Robotic Servicing of Geosynchronous Satellites (RSGS) Proposers Day

Joseph Parrish, Program Manager
DARPA Tactical Technology Office

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

May 22, 2019

DARPA
TTO Strategy
Enterprise Disruption

Dr. Tom Beutner, Deputy Director
DARPA Tactical Technology Office

May 22, 2019
Disrupting the Adversaries’ Calculus

- The U.S. military industrial base is great at making very capable, complex systems
- Our risk-averse processes incentivize performance over cost and schedule
- The result is orders of battle that are predictable, stove-piped, vulnerable, and non-responsive to emerging threats
- To present our adversaries with scenarios that create dilemmas within or completely disrupt their decision calculus, we must disrupt our own warfighting enterprises
Four Domains, Reimagined

After Uncontested Space

Undeterrable Air Presence

Breaking the Symmetry

After the Carrier

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After Uncontested Space

Robotic Servicing of Geosynchronous Satellites (RSGS)

CONTERS

GEO

LEO

Blackjack

Experimental Spaceplane

DARPA Launch Challenge

Hallmark

Artist's Concept

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RSGS Program Overview

Joseph Parrish
RSGS Program Manager

May 22, 2019
Why does DARPA think this is important?

**Problem:** Very high value satellites are isolated and un-serviced
- Anomalies are diagnosed with indirect data and inferences, with great potential for misinterpretation
- There are few opportunities to correct anomalies, even if understood
- End-of-life (EOL) is often dictated by propellant exhaustion, even though other systems are functional

The lack of on-orbit inspection and servicing leads to strategic vulnerability and economic cost

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No end in sight for these anomalies and EOL issues

**Inspect**
- Intelsat 29e, 2019, fuel leak?
- Attribution and diagnostics via survey and ultra-close inspection

**Tug**
- AEHF 1, 2010, propulsion system anomaly
- Rescue, relocation, retirement, fuel-use deferral

**Repair**
- New Dawn, 2011, stuck C-band reflector
- Very high payoff; low occurrence rate

**Augment**
- Upgrade, tech refresh, mission adaptation

None of these capabilities exist today in GEO
DARPA’s answer: Robotic Servicing of Geosynchronous Satellites (RSGS)

Goal: To create a dexterous robotic operational capability in geosynchronous orbit

Benefits:
- Increased resilience for the current U.S. space infrastructure
- The first concrete step toward a transformed space architecture with revolutionary capabilities

Launch: Q4FY22 (notional)

Approach: Public-private partnership
RSGS concept of operations

RSGS Phases:

Initial
- Launch
- Delivery to near GEO
- Activation & checkout
- Performance of DARPA capabilities
  - Inspect
  - Tug
  - Anomaly resolution
  - OAC

Operational
- Partner commercial activities
- Multiple clients per year
- POD retrievals

Refurbishment?

Retirement

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RSGS concept animation
RSGS flight and ground system architecture

Mission Operations Center
- RSV Mission Planning and Execution
- RSV Spacecraft Operations
- RSV Payload Operations

Ground Segment
- Ground Station 1
- Ground Station N

Space Segment
- RSV CMD/TLM
- Robotic Payload TLM

Client Ground Station(s)
- Client CMD/TLM

External Resources
- Client Owner/Operator
- Ground Tracking
- Ground Sites

RSV Operations Planning and Validation Facility

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RSGS payload (layout notional)

Dimensions shown here: 2.3m x 2.4m x 0.6m
(electronics deck not shown)
Payload Components

Payload hardware and software FM assembly, integration, and testing is underway

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RSGS tool changeout at NRL testbed
Vision: A servicing ecosystem in GEO

- Present-day GEO asset
- Future GEO asset
- Future small satellite
- Delivery: ESPA, secondary, dedicated
- Delivery: PODs
- Acquire, transport, unpack
- Rendezvous, Dock
- Spacecraft maneuver
- Restore orbit
- Install
- Replenish

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Related technologies: Payload Orbital Delivery (POD)

- Flight-releasable hosted payload
- Deliver logistics or OAC mass to GEO as ridealong on commercial client host spacecraft during their transit from launch to GEO
- **Flight proven** in 2018
- Concept applicable to any GEO spacecraft with available mass and volume

**PODs enable recurring logistics route to GEO**
Related technologies: On-orbit Attachable Capabilities (OAC)

1) OAC delivered to GEO via POD system
2) RSGS retrieves free floating OAC
3) RSGS installs OAC on client
4) Client with new capability

- Increased GEO fleet resilience
- New ability to modify satellites to meet changing mission needs
- Decouples hosted payload and spacecraft schedules
- New capabilities could lead to new “killer apps”
- On-orbit upgrade could lower cost of access to GEO
- Allows payloads that do not require propulsion or attitude control
- Effects on spacecraft design (on-orbit power/data ports, docking fiducial markings, etc.)

OACs enable space architecture adaptability
RSGS on-orbit animation (OAC installation)
Evolution: expanded capabilities, lower costs

**Evolution:**
- Expanded capabilities, lower costs

**Logistics**
- Expanded coverage, new tools, experiments
- **First steps in GEO logistics**
  - **REPAIR**
  - **REPOSITION**
  - **INSPECT**
  - **AUGMENT**

**Construction**
- Modular spacecraft with on-orbit replaceable units
- Large apertures, structures, and bases

**Technology development and investment**

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www.darpa.mil
Naval Research Laboratory

Advancing research further than you can imagine

Spacecraft Engineering Division

Naval Center For Space Technology (NCST)

An Overview
“The Government should maintain a great research laboratory to develop guns, new explosives, and all the technique of military and naval progression without any vast expense.”

– Thomas Edison, 1915

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

– Josephus Daniels, Secretary of the Navy, 1915
Naval Research Enterprise

Chief of Naval Research & OPNAV N94
RADM David Hahn, USN

Vice Chief of Naval Research & CG, Marine Corps Warfighting Lab
BGen Christian Wortman, USMC

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### Organization ... 18 Research Divisions... $1.3 Billion Executed

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Naval Center for Space Technology: Developing New Capabilities with Operational Impacts

NRL’S FIRSTS IN SPACE
A HISTORY OF ADVANCED TECHNOLOGY TRANSITIONS TO OPERATIONS AND INDUSTRY.

- 1st Satellite Control Ground Station (Blossom Point, 1956)
- 1st Earth Observing/Weather Satellite (Vanguard 2, 1959)
- 1st U.S. Recon Satellite (GRAB, 1960)
- 1st Multiple Satellite Launch (SOLRAD 1, 1960)
- 1st Observatory on the Moon (Far UV Camera on Apollo 16, 1972)
- 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 (ORS) Satellite (TacSat-1, 2004)
- 1st to Fly Many Enabling Components Such as Solar Cells and Atomic Clocks, Cold Gas Thrusters, Onboard Data Storage, 3 Axis Stabilization, Rechargeable NiCad Batteries

Theory without practice is intellectual play, practice without theory is blind.
NCST’s Satellite Operations Enterprise – Spacecraft Operations, Mission Operations

- VMOC provides a single aggregation point for mission tasking, processing, and display

- Neptune software’s common baseline, showcased at Blossom Point Tracking Facility (BPTF) with common ground hardware resources, enables a resilient and flexible, spacecraft C2 architecture

- OCEAN provides precision orbit determination and propagation for ground operations and mission planning

- Blossom Point provides extensive RF connectivity and, using Neptune software, is highly automated

**VMOC, Neptune, OCEAN, and BPTF provide a capable, well-integrated solution to many mission needs**
Spacecraft/Space Vehicle/Payload - End to End
Conceive, Design, Build, Integrate, Assemble & Test

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 10ft Diameter/32ft Length] Multiple Smaller Chambers for Electronics Boxes and Piece Part Bulks outs

Vibe-Acoustic Chamber; 32-10,000 Hz Freq. Range (153dB Acoustic); 30x30x3 ft Electromagnetic Vibration Exactor

Vibration Facilities Has Shakers From 1,000s to 50,000s for Vertical and Horizontal Modes

Coming Soon

DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.
Decades of NRL robotics research have generated significant space, ground, and maritime innovations.

Significant internal investments in facilities, personnel, and research, combined with strong external sponsor partnerships.

Transformational robotics technology will have a lasting impact on our nation.
DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.
• 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 (RSGS), USAF, NASA, and Industry
NRL / DARPA Space Robotics History

2004: SUMO Point Design

2004: SUMO Grapple Demonstration

2005: SUMO RPO & Grapple Demonstration

2008: FREND Flight Prototype Grapple

2008: FREND EDU Grapple Demonstration

2009: FREND Environmental Testing

2013: Phoenix EMI Testing

2013: Phoenix First Contact Discharge R&D

2014: Phoenix Teleoperations Tool Testing
• 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:
  – 2009-2010 – FREND Application Studies
  – 2010-2011 – MGS: Manned Geo Servicing Study, joint study by DARPA/NASA
  – 2011-2013 – Phoenix
  – 2015-… – 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
RSGS Partnership Goals

Joseph Parrish
RSGS Program Manager

May 22, 2019
Why DARPA chose a public-private partnership structure for RSGS

Why GEO?
Large concentration of serviceable, accessible assets

Why commercial?
~5:1 commercial to government
  → More data
  → Reduced cost
  → Available for government when needed

Why not DARPA-only?
We focus on establishing new capabilities, not on operating them

Ongoing commercial enterprise enables long term US servicing presence in GEO
RSGS Program Solicitation recap

• Soliciting Other Transaction (OT) proposals under the authority of 10 USC § 2371b for a public-private partnership

• Commercial partner team would be a U.S. space industry builder-owner-operator
  • Provide a GEO-qualified bus (modified as needed to accommodate robotic payload)
  • Integrate the robotic payload to the bus, creating the Robotic Servicing Vehicle (RSV)
  • Launch the RSV to GTO or GEO on partner-provided U.S.-manufactured launch vehicle
  • Provide mission operations and ground communications across the GEO belt
  • After DARPA-specified on-orbit checkout/demo period, operate the RSV commercially for several years to service many government and commercial clients

• End state is a U.S. commercially-owned and -operated RSV in GEO, carrying the Government-furnished robotic payload
**RSGS partnership responsibilities**

**DARPA**  
*Government Partner for RSGS*

- Program management and technical oversight
- Robotic payload
  - Program management & system engineering
  - Robotic arms, tools, sensors
  - Integration and test, V&V
- Robotic ground control workstation
- Robotic mission operations planning and training

**Partner**  
*Commercial Partner for RSGS*

- Program management and mission system engineering
- Spacecraft bus (heritage GEO bus, tailored for RSGS requirements)
- Integration and test
- Launch vehicle procurement
- Launch vehicle integration
- Mission control center for operations
- Servicing mission execution

**DARPA Funded**  
**Partner Funded**
RSGS program phases

- **Spacecraft and payload development**
  - Government-funded robotic payload development already underway (post-Payload PDR with numerous long-lead flight articles already in production)
  - Partner to commence spacecraft bus development soon after selection

- **Integration and launch**
  - Partner to integrate payload to spacecraft bus => RSV
  - Partner to integrate RSV to launch vehicle
  - Partner to launch RSV to GTO or GEO

- **Capability demonstration**
  - Partner-performed, Government-directed on-orbit checkout and demonstration using Government-arranged client(s)

- **Commercial operations**
  - Partner-operated servicing of Government and commercial clients
The following schedule dates are notional, subject to negotiation between the Government and Partner:

- Payload Critical Design Review (CDR) – Q1FY20
- Bus System Requirements Review (SRR) – Q3FY20
- Bus Preliminary Design Review (PDR) – Q1FY21
- Bus CDR – Q3FY21
- Payload Delivery – Q1FY22
- Bus Delivery – Q1FY22
- IRW Delivery – Q1FY22
- Ground System Readiness Review – Q2FY22
- RSV I&T Complete – Q3FY22

Proposer should provide a schedule that fits their partnership concept
Funding and consideration

• The Government expects to transfer no funding to the Partner
• The Government-funded robotic payload will eventually be owned by the Partner (after the demonstration period)
• The Partner must offer the Government consideration in exchange for the robotic payload
• Some examples of consideration
  • Assured pricing for future missions to service Government clients
  • Agreement to perform robotic experiments for Government clients
  • Provision of operational data and lessons learned from servicing operations
  • Training of Government personnel
  • Other offers consistent with the Partner’s business case
• The total amount of consideration will be a factor in the evaluation of Partner proposals
Let’s get this done!

- We’ve shared what we want to get done on-orbit and why
- We’re looking forward to hearing your ideas for what we can do together
- Let’s work together to make a new reality in space

Cooperatively **inspect** spacecraft experiencing anomalies

Cooperatively **assist** with orbit adjustments

Cooperatively **correct** mechanical problems

Cooperatively **install** self contained payloads on-orbit
Program Solicitation
DARPA-PS-19-01

Chris Glista
DARPA Contracts Management Office

May 22, 2019
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, and does your team have the financial capability and corporate commitment?
• Consideration – What consideration will be given to the government for the GFE and services?
• 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)
Step-by-Step Partner Selection

RSGS Proposers Day

RSGS Partner Selection

PROGRAM SOLICITATION

EXECUTIVE SUMMARIES

SUPPLEMENTAL DATA

ELIGIBILITY

SELECTION

PROPOSALS

OTA NEGOTIATIONS

AWARD

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Three Step Partnership Selection Process

Step 1 – Executive Summary / Eligibility

Step 2 – Proposal Submission / Evaluation / Selection

Step 3 – OT Negotiations / 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.
Proposal structure

Proposal Summary (15 page limit)

Volume 1: Technical Description (75 pages)
T1) System Concept and Summary of Performance
T2) Mission Compatibility and Performance Analysis
T3) Development
T4) Manufacturing
T5) Bus to Payload Integration
T6) Test and Verification
T7) RSV to Launch Vehicle Integration
T8) Launch and Delivery to GEO
T9) Ground Segment Approach and Operator Certification
T10) Technical Risks
T11) Safety and Mission Assurance
T12) Compliance with Evaluation Criteria

Volume 2: Business & Management Plan (110 pages)
B1) Organization Information
   A. Business Strategy
   B. Market
   C. Products and Services
   D. Marketing and Sales
   E. Governance Structure
   F. Management Team
   G. Finance
B2) RSGS Development and Demonstration Plan
   A. Plan and Schedule
   B. Resources
   C. Teaming Arrangements
   D. Performance Milestones
   E. Consideration to Government
B3) RSGS Operational Readiness Plan
B4) Compliance
B5) Cost and Price Information
B6) Compliance with Evaluation Criteria
Step 1 – Eligibility

Submit Executive Summary by 12:00pm ET, June 4, 2019

- 5 Page Summary Limit
- ITAR & U.S. Commercial Provider certifications
- Prohibited countries representation
- 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

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

- 200 page limit
- Includes Proposal 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 – Supplemental Business Data

Submit full proposal by 5:00pm ET, July 23, 2019
Step 2 (cont’d) – Proposal Evaluation & Selection

Proposals will be evaluated in accordance with these evaluation criteria:

- Factor 1 – Technical Capabilities
- Factor 2 – Business and Management Plan
- Factor 3 – Consideration for Government Furnished Equipment and Services

DARPA intends to select a single partnership proposal for OT award
OTs provide flexibility in the structure of the agreement. For example in the areas of:

- Intellectual Property
- Dispute Resolution
- Miscellaneous TBD issues

DARPA OT Template is merely a starting point. However, the following responsibilities are non-tradeable:

- Partner liability for on-orbit operation of the RSV
- Maintenance of appropriate personnel security
Evaluation Criteria

Joseph Parrish
RSGS Program Manager

May 22, 2019
Proposal Evaluations

- All three factors are of equal importance.

- The three factors are all the evaluation criteria that the Government will use to evaluate a Proposer’s proposal.

- There are no unstated evaluation criteria.
Evaluation factors

- Factor 1 – Technical Capabilities
- Factor 2 – Business and Management Plan
- Factor 3 – Consideration for Government Furnished Equipment and Services

In the event of any conflict with the Program Solicitation (PS) document, the PS takes precedence.
Evaluation Factor 1 – Technical Capabilities

Providing a GEO-capable spacecraft bus:

• Extent to which the proposed bus has heritage in GEO operations, along with its ability to execute the RSGS mission operations over a multi-year operational lifetime.

Integrating the RSGS payload with the spacecraft bus:

• Extent to which the bus can accommodate the RSGS payload via extant capabilities and/or adaptations to the existing bus design; ease of integrating the RSGS payload to the bus to provide a complete RSV.

Integrating the combined spacecraft bus and RSGS payload with the launch vehicle:

• Extent to which the RSV can be integrated into the proposed launch vehicle.

*In the event of any conflict with the Program Solicitation (PS) document, the PS takes precedence.*
Evaluation Factor 1 – Technical Capabilities

Providing a launch vehicle:

- Extent to which the Partner-provided U.S.-manufactured launch vehicle is capable of delivering the fueled RSV to GEO orbit, either via GTO or direct to GEO.

Conducting GEO mission operations:

- Ability to conduct servicing operations in GEO, including experience with rendezvous and proximity operations, autonomous grappling operations, coupled stack operations, and robotic manipulator operations, over a multi-year operational lifetime.

Providing ground control station(s) and communications infrastructure:

- Extent to which ground facilities and communication infrastructure can integrate the GFE IRW and provide command and control of the RSV in operation throughout the GEO belt, at the required level of security, over a multi-year operational lifetime.

*In the event of any conflict with the Program Solicitation (PS) document, the PS takes precedence.*
Evaluation Factor 2 - Business and Management Plan

Viability of the public/private partnership:

• Financial capability and corporate commitment to fulfill the Partner’s responsibility in a public-private partnership, including the provision of a GEO-capable spacecraft bus, payload integration, launch vehicle integration, launch vehicle, GEO mission operations, and ground control station/communications infrastructure.

Providing an integrated and complete solution:

• The extent to which the Partner is capable of providing all equipment, personnel, resources, and facilities, without additional Government Furnished Property, Government Furnished Information, or Government Furnished Equipment, beyond those items discussed in this solicitation.

Efficacy of the business case:

• Extent to which a commercial business case exists for revenue-generating servicing operations to be performed upon multiple Government and commercial clients over a multi-year operational lifetime.

In the event of any conflict with the Program Solicitation (PS) document, the PS takes precedence.
Evaluation Factor 3 – Consideration for Government Furnished Equipment and Services

Extent of consideration offered to the Government related to:

- Reduced-price servicing of Government spacecraft
- Hosting of Government payloads/experiments
- Operational data and lessons-learned during the RSGS on-orbit operational lifetime
- Other types of consideration offered by the Proposer

In the event of any conflict with the Program Solicitation (PS) document, the PS takes precedence.
Questions should be addressed to:

DARPA-PS-19-01@darpa.mil
RSGS Payload Overview

U.S. Naval Research Laboratory
May 2019
RSGS Mission Introduction
RSGS Architecture Block Diagram

Control is coordinated between RSV and Client

Robotic Servicing Vehicle (RSV)

External Resources
- Client Owner/Operator
- Ground Tracking
- Ground Sites

RSV Operations Planning and Validation Facility

Client Spacecraft

Mission Operations Center
- RSV Mission Planning and Execution
- RSV Spacecraft Operations
- RSV Payload Operations

Ground Station 1
- Ground Control
- Ground Status
- Tracking Data
- Antenna Pointing Data
- Uplink
- Downlink
- High-Rate Downlink

Ground Station N

Ground Segment

Space Segment

Client Ground Station(s)
RSGS Concept of Operations

- **RSV Launch, Initial Activation, and Checkout**
  - Hours

- **RSV Activation and Checkout/Quiescent Operations**
  - Months

- **Proximity Operations**
  - Week

- **Rendezvous**
  - Days-Weeks

- **Client Grapple/Ungrapple**
  - Hours

- **Client Orbit Modification**
  - Days-Weeks

- **RSV Parking Orbit Transfer**
  - Months

- **RSV Parking Orbit Transfer/Quiescent Operations**
  - Days

- **Client Inspection**
  - (Free Flyer or Grappled)
  - Week(s)

- **Client Anomaly Resolution and Upgrade Installation (Grappled)**
  - Week(s)
Payload Design Summary

• 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 supports eight-year mission life

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

• Protoqualification verification test program

Long-life payload leveraging DARPA investments will enable commercial missions for several years after government demonstration
Payload Components

- 2 Robotic Arm Systems, each with:
  - 1 FREND Arm
  - 1 Rikishi Electronics Unit (REU)
  - 1 External Robotic Arm Electronics (E-RACE)
  - 1 End of Arm (EoA):
    - 2 Cameras
    - 3 Lights
    - 1 Tool Changer
    - 1 End of Arm Control Board (EACB)
- Flight Software (FSW)
  - Includes Payload Mission Manager (PMM)
- Algorithms
  - Marman Ring Detector (MRD)
  - POD Fiducial Detector (PFD)
  - Visual Servo (VS)
  - Position Control (PC)
  - Compliance Control (CC)
  - Torque Feed Forward (TFF)
  - RPO Bearing
- 7 SPDPs (Ports)
- Toolkit (3)
  - 2 Marman Ring Tools (MRT)
  - 1 POD Capture Tool (PCT)
- Rendezvous and Proximity Operations Suite
  - 2 LIDAR Sensors
  - 2 NFOV Cameras
- Proximity Awareness System
  - 1 Color Documentation Camera (CDC)
  - 10 Proximity Imaging Cameras (PICs)
  - 1 Infrared (IR) Camera
- Deck-mounted Lights
  - 10 Proximity Imaging Lights
  - 2 Long-range Lights
- Command, Telemetry, and Data Handling
  - 6 Common Remote Electronics (CRE)
  - 2 Robotics Processing Modules (RPM)
- 3 Power Distribution Units (PDU)
- Calibration Hardware
Payload Component Overview
Payload Components

Payload hardware and software FM assembly, integration, and testing is underway.
Robotic Arm System (RAS) Components
Robotic Arm System Overview

• The Robotic Arm System (RAS) is comprised of
  - The FREND Robotic Arm
  - Robot Arm Control Electronics
    • Rikishi Electronics Unit (REU)
    • External Robotic Arm Control Electronics (E-RACE)
  - End of Arm (EoA) components
    • Tool Changer, EoA Cameras, Lights, EACB, Structure, Harness
SSL-R delivers the RAA components (includes RA, REU, and launch locks)
Oceaneering Space Systems (OSS) delivers Tool Changer
Malin Space Science Systems delivers EoA Cameras
NRL delivers E-RACE, EACB, and the EoA (EoA lights, structure, harness, and thermal) then integrates and delivers the EoA
NRL integrates the RA with the EoA
NRL integrates the E-RACE and harness to complete RAS integration
FRIEND MKII Robotic Arm

Current Status:
- FM actuator assembly in progress
- Arm #1 Delivery: Q3 2019
- Arm #2 Delivery: Q4 2019
Rikishi Electronics Unit (REU)

• Moog Broadreach (MBR), Phoenix, AZ delivers REU to SSLR, Pasadena

• Robot Arm Control Electronics with:
  − 9 Motor Control Boards: 7 Joints, 2 Tool Drive
    • (SY, SP, SR, EP, WY, WP, WR, TD1, TD2)
  − 1 COMM Card
  − 1 Mother Board

• Mark I Rikishi EDU has been operating successfully since 2007

• Mark II FM REU upgrades include:
  − Primary/Redundant Comm interface
  − Individual power feeds per MCB
  − Updated Joint Control and FDIR logic

• Current Status:
  − Two EDU REUs currently in use at SSL-R supporting FM Arm test
  − FM REUs in test
  − FM REU #1 delivery: Q3 2019
  − FM REU #2 delivery: Q4 2019
**External Robotic Arm Control Electronics (E-RACE)**

- **NRL internal development and build**
  - **Purpose**
    - Power filtering and extended arm operations
  - **Key Features**
    - Match output impedance of REU to impedance of RA
    - Protect the REU and spacecraft power system from the back EMF of the motors
    - Provide a brake voltage step down voltage automatically after energization of the brake circuit
    - Joints and Tools
    - Provides ESD protection

- **Current Status:**
  - Brassboard assembly in process, delivery in Q3 2019
  - EM and FM parts procurements underway
  - FM delivery: Q2 2020
End of Arm Overview

- Structure/Harness
- EoA Control Board
- EoA Prototype
- EoA Cameras
- EoA Lights
- Tool Changer
• NRL internal development and build

• Components
  - Camera bracket
  - EACB lower bracket
  - EACB upper bracket
  - Lights brackets
  - Harness
  - Thermal hardware: radiators, PRTs, heaters, Thermostats

• Current Status:
  - FM Brackets complete
  - FM harness assembly underway
  - FM thermal hardware on order
• NRL internal development and build

• Purpose
  - Functions as interface between most of End of Arm (EoA) components & payload
  - Power to and SpaceWire communications with two EoA cameras
  - Power and command to; and telemetry from the mated tools via the tool changer Common Receptacle Subassembly (CRS)
  - Power to and telemetry from the Force Torque Sensor (FTS)
  - Telemetry from the tool changer Confirmation-of-Lock (COL) sensor

• EDU successfully tested with RA Flex Harness and operated since April 2017

• Current Status:
  - EM EACB environmental testing is underway
  - FM EACB #1 & #2 assembly in process
  - FM EACB delivery: Q1 2020
EoA Cameras

- Malin Space Science Systems (MSSS), San Diego, CA
  - Extensive experience with spaceflight cameras
- SpaceWire interface for communications and image output
- Imagery is used as primary input into machine vision algorithms
- Imagery to be recorded for close-proximity, close proximity inspection missions and teleoperations
- Camera placement carefully chosen to work with tools and RSO features

**Current Status:**
- EDU cameras received
- EM camera delivered April 2019
- FM cameras in assembly
- FM delivery: Q3 2019
EoA Lights

- **NRL internal development and build**
  - In conjunction with NRL code 7200 remote sensing group
- East/West lights are designed to be collocated with each camera
- North lights are a light-bar to provide fill illumination
- LEDs completed successful radiation testing in April 2018

**Current Status:**
- EM lights in test
- FM delivery: Q4 2019
**Tool Changer and Receptacle (TCR)**

- **Oceaneering Space Systems (OSS) Houston, TX**
- Provides the common structural, torque, and electrical mechanical interface for on-orbit tool attachment
- Oceaneering prototype has been operating successfully at NRL since 2014
- Common Receptacle Subassembly to be integrated onto all tools, delivered by OSS

**Current Status:**
- EM delivered Q1 2019
- FM #1 assembled and starting performance testing
- FM #2 assembly is underway
- FM delivery: Q3 2019
Toolkit Components
• The Payload Toolkit consists of:
  - 2x Marman Ring Tool (MRT): Grapples via the marman ring launch vehicle interface common on GEO vehicles
  - 1x POD Capture Tool (PCT): Grapples POD via the cooperative POD Grapple Fixture

• 7x Structural, Power and Data Ports (SPDPs)
  - 3x Stow tools for launch and when not in use
  - 4x for POD & OAC staging
Structural, Power and Data Port (SPDP)

- Sierra Nevada Corporation, Durham NC
  - The Active Unit is permanently attached to the spacecraft payload deck.
  - The Passive Unit is permanently attached to a separable item (Tool/POD/OAC).
  - The Port serves two primary functions:
    - Launch restraint and release of tools
    - Storage of Separable Items, Tools/PODs/OACs
      - Repeated on-orbit mate & de-mate
      - Electrical pass-through to separable items for on-orbit operations

- Current Status:
  - EM fabrication is underway
  - EM delivery: Q4 2019
  - FM delivery: Q3 2020
Marman Ring Tool (MRT)

- NRL internal development and build
- Evolved design from FREND Demonstration
- Grapples 1194, 937, & 1666 Marman Rings
- Establishes structural link to RSO
- Includes resistive bleed path for first contact
- Prototype Testing in progress
  - Stiffness testing completed
- Closing FM design trades

- Current Status:
  - EM assembly is underway
  - EM delivery: Q3 2019
  - FM delivery: Q3 2020
• MDA Brampton, Canada
• Evolved version of Orbital Express End Effector
  − Incorporates Telemetry Lessons Learned
  − Updates interfaces to be compatible with RSGS
• Grapples POD via PCT Grapple Fixture

• Current Status:
  − EM delivery: Q4 2019
  − FM delivery: Q4 2020
Avionics and Sensors Hardware Overview
Robotics Processing Module (RPM)

• RPM is a mix of procured and NRL in house developed components

• Functions
  − SpW Router
    • Distributes SpW Time
    • Receives Force/Torque Sensor (FTS) and Joint Command Interface (JCI) TLM via SpWN
    • Receives payload SoH TLM
    • Receives all camera image streams
    • Transmits Mass-memory data to Wide-Band downlink
  − Image pre-processing (JPEG, Threshold, Edge, Moment)
  − Mass storage: 200GB EOL
  − Hosts FSW
    • Image processing, FTS/JCI TLM interpretation, arm commanding, arm collision avoidance
    • Redundant RPM kept in cold standby

• Key Elements
  − GRB Uses a reprogrammable FPGA (RTG4)
    • Not reprogrammable in orbit
  − 5X Maxwell SCS750 Single Board Computers (800 Mhz)
  − One SwRI Mass Memory Unit

• Current Status:
  − EM assembled and performance testing is underway
  − FM card assembly is underway
  − FM delivery: Q4 2019
Common Remote Electronics (CRE)

• NRL internal development and build

• Functions
  – SpW Router/Gateway
    • Primary Interface for lower rate digital data: PDU (LVDS) & REU (RS-422)
    • Distributes SpW Time
    • Supports SpW RMAP
  – Mechanism driver for Tool Changer and SPDP
  – Analog TLM Conversion
  – Provides ESD protection for signals read from components outside the SC structure

• Key Elements
  – Uses a reprogrammable FPGA (RTG4)
    • Not reprogrammable in orbit
  – Uses LX7730 Analog Telemetry processor (Reconfigurable on orbit)
  – Identity connector to load box unique configurations

• Current Status:
  – EM assembled and performance testing is underway
  – FM card assembly is underway
  – FM delivery: Q2 2020
Power Distribution Unit (PDU)

• **NRL internal development and build**
  - Housekeeping card (HSK)
  - Regulated Power Card (RPC)
  - Lighting Card (LC)
  - Mother board

• Each PDU has a different set of cards based on the loads it is servicing

• **Functions**
  - Provides regulated power to:
    - Narrow Field of View (NFOV) Cameras
    - Proximity Imaging Cameras (PICs) and PIC Lights
    - Infrared (IR) Camera and Color Documentation Camera (CDC)
    - Long Range (LR) Lights
    - Voltage compensated circuits for End of Arm Components
      - End of Arm Control Board (EACB)
      - End of Arm (EoA) Cameras and Lights
  - Provides command and telemetry interfaces to the Command, Telemetry, and Data Handling (CT&DH) system
  - Provides overcurrent protection

• **Key Features**
  - PDU Uses a reprogrammable FPGA (RT4G)
    - Not reprogrammable in orbit

**Current Status:**
- EM assembled, performance testing is underway, environmental testing is pending
- FM card assembly in underway
- FM delivery: Q3 2020
Sensors and Lighting Hardware Overview
LIDAR Overview

- **NEPTEC Design Group Kanata, Canada**
  - Variants have Flown on Shuttle and Cygnus Mission

- **Functions**
  - 3D POSE range <1km
  - 6D POSE range <50 m
  - Generate Point Cloud to support building models of client Spacecraft

- **Key Elements**
  - Reprogrammable FPGA (RTG4)
  - Optics are based on heritage designs
  - Heritage FSW use for POSE calculation

- **Risk Reduction**
  - Neptec has performed significant mechanism life tests
  - Extensive modelling/Simulation capability

- **Current Status:**
  - EDU delivery: Q4 2019
  - FM delivery: Q3 2020
NFOV Camera Overview

- **Malin Space Science Systems (MSSS), San Diego, CA**
  - Cameras flown on Interplanetary and selected for RESTORE mission

- **Functions**
  - Bearing POSE range >1km
  - Inspection of RSOs from distance and Close-in

- **Key Elements**
  - On-Semiconductor CMOS Imager
  - Optics are based on heritage designs

- **Risk Reduction**
  - EDU Units have been developed and tested
  - Performed testing with COTS version of flight imager
  - EM NFOV camera currently in test

- **Current Status:**
  - EM NFOV delivered in April 2019
  - FM delivery: Q4 2019
PIC, CDC, IR Cameras

• **Malin Space Science Systems (MSSS), San Diego, CA**
  - Cameras flown on Interplanetary and selected for RESTORE mission

• **Functions**
  - PICs: Witness Robotic Operations
  - CDC: Color inspections of RSOs
  - IR: Thermal inspections of RSOs

• **Key Elements**
  - Visible: On-Semiconductor CMOS Imager
  - IR: ULIS Microbolometer
  - Optics are based on heritage designs

• **Risk Reduction**
  - EDU Units have been developed and tested
  - Commercial Version of the Sensor have been used to support testing at NRL

**Current Status:**
- EM IR & CDC Cameras delivered April 2019
- EM PIC delivery: Q3 2019
- FM camera delivery Q4: 2019
Deck Lights

• NRL internal development and build

• Functions
  − PIC Lights: Support PIC camera imaging of robotic operations
  − Long Range Lights: Support imaging of RSO from 5m

• Key Elements
  − OSRAM LEDs selected
  − Lights contain a current balancing circuit
  − 50 mils of glass added for radiation shielding

• Risk Reduction
  − Total Dose testing performed on LED at NRL
  − Displacement Dose Damage Testing performed at University of Washington
  − Lights are within their allocated losses

• Current Status:
  − EM Deck Lights in environmental testing
  − FM delivery: Q4 2019
# Sensor & Lighting Operating Range Summary

<table>
<thead>
<tr>
<th>Range</th>
<th>1000 km</th>
<th>100 km</th>
<th>10 km</th>
<th>1 km</th>
<th>100 m</th>
<th>50 m</th>
<th>1 m</th>
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<tbody>
<tr>
<td>Key Waypoint Stations</td>
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<td></td>
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<tr>
<td><strong>Initial Detection</strong></td>
<td>NFOV 1,2</td>
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<tr>
<td><strong>RPO Pose Tracking</strong></td>
<td>NFOV 1,2</td>
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<td></td>
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<tr>
<td><strong>Inspection</strong></td>
<td>NFOV 1,2</td>
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<td></td>
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<tr>
<td><strong>Event Witnessing</strong></td>
<td>CDC</td>
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<tr>
<td><strong>Machine Vision</strong></td>
<td>EoA Cameras</td>
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<tr>
<td><strong>Illumination</strong></td>
<td>Sun</td>
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</tr>
</tbody>
</table>

## Sensor & Lighting Operating Range

- **Initial Detection**
  - NFOV 1,2

- **RPO Pose Tracking**
  - NFOV 1,2
  - LIDAR 1,2

- **Inspection**
  - NFOV 1,2
  - CDC
  - IR
  - LIDAR 1,2
  - PICs
  - EoA Cameras

- **Event Witnessing**
  - CDC
  - PICs
  - EoA Cameras

- **Machine Vision**
  - EoA Cameras

- **Illumination**
  - Sun
  - Long Range Lights
  - PIC Lights
  - EoA Lights

---

**DISTRIBUTION STATEMENT A.** Approved for public release: distribution unlimited.
Controls & Algorithms Overview
Algorithm Overview

- The RSGS algorithm stack–up is very similar to the stack–up that was used for the FREND demos (circa 2007–2008) and for all subsequent demos and development efforts
  - Inverse kinematics and collision avoidance algorithms (known here as “Position Control”) were rewritten from scratch for RSGS
- Status:
  - All algorithms are complete and algorithm level verification is underway
  - Implemented in FSW:
    - Compliance Control, Position Control, Marman Ring Detector, POD Fiducial Detector
  - FSW Implementation in process:
    - Visual Servo
Flight Software (FSW) Overview
• The RSGS Payload Flight Software (FSW) resides in the RPM
• The FSW provides control of the 2 robotic arms
• The FSW implements the various robotic control algorithms, including:
  - Machine Vision Detectors (Marman Ring Detector, POD Fiducial Detector)
  - Position Control
  - Visual Servoing
  - Compliance Control
  - Torque Feed Forward
  - RPO Bearing Estimation
• The FSW implements the payload mission management and FDIR
• The FSW provides a high-level scripting capability and time based commanding
• The FSW provides an interface to the spacecraft bus to accept commands and provide telemetry
• The FSW collects and reports payload state of health and diagnostic telemetry
• The FSW provides configuration, command and status collection of the CTDH and other payload hardware
• FSW executes on 5 Maxwell SCS750 processors in the RPM and utilizes WindRiver’s VxWorks OS
Simplified FSW Architecture
Payload FSW Modes Diagram
# Detailed Software Schedule

<table>
<thead>
<tr>
<th>Build</th>
<th>Date</th>
<th>Name</th>
<th>Major Content</th>
<th>Stakeholders</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSW 3.4</td>
<td>4/10/19</td>
<td>MP I</td>
<td>• Initial position control&lt;br&gt;• Joint control&lt;br&gt;• PMM triggers</td>
<td>• Box Test</td>
</tr>
<tr>
<td>FSW 4.0</td>
<td>7/10/19</td>
<td>MP II</td>
<td>• Position Control&lt;br&gt;• Machine Vision&lt;br&gt;• Scripting</td>
<td>• ROTB</td>
</tr>
<tr>
<td>FSW 4.1</td>
<td>October 2019</td>
<td>VS &amp; FM</td>
<td>• Visual Servoing&lt;br&gt;• Tool Changing&lt;br&gt;• PMM Scripts &amp; Responses&lt;br&gt;• Fault Indicators</td>
<td>• ROTB&lt;br&gt;• RTB&lt;br&gt;• FSW Verification</td>
</tr>
<tr>
<td>FSW 5.0</td>
<td>February 2020</td>
<td>Full Robotic Capability</td>
<td>• Tool control</td>
<td>• ROTB&lt;br&gt;• RTB&lt;br&gt;• FSW Verification</td>
</tr>
<tr>
<td>FSW 6.0</td>
<td>February 2021</td>
<td>Bus Interfaces Full Mission Capability</td>
<td>• Bus Interfaces&lt;br&gt;• Mission/Bus FM</td>
<td>• ROTB&lt;br&gt;• RTB&lt;br&gt;• FSW Verification</td>
</tr>
</tbody>
</table>
Mission Planning and Integrated Robotics Workstation
Concept of Operations, PSM, Payload Operational Procedures

- **Phase State Matrix (PSM)**
  - Captures Mission Phases
    - Steps/Sub-Steps
  - Captures CONOPS quantitatively
    - RMMV Configurations
    - States and Modes information
    - Operational durations
  - Used for:
    - Payload Subsystem analysis
      - Data budgets
    - Requirements development
    - Design trades
  - Iterates with:
    - Operational flows
    - FSW use cases
    - Design trades

<table>
<thead>
<tr>
<th>Phase/Step</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Phase 1: RMMV Launch, Initial Activation, and Checkout</td>
</tr>
<tr>
<td>2.0</td>
<td>Phase 2: RMMV Parking Orbit Transfer</td>
</tr>
<tr>
<td>3.0</td>
<td>Phase 3: RMMV Activation and Checkout/Quiescent Operations</td>
</tr>
<tr>
<td>4.0</td>
<td>Phase 4: RSO Rendezvous</td>
</tr>
<tr>
<td>5.0</td>
<td>Phase 5: RSO Proximity Operations</td>
</tr>
<tr>
<td>6.0</td>
<td>Phase 6: Cooperative RSO Grapple</td>
</tr>
<tr>
<td>7.0</td>
<td>Phase 7: RSO Orbit Modification</td>
</tr>
<tr>
<td>8.0</td>
<td>Phase 8: Cooperative RSO Release</td>
</tr>
<tr>
<td>9.0</td>
<td>Phase 9: RSO Inspection (Free Flyer)</td>
</tr>
<tr>
<td>10.0</td>
<td>Phase 10: DAC Installation</td>
</tr>
<tr>
<td>11.0</td>
<td>Phase 11: RSO Inspection (Grappled)</td>
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<tr>
<td>12.0</td>
<td>Phase 12: RSO Anomaly Resolution (Grappled)</td>
</tr>
<tr>
<td>13.0</td>
<td>Phase 13: POC Approach</td>
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<tr>
<td>14.0</td>
<td>Phase 14: POC Capture and Stow</td>
</tr>
<tr>
<td>15.0</td>
<td>Phase 15: RMMV Parking Orbit Transfer/Quiescent Operations</td>
</tr>
</tbody>
</table>

**Mission Phases**
- Phase 6: Cooperative RSO Grapple

**Steps**
- Step 6.16: Perform Autonomous Grapple

**Sub-Steps**
- Sub-Step 6.16.2: RA enabled for grapple

**Operation procedures**
- Payload Operations Procedures 6.16.2.5
• The PMM is implemented in FSW and has 2 primary roles:
  – Provide automated, supervisory, and autonomous control of payload to operator (defined in controls section)
  – Provide coherent payload Fault Management capabilities

• PMM scripts are developed by Operators to be executed onboard by the PMM application in FSW

• FM is developed by the Payload Fault Management Team (SE) and implemented via PMM, FSW, and hardware
  – Protects the Payload and the operation (RSO) from a fault when ground is too slow to respond or unable to respond. And protects the health and safety of Payload from some standard operator errors (not malicious).
Integrated Robotics Workstation (IRW) Overview

• IRW functions as payload control element in the ground system
  − IRW also provides payload control functions for NRL’s test bed assets

• Used for
  − Planning payload operations
  − Verifying payload operations plans
  − Executing payload operations
    • Scripted operations
    • Teleoperations
    • Operator situational awareness
  − Analyzing payload operation results

• Communicates to the Robotics Payload through the Mission Control Center and the RMMV bus
IRW – Notional Desktop

Robot Motion Planner and Visualizer

Operation Planning Tool

Operation Verification Tool

DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.
Payload & Mission Level Analyses
Verification & Validation Plan
## RSGS Overview

### Mission

#### Inspection (Far and Grappled)
- RSO Grapple (MRT)
- RSO Release (MRT)
- RPO Support
- Far Inspection
- Grappled Inspection

#### Orbit Modification
- RSO Grapple (MRT)
- RSO Release (MRT)
- RPO Support
- Tool Changing
- Orbit Modification

#### Anomaly Resolution
- RSO Grapple (MRT)
- RSO Release (MRT)
- RPO Support
- Tool Changing
- Force Application

#### OAC Installation
- RSO Grapple (MRT)
- RSO Release (MRT)
- RPO Support
- POD Grapple
- POD Stow
- OAC Placement & Detach

### Payload Function

#### 11 Unique Payload Functions
- Tool Changing
- OAC Placement & Detach
- POD Stow
- Orbit Modification
- Force Application

#### Verification Grouping
- Inspection & RPO Support
- Grapple and Release
- Pick and Place
- Orbit Modification
- Force Application
Grapple & Release V&V Plan (Example from Payload PDR)

Verification of robotic reachability and dexterity to perform grapple & release
Payload Controls Analyses
Free-Space Motion: Position Control Preliminary Results

- IK is running in real time with 20% margin (albeit on a non-flight processor)
- IK is using non-gradient-based optimizer; gradient-based optimizer should improve running speed ~5x, and error ~2-3x

Position Control meets tracking performance requirements
Visual Servo System Performance

- Visual Servo simulation performed to assess tracking performance
  - Marman detector noise model was used
  - Assumed worst case servicer to RSO relative rate of 7 mm/sec
  - Assumed worst case instantaneous direction change at edge of capture box
  - Assumed worst case camera-to-ring distance of 0.7 m (noise improves with decreased range)
- Performance spec must be met at <0.5 m)

**Visual Servo System meets tracking requirements**
Machine Vision Subsystem Testing

- **Performance Requirement:**
  - Bias $< 3$ mm
  - Noise $< 5$ mm ($2\sigma$)

- **Test configuration:**
  - Variable lighting, blanketing, ring types, and alignment geometries per the RSO IDD

- **Preliminary Results:**
  - Bias $< 2.5$ mm (range dependent)
  - Noise $< 2.3$ mm ($1\sigma$) (range dependent)

- **Image sequences have been analyzed with the MRD and results have been used to generate a mathematical noise model that represents MRD performance**
  - Noise model is used in Visual Servo analysis and the MissionSim

Machine Vision meets requirements over a range of blanketing, lighting, and ring configurations
Simplified rigid-body planar 3-joint simulation of Marman Ring grapple predicts that a 10 mm/s approach rate will yield adequate time (> 2 seconds) to close the gripper before excessive separation develops between the tool and Marman Ring.

Note - Compliance Control is operating continuously (not triggered upon contact). Trigger will be simulated for CDR level analysis.
MsnSim Simplified Block Diagram (Build 2)
MR Grapple Animations
Payload Structural and Thermal Analyses
Structures and Thermal Design and Analysis

- Structural and thermal models and analysis processes have been built
- Initial results show a wide range of payload operability
- Partner bus performance characteristics and operations details will be used to update analysis results
- Customer specific analyses are also expected
# I&T and Mission Operation Plans

## Development

<table>
<thead>
<tr>
<th>Phase</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>Move to early FSW, Mix of BB and EDU HW, Validate FSW, Verify Flight Operational Flows, Verify Flight Procedures, Mature PMM, Mature FDIR, Support Subsystem I&amp;T</td>
</tr>
<tr>
<td>Phase 2</td>
<td>FSW, EDU and EM HW, Verify Flight Operational Flows, Verify Flight Procedures, Validate FSW, Verify Flight PMM, Verify Flight FDIR, Support Subsystem I&amp;T</td>
</tr>
<tr>
<td>Phase 3</td>
<td>Verify FSW, Verify Flight HW, Verify Flight PMM, Verify Flight FDIR, Support Subsystem I&amp;T</td>
</tr>
</tbody>
</table>

## Verification

- Operational Requirements Verification
- Final Operational Flow Verification
- Final Procedure Verification
- High Level HW and SW Verification

## Flight

- Demo REO Ops
- Procedures Rehearsals Training

## Schedule (end date)

<table>
<thead>
<tr>
<th>Phase 1</th>
<th>Payload PDR: 60 10/2018</th>
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<tbody>
<tr>
<td>Phase 2</td>
<td>Payload CRD: 6/2019</td>
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<td>Phase 3</td>
<td>RAS #1 I&amp;T: 2/2020</td>
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<tr>
<td>Phase 4</td>
<td>Payload PSR: 6/2020</td>
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## Test Bed

<table>
<thead>
<tr>
<th>Test Bed</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HW: COTS arm, BB support HW ESGE: RT68 Rack</td>
<td>ROTB and RTB: HW: COTS arm and EDU arm with ESGE: HB, EDU/EVM support HW ESGE: RT68</td>
</tr>
<tr>
<td>SW: Legacy RTB SW PMM: N/A - Director / Procedure FDIR: N/A - Director / Procedure IRW: Prototype</td>
<td>SW: FSW Build 384 PMM: Early scripts FDIR: Early logic IRW: Build 01</td>
</tr>
<tr>
<td>FTB: Flight Arms, flight P/L HW</td>
<td>Ground Test Beds: GH: Updated ROTB SW: FSW + PMM: verified scripts FDIR: verified logic IRW: Build 2+</td>
</tr>
</tbody>
</table>
Facilities
NRL Major Facilities for Satellite Servicing and In-Space Assembly

- **Proximity Operations Testbed**: Facilitates full scale hardware-in-the-loop rendezvous docking and servicing rehearsals.
- **Gravity Offset Testbed**: Large air-bearing table facilitates high precision contact dynamics rehearsal and validation.
- **Machine Vision Lab**: Optical testbed for development and characterization for flight machine vision sensors, illuminators, and algorithms.
- **Modeling and Simulation**: Robust Monte-Carlo simulation capability validates performance of robotic operations.
- **Integrated Robotics Workstation**: Robotic operations control station, supports high fidelity rehearsals and training.
- **Single Joint Actuator**: Provides extremely detailed correlation between predicted robotic hardware behavior and controls simulations.
- **Robotic Operations Testbed**: Enables integrated procedure development, testing, and training of RSGS end-to-end operations on non-flight system.
- **Flatsat Testbed**: Integrated avionics testbed facilitating end-to-end test of payload electronics.
NRL Environmental Test Facilities

Thermal Vacuum Chamber

Vibration and Shock Lab

EMI Chamber

Space Charge/Plasma Chamber