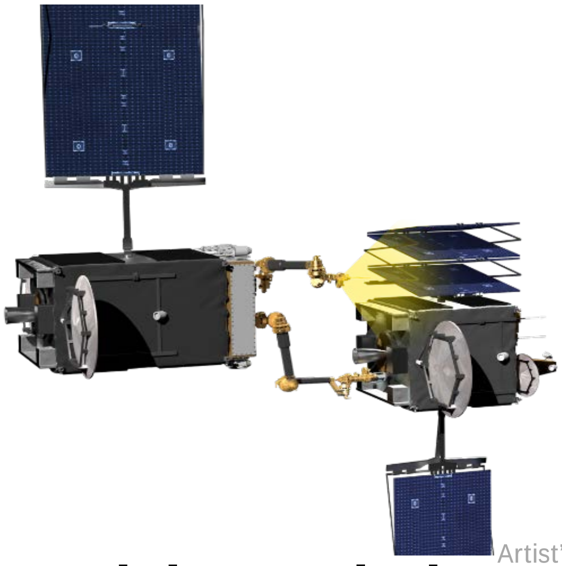
RSGS: Resilience and transformation

Goal: To create a dexterous robotic operational capability in geosynchronous orbit, that could both provide increased resilience for the current U.S. space infrastructure, and be the first concrete step toward a transformed space architecture with revolutionary capabilities



Artist's Concept

The DARPA baseline mission set

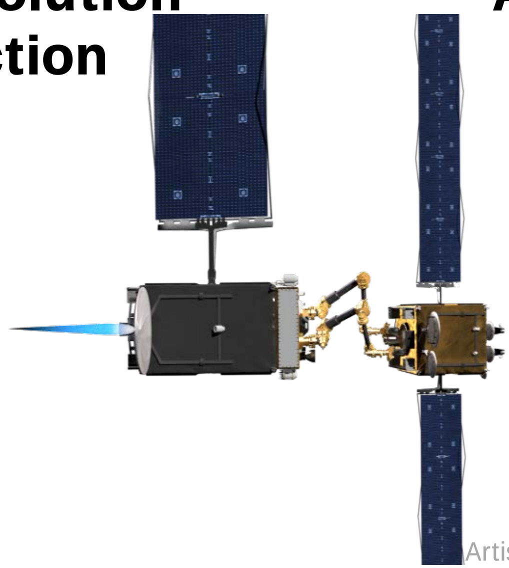


Artist's Concept

High-Resolution Inspection

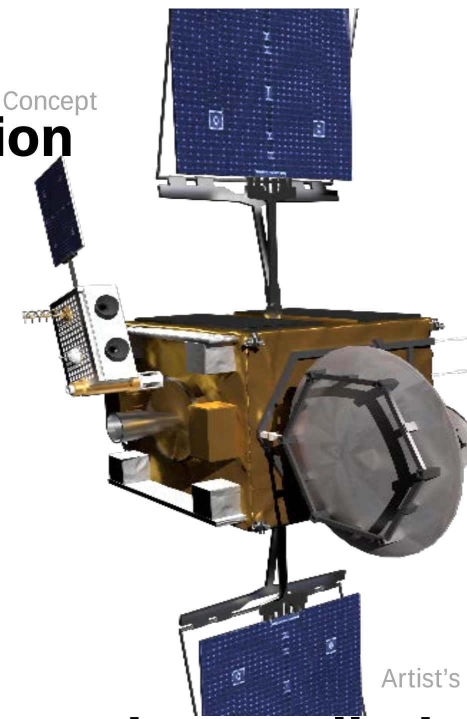
Artist's Concept

Anomaly Correction



Artist's Concept

Cooperative Relocation



Artist's Concept

Upgrade Installation

RSGS: THE MOVIE

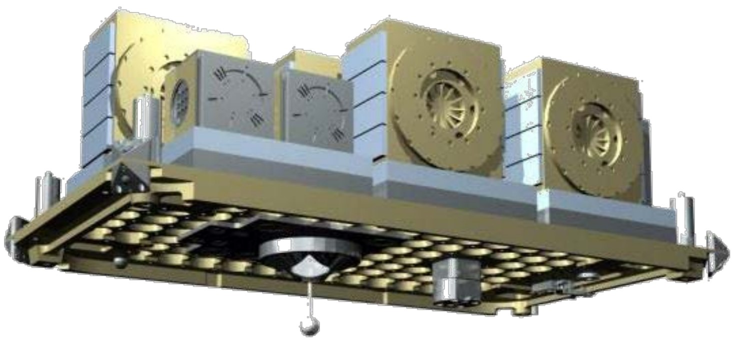

DARPA
Robotic Servicing of Geosychronous Satellites (RSGS)
Concept Video

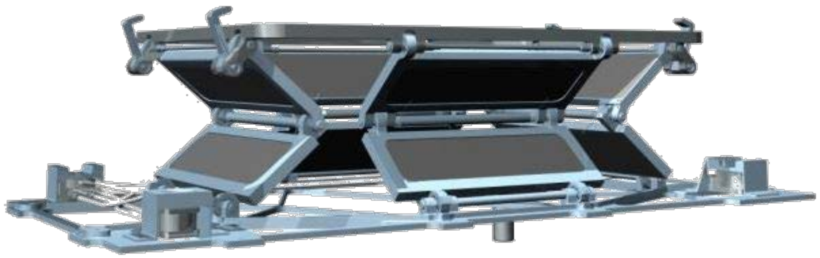
RSGS: Resilience and transformation

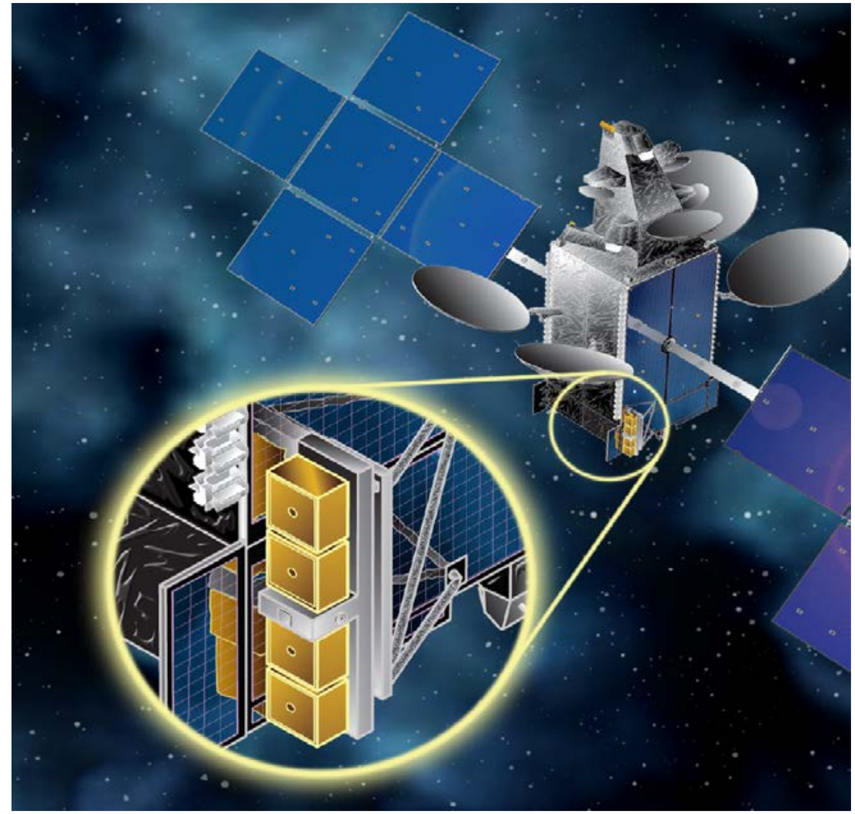
Goal: To create a dexterous robotic operational capability in geosynchronous orbit, that could both provide increased resilience for the current U.S. space infrastructure, and be the first concrete step toward a transformed space architecture with revolutionary capabilities

Artist's Concept

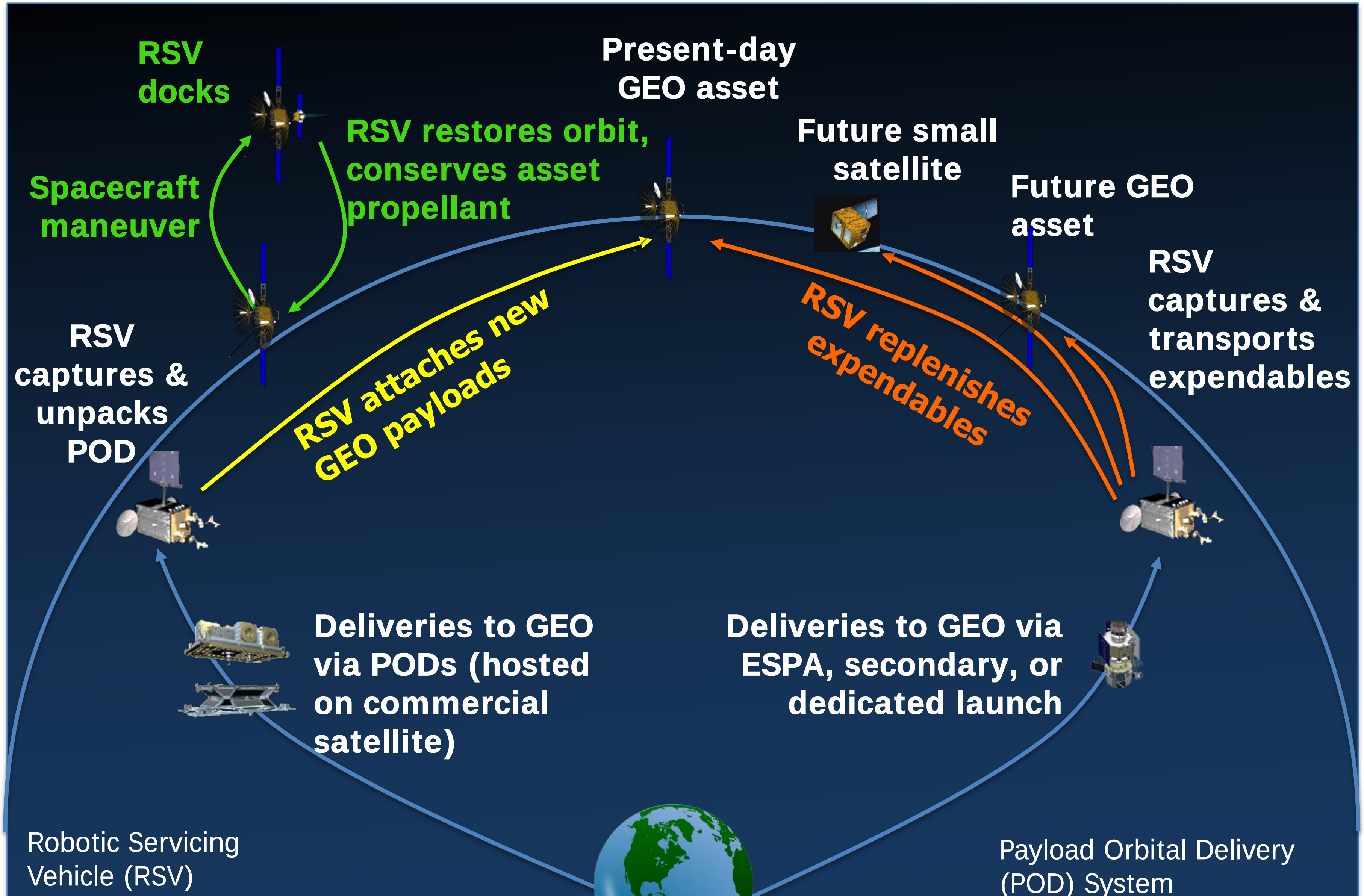
Space logistics: Payload Orbital Delivery (POD) System



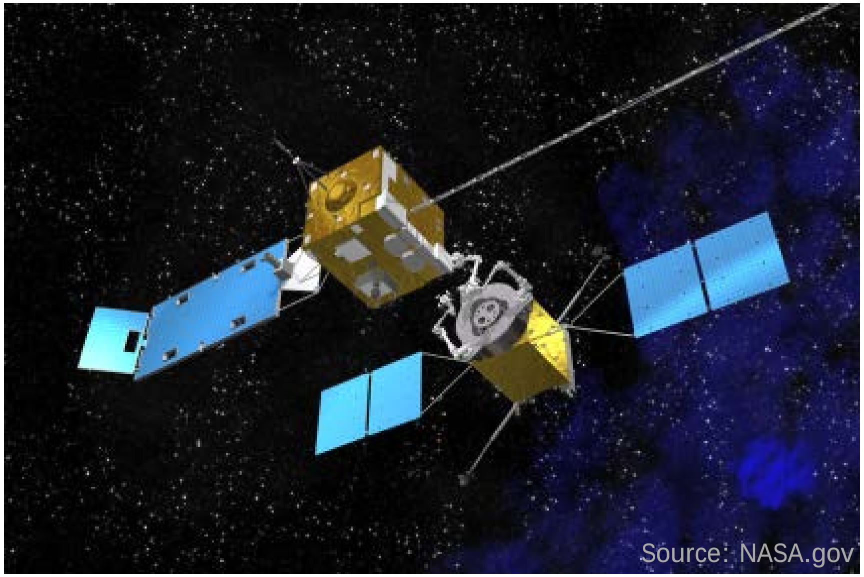


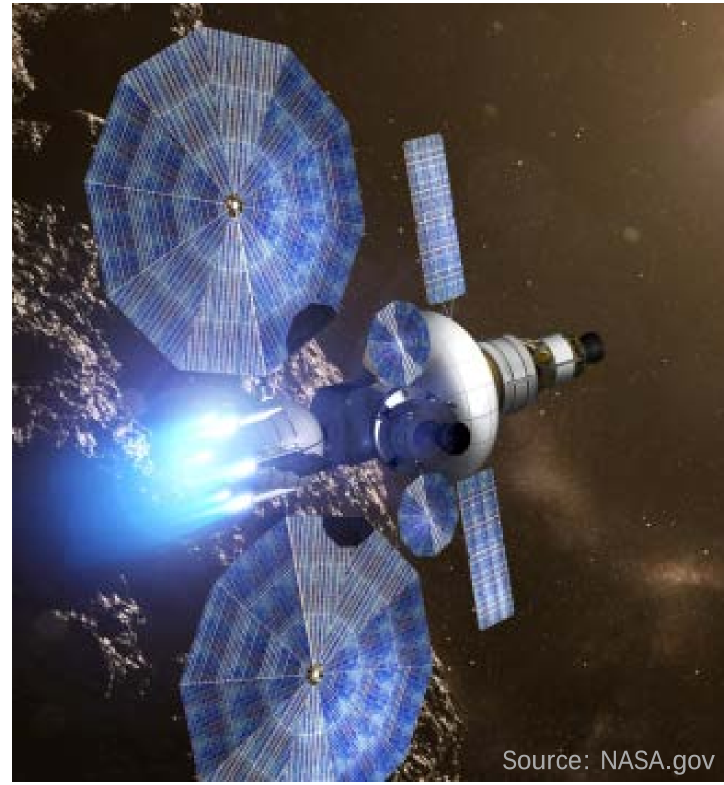


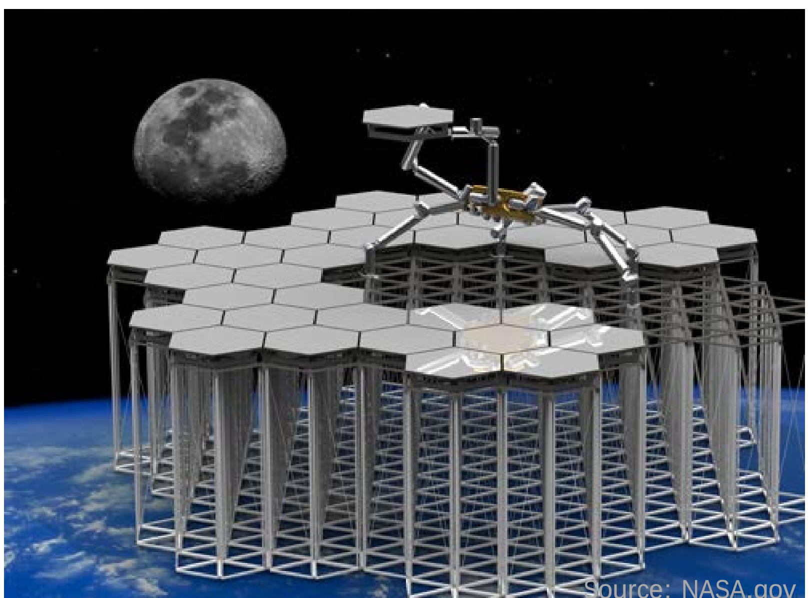
RSGS + POD = *future logistics infrastructure*



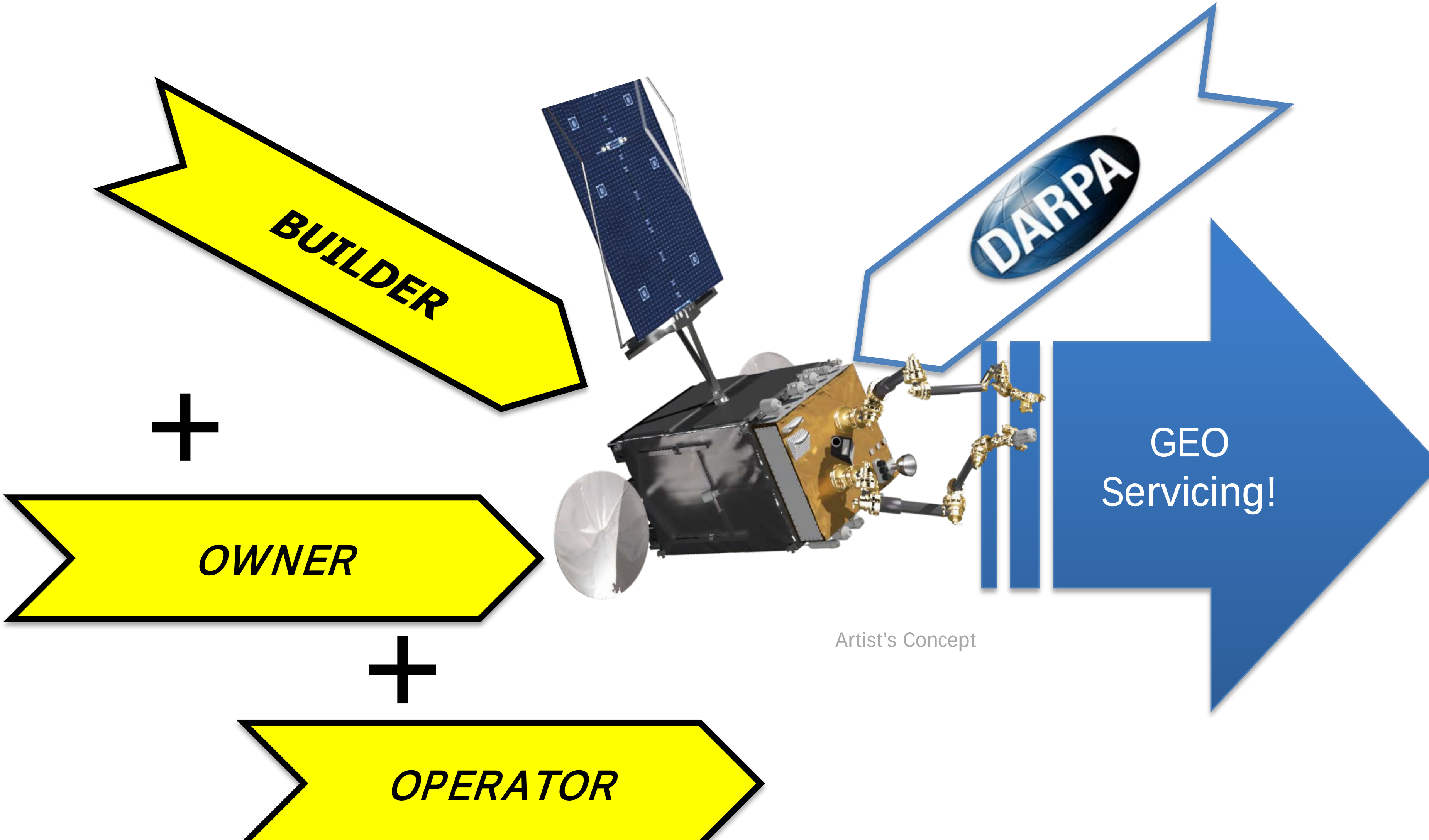
Robotics: Centerpiece of future growth





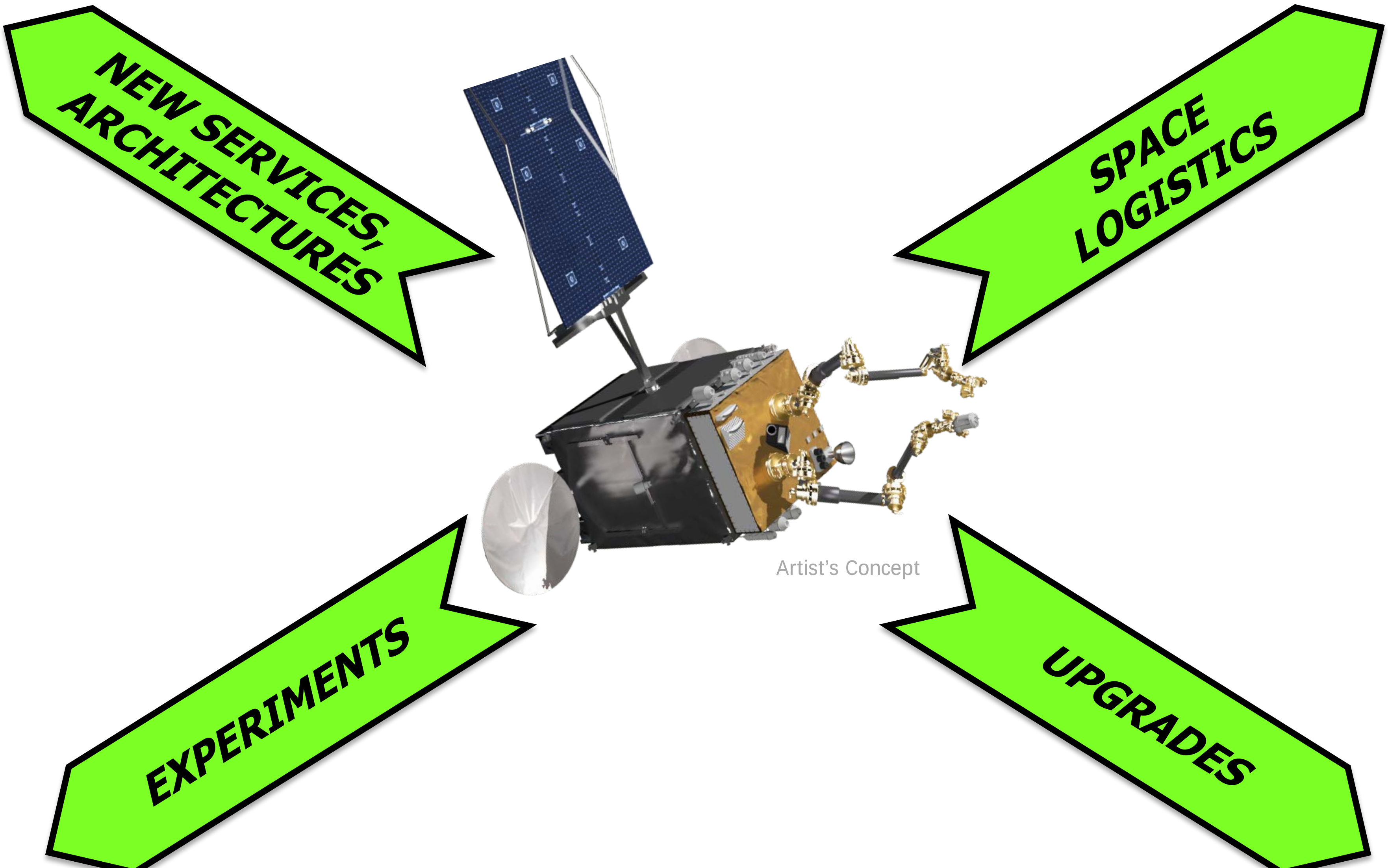


We are looking for our partner



Artist's Concept

Nurturing the transformation



The Plan

An innovative partnership

What

- Government contribution: robotic payload, launch, milestone payment upon demo completion
- Partner team: GEO heritage spacecraft bus, integration, ground segment

Why

- More potential customers
- More opportunities to learn
- Help close the servicing business case
- Government access, favorable terms

How

- Other Transactions (OT) for prototype: ***true partnership***
- DARPA to partner with builder-owner-operator team from U.S. space industry
- Management structure proposed by partner
- Collaborative decision making

Capability demonstration and after

- DARPA will arrange for one or more GEO vehicles as test customers
- Once on orbit, RSGS vehicle would:
  - Complete a checkout and calibration phase
  - Demonstrate capabilities that support inspection, tug, anomaly resolution, and upgrade capabilities
  - Perform servicing operations for an estimated 6-9 months, followed by milestone payment
- Following demo, partner has opportunity for revenue generating operations
  - Commercial satellite servicing
  - Government fee-for-service missions

Payload being designed for 5-8 years of GEO operations to facilitate partner ROI

Notional schedule and milestones

Partner selection ~ November 2016

Bus/Payload component assembly and test 2019

Bus and Payload integration 2020

RSGS launch NLT March 2021

Capability demonstration 6-9 months

Join us

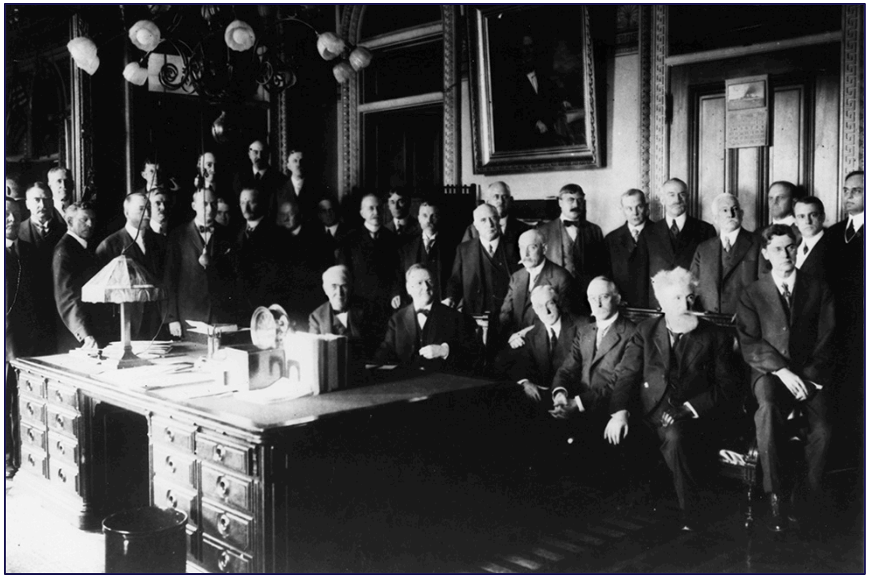
www.darpa.mil

Naval Research Laboratory

Naval Research Laboratory (NRL) Overview

Mr. John P. Schaub, SES
Acting Director, Naval Center for Space Technology
Superintendent, Spacecraft Engineering Department (Code 8200)

92 Years of Innovation



"One of the imperative needs …is machinery and facilities for utilizing the natural inventive genius of Americans to meet the new conditions of warfare."

–SECNAV Josephus Daniels, 1915

A Department of the Navy Laboratory

Assistant Secretary of the Navy (RD&A)

Chief of Naval Research | N84

Vice Chief of Naval Research

U.S. Naval Research Laboratory
CO|DOR

Business Operations

Systems Directorate
- Radar
- Electronic Warfare
- Optical Sciences
- Information Technology

Materials Science and Component Technology
- Chemistry
- Materials Science & Technology
- Comp. Phys & Fluid Dynamics
- Plasma Physics
- Electronics Science & Tech
- Bimolecular Science & Engineering

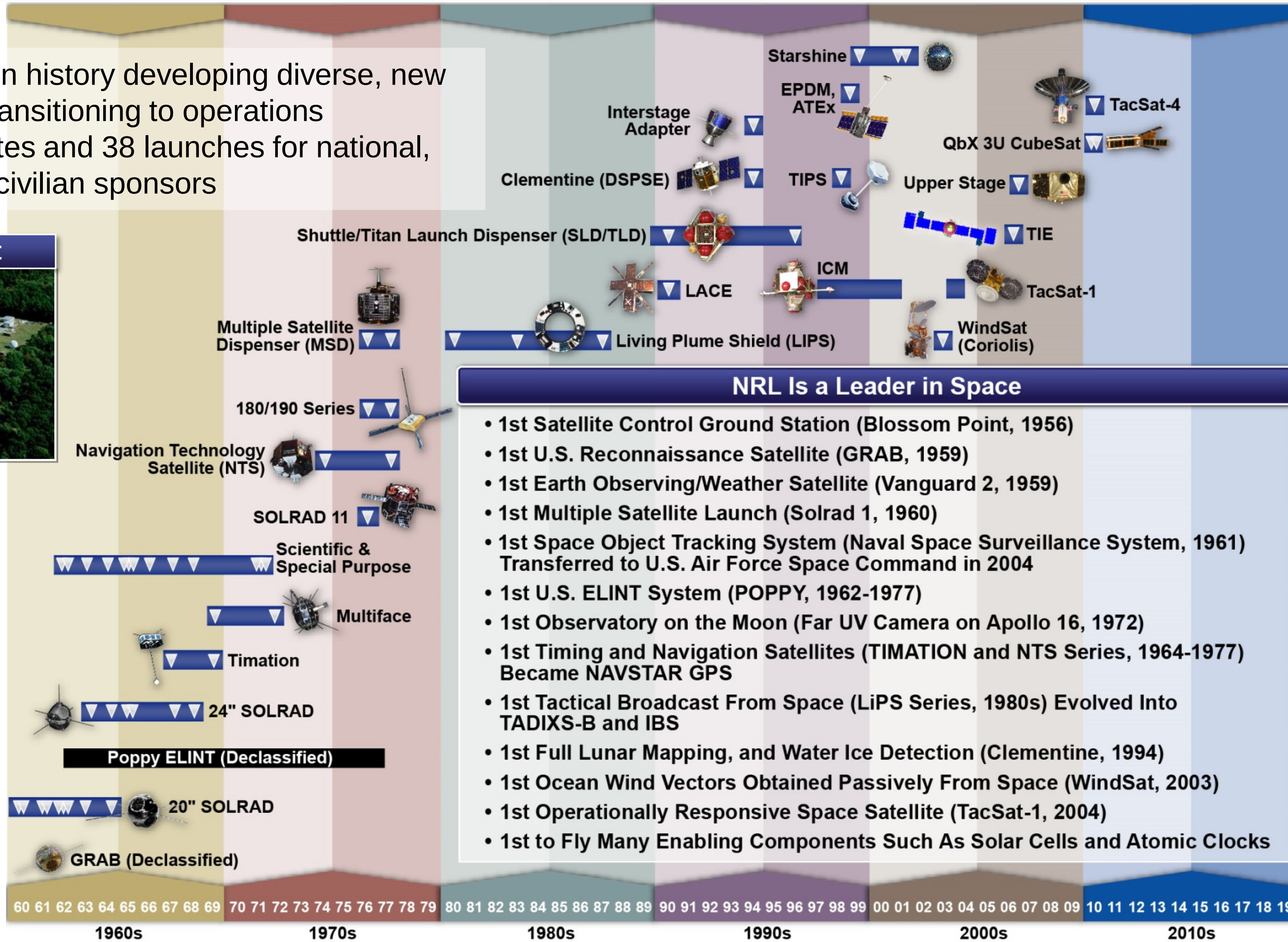
Ocean and Atmosphere Science & Technology
- Acoustics
- Remote Sensing
- Oceanography
- Marine Geosciences
- Marine Meteorology
- Space Sciences

Naval Center for Space Technology
- Space Systems Dev
- Spacecraft Engineering

Naval Research Laboratory's Space History
Developing New Capabilities With Operational Impacts

- NRL has proven history developing diverse, new systems and transitioning to operations
  - 100 satellites and 38 launches for national, DoD, and civilian sponsors

Blossom Point



NRL Is a Leader in Space

- 1st Satellite Control Ground Station (Blossom Point, 1956)
- 1st U.S. Reconnaissance Satellite (GRAB, 1959)
- 1st Earth Observing/Weather Satellite (Vanguard 2, 1959)
- 1st Multiple Satellite Launch (Solrad 1, 1960)
- 1st Space Object Tracking System (Naval Space Surveillance System, 1961) Transferred to U.S. Air Force Space Command in 2004
- 1st U.S. ELINT System (POPPY, 1962-1977)
- 1st Observatory on the Moon (Far UV Camera on Apollo 16, 1972)
- 1st Timing and Navigation Satellites (TIMATION and NTS Series, 1964-1977) Became NAVSTAR GPS
- 1st Tactical Broadcast From Space (LiPS Series, 1980s) Evolved Into TADIXS-B and IBS
- 1st Full Lunar Mapping, and Water Ice Detection (Clementine, 1994)
- 1st Ocean Wind Vectors Obtained Passively From Space (WindSat, 2003)
- 1st Operationally Responsive Space Satellite (TacSat-1, 2004)
- 1st to Fly Many Enabling Components Such As Solar Cells and Atomic Clocks

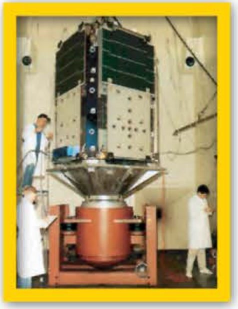
Extensive Space System Facilities

Building A59 Payload Processing Facility – 188,000 ft² Total Area

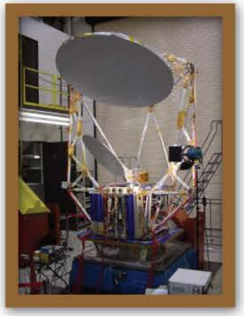
Assembly and Integration Area With High Bay and Bridge Crane (12m High); Support Facilities; Fab Machinery; and Controlled Access

Harness Fabrication and Assembly Area With Calibrated Tooling, Fixtures, and Materials for Fab, Validation, and Qual

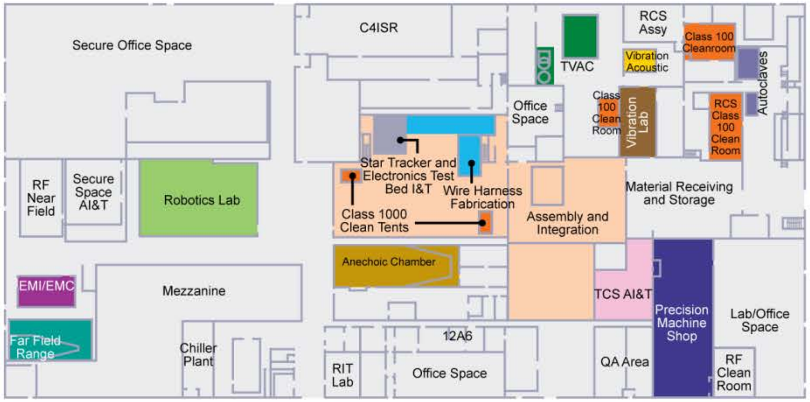
3 Large TVAC Chambers (10-7 Torr) (Largest Is 18ft Diameter/32ft Length). Multiple Smaller Chambers for Electronics Boxes and Piece Part Bakeouts

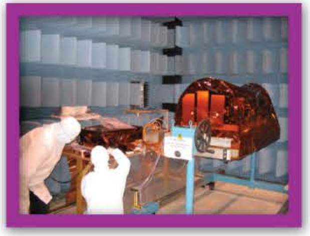


Vibro-Acoustic Chamber; 32-10,000 Hz Freq. Range (153dB Acoustic); 30klbf Electrodynamic Vibration Exciter

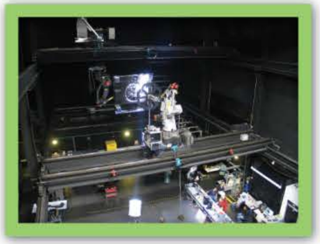


Vibration Facilities Has Shakers From 1klbs to 50klbs for Vertical and Horizontal Modes





EMI/EMC Test Facility: 100dB Attenuation From 10kHz to 20 GHz; Standard and Non-Standard (Single Event Switching Transients; Abnormal Voltage, Surge Voltage) Capabilities



Proximity Operations and Robotics Laboratory

Multiple Clean Rooms/Tents From Class 1k to 100; Largest Has 960 ft² Area; Laminar Flow Benches and Orbital Welding and Fab

Far Field Range: 704 ft² Chamber; 5 ft Diameter Spherical Quiet Zone; 100dB Attenuation From 50MHz -100GHz Frequencies; 150dB Isolation

3,720 ft² Shielded Anechoic Chamber

3,400 ft² Work Space for Analysis, Design, Fab, Assembly, Qual, and Test of Thermal Control Systems

Precision Machine Shop: Gantry Router (5' x 10' Table); 5 Axis Mill (64" x 24" x 24"); Tool Room; Lathe; Support Equipment

Large and Small Autoclaves; Lab Work Space; CTE Measurement Capability for Design and Fab of Composite Articles

A59_Floorplan_v5.ai

Blossom Point:
NRL's Spacecraft Operations Center

Space Segment

C3 Segment

Launch Support via WAN or VPN

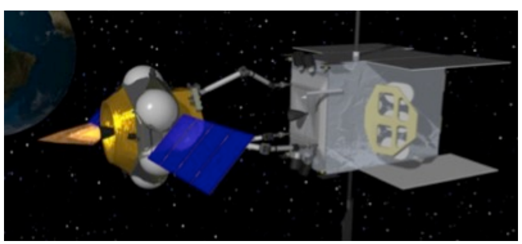
AFSCN Connectivity via WAN

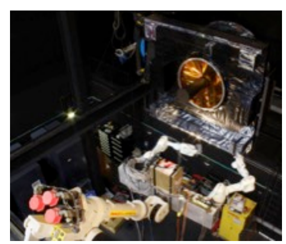
- Established in 1956 to support MiniTrack and Vanguard
  - First CONUS ground station
- Highly automated to support both operational and experimental spacecraft
  - 100-200 contacts per day; staffed 8 x 5, operations 24 x 7
- Demonstrated resiliency in operations for decades with unique, "pooled" hardware architecture
  - Includes dedicated antennas and interface to AFSCN
  - Easily extended to Commercial Ground
- Controlled by Neptune® multi-mission Command and Control (C2) software
  - Controls pooled hardware resources
  - Meets satellite C2 requirements through all phases with flexible core architecture supplemented by mission-unique software
  - Common baseline for all missions
  - SOC2SOC capability enables resource sharing at geographically separated SOCs
- VMOC is option for mission operations and tasking
- NRL's Neptune and VMOC also support several other DoD and National organizations

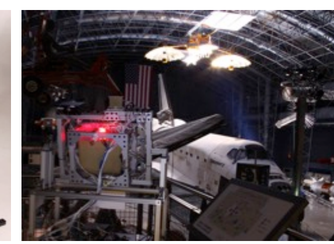
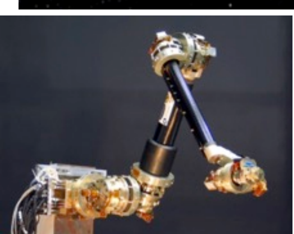
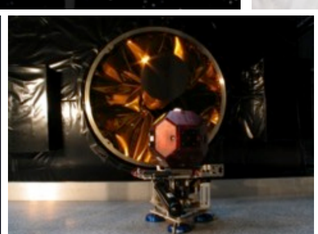
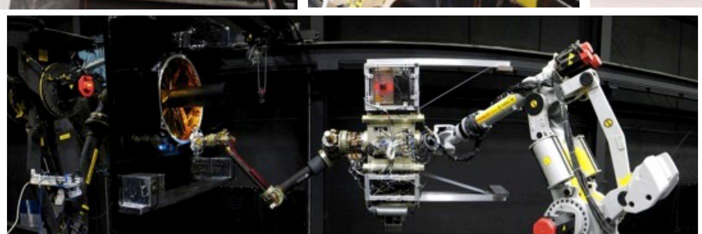
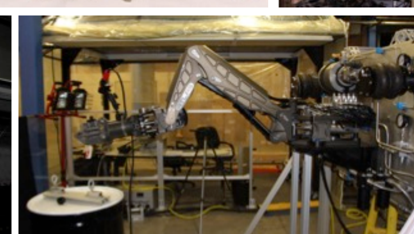
NRL ground resources form baseline for resilient ground architecture

DoD Center of Excellence for Space Robotics

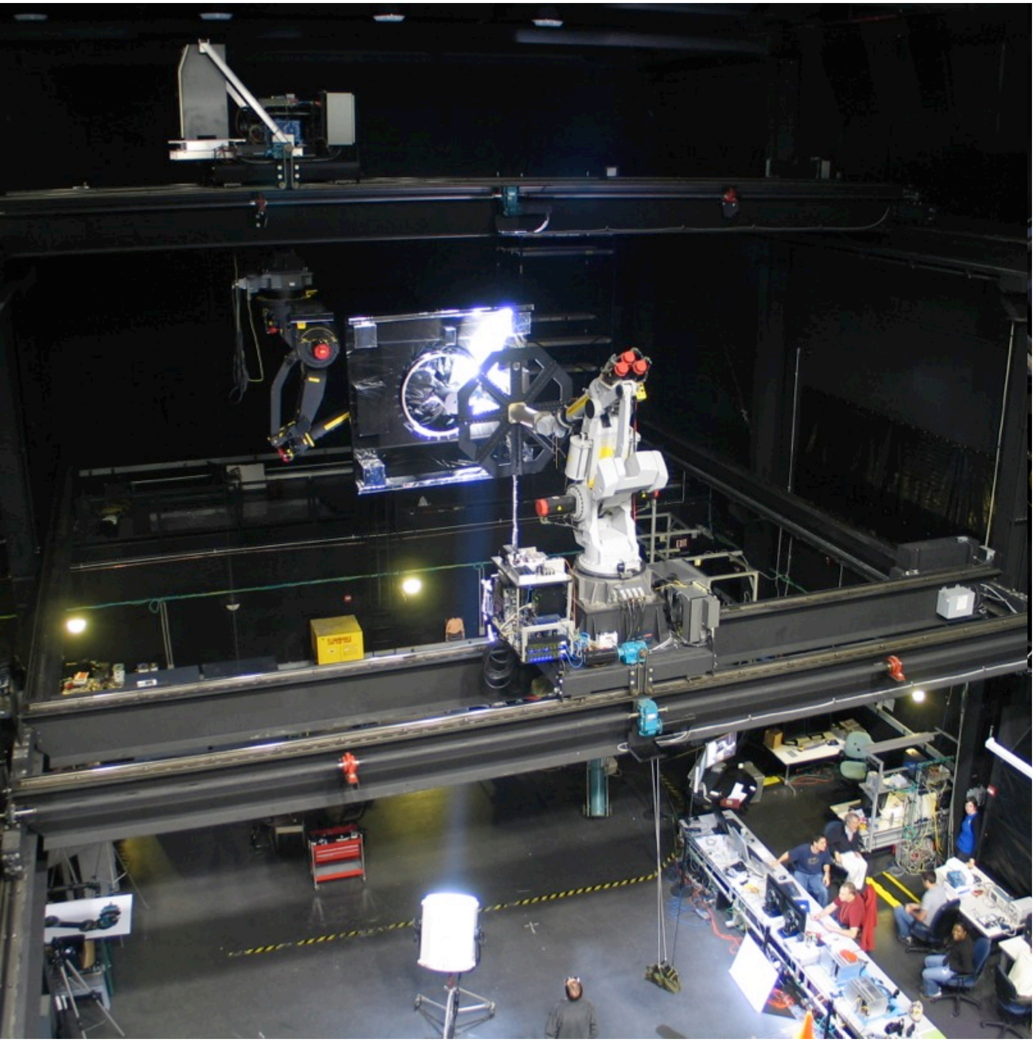
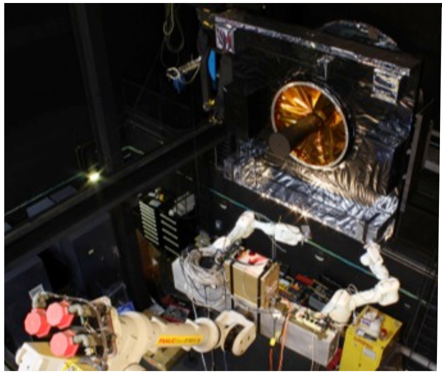
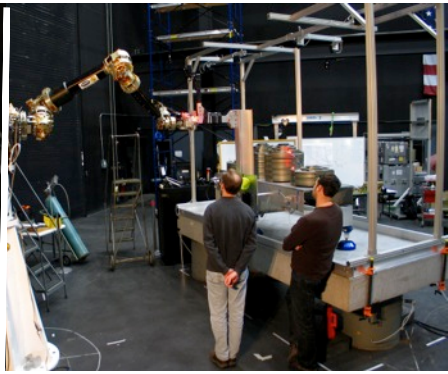
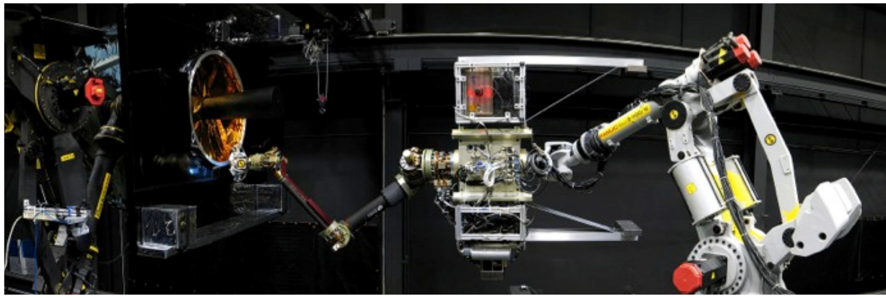
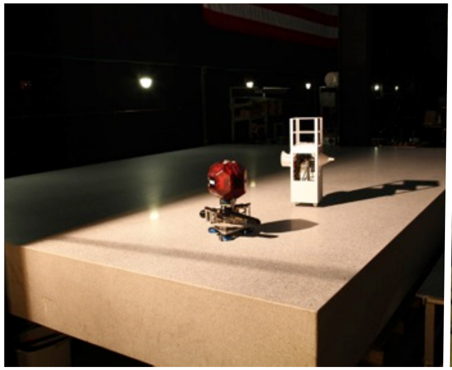
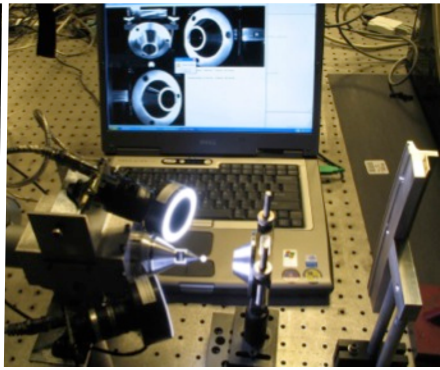
- Significant NRL internal investments in facilities, people, and research applying to long-range goals since the late 1990s
- Leading national efforts in developing new space robotics capabilities and policy
- Nationally unique capabilities in robotic control algorithms and software, innovative mechanism design, systems engineering, and system testing and validation
- NRL robotics has attracted external funding from DARPA, USAF, NASA, and Industry



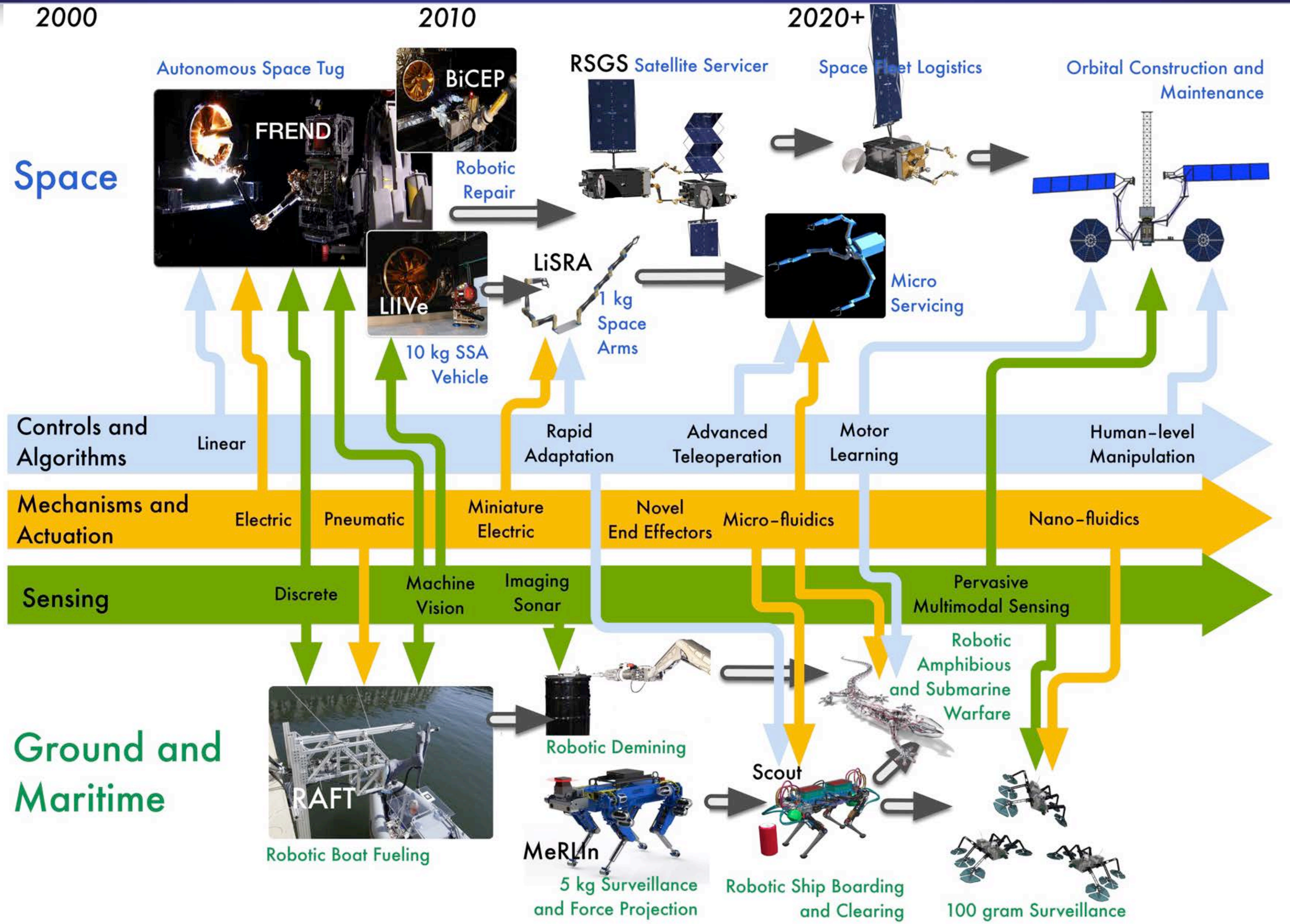



NRL Space Robotics Laboratory

NRL Robotics Vision of Transformation



Partnership Vision

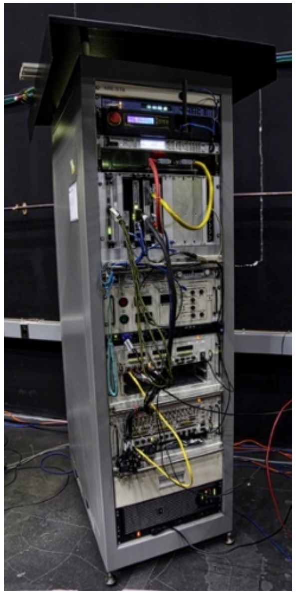
Dr. Gordon Roesler
RSGS Program Manager

May 25, 2016

Combining Government technologies

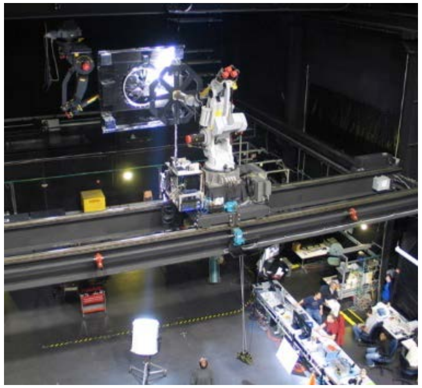
FREND Robot Arm

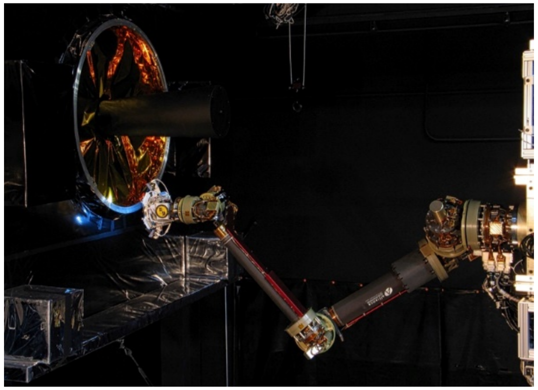
Prototype Robotics Tools

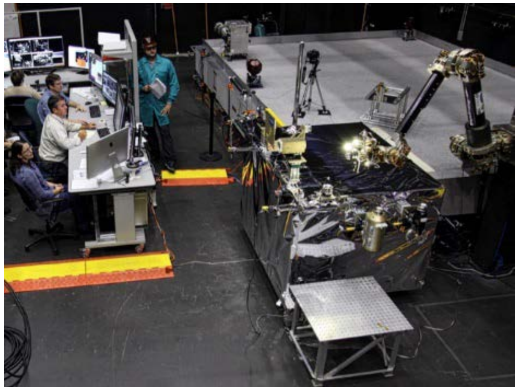


Flight Software Testbed

Prototype Robotics Ground Station

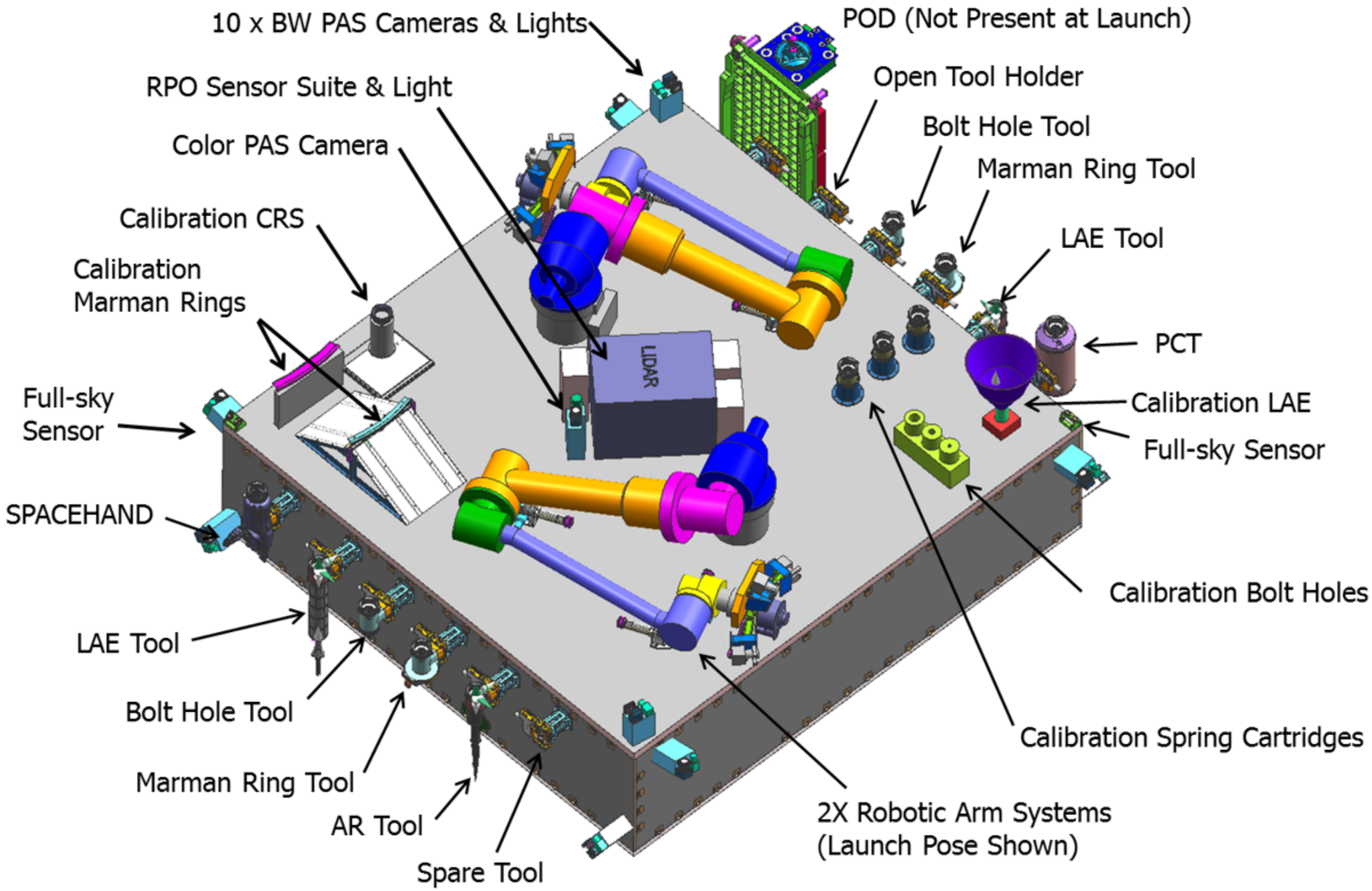






RPO and Contact Dynamics Testbeds

Robotic payload



Partner task description

- Provide the GEO bus
- Provide the ground segment
- Receive integrated robotic servicing payload
- Integrate payload onto bus
- Provide launch vehicle integration
- Execute demonstration mission
- Operate RSV for its lifetime

Ideal partner team has:

- Built GEO buses
- Operated in GEO
- Done RPO
- Lived the GEO business case
- Has a plan to grow satellite servicing and space logistics

Collaborative activities

- RSV design
- Mission planning
- Training of operators
- RSV operations

Key partner attribute:

Commitment to success and growth

This is hard

Show us you understand the problems (e.g., Cyber)

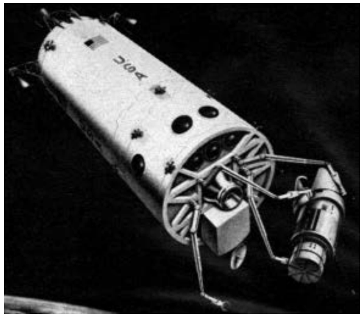
Show us you have options to resolve the hard problems before flight

There will be tradeoffs that we make together

Communicating with us

DARPA-PS-16-01@darpa.mil

Credits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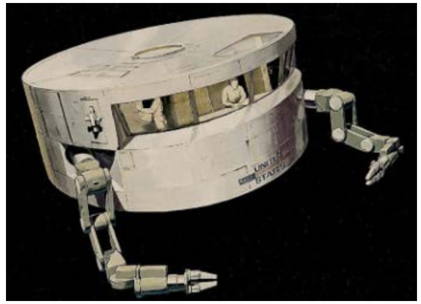
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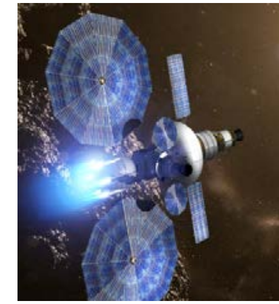
Astronautix.com


orbitalrecovery.com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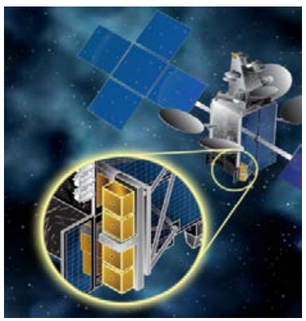
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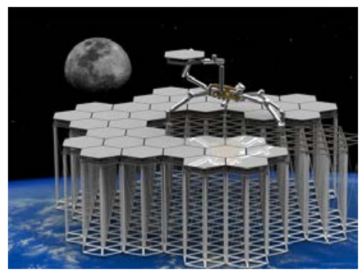
MDA-SSL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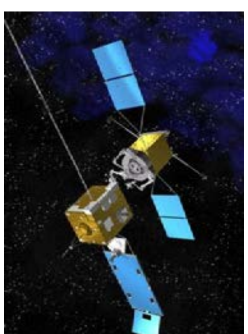
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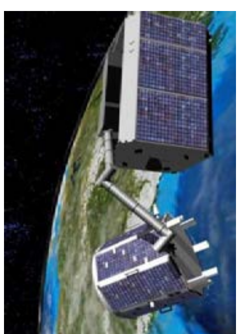
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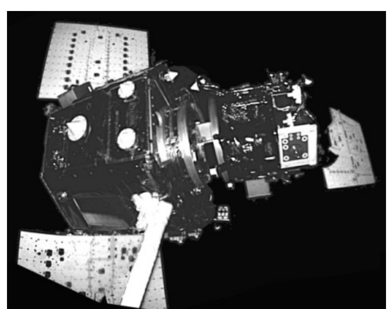
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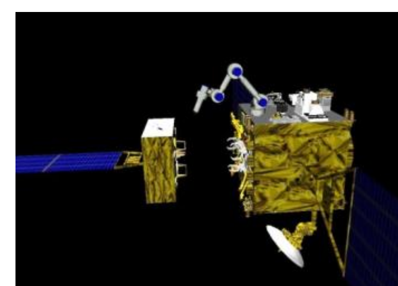

astro.mech.tohoku.ac.jp

Program Solicitation DARPA-PS-16-01

Mark Jones
DARPA Contracts Management Office

May 25, 2016

DISCLAIMER

If the Program Solicitation contradicts any information in these slides,

the Program Solicitation takes precedence.

DARPA RSGS Award Process

Agenda

- Other Transaction Agreement / Program Solicitation
  - What is it
  - Why are we using it
- Program Goals and Evaluation Criteria
  - Evaluation areas
  - Partnership
- Step-by-Step Solicitation Process

Other Transaction (OT) Agreement/Program Solicitation

The Government intends to award a single OT agreement to the offeror whose proposal is determined to be the most advantageous to the Government.

What is it?

- OT is awarded under the authority of 10 U.S.C. § 2371b
- Program solicitation is OT acquisition method
- Non FAR/DFARS based award – e.g. not required to follow Government accounting rules
- OT intended to reflect commercial agreements

Why?

RSGS partnership is a unique method – OT agreements give the parties the freedom to approach this in a more commercial-like manner.

Program Goals and Evaluation Criteria

Evaluation areas

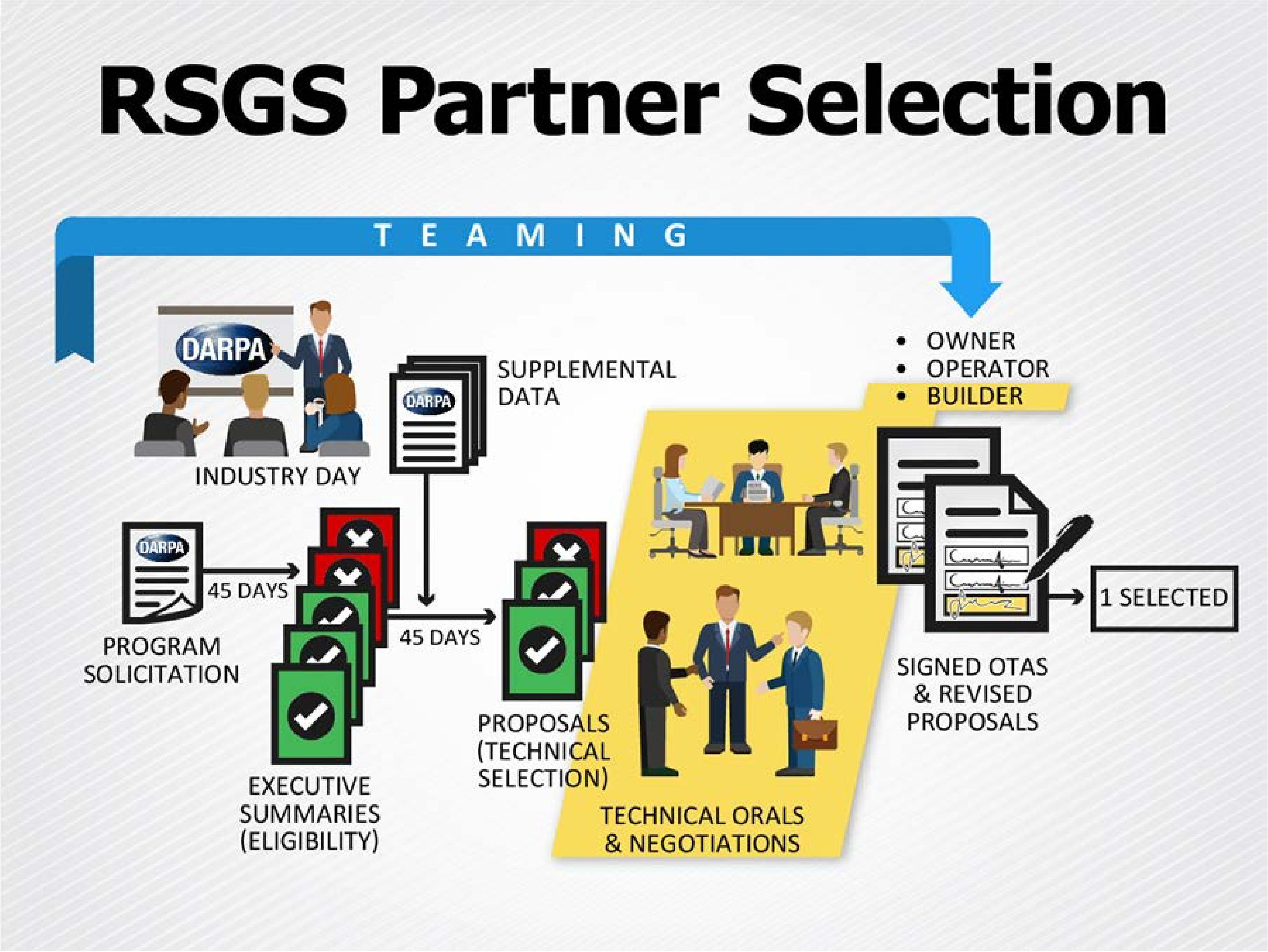
- Technical – can your team technically perform
- Business – not only can your team financially manage, but will your team successfully transition this effort into a persistent servicing capability
- No Traditional Cost Evaluation

Partnership

- Partner team must include a bus manufacturer and the ultimate robotic servicing satellite owner/operator (which may be the same or different commercial entities)
- Teaming partnership matures throughout solicitation process

RSGS Proposers Day

Step-by-Step Partner Selection



Four Step Partnership Selection Process

Step 1 – Eligibility

Step 2 – Proposal Submission / Negotiation Pool

Step 3 – Orals/Negotiations

Step 4 – Final Evaluation/Award

Notes on Submissions

- DARPA will receive unclassified submissions via its web-based upload system. Submission must be in a single zip file not exceeding 50 MB.
- DO NOT include any classified information in the unclassified portion of the submission or it may be deemed non conforming. Follow the appropriate classified submission method as indicated in the program solicitation
- DO NOT wait until the last minute to make submissions – the submission deadlines as outlined in the program solicitation or in subsequent proposal submission instructions will be strictly enforced!
- DO NOT forget to FINALIZE your submission in the submission tool! Failure to finalize will prevent the Government from proper receipt.

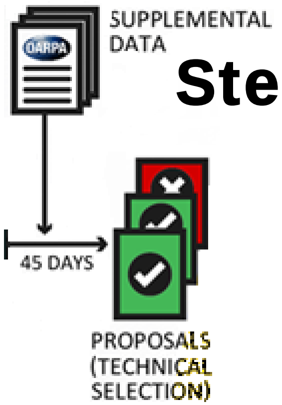
Step 1 – Eligibility

Submit Executive Summary by 5:00pm ET, July 5, 2016

- 15 Page Summary Limit
- Must Prove Eligibility / ITAR Compliance
- Describe overall capacity to meet RSGS program requirements

Government will notify submitters whether qualified to propose

Those qualified will move to Step 2 . . .



Step 2 – Proposal Submission / Negotiation Pool

Eligible proposal submitters will receive supplemental package and proposal submission instructions/due date

- Minimum 45 days to submit
- 200 page limit
- Includes Executive Summary
- Must have "team" defined and bus builder identified

Copy of OT template / terms included in supplemental package – submit updated OT with proposal as Appendix 1.

Appendix 2 – Supplement Business Data

Step 3 - Orals

Proposals deemed most advantageous will progress to technical oral discussions and OT negotiations

- Oral presentations done at proposer facility
- Multiple visits anticipated to cover technical and business management areas
- All proposer teams will complete and submit signed OT at the end of negotiations – all team members must sign and be responsible for final agreement

Step 4 – Final Selection and Award

www.darpa.mil

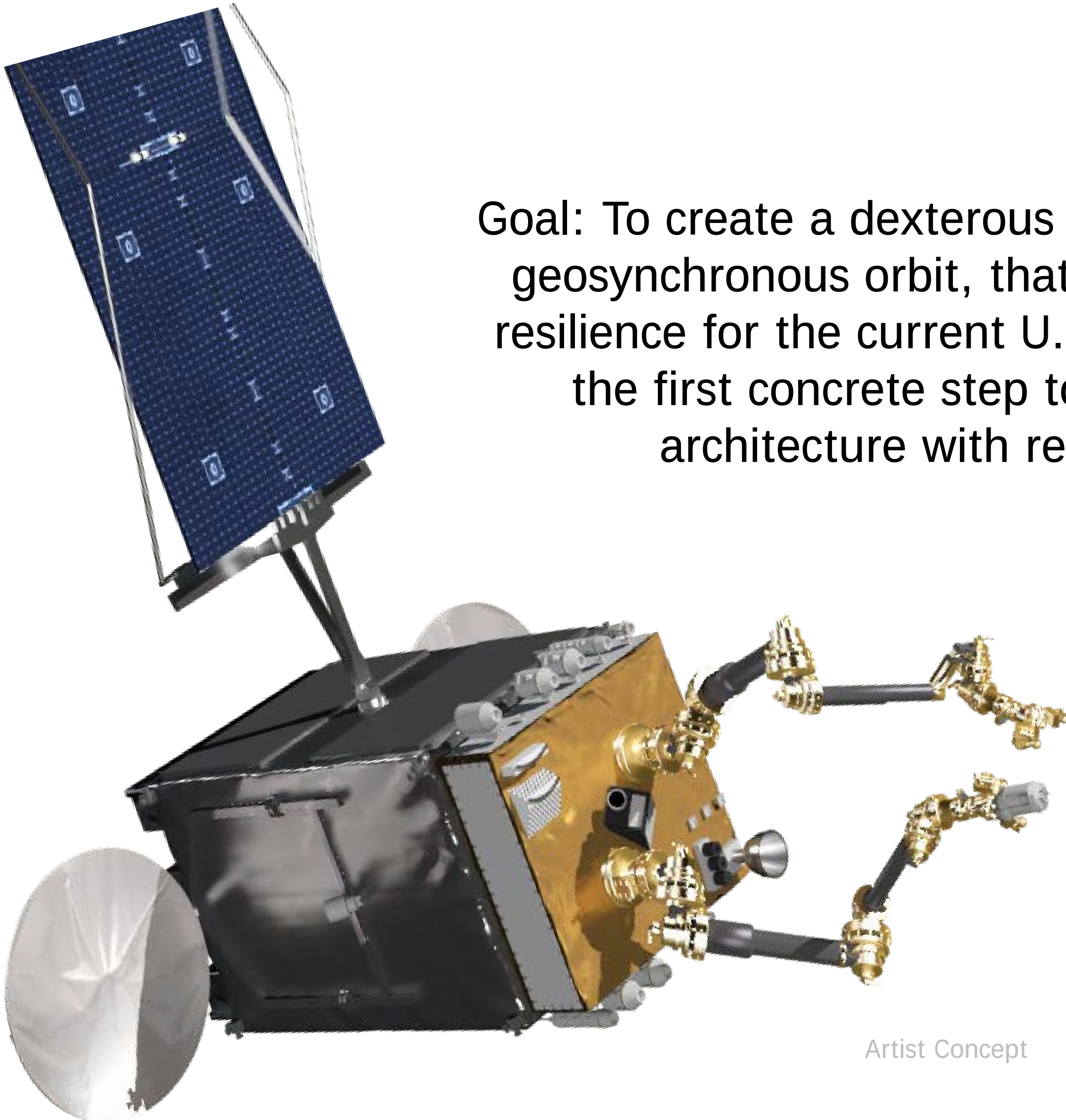
Evaluation Criteria and Partner Selection

Dr. Gordon Roesler

RSGS Program Manager

May 25, 2016

RSGS aims for resilience and transformation



Goal: To create a dexterous robotic operational capability in geosynchronous orbit, that could both provide increased resilience for the current U.S. space infrastructure, and be the first concrete step toward a transformed space architecture with revolutionary capabilities

Artist Concept

Top-level evaluation criteria

- Technical approach
  - Consistency, heritage and supportability
  - Rendezvous and proximity operations (RPO) solution
  - Communications solution
  - Information assurance and cyber security
  - Mission assurance approach
  - Payload accommodation
  - Propulsion solution
  - Mission planning and simulation
  - Expertise of technical team
  - Mission operations center
  - Ground station and network
- Business approach
  - Long range vision for space servicing
  - Investment strategy
  - Financing terms
  - Liability and insurance
  - Customer outreach
  - Management approach, plan and schedule
  - Market analysis
  - Servicing road map and servicer fleet growth
  - Satellite design transformation
  - Government terms for servicing missions
  - Desired teaming approach

Evaluation subfactors (1 of 11)

- Consistency, heritage and supportability of overall approach
  - Extent to which proposed bus solution retains heritage from reliable GEO bus solution and yet consistently meets RSGS objectives
  - Extent to which modifications to bus can be designed and bus delivered on RSGS timeline
  - Extent to which proposed solution is consistent with business approach

- Rendezvous and proximity operations solution
  - Extent to which RPO solution has heritage from past/present RPO sensors, control approaches, and operational practices
  - Extent to which RPO approach relies upon available hardware and software solutions
  - Extent to which RPO approach is consistent with RSGS objectives

Evaluation subfactors (2 of 11)

- Communications solution
  - Ability of proposed comms solution to obtain required spectrum
  - Ability to operate in proximity to client satellites without causing electromagnetic interference or damage to client receivers
  - Ability of proposed comms solution to operate continuously during all phases of RSGS operations
  - Ability of proposed bus to accommodate proposed comms solution

- Information assurance and cyber security
  - Ability of information assurance and cyber security approaches to assure mission performance in a cyber contested environment

Evaluation subfactors (3 of 11)

- Mission assurance approach
  - Ensure mission assurance approach is consistent with RSGS objectives for reliability and endurance
  - Ability to achieve program schedule while implementing proposed mission assurance plans and procedures

- Payload accommodation approach on proposed bus
  - Evaluate analysis of payload impact on proposed bus, including structure, mass, moment of inertia, thermal, electrical, and control
  - Evaluate degree to which proposed bus has considered and evaluated alternative payload accommodation schemes compared to baseline single-module payload

Evaluation subfactors (4 of 11)

- Propulsion solution
  - Ability of proposed propulsion solution to achieve multiple servicing missions
  - Ability of proposed solution to provide adequate thruster authority during proximity operations
  - Ability to minimize pluming of client satellite
  - Maturity of propulsion solution

- Mission planning and simulation
  - Ability of proposer’s simulation environment to provide high-fidelity mission simulations, including robotic actions
  - Ability of mission planning capability to support efficient planning of servicing missions with short lead times

Evaluation subfactors (5 of 11)

- Expertise of technical team. Past performance and expertise in:
  - Rendezvous and proximity operations
  - GEO satellite design, manufacture and operations
  - Bus-to-payload integration
  - Launch campaign support
  - Agile software development
  - Commercial space operations and business practices
  - Government GEO space operations and procedures
  - Information assurance and cyber security

- Mission operations center
  - Ability of proposed ground solution to incorporate robotic payload operations
  - Ability to implement security procedures for servicing of national security spacecraft
  - Ability to support efficient RPO and servicing operations, including integration with NRL-developed Integrated Robotic Workstation

Evaluation subfactors (6 of 11)

- Ground station and network solution
  - Ability to provide 360-degree coverage of GEO belt, consistent with proposed communications solution
  - Analysis of time delays resulting from network infrastructure
  - Ability to provide cyber secure operations

- Long range vision for space servicing
  - Consistency of long range vision with corporate capabilities and proposed RSGS solution
  - Extent to which economic analysis supports long range vision
  - Growth potential of long-range vision and ability to address national security and commercial interests

Evaluation subfactors (7 of 11)

- Investment strategy
  - Extent to which outyear plan for investment results in stable, persistent servicing capability
  - Extent to which strategy includes assessments and decision points relevant to investment timing
  - Extent to which investment strategy will promote growth of servicing market

- Financing terms
  - Ability of financial approach to support delivery of all required RSGS products on schedule
  - Extent to which term sheets have been obtained for all external financing
  - Extent to which internal financing has been approved by Board of Directors

Evaluation subfactors (8 of 11)

- Liability and insurance
  - Extent to which proposer has interacted with insurers to explore rates and terms
  - Extent to which proposer's liability plan will advance the acceptance of space servicing by commercial space operators

- Customer outreach
  - Comprehensiveness of proposer outreach plan for establishment and growth of space servicing market

Evaluation subfactors (9 of 11)

- Management approach, plan and schedule
  - Extent to which management plan will support an effective partnership for design, development and demonstration of RSGS
  - Extent to which proposed schedule will support RSGS timeline
  - Extent to which management plan will support prompt resolution of emergent technical issues
  - Ability of partnership communication plan to maintain ideal partnership functionality

- Market analysis
  - Consistency with long range vision, investment strategy, and financing

Evaluation subfactors (10 of 11)

- Servicing road map and servicer fleet growth
  - Evaluate servicing road map and growth plan for consistency with long range vision, investment strategy, and financing

- Satellite design transformation
  - Ability of proposed servicing approach to influence design of future GEO satellites
  - Ability of team to affect satellite design and requirements
  - Ability of team to communicate advantages of transformed satellite designs to customers

Evaluation subfactors (11 of 11)

- Assured Government terms for servicing missions
  - Extent to which business case depends upon Government business for sustainability, and what terms are required to achieve sustainability
  - Extent to which proposers have held discussions with Government customers to establish servicing needs
  - Extent to which proposers have developed conceptual servicing missions and payloads to address projected Government requirements

- Desired teaming approach and terms
  - Extent to which team decision process supports execution of RSGS program
  - Extent to which terms of the proposed Other Transactions agreement support RSGS objectives, corporate objectives, and long-term development of space servicing

Tell us what supplemental data you need for your proposal

DARPA-PS-16-01@darpa.mil

www.darpa.mil

RSGS Payload Technical Overview

Bill Vincent
NRL Program Manager

May 25, 2016

Outline

- NRL space robotics history
- RSGS mission introduction
- Robotic servicing vehicle (RSV) overview
- GEO robotics payload overview
- GEO robotics payload components
  - Robotic arm system (RAS)
  - Tools and docking system
  - Payload rendezvous and proximity operations (RPO) suite
  - Proximity awareness system (PAS)
  - Payload electronics
  - Robotic control algorithms
  - Payload flight software
- RSV bus assumptions and expected interfaces
- Ground system
- Mission concept of operations
- NRL test and development capabilities
- Mission areas: “What Could the Payload Do?”

NRL Space Robotics History

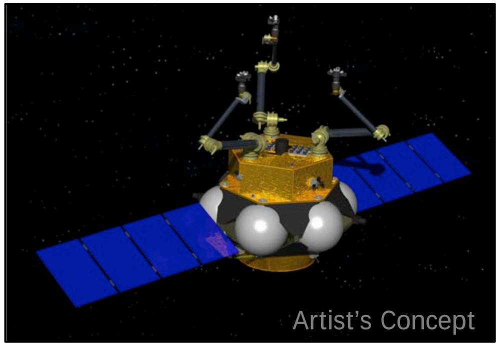
NRL Space Robotics History

- RSGS is benefiting from multiple past DARPA programs with substantial technology development performed at NRL.

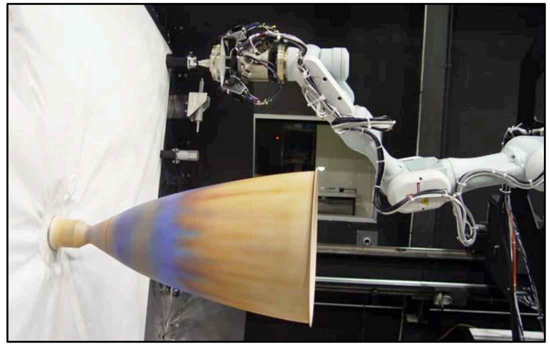
- The core focus of the technology development has been maturing elements of robotic servicing for government and commercial missions:
  - 2002-2005 – SUMO: Spacecraft for the Universal Modification of Orbits
  - 2005-2009 – FREND: Front-end Robotics Enabling Near-term Demonstration
  - 2009-2010 – FREND Application Studies
  - 2010-2011 – MGS: Manned Geo Servicing Study, joint study by DARPA/NASA
  - 2011-2013 – Phoenix
  - 2014-2015 – Phoenix (GEO Robotics)
  - 2015-Launch – Robotic Servicing of Geosynchronous Satellites (RSGS)

- Focus throughout has been:
  - Systems engineering to identify where development is needed to enable robotic servicing as a national capability
  - Risk reduction and technology development to mature capability
  - Robust laboratory testing to validate technologies and system integration

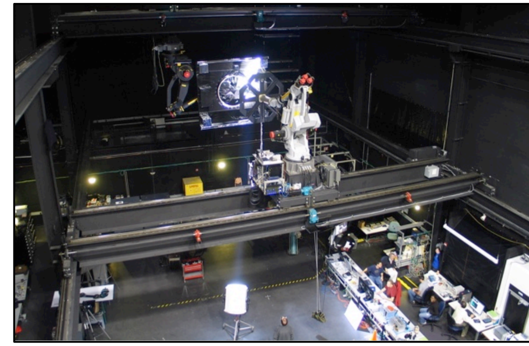
DARPA/NRL Space Robotics History Highlights



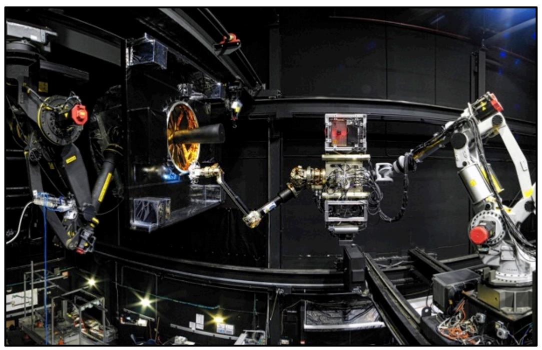
2004: SUMO Point Design



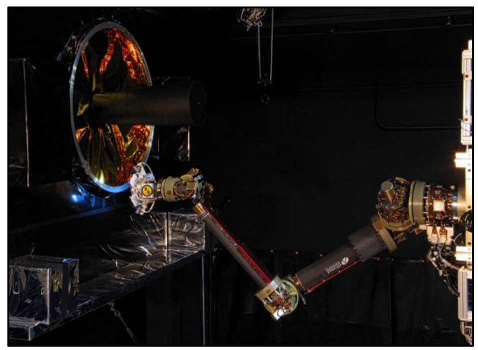
2004: SUMO Grapple Demonstration



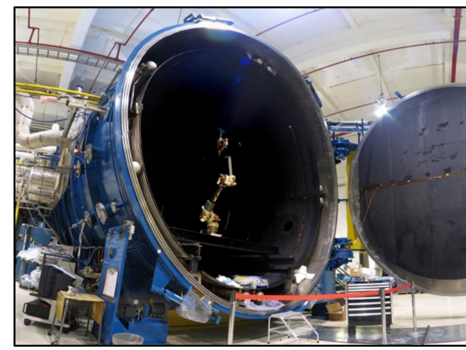
2005: SUMO RPO & Grapple Demonstration



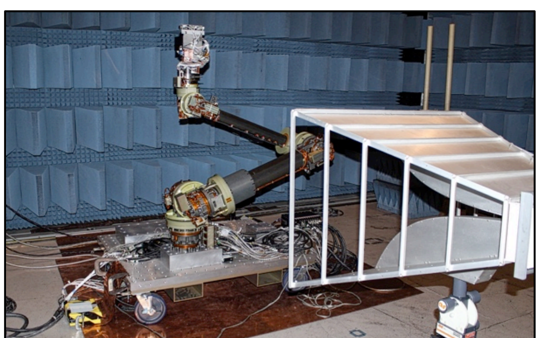
2008: FREND EDU Grapple Demonstration



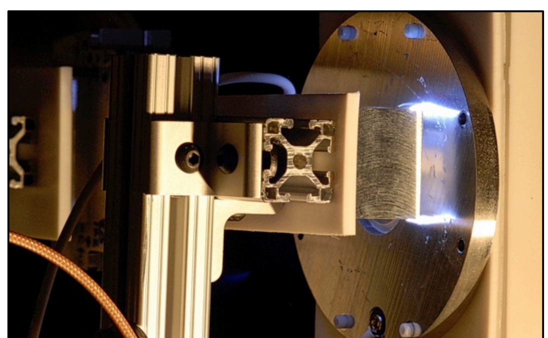
2008: FREND Flight Prototype Grapple



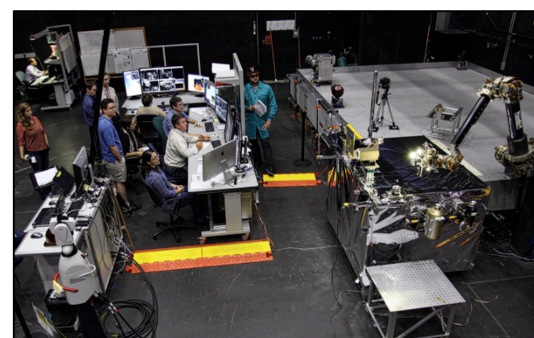
2009: FREND Environmental Testing



2013: Phoenix EMI Testing



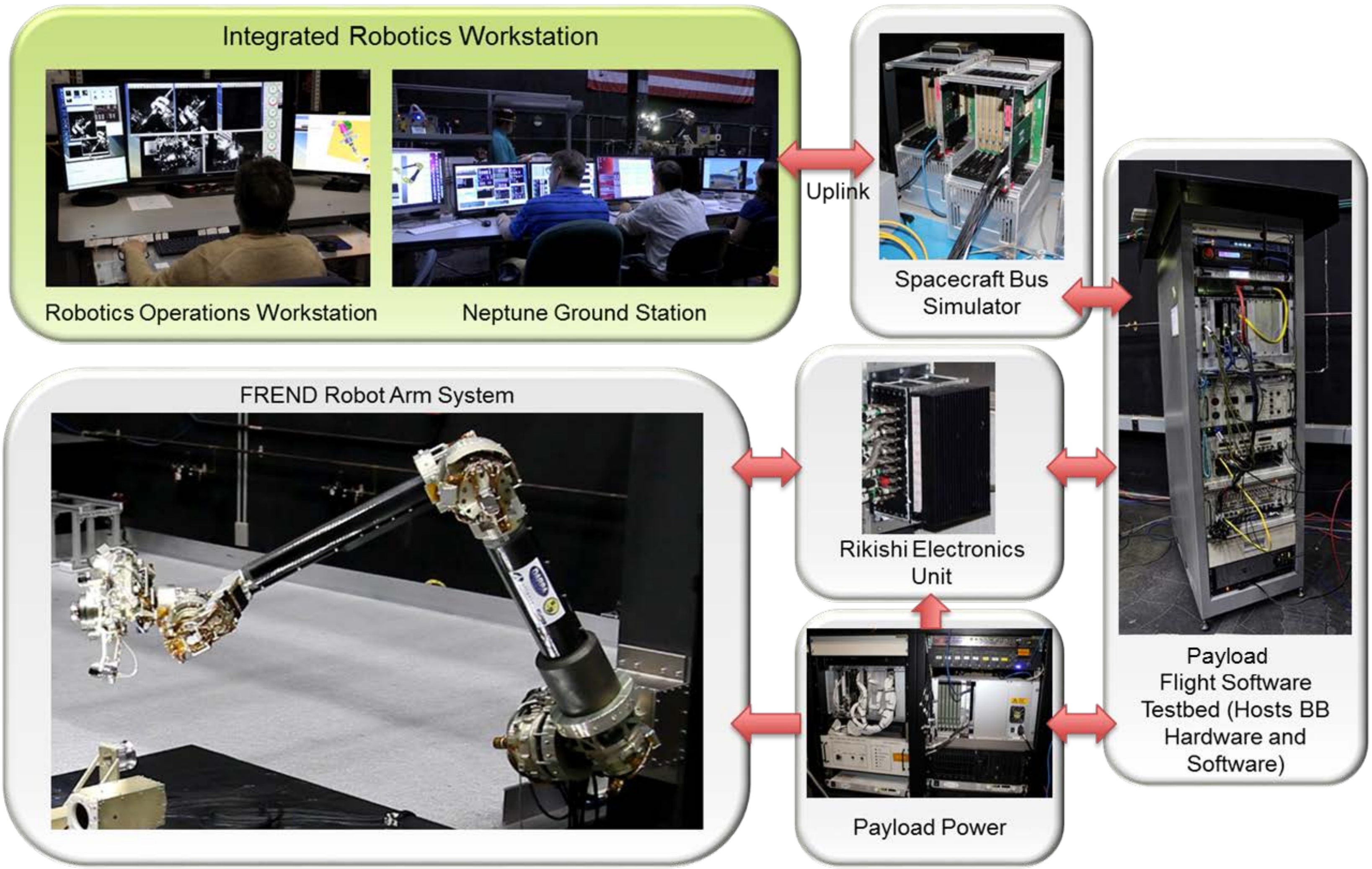
2013: Phoenix First Contact Discharge R&D



2014: Phoenix Teleoperations Tool Testing

NRL Images

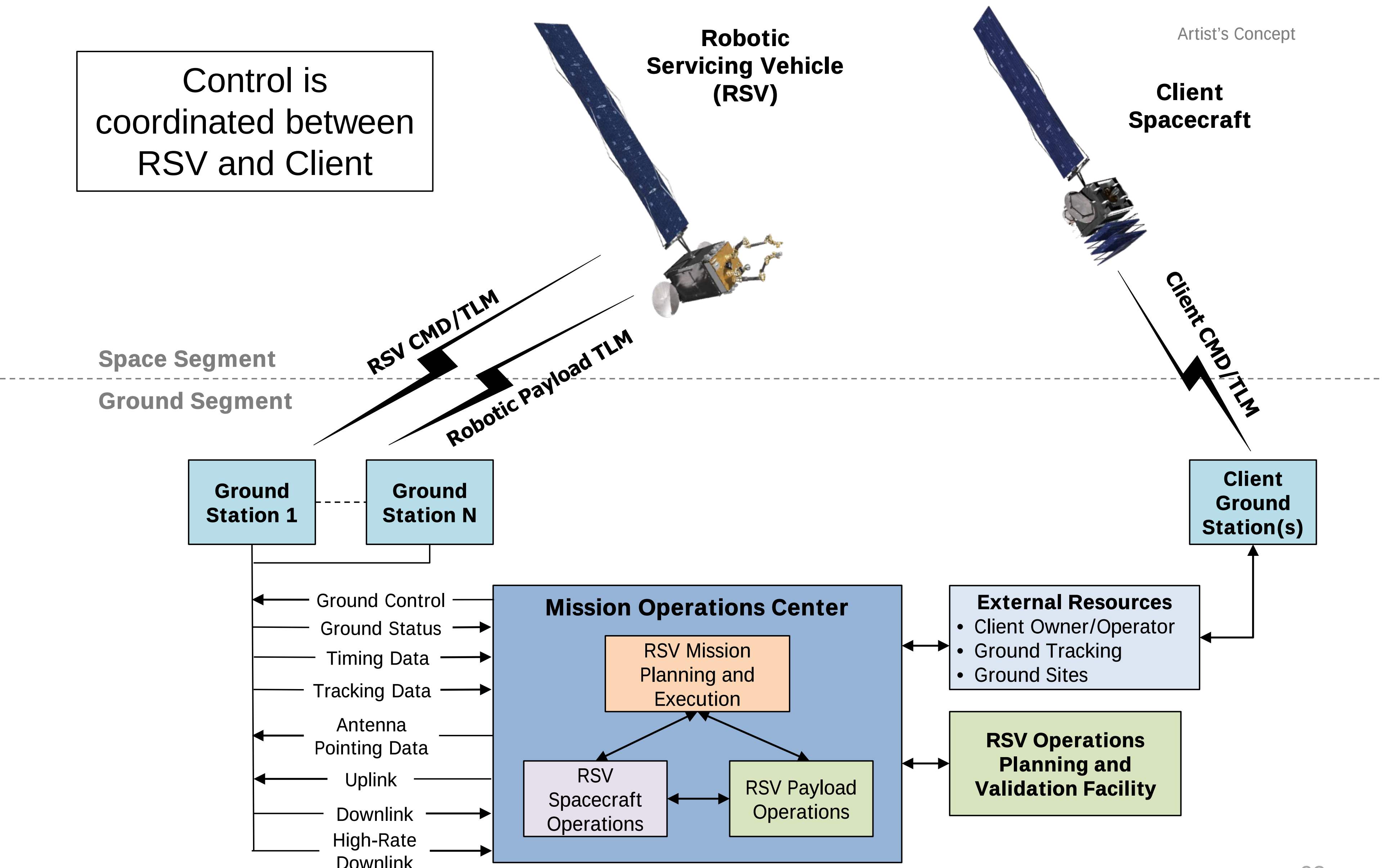
2015: RSGS Flight Architecture Demo 0



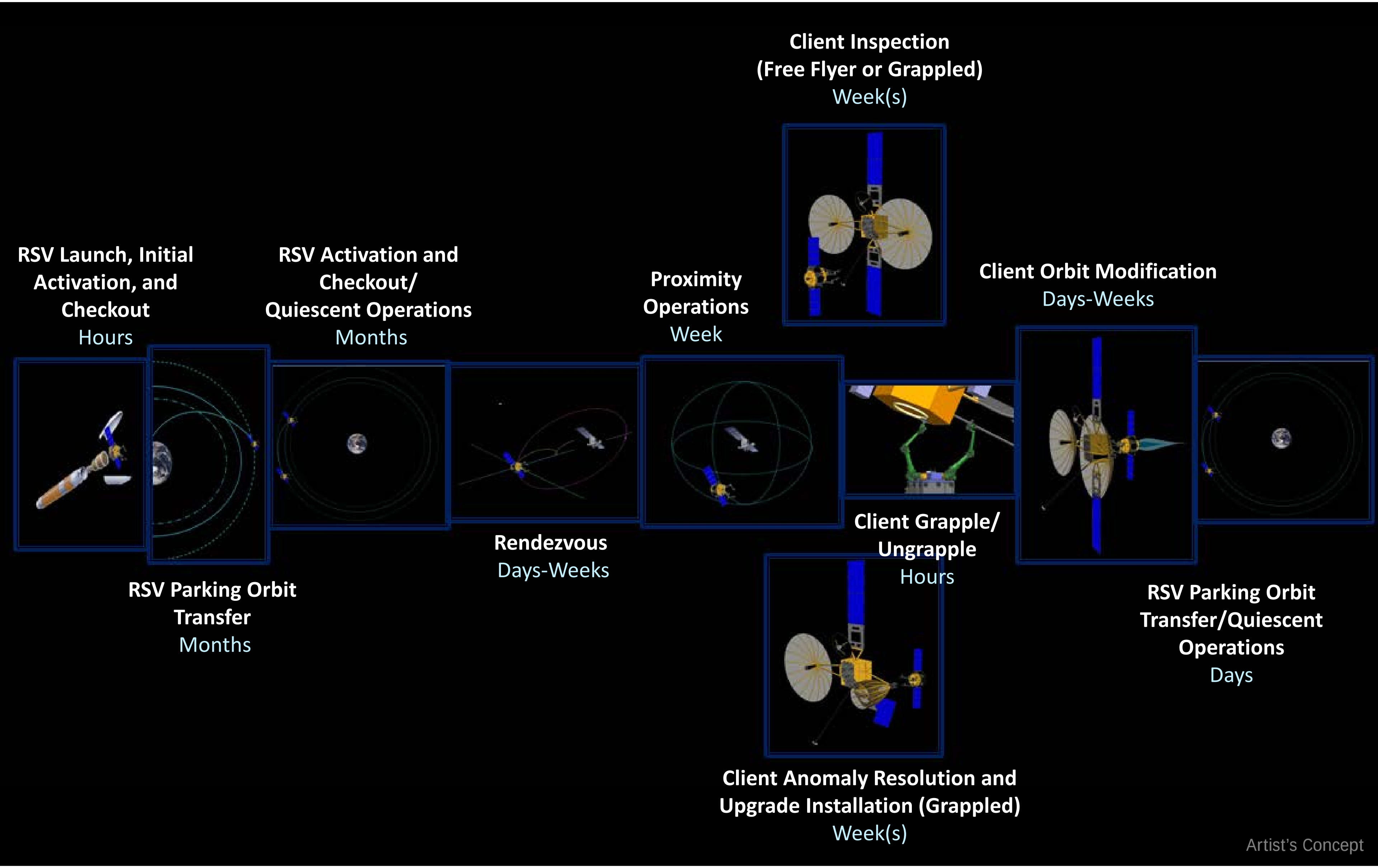
Demonstrated end-to-end flight architecture signal chain

RSGS Mission Introduction

RSGS Architecture Block Diagram



RSGS Concept of Operations



Top-Level Payload Objectives

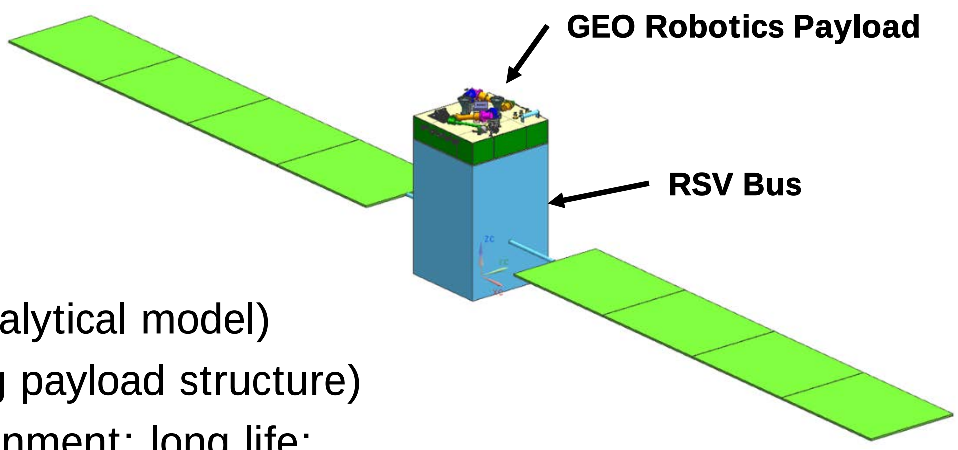
- Design objectives
  - RSV design based on Phoenix and FREND technologies
  - Program is a DoD Class B Mission
    - Single-point failures should be avoided if critical or where cost-effective
    - Level 2 Parts per EEE-INST-002
    - Redundancy used in some critical functions or where cost-effective
  - The RSV is designed to be single-fault tolerant to a loss of primary mission for long life
    - Designed for graceful degradation
    - Block and functional redundancy used as needed to support design philosophy
    - Quality of components and design practices should result in five-year to eight-year payload mission life

- Operational objectives
  - Conduct a government on-orbit checkout, commissioning, and demonstration period that is nominally 6-9 months
  - Perform post-demonstration servicing missions under the management and control of an organization outside the government
  - Perform cooperative autonomous grapple/ungrapple of GEO satellites
  - Be capable of performing cooperative servicing missions anywhere in the GEO ring
  - Be capable of grappling Liquid Apogee Engine (LAE), bolt hole, and Marman ring interfaces on GEO satellites

Robotic Servicing Vehicle (RSV) Overview

Pre-Selection RSV Concept

- To date, DARPA and NRL development efforts have focused on the payload technologies required to support the mission
- In lieu of having a bus defined, NRL has created a high-level functional allocation of RSV subsystems between the RSV bus and the GEO robotics payload to allow the payload design to mature
  - The RSV concept design was used as a point of departure for the payload design and requirements development
  - A "generic" RSV is being used as a baseline "stand-in" to perform required RSV-to-client system-level analysis and trades



Artist's Concept

- RSV assumptions overall
  - "Generic" RSV mass (wet): 4,500 kg (analytical model)
  - RSV payload mass: ~1,000 kg (including payload structure)
  - Class B per DOD-HNDK-343; GEO environment; long life; block redundant power and avionics
  - Two-arm configuration (two FREND MKII RAs) and supporting equipment
  - GEO robotics payload requires coordinated control of RSV and Client

GEO Robotics Payload Overview

Payload Point Design Description

- NRL's point design has focused on a monolithic payload with two robotic arms designed to fully meet the government mission objectives for cooperative servicing
- To match government objectives with commercial objectives, variations from this starting point may be desired

- DoD Class B reliability: Single-fault tolerant to criticality 1 (mission-ending) failures
  - Block-redundant Robotic Arm Systems
    - Based on the assumption that 1 RAS is adequate to perform the full mission
  - Block redundant avionics
  - Block redundant orbit-modification mission tools (first grapple tools)
  - Functionally redundant RPO
  - Robotic arm design allows for graceful degradation to arm faults

- Design practices, component selection, and design tolerance against single faults expected to result in five-year to eight-year payload mission life

- 100 krad/Level 2 parts per EEE-INST-002; GEO Env

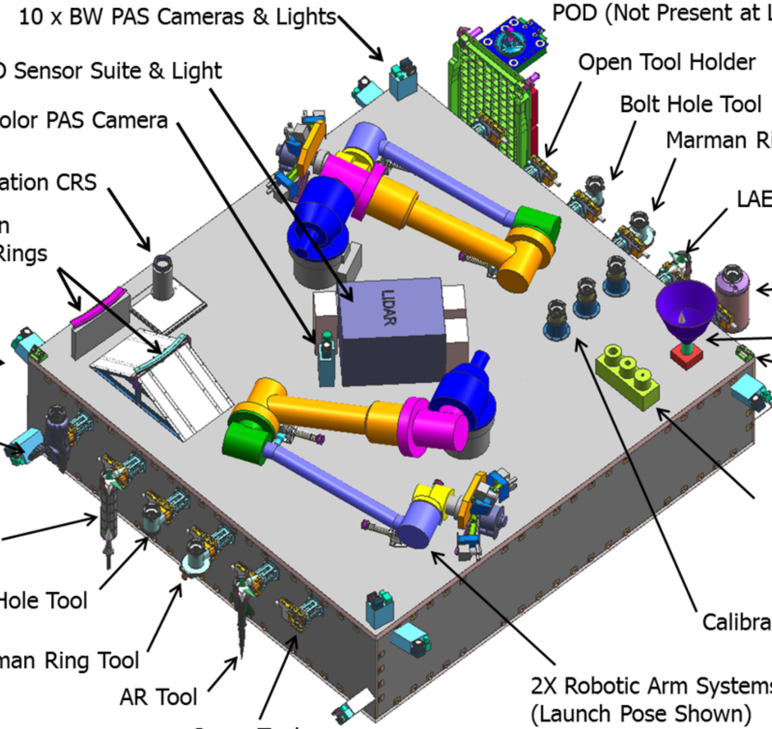
- Protoqualification verification test program

Long-life payload would leverage DARPA investments

Payload Notional Layout (Stowed)

- 2 Robotic Arm Systems
- 1 POD accommodation
- 12 tool/POD holding slots
- 2 CT&DH and EPS chains (internal)
- Toolkit (10)
  - 2 Marman Ring Tools
  - 2 Bolt Hole Tools
  - 2 Liquid Apogee Engine Tools
  - 1 Anomaly Resolution Tool
  - 1 PODS Capture Tool
  - 1 Spacehand
  - 1 Spare Tool
- Proximity Awareness Sensors
  - Deck mount BW cameras
  - Deck mounted lights
  - 1 Color Camera
  - Full-sky coverage sensors

NRL Image

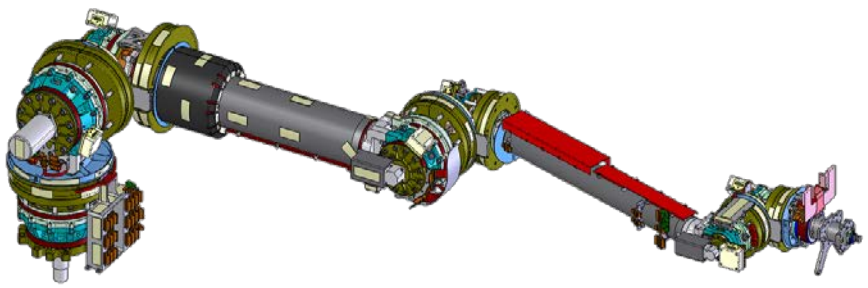


- RPO Sensor Suite
  - LIDAR
  - Narrow Field Cameras, Wide Field Cameras, and Lighting
  - Infrared Camera
- Calibration Hardware

GEO Robotics Payload Components

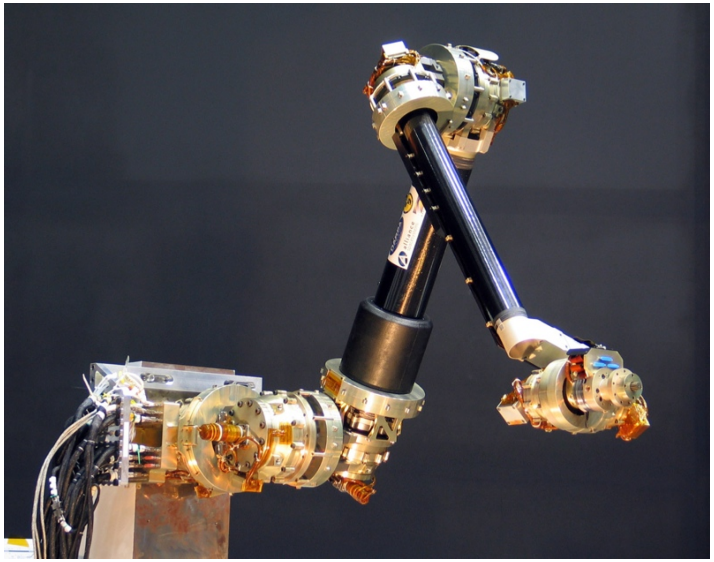
Robotic Arm System

Robotic Arm System (RAS) Definitions

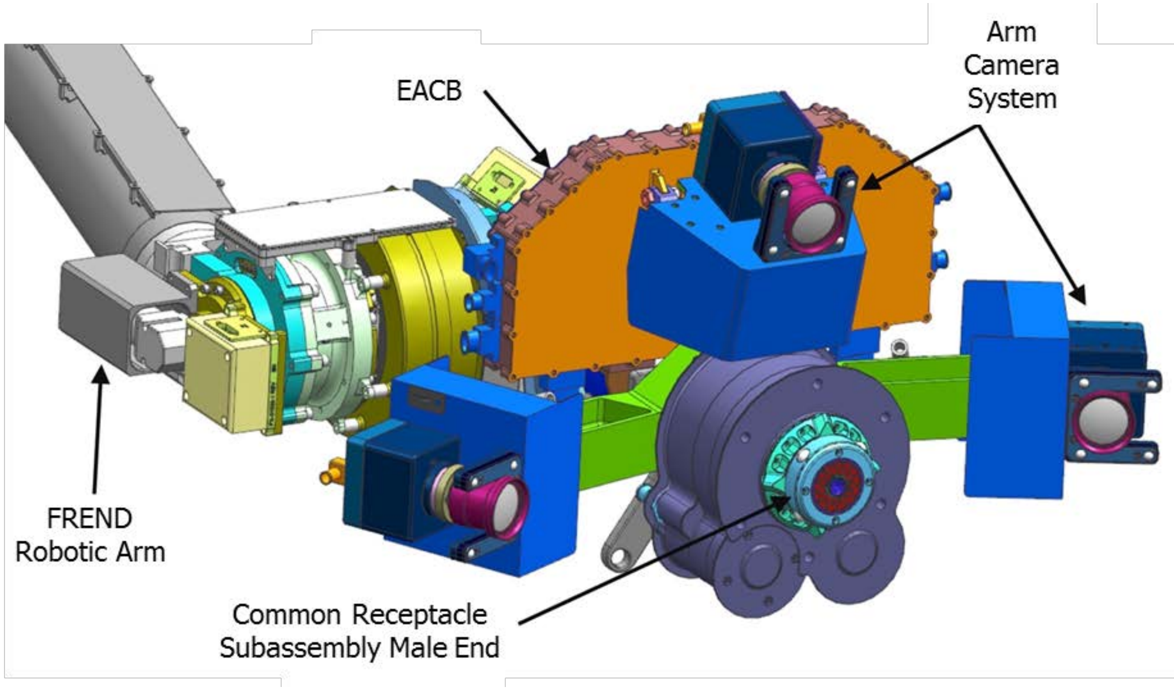


FREND MKII Robotic Arm

- Robotic Arm System:
  - Front-end Robotics Enabling Near-term Demonstration (FREND) Robotic Arm (RA)
  - Rikishi Electronics Unit (REU)
  - End-of-Arm (EoA) Subassembly
    - o End-of-Arm Control Board (EACB)
    - o Tool Changer
    - o Camera system with lens-mounted lights

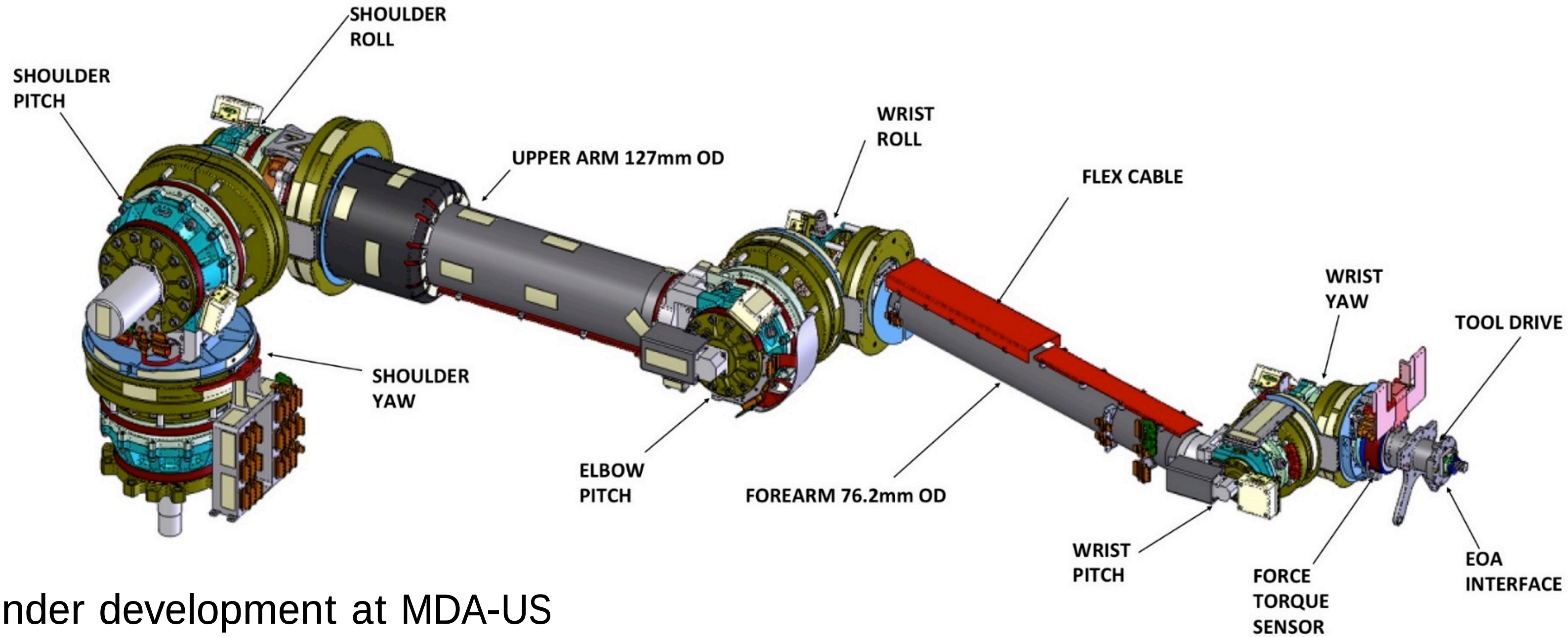


FREND EDU Robotic Arm



End-of-Arm Subassembly

FREND Mark II Robotic Arm

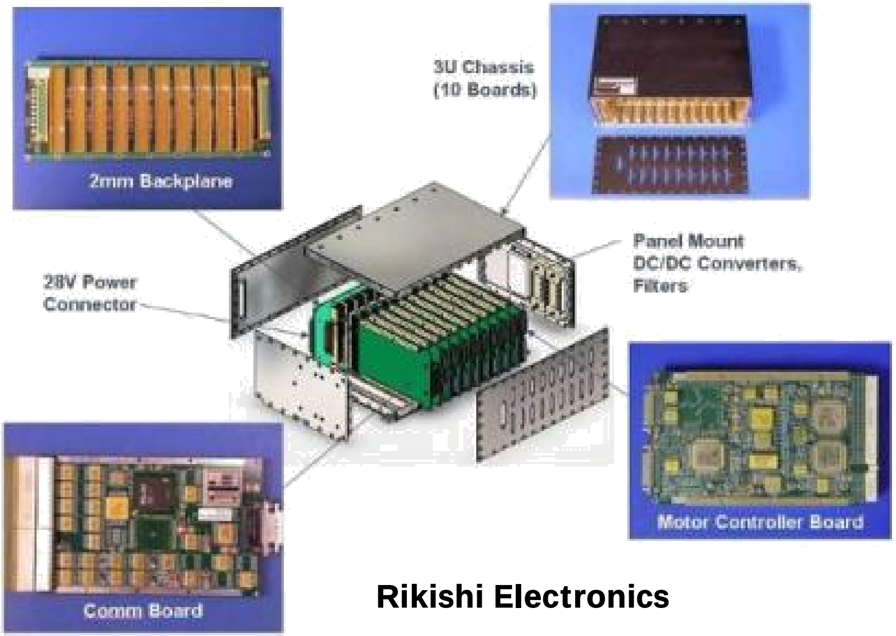


- Under development at MDA-US
- 2 Meter Class, 7-DOF Robotic Arm
- Capable of 1g operations – critical for robust system-verification testing
- FREND Mark II arm incorporates several design improvements, including upgraded resolver electronics, improved grounding, and enhanced flex harness design
- First-generation FREND EDU used extensively for system-level testing for the last 8 years
- First-generation FREND FPU completed flight-qualification testing (vibe, TVAC, EMI) in 2008
- Mark II flight units planned for delivery in 2018

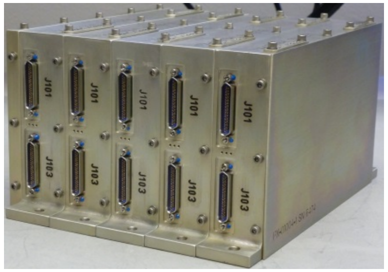
FREND 7-DOF arm design is robust and is designed to enable multiple missions

Robotic Arm Electronics

- Rikishi arm control electronics - under development at Moog Broad Reach under contract to MDA-US
  - 9 Motor Control Boards (MCBs) (SY, SP, SR, EP, WY, WP, WR, TD1, TD2)
  - 1 COMM Card
  - 1 Mother Board
- Motor and power filter boxes – under development at MDA-Brampton under contract to MDA-US
- Mark I Rikishi EDU has been operating successfully at NRL since 2007
- EM units planned for late 2016, flight units planned for 2018



Rikishi Electronics



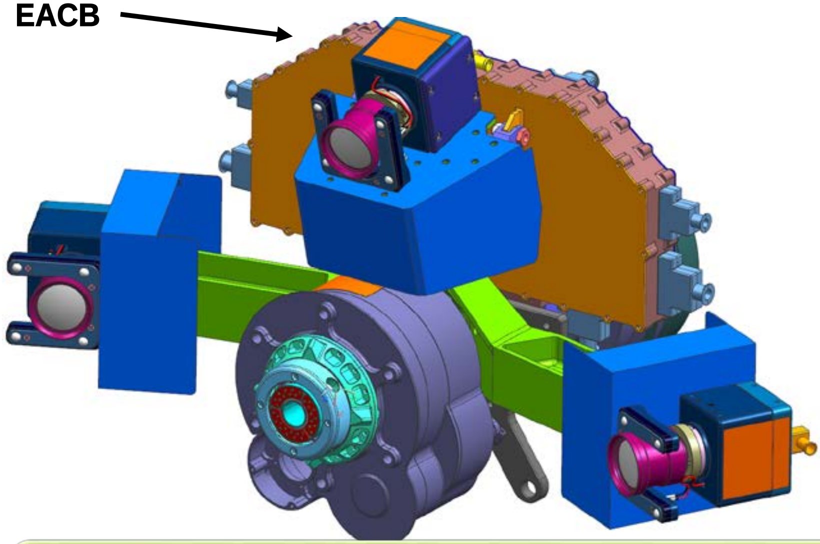
EM Motor Filter Box

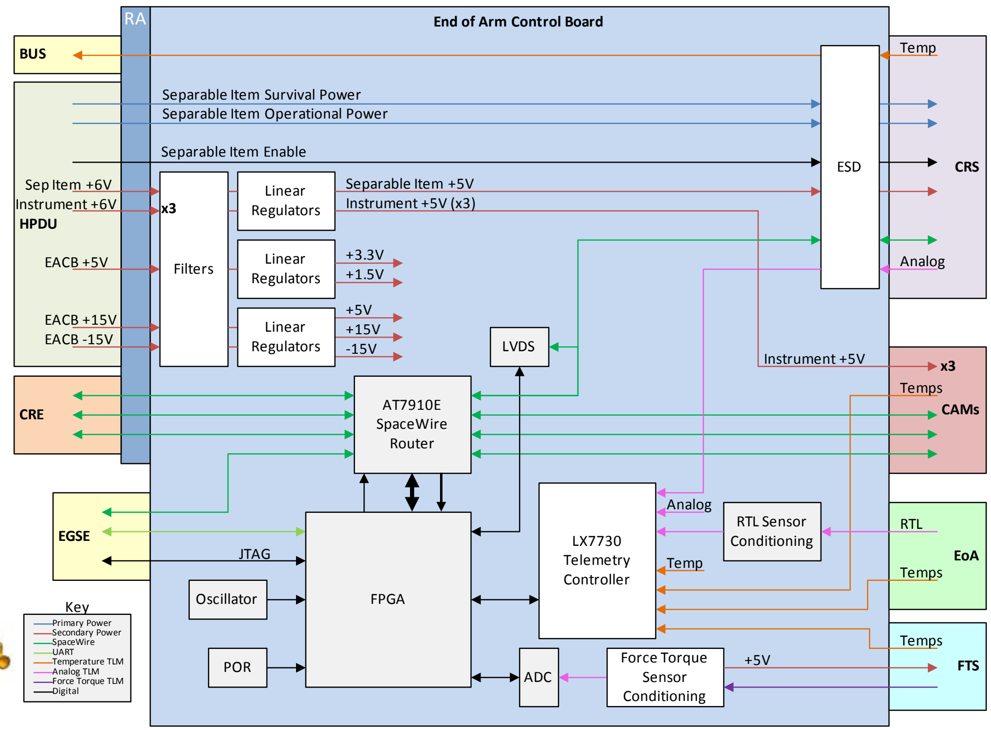
Arm electronics would provide system reliability through test-proven design

End-of-Arm Control Board (EACB)

- Under development at NRL
- Provides digital control of end-of-arm cameras, lighting, and Tool Changer
- Provides Force/Torque Sensor signal conditioning
- Provides SpaceWire router to switch between camera and tool sources
- Breadboard EACB in production
- EDU expected in 2017
- Flight units expected in late 2018

EACB





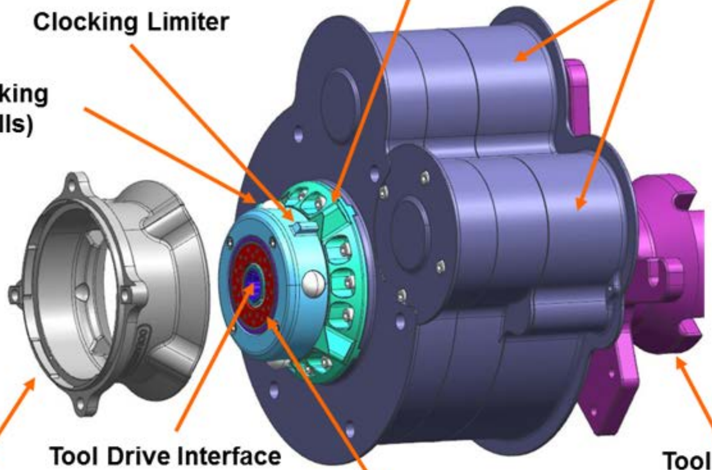
EACB provides reliable digital signals via FREND arm flex harness

Tool Changer System

- Under development at Oceaneering
- Provides the common electrical and mechanical interface for on-orbit tool attachment
  - Supports attachment and detachment of a wide range of tool types
  - Provides power, analog data, and digital data interface for changeable tools
  - Passes torque from FREND arm tool drive to tools
- Prototype has been operating successfully at NRL since 2014
- EM units planned for delivery spring 2017
- Flight units planned for early 2019

Prototype CRS

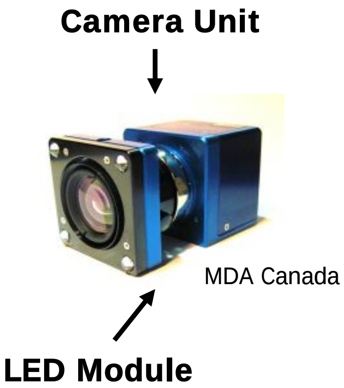
Prototype Tool Changer

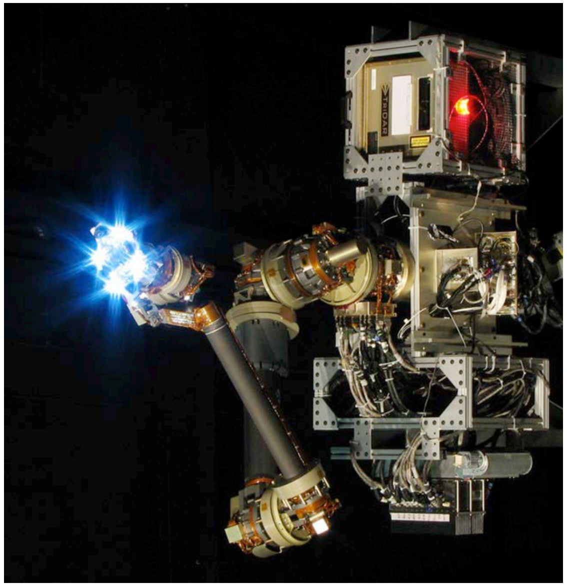


Tool Changer enables mission flexibility and reliability

End-of-Arm Camera with Lighting

- Imagers are planned to be small, lightweight, 5MP or better
- Imaging system includes an LED lighting system
- SpaceWire interface used for communications and image output
- Imagery is used as primary input into machine vision algorithms
- Imagery to be recorded for close-proximity, high-resolution inspection missions
- Engineering models needed in early 2018, flight units by early 2019





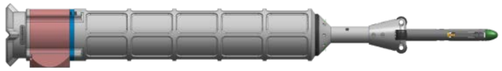
End-of-arm cameras for machine vision and precision inspection

Tools and Docking System

Baseline Payload Tools

- Baseline suite of 10 tools:
  - LAE Grapple Tool (quantity: 2)
  - Marman Ring Grapple Tool (quantity: 2)
  - Bolt Hole Grapple Tool (quantity: 2)
  - Spacehand (quantity: 1)
    - Being developed by DLR
    - German technology demonstration with DARPA
  - PODS Capture Tool (PCT) (quantity: 1)
  - Passive Anomaly Resolution Tool (quantity: 1)
  - Spare Tool (quantity: 1)
    - Slot reserved for future expansion or new mission requirement/capability

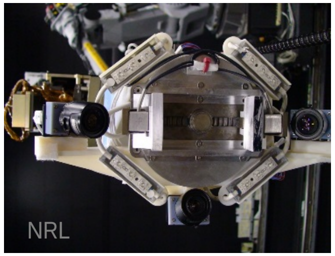
Artist's Concept



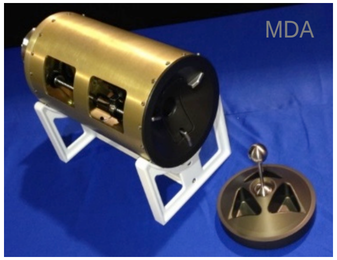
LAE Tool Concept

Artist's Concept

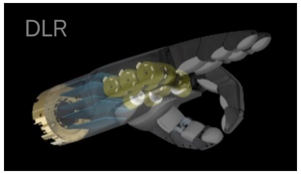
Anomaly Resolution Tool Concept



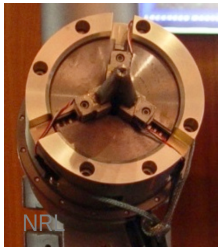
Marman Ring Tool



PODS Capture Tool



Spacehand

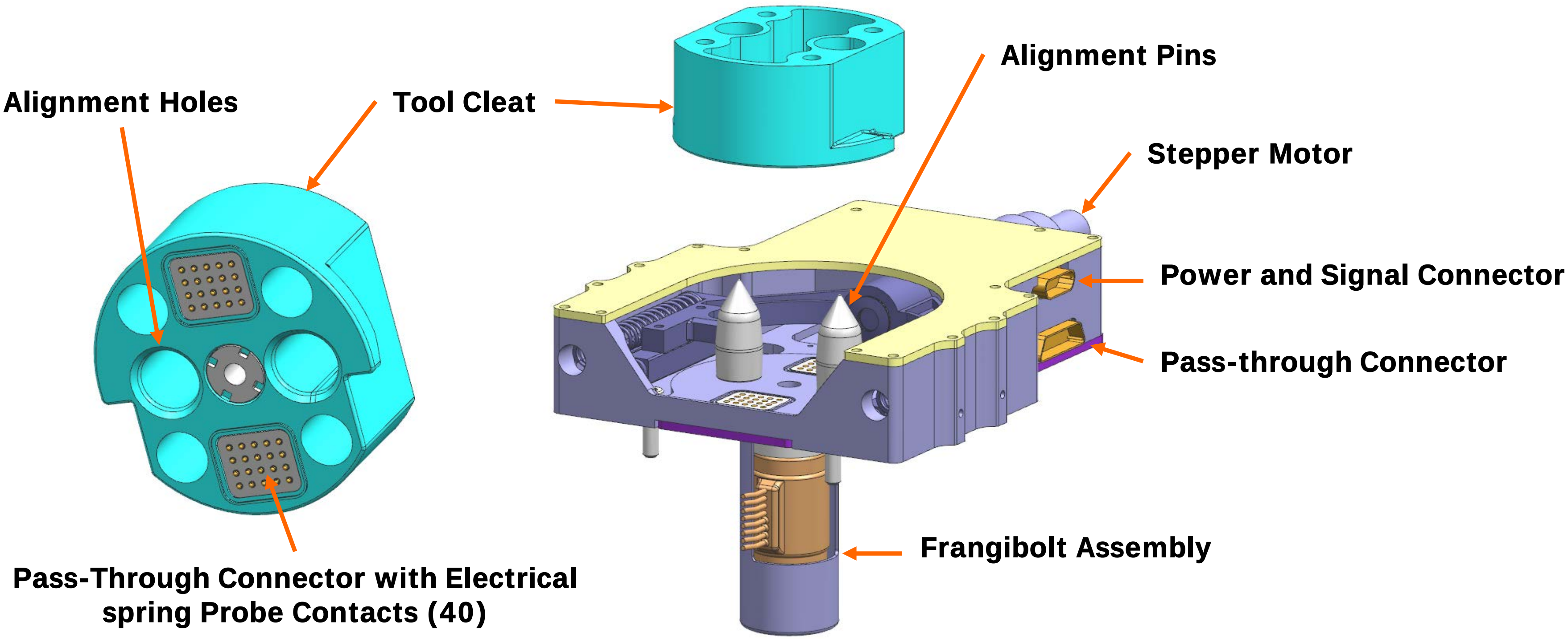


Bolt Hole Tool

Tool suite for redundancy, robustness, flexibility, and expandability

Tool and POD Holder

- Provides a standard launch interface for tools
- Provides an on-orbit restraint and release system to structurally mount tools and PODs to the RSV payload for storage
- Provides mounting points for future assembly missions
- Passes survival power to and reads data from tools and PODs
- POD UDS from MDA-US is shown, alternate approaches are being studied



Standard interface for mission flexibility

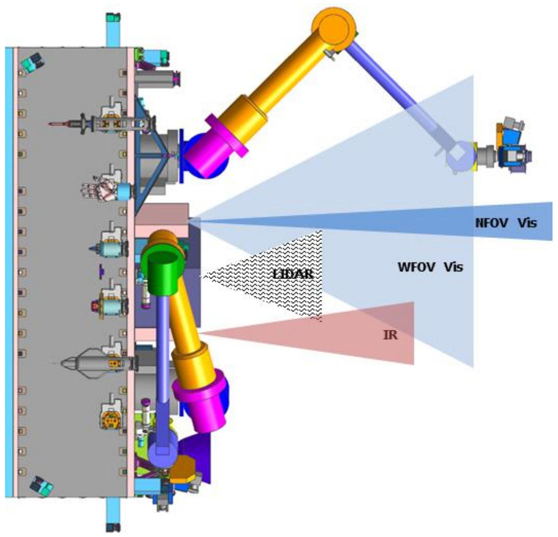
Payload Rendezvous and Proximity Operations Suite Point Design

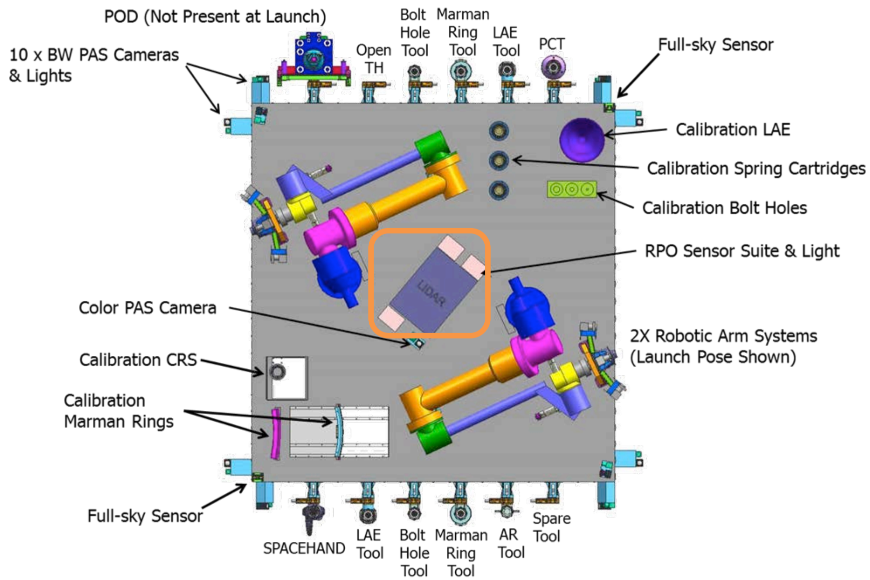
Rendezvous and Proximity Operations (RPO)

- The RPO Suite consists of the RPO sensors and pose estimation code
- The notional RPO sensors consist of two visible cameras, one IR camera, and one LIDAR
- Payload avionics process RPO sensor data and calculate range and bearing at long distances and relative pose for close-proximity operations
- Range/bearing or relative pose solution is sent to the bus as input to the relative navigation filter
- Filtered pose is transmitted back to the payload from the bus during grapple operations for use in the robot arm trajectory planner
- Partner experience, expertise, and preferences in RPO sensor suite selection are welcomed both in responses and in potential future negotiations

Highly capable suite for RPO and grapple without fiducials

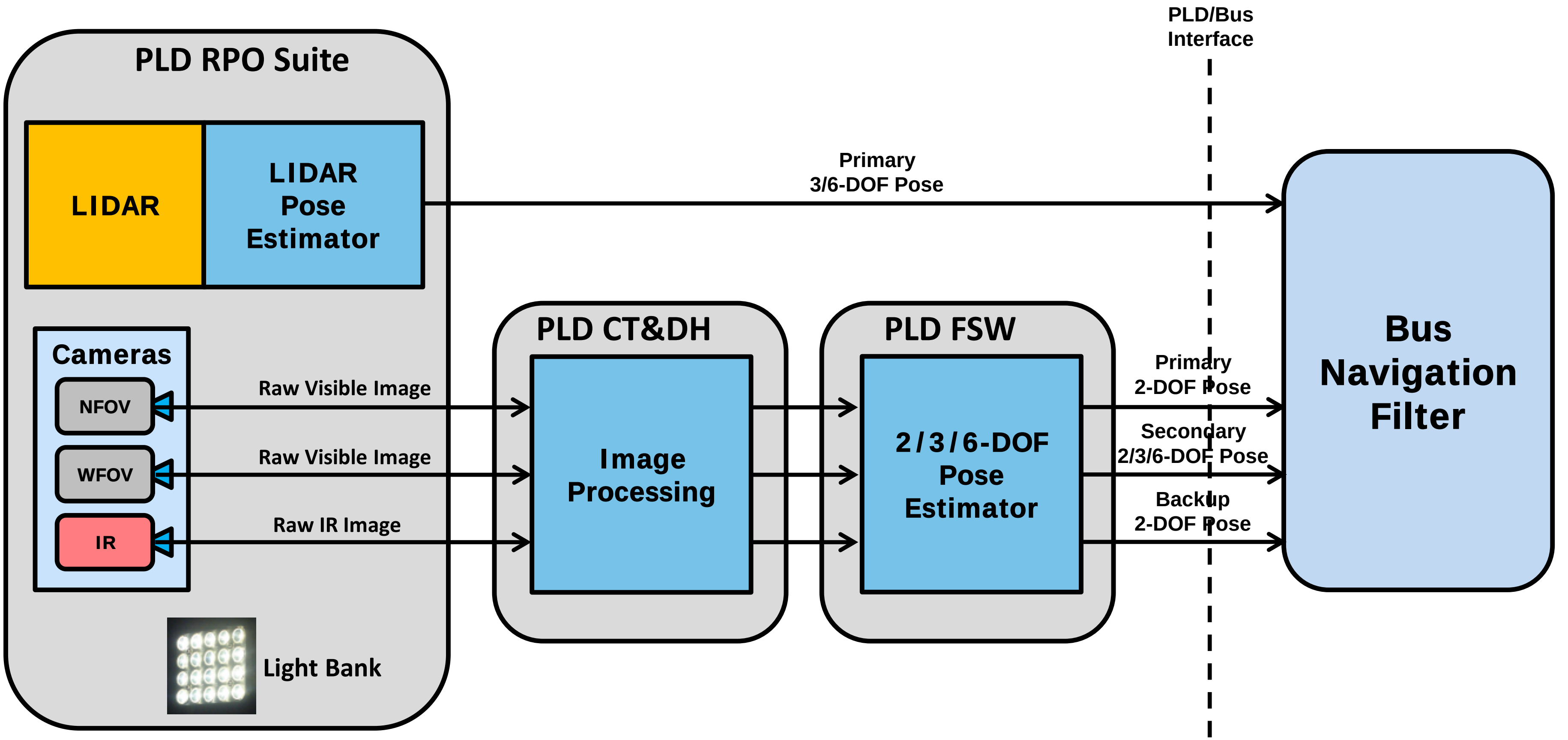
RPO Point Design





- The RPO suite generates relative pose information and imagery
  - 1 NFOV visible camera
  - 1 WFOV visible camera
  - 1 IR camera
  - 1 LIDAR pose sensor
  - 1 light bank
- NFOV camera and LIDAR pose sensor serve as primary sensors from acquisition to grapple
- WFOV camera serves as secondary sensor from acquisition to grapple, providing imagery to PLD FSW for secondary pose calculation
- Optional configuration could replace WFOV camera with second LIDAR or a WFOV pose camera, bypassing the need for secondary pose calculation in the PLD FSW

RPO Block Diagram



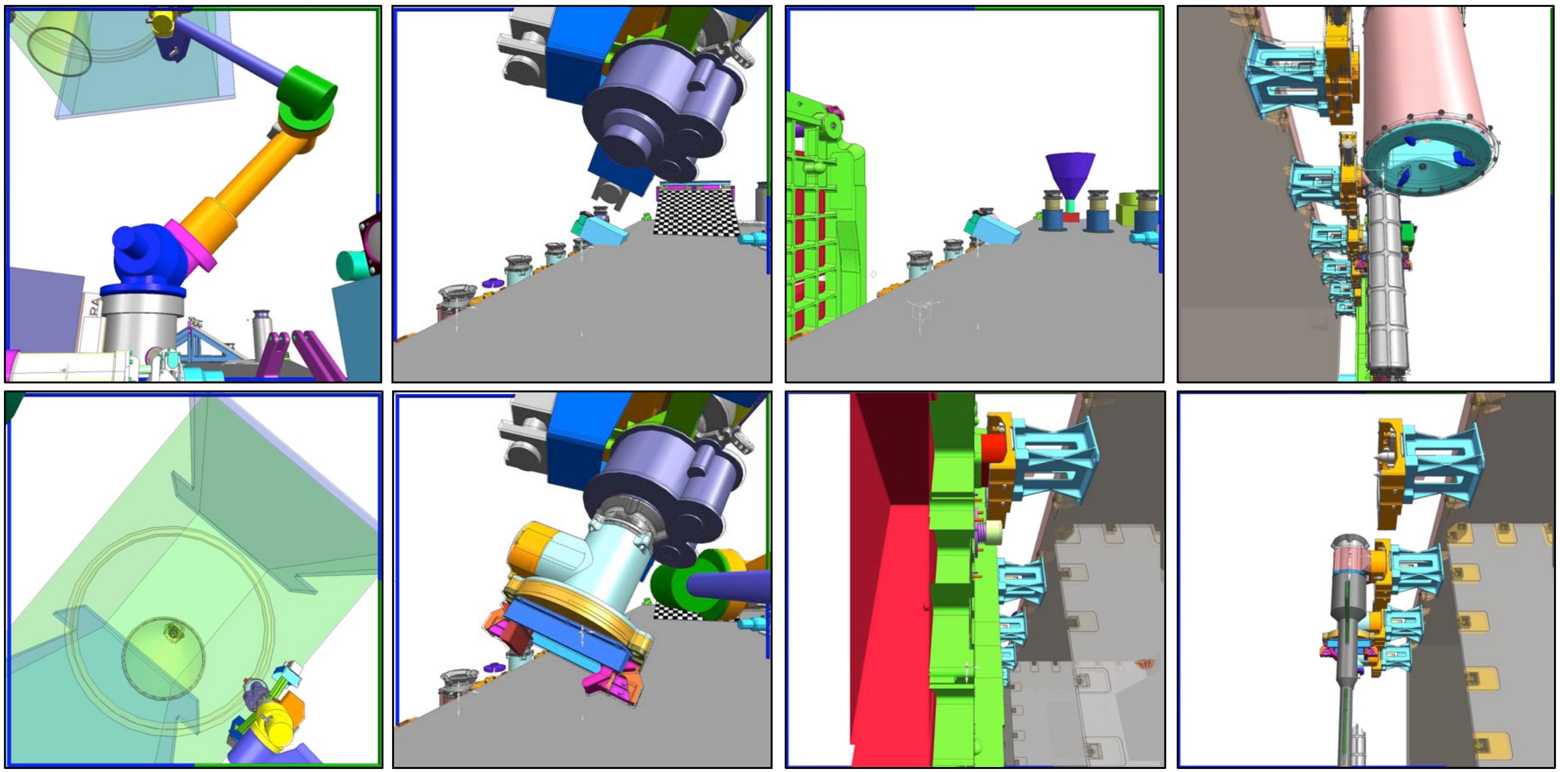
- Note that the baseline RPO suite provides LIDAR-derived pose, but not camera-derived pose
- Camera-derived pose is generated in FSW from camera images

Proximity Awareness System

Proximity Awareness System (PAS)

- The PAS consists of multiple payload body mounted cameras
- Provides a wide range of payload monitoring, mission monitoring, and inspection capabilities
- Includes body-mounted color documentation camera for color inspection imagery
- Incudes full-sky coverage sensor for complete proximity awareness

Example Views:



Multiple on-board cameras would facilitate safe operations and enhanced inspection

Payload Electronics

Payload Avionics

- Processes uplink command packets received from the ground thru the bus
- Collects and formats telemetry packets for transmission to the ground through the bus
  - State of health
  - Operating mode
  - Faults and warnings
- Receives image data from a number of different cameras
  - FREND Mark II arms
  - RPO
  - PAS
- Processes image data cameras
  - JPEG compression
  - FTA acceleration processing
  - Raw image collection and storage
- Formats mission data packets for transmission to the ground through the wideband data communications channel
- Implements mechanism release for all payload components
- Maintains control authority over FREND arms

Payload avionics are reprogrammable to enable new missions

Payload Avionics Details

Robotics Processing Module (RPM) consists of:

- Motherboard
  - Custom cPCI Backplane
- Mass Memory Unit (MMU)
  - Data storage
- Gateway Router Bridge (GRB)
  - A custom card, added to the architecture in an attempt to offload some functions better suited to perform direct interfacing between the processors and the MMU
- Single Board Computers (5x)
  - Identical, re-assignable functionality (in-flight)
  - Minimum number required to support all mission phases
    - Feature Tracking Algorithm Processor (G1P, G2P)
    - Robotic Arm Control Processor (RAP)
    - RM Control Processor (RCP) / Trajectory Planning Processor (TPP)
    - Sensor Data Processor (SDP)
- Power Supply Card (PSC)
  - Provides regulated power for/to cards

Common Remote Electronics (CRE)

- Performs the functions of command distribution, telemetry collection, wideband downlink data formatting, separable component interface and Robotic Arm Control Interface.
- Drives, monitors and otherwise controls cameras including end-of-arm, situational awareness, and (notional) RPO cameras
- Multiplexes cameras to multiple “destinations”, including FTA Processing, RPO processing, Narrowband down link, Wideband downlink (e.g., teleops) or onboard storage (e.g., MMU such as during RPO mapping ops)
- Mechanism Release Electronics (MRE) drives, monitors, and otherwise controls all launch locks / release devices, Tool Holders, and Tool Changers (one per FREND arm)

Power Distribution System (PDS)

- All electrical energy received from the bus is passed through the power distribution system (PDS)
- Single-point ground is located on the bus
  - PDS provides isolated primary voltages to all payload electronics with a primary voltage need
- PDS manages payload component power distribution and conversion
  - PDS provides secondary voltages as needed for payload equipment, including cameras and lighting
  - PDS provides survival voltage pass-thru from bus to payload Components
- PDS provides state-of-health telemetry
  - Secondary voltages, temperature, mode of operation, switch status, current monitoring
- PDS is the first payload component to power "ON" following successful bus activation

PDS would provide power interface flexibility with bus

Robotic Control Algorithms

Robotic Control Algorithms Overview

- The algorithms and software that control space robotics are the invisible half of the program…
  - Equally as important as the robotics hardware, equally complicated, and equally as important to protect as a national capability

- Autonomous approaches are being used to the extent necessary to improve system safety and reliability

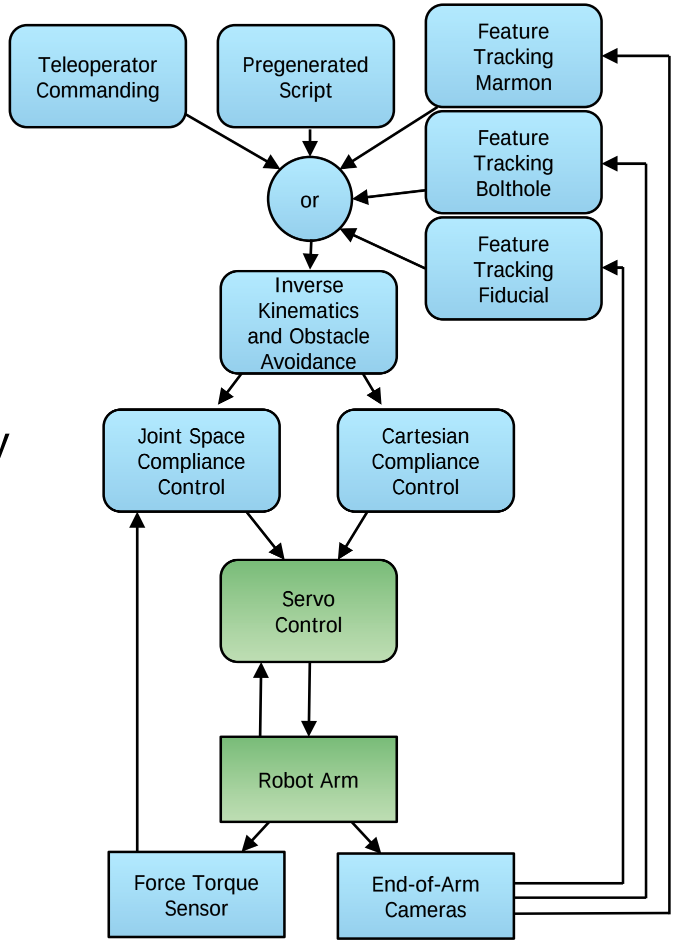
- FREND robotics control algorithms development and testing have been an NRL focus since the beginning of program development

- Robotic control modes, as defined by NRL
  - Scripted: The robot carries out pre-planned trajectories, using only proprioceptive sensors
  - Tele-operated: The robot carries out continuous human–generated trajectories, using only proprioceptive sensors
  - Partial autonomy: The robot carries out sequences of operations using both proprioceptive and environmental sensors, pausing at state changes and waiting for human authority to proceed
  - Fully autonomous: The robot carries out sequences of operations using both proprioceptive and environmental sensors, without waiting for human authority to proceed at state changes

Algorithms for enhanced system safety during payload operations

Arm-Level Behaviors

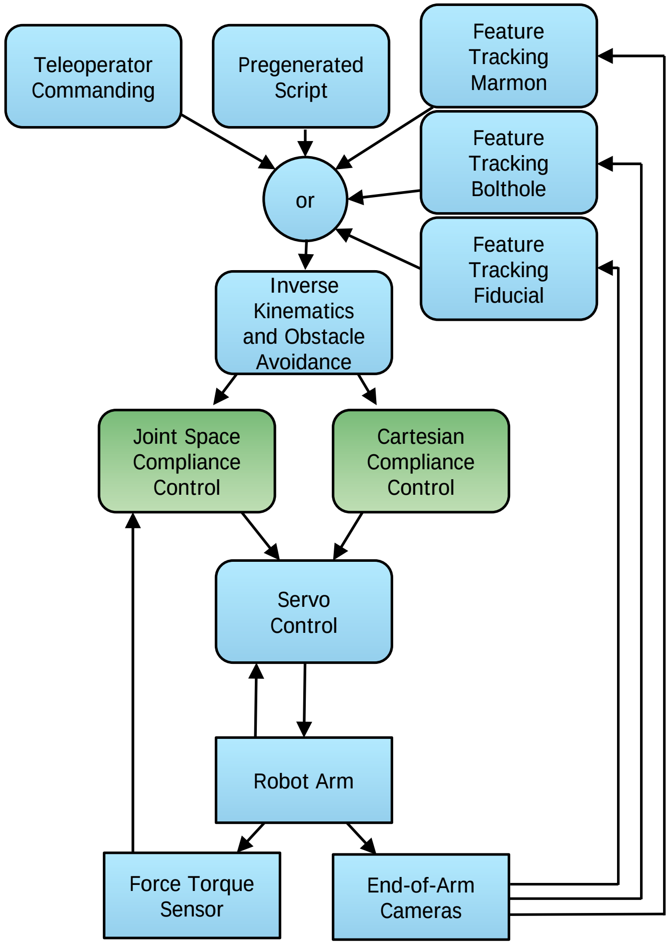
- Developed by Moog Broad Reach under contract to MDA-US
- Basic fault checking and arm safing
- In the absence of commands or when a tracking error, overcurrent, overtemp, or joint range violation occurs, the arm safes itself
  - "safe" = stops accepting new commands, actively holds the last good position



Extensive arm testing has demonstrated safe operations

Compliance Control Algorithm

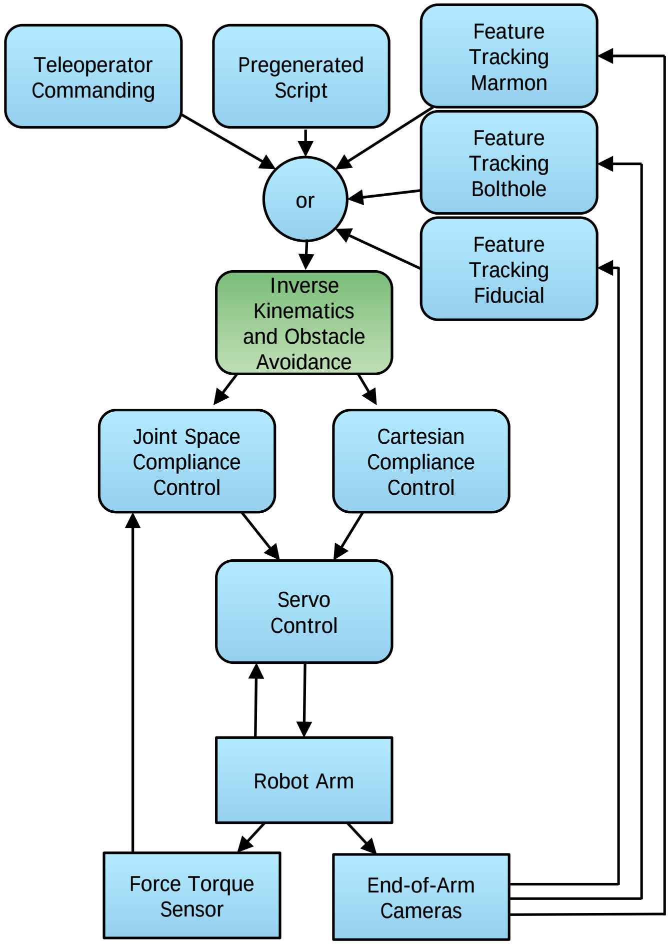
- Developed by NRL
- Reacts to sensed forces and changes joint commands to reduce those forces
- This technique is primarily used to minimize contact forces during initial grapple contact
- Prototype algorithm used extensively during 8 years of testing
- Flight development efforts are underway



Compliance control increases system robustness

Inverse Kinematics/Obstacle Avoidance Algorithms

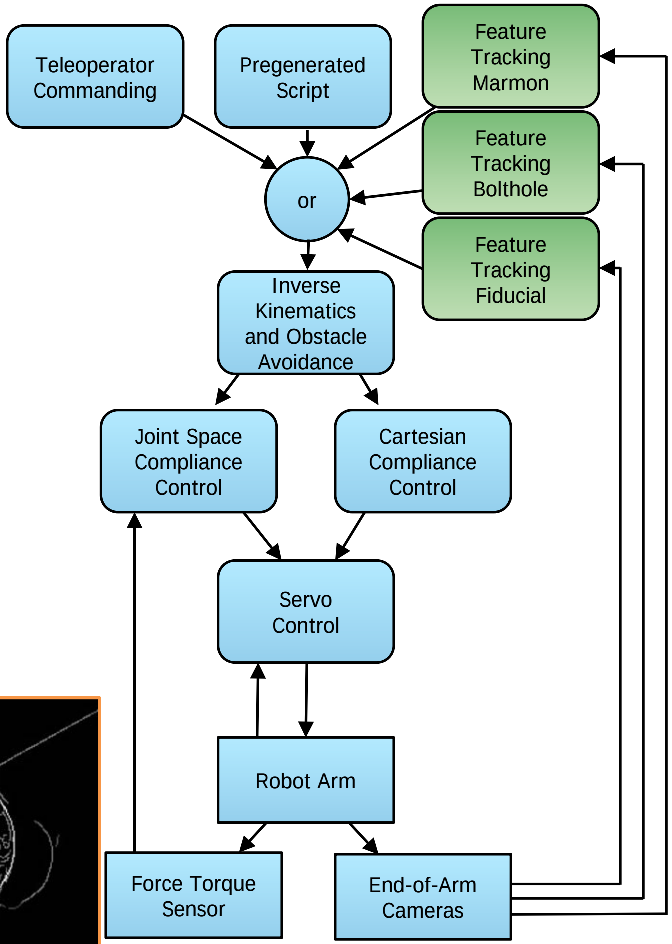
- Commands from teleoperators, machine vision, etc. are in Cartesian coordinates
- Commands are transformed into joint angles using a technique known as "Resolved Motion Rate Control (RMRC)"
- FREND arm has 7 DOF; 6 DOF are required to follow arbitrary Cartesian trajectories, the other is "free"
- We take advantage of free DOF to avoid obstacles, joint limits, and singularities
- Prototype algorithms used during 8 years of testing
- Flight development efforts are underway

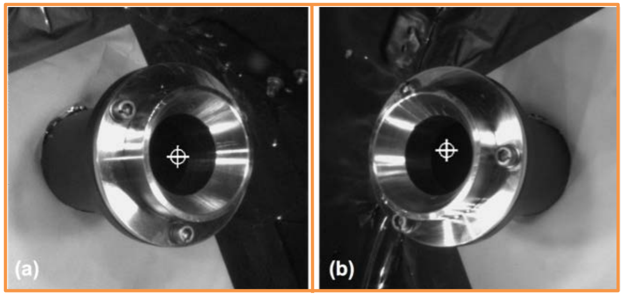


Obstacle avoidance algorithm enhances system safety

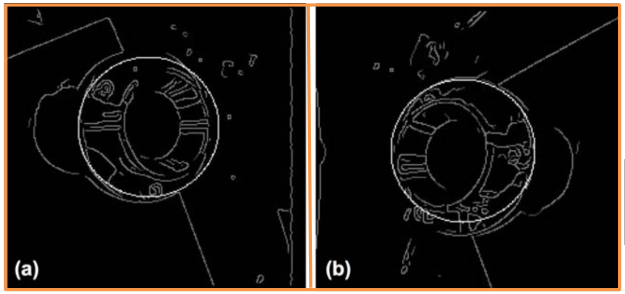
Machine Vision

- Developed by NRL
- Each machine vision algorithm is custom-written to identify a specific type of feature
- Output is location of feature in robot arm end-of-arm frame
- Machine vision output is fed back to the kinematics algorithm to align EoA with feature
- Prototype algorithms used during 8 years of testing
- Flight development efforts are underway





Raw Camera Imagery

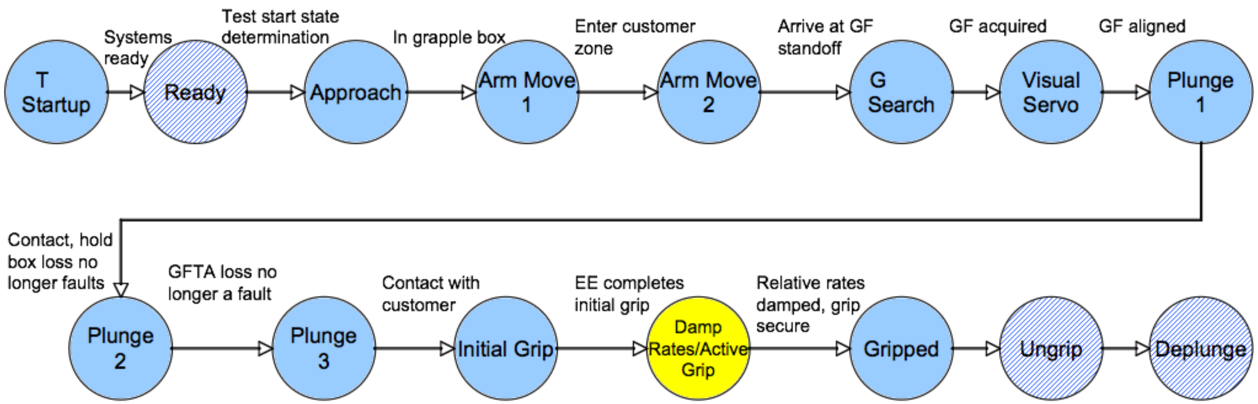


Machine Vision Solution

Machine vision provides fine alignments for robust operations

Payload Mission Manager and FDIR

- Developed by NRL to manage all of the other payload components
  - Turns on/off, changes states depending on current mission mode
  - Detects and responds to faults
- Using a state machine, we attach "telemetry monitors" that detect state changes and inform the state machine
- Prototype algorithms used extensively during 8 years of testing
- Flight development efforts are underway
- Interactions with spacecraft bus mission management software to be defined after partner selection



Payload Mission Manager would constantly verify safe payload operation

Payload Flight Software (FSW)

Payload FSW

- Payload FSW Status
  - Under development at NRL
  - Prototype code has been used extensively during system testing
  - Build 1 flight code development is underway

Payload Flight Software Functions	
• Robotic arm control of multiple arms o Compliance control o Inverse kinematics o Collision avoidance • Arm trajectory planning o Cartesian spline trajectory plan o Joint spline trajectory plan • Tele-ops control • Autonomous control using machine vision • End-effecter tool control • Rendezvous sensor processing	• Proximity awareness sensing • Fault detection, isolation, and recovery • Thermal and power control • Framework o Command and telemetry management o OS abstraction o Event logging o File system management o Time management o MMU management

Payload FSW architecture supports mission flexibility

Payload FSW Functional Breakdown

Compliance & Resource (0000)

PFSW Application CSCI

Payload Management (1000)
- PFSW Modes
- Scripts and Rules
- FDIR
- Scheduled Cmds

Robotic Control (2000)
- Arm Operations
- Arm Position Control
- Arm Joint Control
- Tool Control
- Tool Changing

CT&DH (5000)
- Commands
- Telemetry
- Data Storage
- Thermal and Power
- CT&DH Management
- IRW & Bus Interface

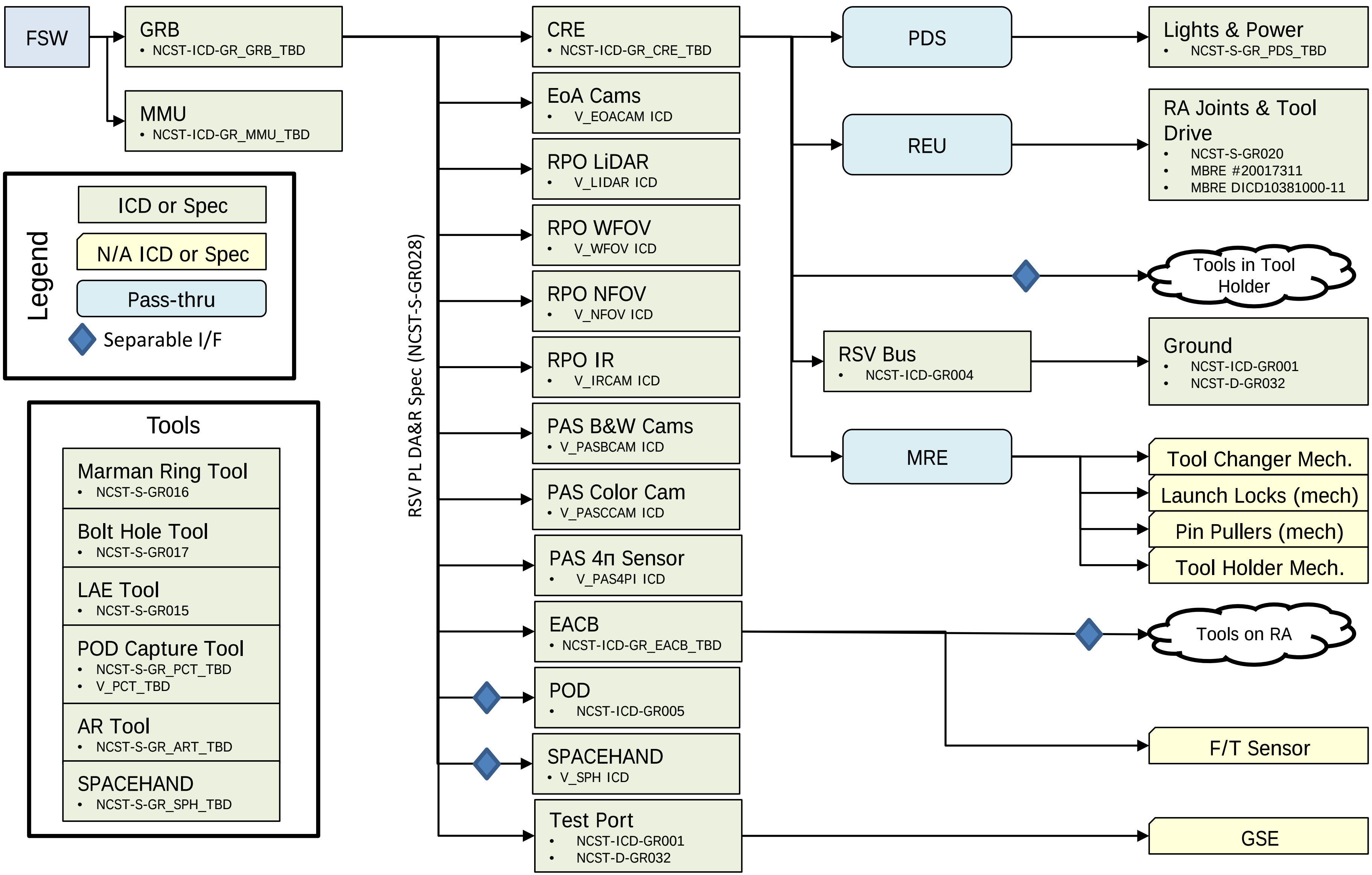
Vision (3000)
- Marman Ring
- Bolt Hole
- PODs
- PAS
- Camera Control

RPO (4000)
- RPO Control

Framework (8000)
- App Mgmt
- Events
- Memory Mgmt
- Config
- Time
- Logging
- Objects
- Diagnostics
- Reset
- Interrupt
- Patch

SUROM CSCI (9000)
- Initialization
- Application Load
- Diagnostics
- Exceptions

Payload FSW Interfaces



RSV Bus Assumptions and Expected Interfaces

Top-Level Bus Assumptions

- Provide and maintain vehicle attitude and electrical power using:
  - Propulsion and attitude control electronics
  - Command and telemetry uplink and downlink electronics
  - Solar conversion and energy storage

- Interface with the payload to provide:
  - Power
  - Uplink command path
  - Downlink telemetry path
  - Payload initialization
  - Vehicle safe mode in response to certain fault scenarios

Bus assumptions are a point of reference for negotiation

Bus GNC Assumptions

- Provide 6-DOF control

- Maintain Center of Mass (CM) position within a small control box in close vicinity to a Client with the control box fixed to the Client as it rotates up to 0.5 deg/sec about any axis
  - 20 cm x 20 cm x 10 cm position control box
  - 2 deg x 2 deg x 2 deg attitude control box

- Maintain a small relative velocity while limit cycling within the control box

Bus RF Assumptions

- Provide minimum RF uplink data rate of 10 kbps for payload commanding during teleoperations

- Provide minimum RF downlink data rate of 10 Mbps for payload data during high-resolution inspections and robotic teleoperations

Bus Propulsion Assumptions

- NRL has developed propulsion point design for evaluation of payload requirements against government mission concept of operations
- Notional RSV:
  - 4,500 kg (wet mass)
  - 1,000 kg Robotic Payload
  - RSV Propulsion System
  - Chemical and Electric Propulsion systems (N2H4/Xe), 1,000 kg each)
- Notional mission delta-V budget supports:
  - RSV executing GTO to GEO burn
  - RSV checkout and commissioning demonstration
  - Ensures robust ΔV capability remains for commercial operations after government demonstration
  - RSV servicing assumptions:
    - RSV parking orbit at GEO +300 km, 0 deg inclination
    - Servicing missions take place in GEO and RSV returns to parking orbit upon mission completion
    - Orbit-modification missions include N/S station-keeping and/or retirement burns
    - Inspection and anomaly resolution missions include far/near RPO surveys and potentially grappled operations
- Important to ensure bus propulsion is able to meet both government and commercial mission requirements

Bus Power Interface Assumptions

- Support payload power interface

	Baseline Payload
Payload Operational Voltage	30 V – 34 V
Average Operational Power	3 kW
Peak Operational Power*	5 kW
Average Survival Power	1.5 kW
Peak Survival Power	3.3 kW

* Peak power duration < 30 seconds for autonomous grapple operations

- Payload energy storage requirement: 300 amp-hours above 28 V

Bus Mechanical Interface Assumptions

- Current NRL point design created so that payload development could begin ahead of partner selection
  - Point design intended to be able to be accommodated by a variety of commercial GEO spacecraft
  - Alternate interface approaches and/or more tightly coupled payload interfaces for improved system performance are invited
- Provide surface for mounting of payload components (robotic arms, electronics boxes, sensors, etc.)
  - 7-8 m^2 of payload component mounting area
  - All components could be bolted on bus external surfaces or some combination of internal and external surfaces of an existing bus structure
  - The baseline dedicated payload structure is estimated at 200 kg
- Support payload component height
  - <0.6 m for stowed robotic arms
  - <0.4 m for all other components
- Support payload Non-Explosive Actuator (NEA) drive signals

Bus Data Interface Assumptions

- Provide full-duplex differential serial communications link
  - 10 Mbps telemetry
  - 10 kbps command
- Support temperature sensors
  - ~50 PRT type
  - ~32 Thermistor type
- Provide PPS signal
- Support differential for command and HK: 32 kbps in each direction

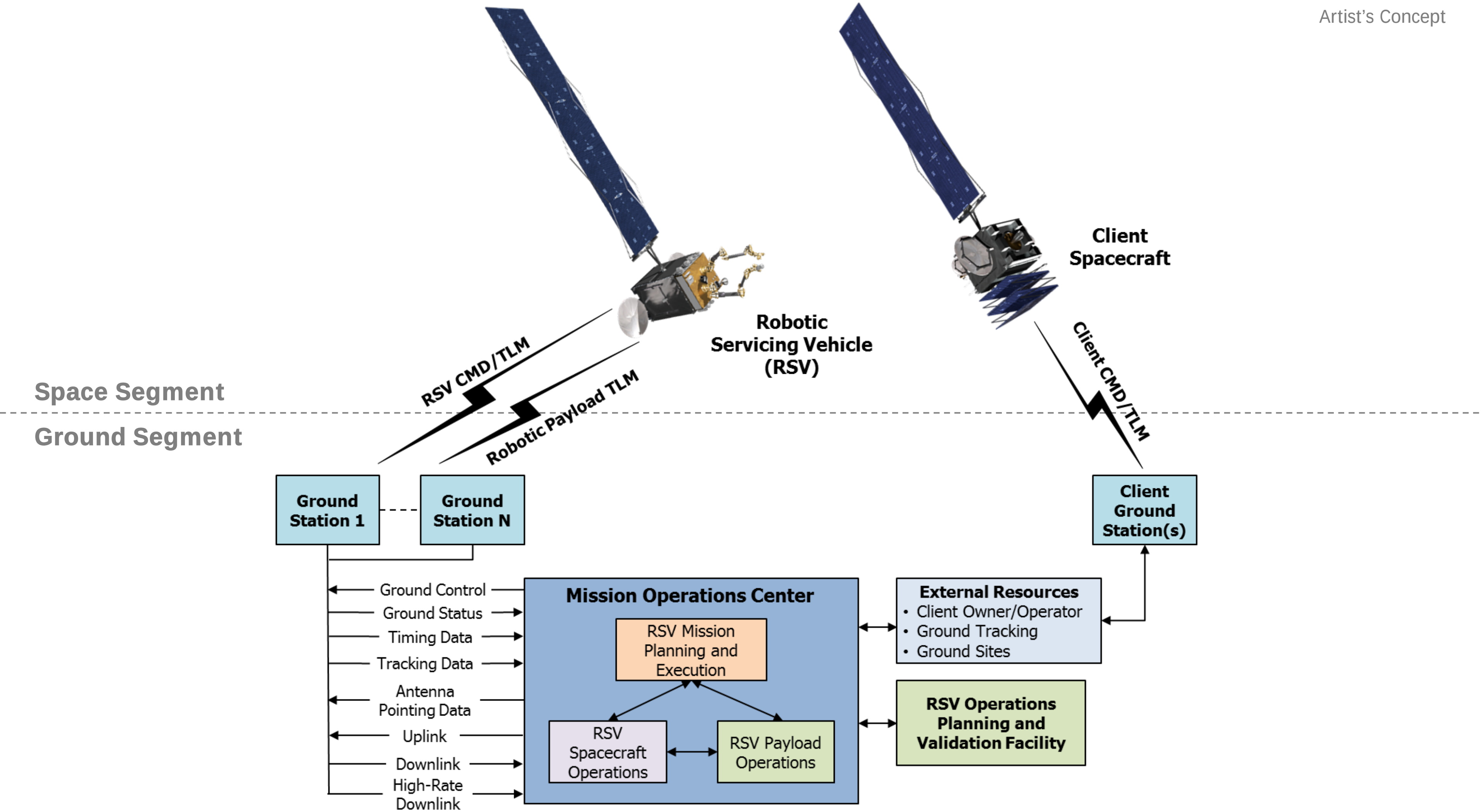
Bus Thermal Interface Assumptions

- Payload passes 1,000 W of thermal energy to the bus
  - Alternate approaches with minimal thermal exchange are feasible with increased payload mass
- Support temperature range for interface: 10°C - 50°C
- Accommodate blankets mounted across the interface

Ground System

Mission Architecture Block Diagram
Point Design

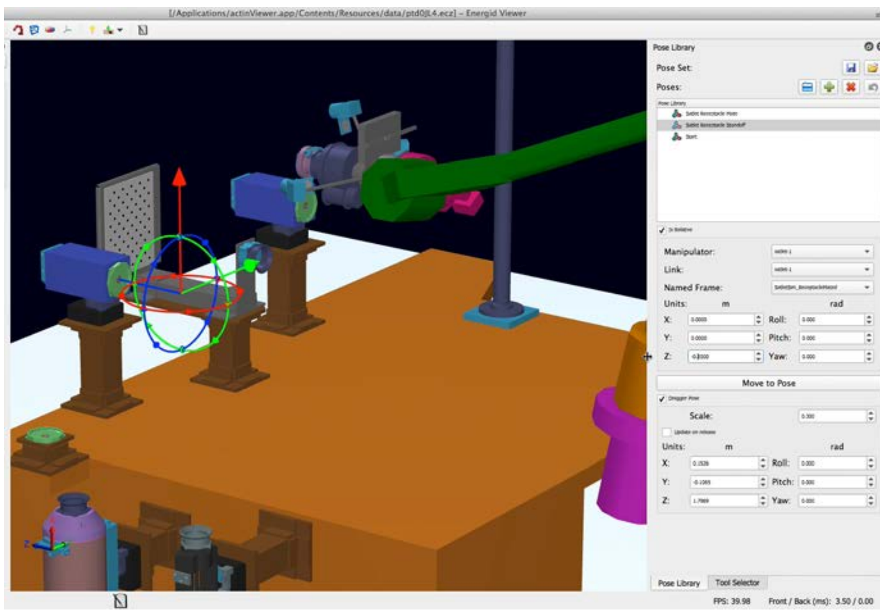
Artist's Concept



Point design used to evaluate government mission CONOPS, pending availability of partner solution

Integrated Robotics Workstation (IRW)

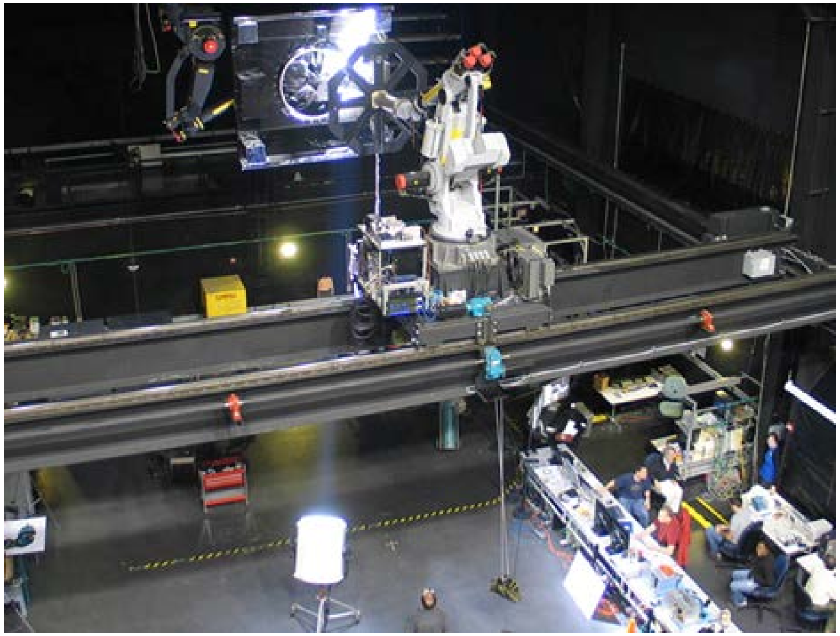
- NRL is developing the Integrated Robotics Workstation (IRW) as the ground control station for both robotics mission planning and robotics mission execution
- For mission planning, the IRW permits ground team to develop, rehearse, and validate planned operations
- For mission execution, the IRW provides displays for both simulated views and downlinked telemetry views, including on-board and on-arm cameras
- For teleoperation execution, IRW provides means of sending direct robotics controls, either via hand-controller input or other means
- Information on partner-developed solutions is welcome



Test and Development Capabilities

Proximity Operations Testbed (POT)

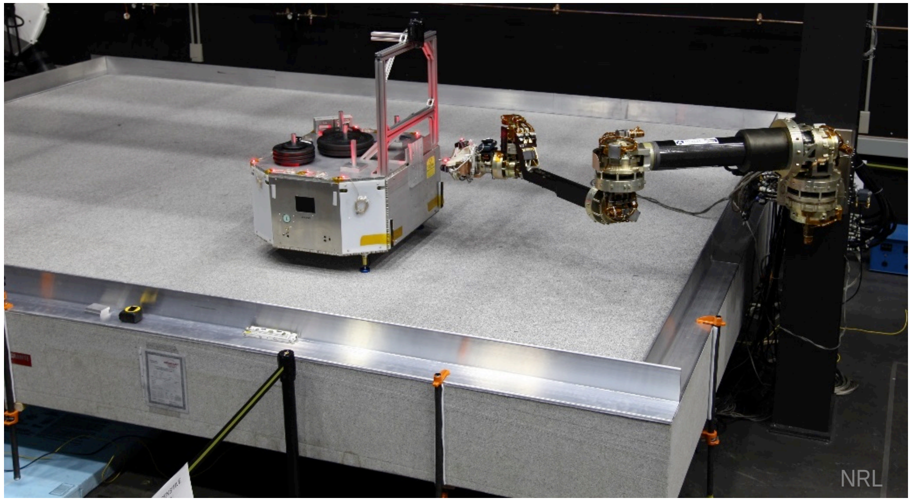
- Advanced dual-platform motion simulator
  - Allows full three-dimensional (6-DOF) replication of two spacecraft for rendezvous and docking under realistic dynamic conditions
  - Allows developmental testing with hardware-in-the-loop robotic sensors, mechanisms, and flight code prior to launch
  - Allows full scale mission rehearsal with realistic satellite hardware
- Pre-launch, extensive operator training could be performed with client models
- On-orbit inspection data could facilitate rapid creation of an “as-is” model of client spacecraft for finalization of servicing plans
- Post-launch training and rehearsals for new clients and unique missions could be performed at NRL



World-class facility used for system development testing

Gravity Offset Testbed (GOT)

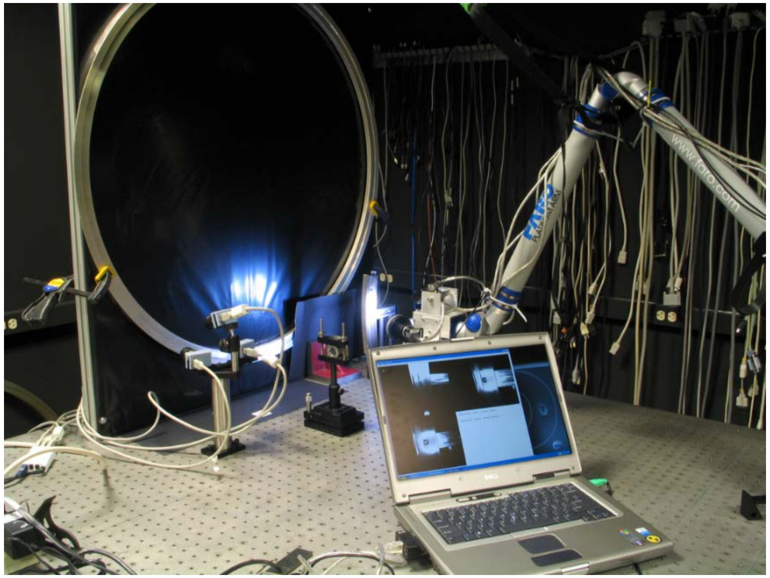
- 3-DOF, very low friction air-bearing facility
- Allows high-fidelity contact dynamics simulation to ensure ability to grapple in simulated zero-G conditions
- Realistic customer mass and inertias
- Used for developing, characterizing and validating
  - Robotics compliance control sensors and algorithms
  - End-of-arm hardware design
  - Grapple-control software
- Used for system integration and characterization of grapple-related subsystems

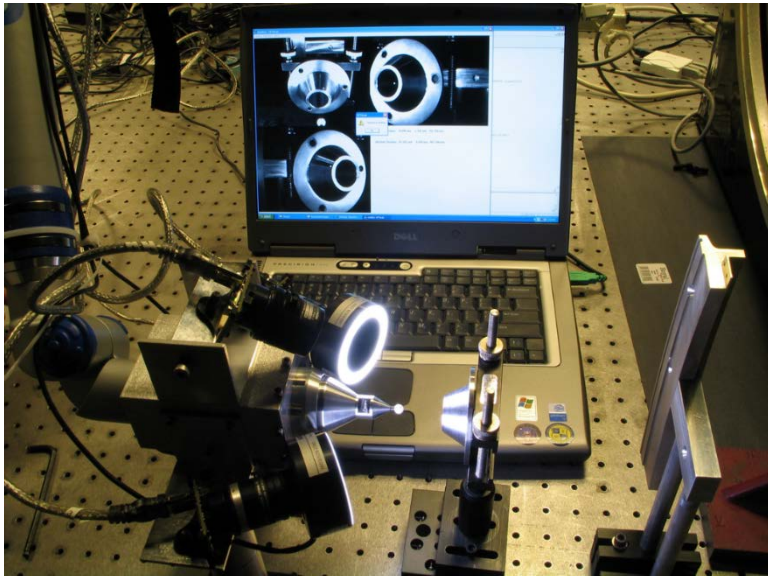


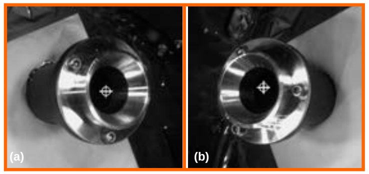
Supports contact dynamic system testing and model correlations

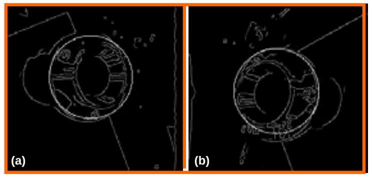
Machine Vision Testbed

- Optical testbed for development and characterization facility for flight machine vision sensors, illuminators, and algorithms
- Allows high-fidelity orbital lighting simulation
- Testing against wide range of grapple features, blanketing materials, and lighting conditions







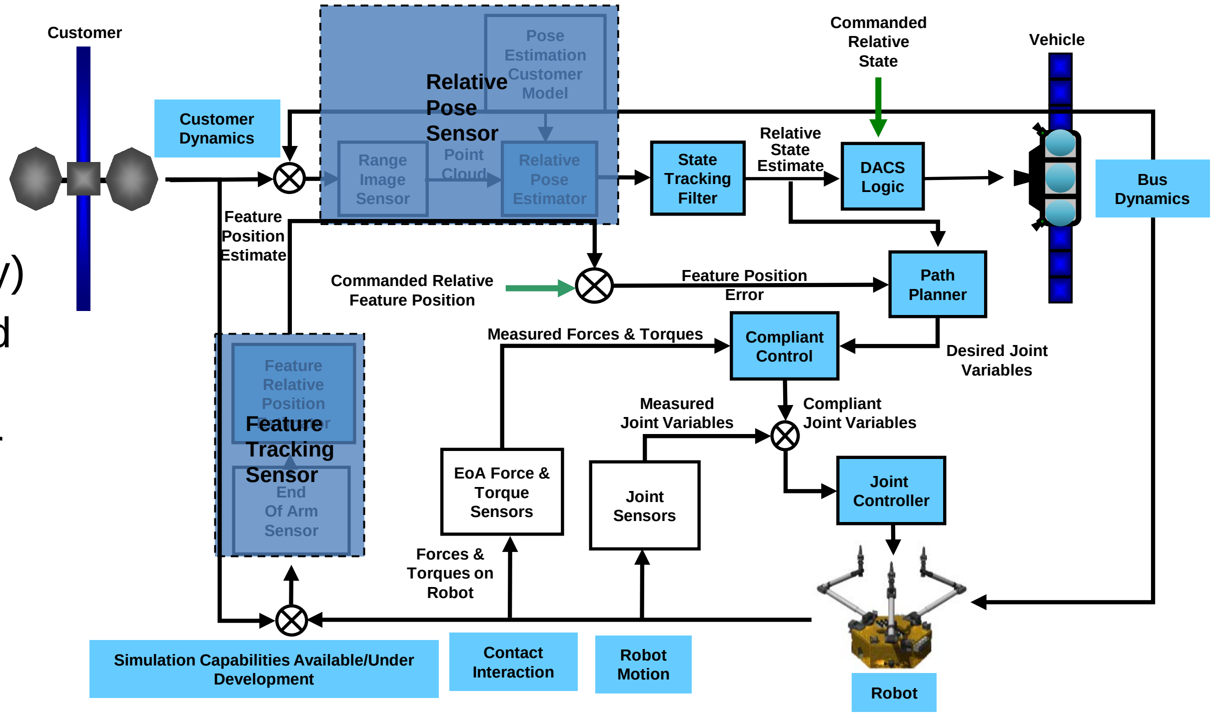


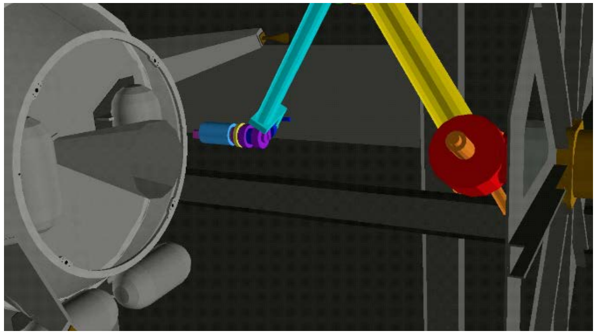
NRL Images

Supports testing of a wide range of grapple features and algorithms

System Simulation Testbed

- Full system dynamics simulation
  - Including sensors and lighting
- Software-in-loop (ultimately)
- Allows complete end-to-end scenario validation
- Validates results from other test facilities
- Development in progress
  - Currently has full system dynamics
  - Does not yet have sensor simulation capability
  - Not yet software-in-loop
- Supports mission training and operations rehearsals



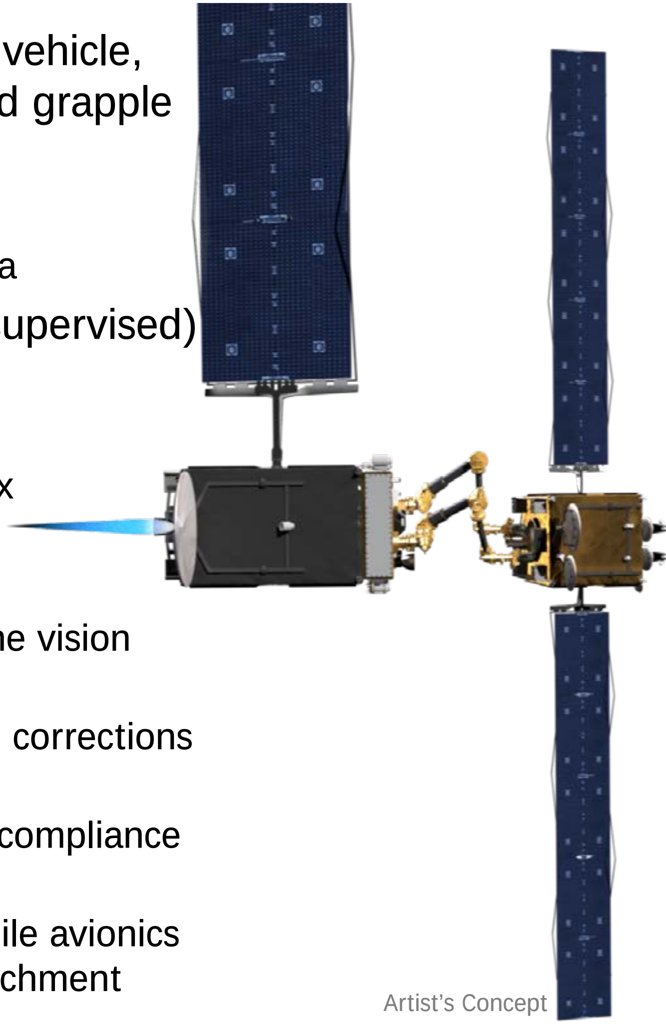


Modeling and simulation is required to validate all operation regimes

Mission Areas: “What Could the Payload Do?”

Rendezvous and Grapple

- Servicer would perform cooperative survey of client space vehicle, collecting necessary data for ground-planned approach and grapple
  - Using ground-based design documentation
  - Using on-orbit data collected from the RPO suite
  - Using ground-developed 3-D models generated from LIDAR data
- Approach and grapple would be performed using partial (supervised) autonomy to maximize mission safety for both vehicles
  - Using RPO suite for relative pose solution
  - Relative pose solution would be used by bus to hold capture box
  - Relative pose solution would be used by payload for arm positioning during grapple
  - End-of-arm cameras with lights would provide input into machine vision algorithms
  - Machine vision would track grapple location and provide precise corrections to guide arm to contact
  - Force/Torque Sensor would detect grapple contact and provide compliance control input
  - Compliance control algorithm would minimize contact forces while avionics command tool actuation would provide positive mechanical attachment



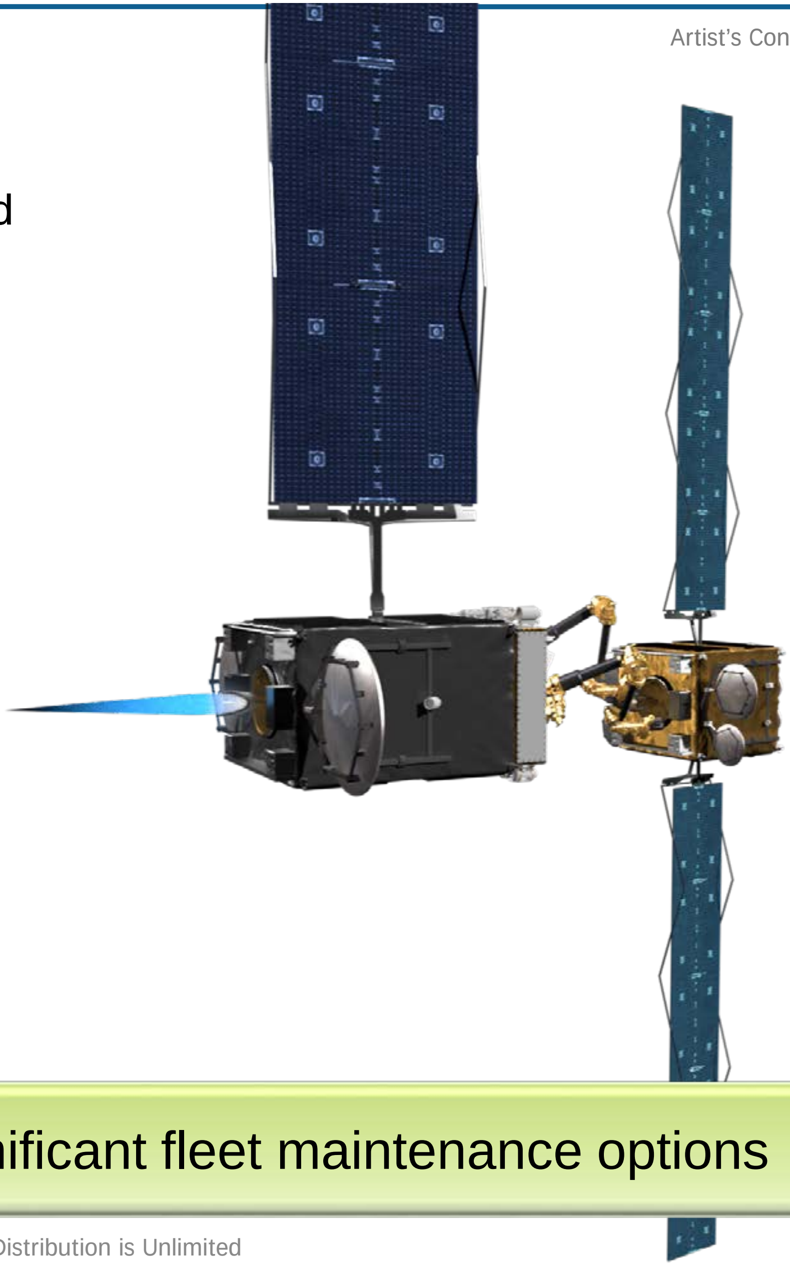
Artist's Concept

Payload must have the flexibility and capability necessary to accommodate many missions

Orbit Modification

Artist's Concept

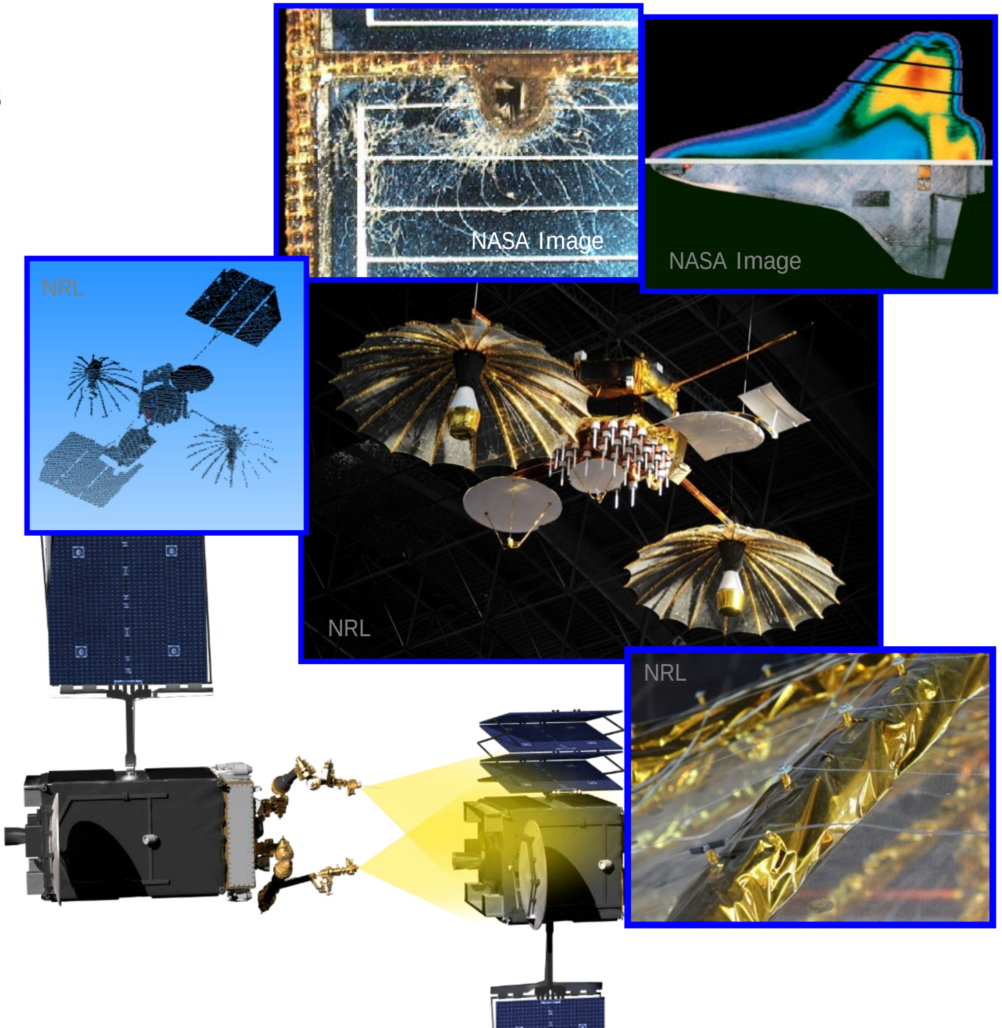
- Ground-controlled orbit modification capabilities would include North-South inclination correction, orbital slot change, and repositioning into or out of Geosynchronous belt, including transit to/from the GEO graveyard
  - Structural analysis and controls analysis have been performed to show that a single arm attachment is sufficient for stack control
  - Multiple arm grapples could be used to increase stack stability



Orbit modification would enable significant fleet maintenance options

Inspection Capability

- Without contact, cooperative inspections could be performed at ranges from kilometers to centimeters
  - Using NFOV visual and IR RPO sensors at long range (<1 km)
  - Using WFOV visual, LIDAR, and PAS cameras at short range (<100 m)
  - Using EoA cameras and lighting at very short range (<1 m)
- After cooperative grappling, inspection could be performed with second robot arm
  - Using PAS cameras for workspace awareness
  - Using second arm EoA cameras for extremely close detailed inspections (<10 cm)



Artist's Concept

Inspection would enable transformational attribution and troubleshooting

Anomaly Resolution Capability

- Close inspection provides an inherent anomaly resolution capability by providing detailed situational awareness to the ground
- On-board robotics would provide ability to provide controlled contact forces at appropriate locations
  - Using RPO sensors to hold capture box when required
  - Using robotic arm with force/torque sensor to apply controlled forces
  - Using partial autonomy or teleoperated arm control
- Analysis of past anomalies has found that very low force levels applied at the appropriate location could be sufficient to free many stuck-deployable problems
- Anomaly resolution would be episodic, but would have very high value

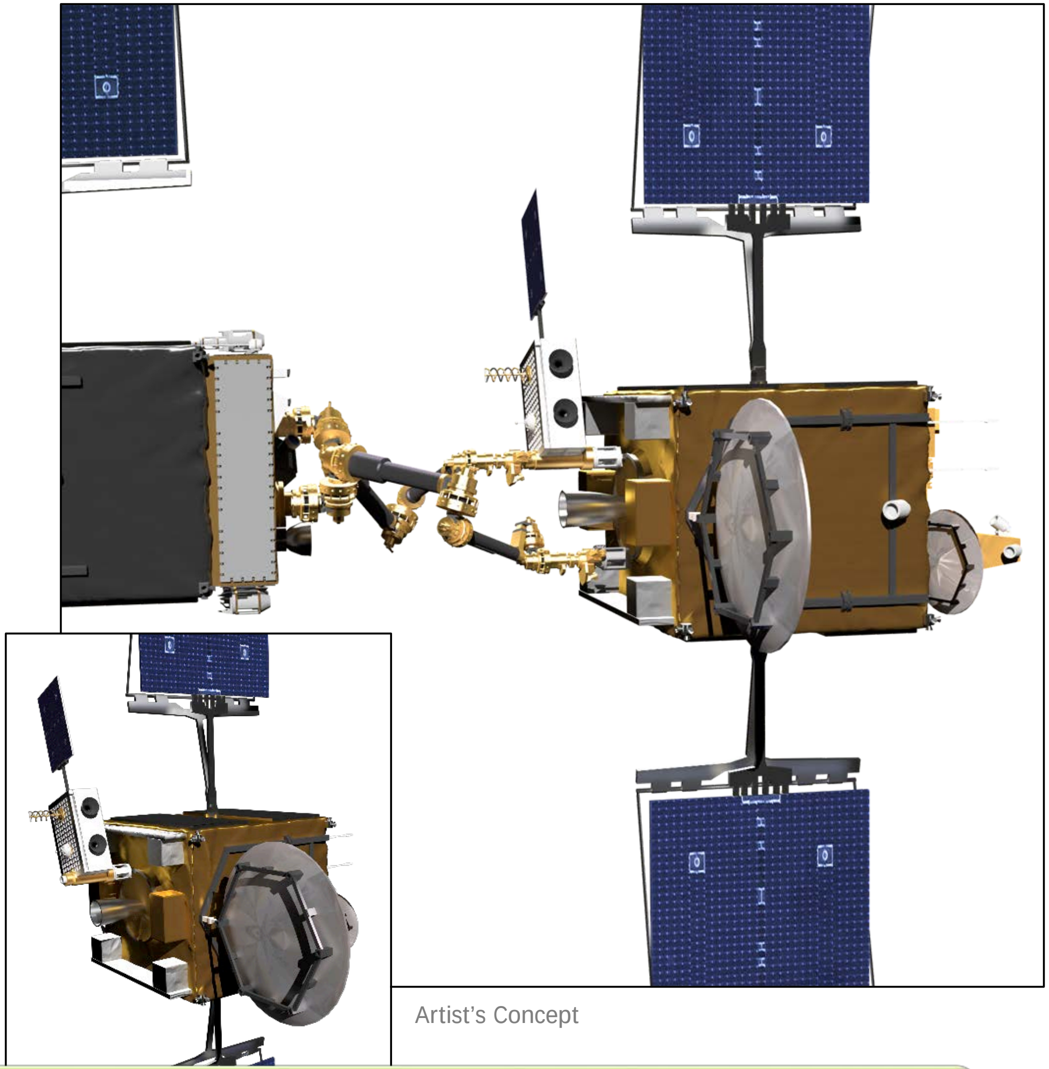
Stowed Configuration

Artist's Concept

Anomaly resolution is a revolutionary capability

Cooperative Installation of Upgrade Packages

- Ability to deliver new attached capabilities would provide a breadth of new mission capabilities to U.S. space vehicles already on orbit
- Installation of upgrades would need no accommodation from host vehicle other than structural hard point for attachment
- Initial analysis shows potential viability of small external payloads with independent communications, sensing and power
- Future space vehicles could be designed to provide docking ports with power/data links to/from external upgrade payloads



Artist's Concept

Delivering on-orbit upgrades would support space architecture transformation

Future Mission Areas

- Beyond the government mission areas envisioned at this time, a robust robotic servicing vehicle at GEO would inherently be a “Swiss Army Knife” in space
- Additional commercial missions would be welcomed
- New mission areas could be devised post launch, validated in hardware and software simulation on the ground, have operators trained and be able to execute in a timely manner
- These mission areas could involve new tools or test articles being delivered to the robotic servicer post launch and be a means of meeting new national needs to evolve rapidly or new robotic experimentation concepts
- Operating a robotic servicer on-orbit in the near-term would allow future mission areas to be designed to better be maintained by a robotic vehicle, leading to transformative impact in national capability in space

Artist's Concept

Resilience, transformation, revolution

www.darpa.mil

Robotic Servicing of Geosynchronous Satellites (RSGS) Proposers Day

Dr. Gordon Roesler, Program Manager

DARPA Tactical Technology Office

Briefing prepared for Robotic Servicing of Geosynchronous Satellites (RSGS) Proposers Day

May 26, 2016

A Future Space Vision

Dr. Gordon Roesler
RSGS Program Manager

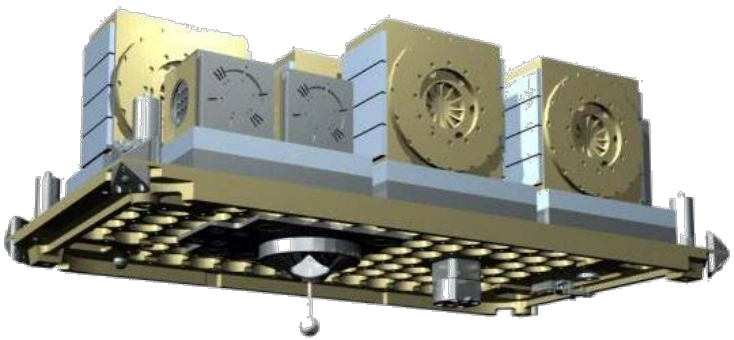
May 26, 2016

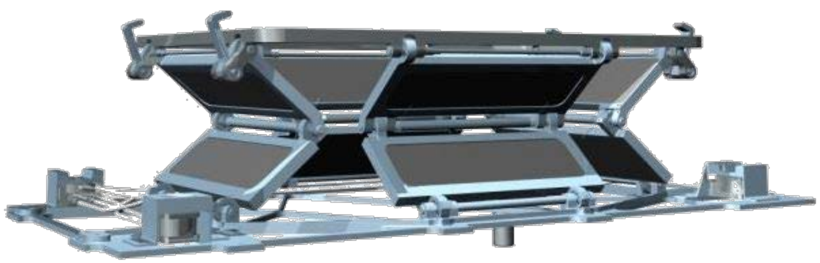
Once RSGS is on orbit, everything is going to change

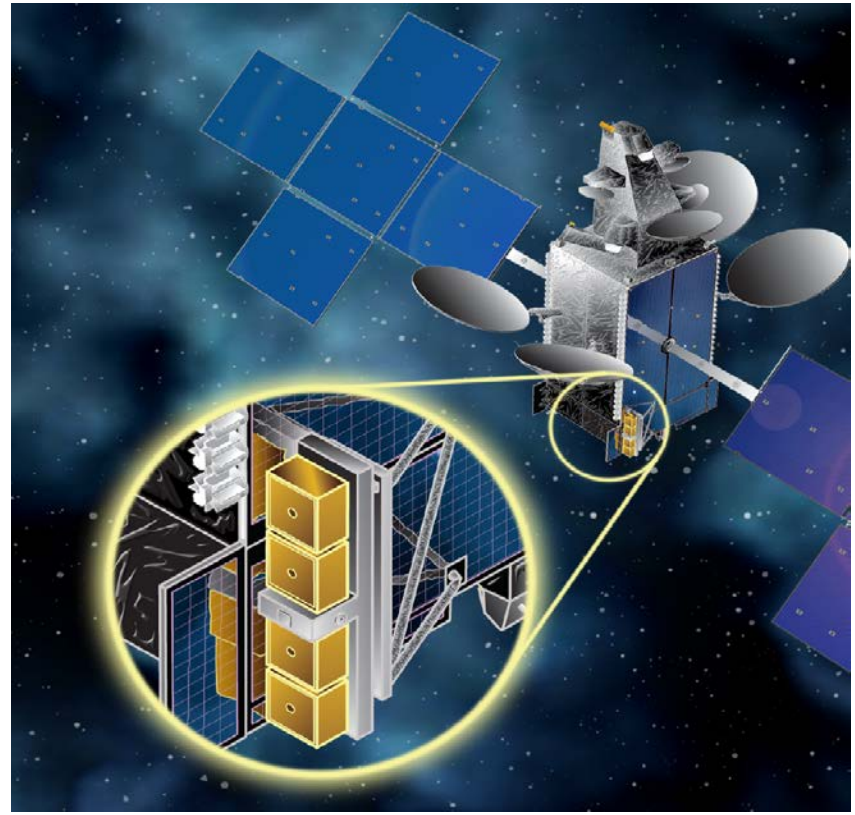
RSGS paves way for:

- Servicing by design
- Modular repair / upgrade
- New commercial services in GEO
- On-orbit assembly of large structures / apertures

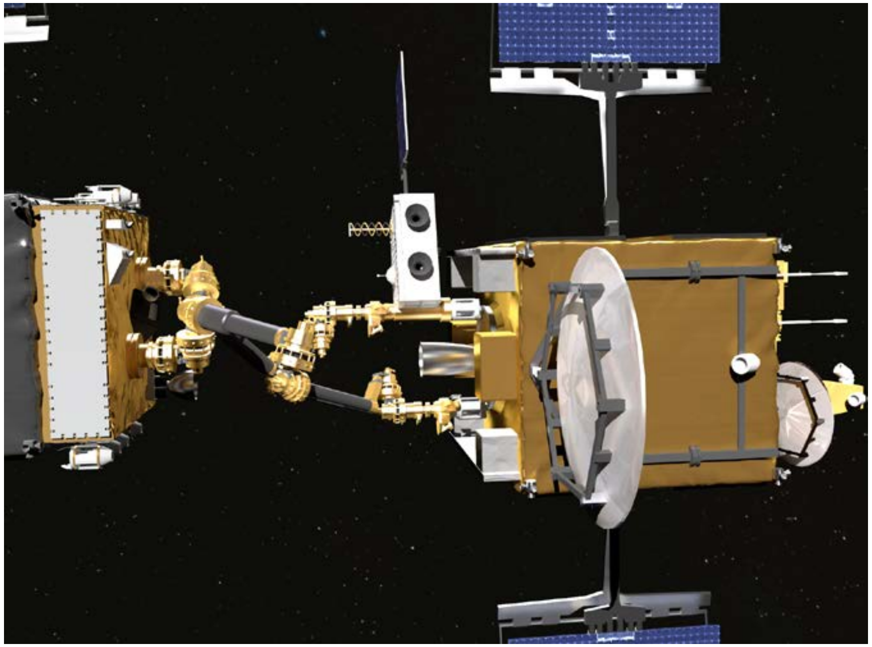
Payload Orbital Delivery (POD) System

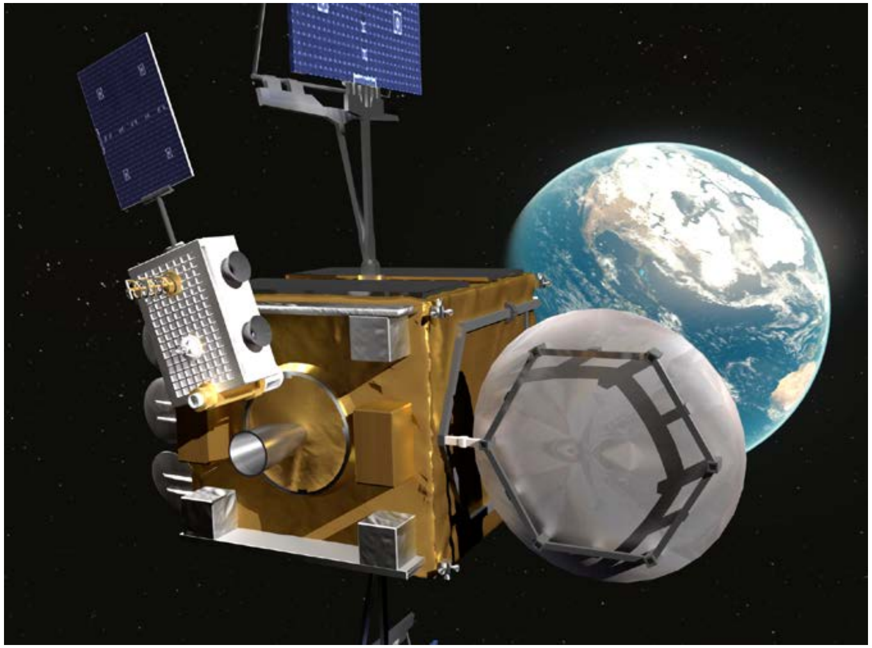




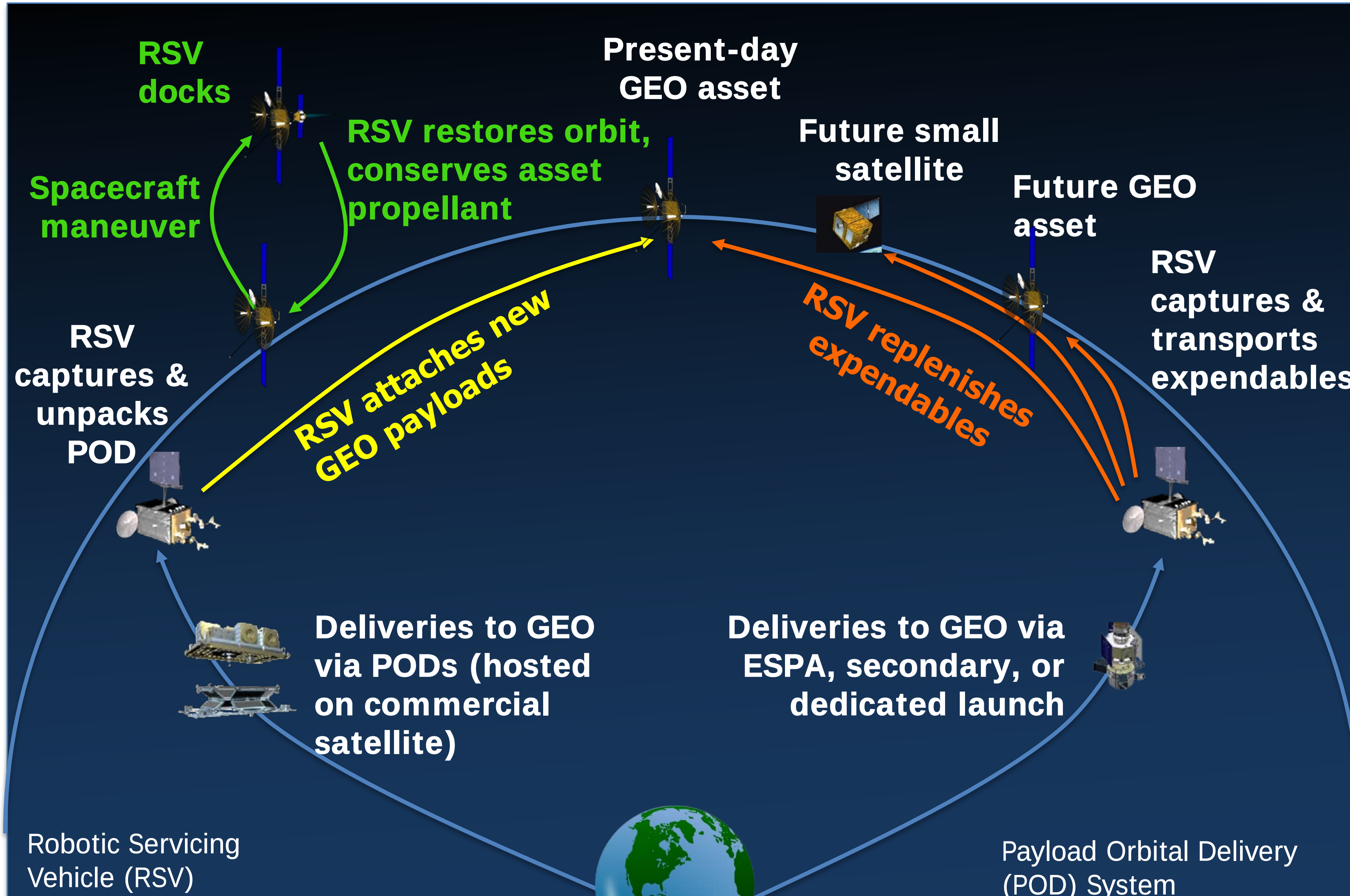


Post-launch upgrades





RSGS enables space logistics infrastructure



Robotics are the core technology for *transforming the entire space architecture*

GRAPPLING/DOCKING

Multi-mission demonstrations in GEO

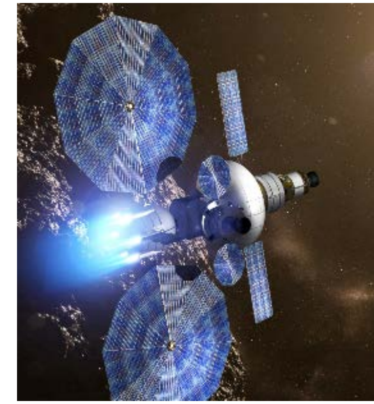
1st step in transformation

Artist Concept

Artist Concept

Commercial providers expand coverage

Automated, scheduled refueling



LEO-to-GEO space tug

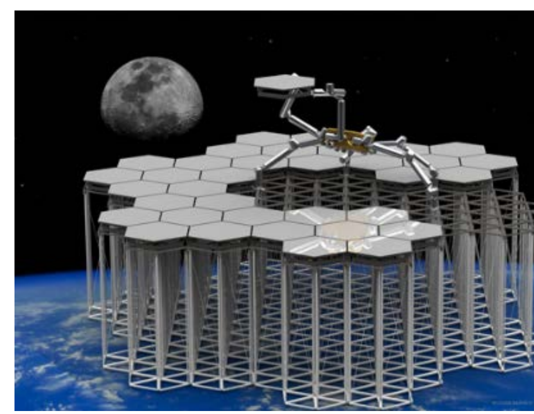
Technology development and investment

MANIPULATION

- On-orbit replaceable units
  - Modular spacecraft

- Reduced redundancy
- Lightly fueled at launch
- Assembly experiments

Large apertures, structures, and bases



All other images: NASA

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NRL's Programmatic View of the Partnership

Bill Vincent

NRL RSGS Program Manager

NRL's Role on RSGS

- Mission systems engineering for RSGS missions – inspection, orbit modification, anomaly resolution, and attachable payloads
  - Plan to transition lead role to commercial partner when appropriate and shift to a support role
- Space vehicle systems engineering for RSV:
  - Initial mission-to-space vehicle requirement allocations
  - Initial space vehicle-to-bus and -payload requirement allocations
  - Draft bus-to-payload ICD
  - Draft bus capabilities document
  - Initial space vehicle mass budgets for launch vehicle efforts and initial propellant loading allocations for mission analyses
  - Plan to transition lead role to commercial partner when appropriate and shift to a support role
- GEO robotics payload lead:
  - Lead role for all payload systems engineering, design, development, integration, and test
- GEO robotics – integrated robotic workstation lead:
  - Lead for all payload ground control terminal development, integration, and test
- GEO robotics mission operations simulation and training environment lead:
  - Develop and support all necessary simulation and training testbeds necessary to develop and rehearse GEO Robotics payload operations
- RSGS technical SMEs supporting DARPA

Partner Role in RSV Design, Build, and Integration

- Mission systems engineering for RSGS and commercial missions:
  - Assume lead RSGS role from NRL when appropriate
- Space vehicle systems engineering for RSV:
  - Final mission-to-space vehicle requirement allocations
  - Final space vehicle-to-bus and -payload requirement allocations
  - Final bus-to-payload ICD
  - Final bus capabilities document
  - Final space vehicle mass budgets for launch vehicle efforts and propellant loading allocations for mission analyses
  - Assume lead RSGS role from NRL when appropriate
- Commercial payload lead (if applicable):
  - Lead role for all commercial payload systems engineering, design, development, integration, and test
- Commercial bus provider:
  - Includes payload systems engineering, design, development, integration, test, delivery, and support
- RSV integration and test lead
- RSV launch integration lead
- Mission operations and ground system provider

NRL Staffing Insights

NRL Team Leadership

- Of the current 18 lead engineers at NRL:
  - The average professional experience is 20 years
  - The average tenure at NRL is 17 years

  - 50% have a bachelors of science as their highest degree (9 of 18)
  - 22% have a masters (4 of 18)
  - 28% have a doctorate (5 of 18)

  - 83% are NRL government employees (15 of 18)
  - 17% are NRL contractor employees (3 of 18)

Staffing Levels

- Currently at 65 FTEs
  - 15 FTEs at the mission/SV level
  - 50 FTEs at the payload and ground system development level

- By December 2017, staffing levels are expected to be:
  - 22 FTEs at the mission/SV Level
  - 124 FTEs at the payload and ground system development level

- On-site interface staffing should be discussed
  - Partner may provide on-site support at NRL for deep insight into payload progress and facilitate communication
  - USG may provide on-site liaison(s) at partner location for deep insight into bus progress and facilitate communications

Current System Engineering Processes

Program Documentation Approach

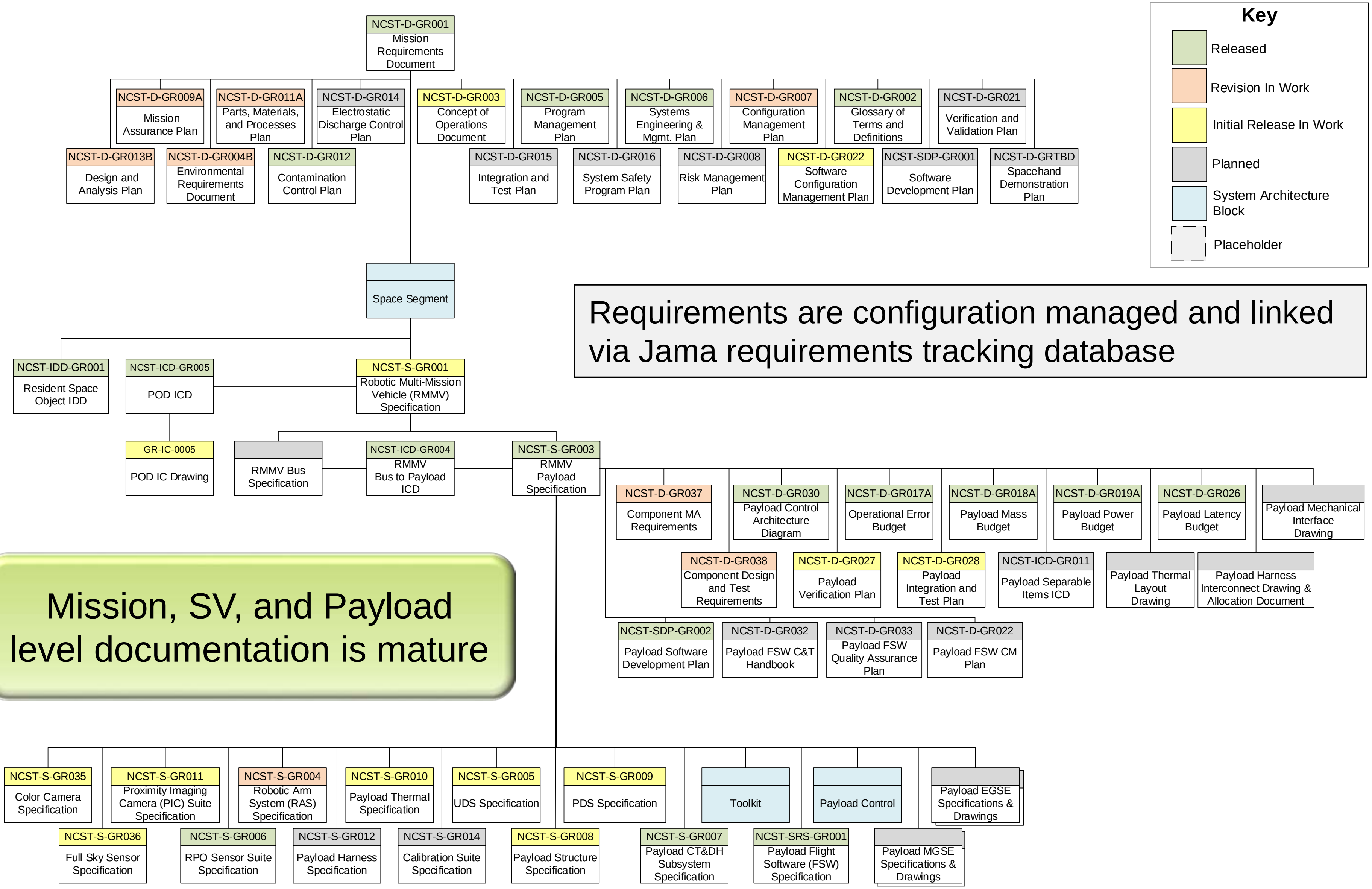
- Documentation approach
  - Supports initial steps for mission and payload technology transfer to commercial partner
  - Supports anticipated needs for servicing clients to vet safety of servicing vehicle

- Requirements traceability from mission requirements to payload requirements to component requirements using configuration-controlled database

- Standard CDRL/SDRL documentation planned across all payload components

- Formal document release procedures and configuration management

RSGS Specification Tree



Requirements are configuration managed and linked via Jama requirements tracking database

Mission, SV, and Payload level documentation is mature

Current Program Development Status

Mission/Payload Development Milestones – Completed

- December 2014 - Mission Concept Review
- September 2015 – Payload SRR
- December 2015 – Algorithms SRR
- December 2015 – Payload CT&DH SRR
- Feb 2016 – Payload FSW SRR
- February 2016 - RPO SRR
- March 2016 – End-of-Arm Control Board SRDR
- April 2016 – Proximity Awareness Suite SRR
- April 2016 – Initial Payload FMECA Completed
- May 2016 – Payload Structures SRR
- May 2016 – Payload Thermal SRR

Mission/Payload Development Milestones – Upcoming

- June 2016 – End-of-Arm Camera SRR
- June 2016 – Payload Power Distribution System SRR
- July 2016 – Harness SRR
- July 2016 – Payload Ground Support Equipment SRR
- July 2016 – Payload Calibration Suite SRR
- August 2016 – Payload Lighting SRR
- September 2016 – FREND Mark II Arm System PDR
- October 2016 – Tool Changer Delta-PDR
- Feb 2018 – Payload PDR
- Feb 2019 – Payload CDR
- April 2020 – Payload Delivery

Mission/Payload Development Milestones – Key Partner Lead Milestones to be Scheduled

- 2017 – Mission SRR, Space Vehicle SRR, Bus-to-Payload ICD, Bus SRR, Bus PDR
- 2018 – RSV PDR, Bus CDR
- 2019 – RSV CDR, Bus Delivery
- 2020 – RSV AI&T
- 2021 – RSV Launch

Current Payload Component Contracts

- FREND Mark II Robotic Arm Assemblies (RAAs) – MDA-US in Pasadena, CA
  - RAA consists of robotic arm, arm control electronics, motor filter box, power filter box, and associated harnessing
  - On contract to deliver 2 flight RAAs by November 2018
  - PDR planned for September 2016
  - CDR planned for March 2017

- Tool Changer – Oceaneering Space Systems in Houston, TX
  - On contract to deliver:
    - 2 Flight units
    - 1 Flight spare
    - 4 Engineering models
    - 19 Flight Common Receptacle Subassemblies (CRS)
    - 19 EM CRS
  - Delta-PDR planned for October

Pending Payload Component Contracts

- RPO sensors
  - LIDAR, NFOV Visible, WFOV Visible, IR
- Proximity awareness sensors
  - Proximity imaging cameras
  - Color documentation cameras
  - Full sky coverage sensor
- End-of-Arm cameras
- Tool Holder/POD Holder
- Tools

Most components planned to be on contract by early 2017

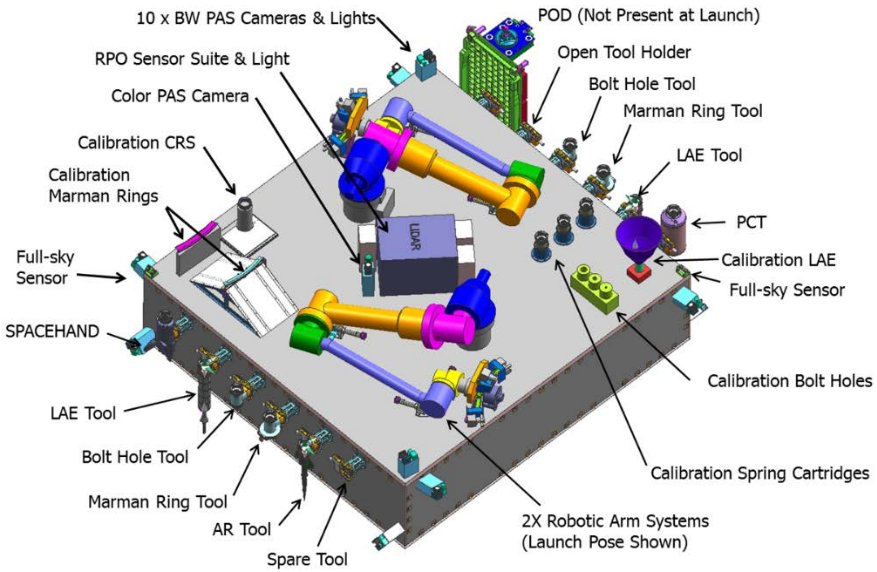
System Trades

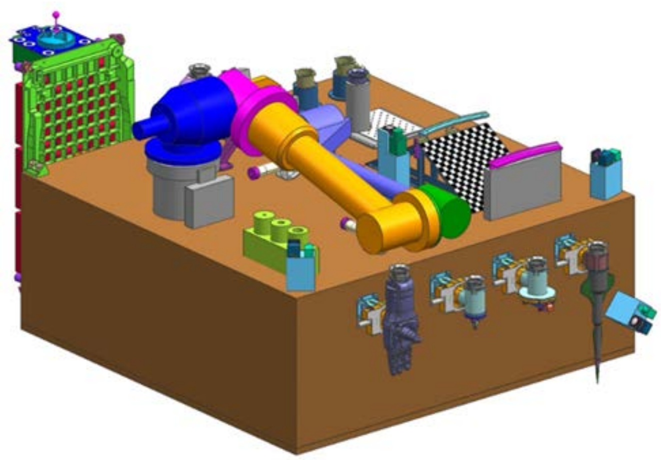
System-Level Trades

- Several key system-level trades are expected to be worked once the commercial partner is selected
- These trades are intended to define roles and responsibilities between NRL and the Commercial Partner and to define detailed interfaces between the bus and the payload
- Partnership proposals should provide initial expectations for these trades
- Negotiation phase should finalize these trades

Government Payload Configurations

- Full two-arm payload (baseline)
- One-arm payload delivered as an integrated unit
- One-arm payload delivered as components to be integrated on the partner spacecraft





NRL Images

RPO Sensor Suite and Processing Trade

- Baseline RPO sensor suite and processing plan
  - Baseline Sensors hosted on payload deck:
    - LIDAR that produces 6DOF pose
    - NFOV Camera
    - WFOV Camera
    - IR Camera
  - Baseline processing in payload avionics:
    - 2-DOF range and bearing solution for single NFOV, WFOV, or IR images
    - 3-DOF position solution for single WFOV or IR images
    - 6-DOF pose solution is provided from single WFOV images
    - 6-DOF pose solution is provided from LIDAR sensor
  - Baseline processing in partner-provided bus avionics:
    - Filtered RPO guidance solution to support bus RPO control and Payload robotics control

- Potential trades:
  - Alternate sensor suites
  - Hosting partner provided RPO sensors on the payload
  - Processing raw payload sensor data in bus avionics
  - Payload avionics provides filtered RPO guidance solution based on raw bus sensor data

Bus to Payload Interface Trades

- Structures – Payload layout compatibility with bus
- Thermal – Conductive (baseline) vs Isothermal
- Power – Unregulated bus power (baseline) vs. regulated power services (preferred)
- Communications – SpaceWire (baseline), LVDS, RS422, 1553
- Mission Management Functionality – Split between bus and payload (baseline), fully run by bus, or fully run by payload

NRL Technology Transfer

- NRL has a long history in developing first-of-a-kind systems and supporting technology transfer to industry
  - NRL aspires for robotic servicing to be another success story

- NRL-developed products for RSGS include:
  - Full Set of Mission Development Documentation
  - Developmental Requirements
    - FREND arm requirements
    - Circa 2005 – Initial requirements used to develop FREND arm
    - Circa 2015 – FREND MK2 updated requirements
    - Spacecraft bus requirements for RSGS Government missions
    - Full payload development and component requirements
  - Full set of Mission, Environmental, Test Requirements
  - ICDs
  - System Engineering
    - Concept of operations
    - Trade studies
    - Error budgets
  - NRL Algorithms
    - Control schemes and design analysis
  - NRL Flight Software
  - NRL Electronics Board Design/Layouts/ Schematics
  - NRL Mechanical/Structural Design Information
  - NRL Ground Control System/IRW
  - NRL Simulations
  - Test Reports
  - Parts Lists

Partner-Developed Components

Partner-developed components under contract in baseline with Government Purpose Rights:

- MDA-US:
  - FREND arm
- Oceaneering
  - Tool Changer
  - Common Receptacle Subassembly (CRS)

Partner-developed components under contract in baseline with Limited Rights:

- Moog Broad Reach (subcontractor to MDA-US)
  - Rikishi control electronics, subset of the software was not developed under DARPA/USG funding
- MDA Canada:
  - PODS capture tool, design developed under MDA/CSA cofunding for Orbital Express

Partner-developed components in baseline under CRADA:

- DLR Institute of Robotics and Mechatronics
  - Spacehand is fully developed under DLR funding
    - o Design rights are not transferred between DARPA and DLR
    - o CRADA covers use rights on-orbit only during the USG demonstration period

Conclusion

Conclusion

- Our goal is to help the DARPA mission succeed by delivering a payload that meets mission needs AND allows our commercial partner to create a successful satellite servicing business
- The RSGS Mission and GEO Robotics Payload development is well underway and making good progress toward launch
- NRL developments to date provide a unique combination of technologies that makes the RSGS mission transformational

CONFERS: Consortium For Execution of Rendezvous and Servicing Operations

Todd R. Master

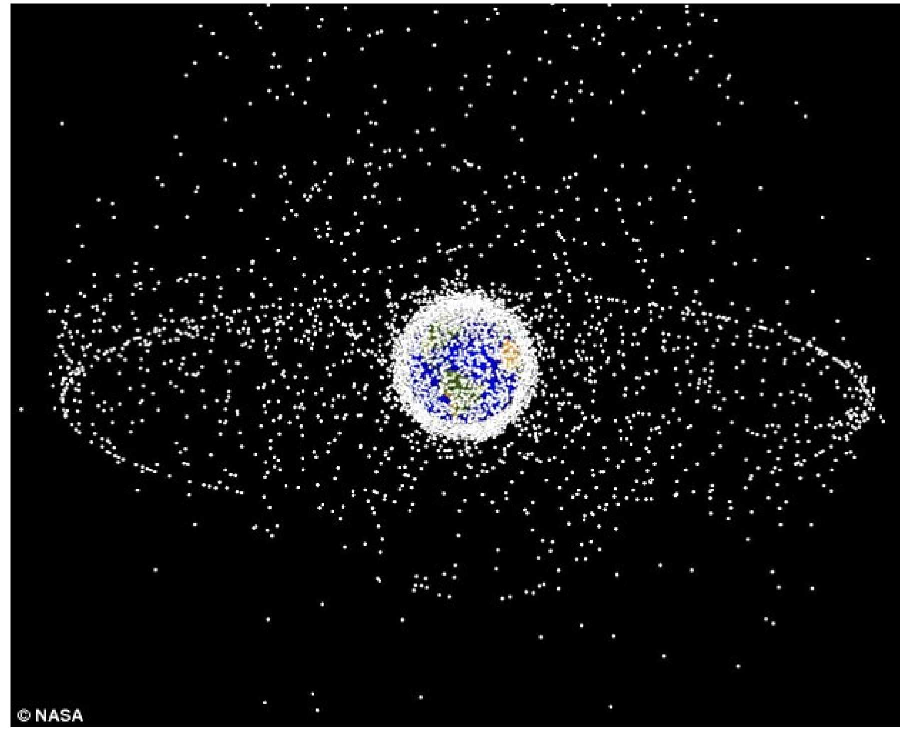
TTO Program Manager

May 26, 2016

DARPA

The emergence of advanced commercial space operations

Government and commercial industry have mutual interests in safe and continuous utilization of the geosynchronous orbit regime due to its unique benefits and strategic nature.



In addition to DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS) program, other commercial and government programs have plans to conduct servicing operations in geosynchronous orbit, which offers tremendous potential opportunities for advancing our use of space, but...

- ***There is no clear regulatory authority to allow or disallow such operations to take place***
- ***There is no clear definition for safe and responsible servicing operations***
- ***There are many stakeholders, both commercial and government, potentially affected by these operations***

Current regulatory authority in space operations

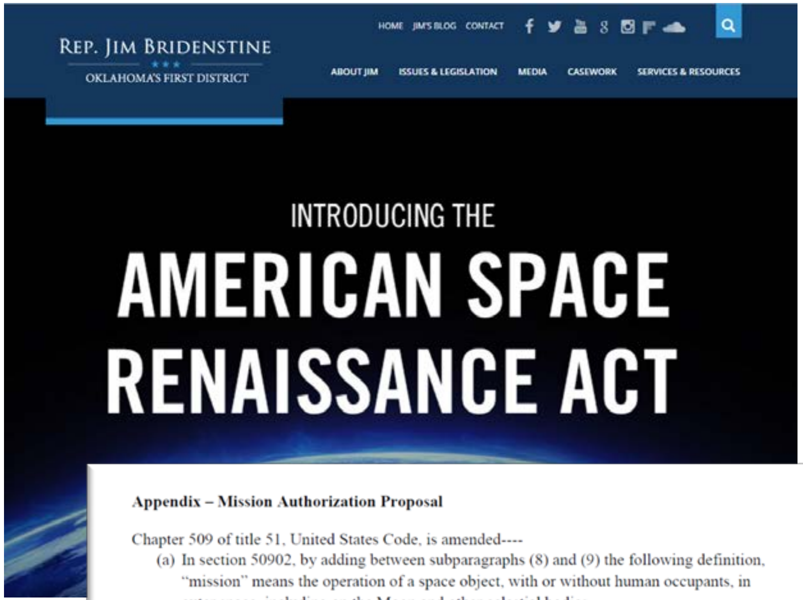
Today, U.S. Government regulatory authority for space operations falls into three categories:

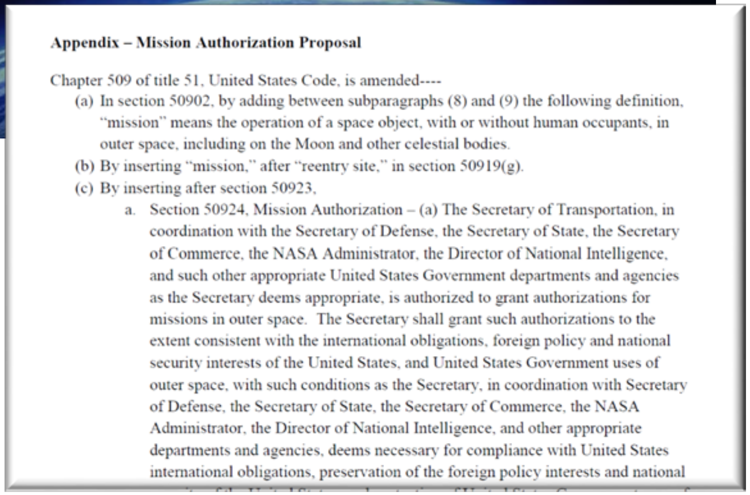
- Frequency licensing: FCC manages the U.S. licensing process for utilization of RF spectrum in space
- Remote sensing licensing: NOAA manages Commercial Remote Sensing (CRS) licenses for space systems utilizing remote sensing systems, focused around earth observation
- Launch licensing: FAA manages the licensing process for launch systems and conducts payload reviews (with a focus on launch safety and liability)

None of the government processes above directly address the unique aspects of on-orbit servicing and its supporting rendezvous and proximity operations

Proposed regulatory authority for space

- There are major pushes within both the executive and legislative branch to create a space “mission authorization” approval
  - The goal of these proposals is to allow for the expansion of commercial activities, while allowing for compliance with the Outer Space Treaty
- The responsible agency for mission authorization is not yet defined – but has been proposed to fall under the Department of Transportation, with extensive coordination throughout government
  - DoD and NASA are not regulatory agencies





Appendix – Mission Authorization Proposal

Chapter 509 of title 51, United States Code, is amended----

(a) In section 50902, by adding between subparagraphs (8) and (9) the following definition, “mission” means the operation of a space object, with or without human occupants, in outer space, including on the Moon and other celestial bodies.

(b) By inserting “mission,” after “reentry site,” in section 50919(g).

(c) By inserting after section 50923,

a. Section 50924, Mission Authorization – (a) The Secretary of Transportation, in coordination with the Secretary of Defense, the Secretary of State, the Secretary of Commerce, the NASA Administrator, the Director of National Intelligence, and such other appropriate United States Government departments and agencies as the Secretary deems appropriate, is authorized to grant authorizations for missions in outer space. The Secretary shall grant such authorizations to the extent consistent with the international obligations, foreign policy and national security interests of the United States, and United States Government uses of outer space, with such conditions as the Secretary, in coordination with Secretary of Defense, the Secretary of State, the Secretary of Commerce, the NASA Administrator, the Director of National Intelligence, and other appropriate departments and agencies, deems necessary for compliance with United States international obligations, preservation of the foreign policy interests and national

Any USG body granted regulatory authority today over on-orbit servicing operations would likely be challenged to execute such authority due to lack of standards or norms

Creation of a new consortium

- In the absence of clear legal or policy precedents for these operations, DARPA is using its unique domain expertise and position within the US Government to facilitate the creation of a government / industry consortium to address these issues:

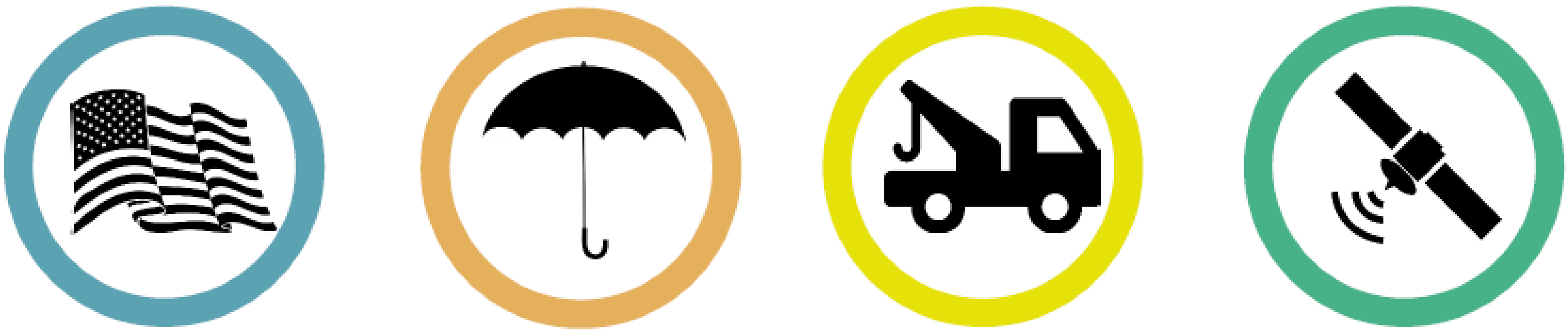
Consortium For Execution of Rendezvous and Servicing Operations (CONFERS)

The initial goals of CONFERS:

- Develop *non-binding industry consensus standards* for safe operational techniques, including rendezvous and proximity operations, and robotic servicing operations
- Serve as a forum to discuss related policy issues, simplifying USG collaboration with industry
- Develop means to share data and experience between participants while protecting participants' financial and/or strategic advantages

CONFERS membership

- CONFERS membership is anticipated to include, at a minimum:



U.S. GOVERNMENT	INSURANCE INDUSTRY	SERVICING ENTITIES	COMMUNICATIONS OPERATORS

-DARPA -OSD
-NASA -Dept of State
-OSTP -FAA/OST

-RSGS Owner/operator*
-Other servicing companies

*Participation is mandatory for RSGS award

- Members and stakeholders' degree of interest, involvement, and impact is variable, and expected to change over time
- Wide USG involvement would allow for one-stop-shopping for industry

Standards development

- In the interest of safe operations and streamlining of future regulatory authority, CONFERS seeks to develop non-binding consensus standards
  - Would allow commercial industry to continue to develop their businesses prior to regulations coming into place

Immediate

- CONFERS members would convene and seek consensus best practices based on USG and commercial expertise, existing policies, and proposed commercial business plans

Near-term (next year)

- CONFERS best practices would be codified into a set of published standard, to which conforming entities could demonstrate adherence

Future

- USG “mission authorization” regulatory body could leverage or adopt published standard as the basis for its approval authority – streamlining its process

CONFERS next steps and takeaways

- In the coming weeks, DARPA will work to investigate best practices from other analogous government/industry consortium constructs (nuclear safety industry, food safety industry, etc.)
- DARPA is soliciting industry and government feedback – particularly relevant to concerns, such that they can be mitigated early
  - Containment of IP between consortium members is noted as a concern and the CONFERS construct will be planned to address this

- **CONFERS is a separate, complementary effort from RSGS**
- **CONFERS success is critical to the execution of the RSGS program**
- **CONFERS relies on strong participation from industry**
- **CONFERS is anticipated to be a key element in enabling future commercial on-orbit servicing activities**

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