Phoenix Operations BAA: Technical Elements and Interfaces

Mr. David Barnhart, TTO Program Manager

Briefing Prepared for Phoenix Operations Proposer's Day

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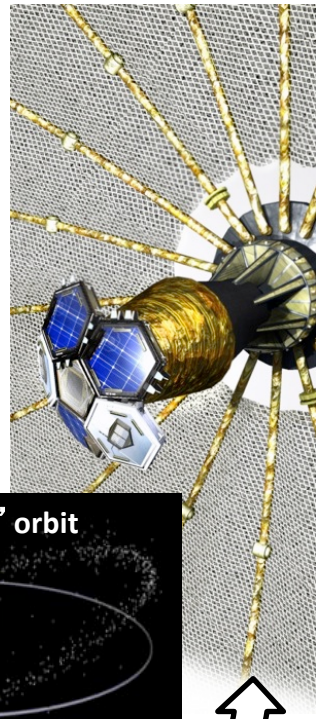
Distribution Statement "A" (Approved for Public Release, Distribution Unlimited).

Three basic concepts combine to create the Phoenix architecture

Re-define morphology of satellites

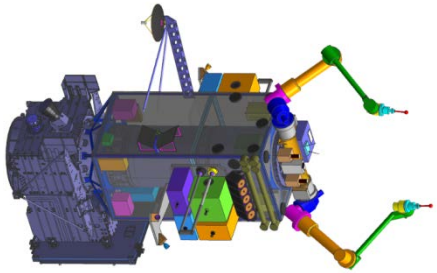
Repurposing retired components into value added systems or services

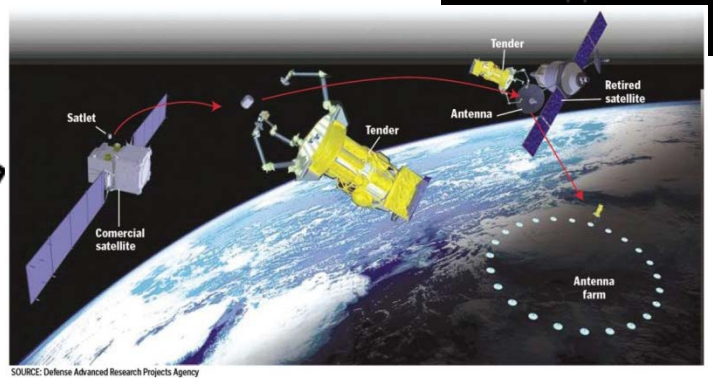


Increase tempo of small mass by expanding a commercial service

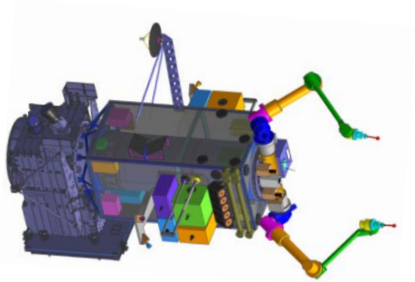
SES-2, host to CHIRP

Tele-operations control of on-orbit Robotic Servicer/Tender



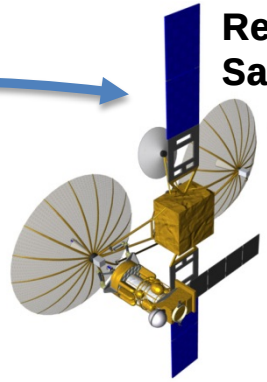


The concepts are then broken into individual technical elements.

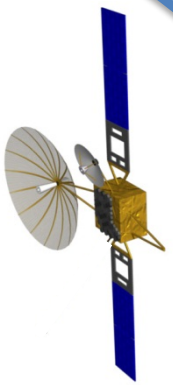


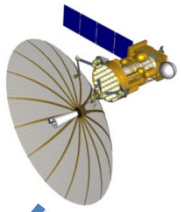
Servicer/Tender Spacecraft

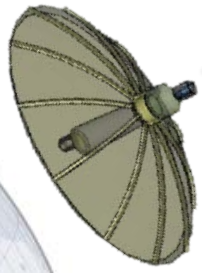
- Spacecraft Bus.
- RPO Sensors.
- Primary Robotics (FREND Arms).
- Tools/end effectors and Tool Changers.
- Next generation hyper-dexterous manipulators
- Toolbelt and/or Toolcaddy.
- High performance Ground-Servicer/Tender Comms.
- Tele-operations algorithms and S/W.



Retired Communications Satellite

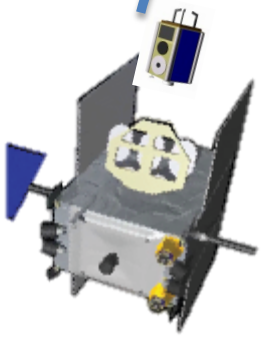






ApSat

- Harvested aperture.
- Satlets.
- Tended by S/T.



Commercial Communications Satellite to host Ridealong PODs

New Technologies

- PODs (Payload Orbital Delivery system).
- Satlets (contained within PODs containers).

On Earth

- Ground Communication Facility for Service/Tender.
- Ground Operations Facility for Robotics Payload Suite.
- N-DOF Test Facility for Robotic and Ops Validation.

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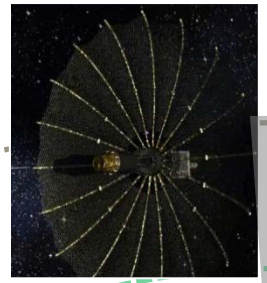
Phoenix operational goals support sustainable and repeatable low cost repurposing logistics in Graveyard Orbit.

Once the aperture is repurposed, the ultimate goal is to transfer the repurposed aperture to a useful position for demonstration operations.



For the demonstration, a sample POD with satlets and tools will be launched by an independent GEO communications satellite prior to or at the same time as the Phoenix vehicle.

Aperture Repurposing

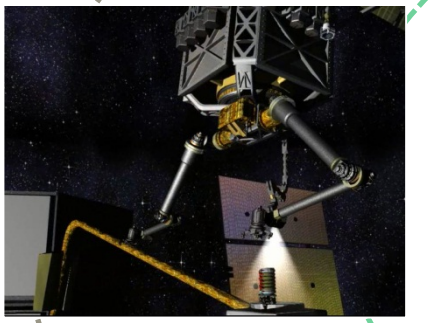
GYO

Commercial Hosted Payload Launch

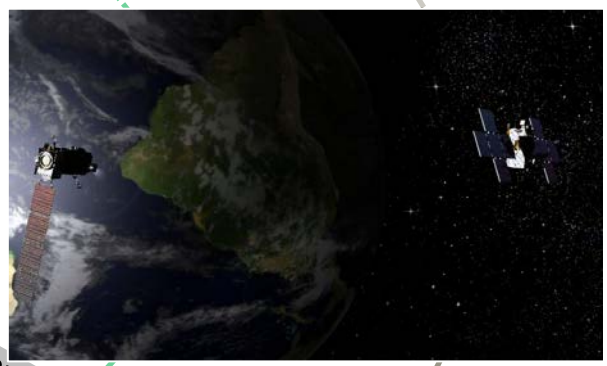
Servicer/Tender Launch and Checkout

GEO

Validated operation from value added resellers (VAR) for satlets

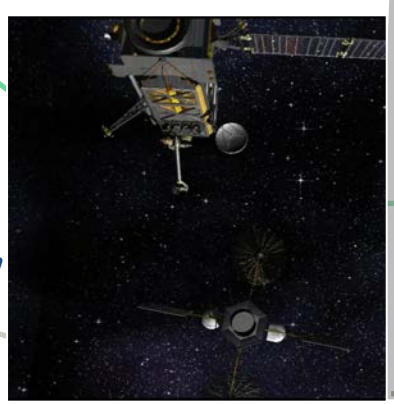


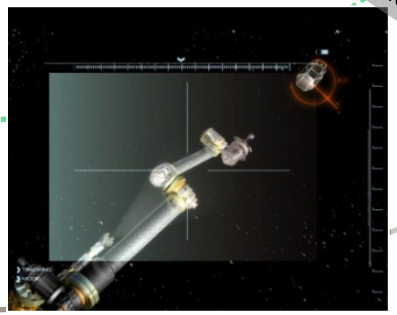
Validated qualification of Phoenix robotics operators through internal training



Servicer/Tender to GYO and Retired Satellite Rendezvous

PODS Release and Rendezvous and Grapple





- *Positive ground communication with retired GEOSat ownership chain*
- *Positive approval between GEO-Sat and USG for RPO ops*

Positive ground communication with GEO Host

Phoenix Program technical elements/components

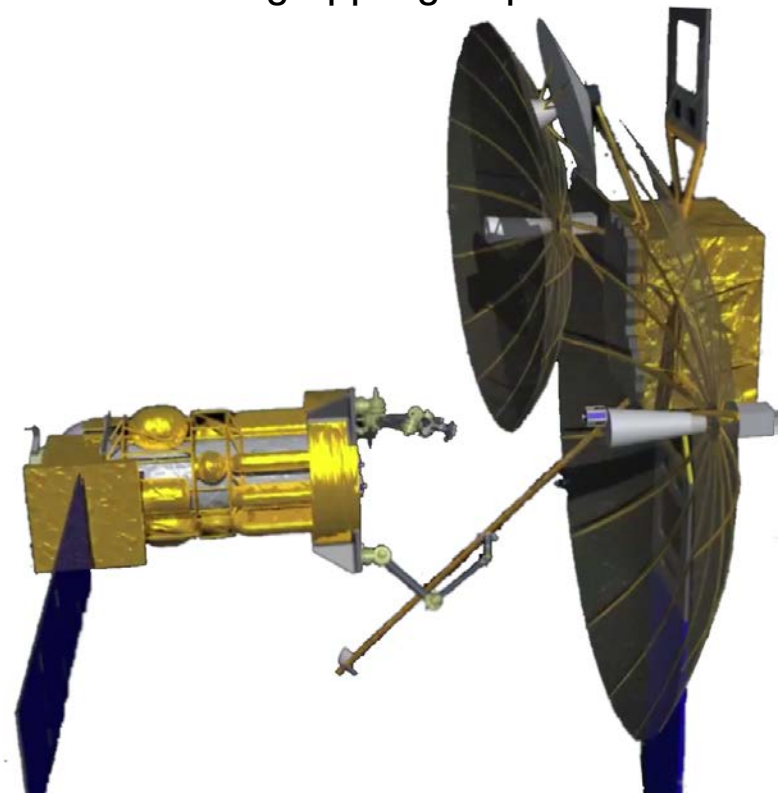
(See DARPA TTO Phoenix webpage for information on BAA-12-02.)

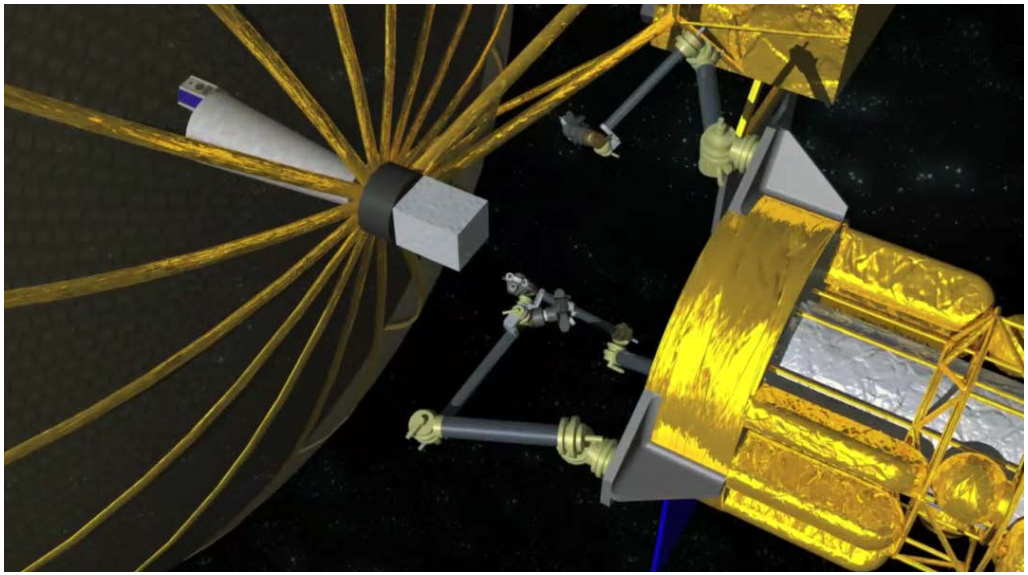
TA	Major Interface Elements	Gov't Provided	BAA
	Servicer/Tender Integration	√	
	- Spacecraft bus completion	√	
8	- Integrated Proximity Awareness System (IPAS)		BAA-13-12
9	- Rendezvous sensor suite		BAA-13-12
	Robotics Payload Integration	√	
	- Primary Robotic Arm (FREND)	√	
1	- Tools (i.e. secondary end effectors, saws, grips, changers etc.)		BAA-12-02
	- High performance Ground-to-Servicer/Tender communications	√	
2	- Tele-operations algorithms and S/W (Training and validation)		BAA-12-02
3	- Next generation hyper-dexterous manipulators		BAA-12-02
4	**Toolbelt and/or Toolcaddy**		BAA-12-02
5	**Satlets (Multiple variants)**		BAA-12-02
6	**PODs**		BAA-12-02
7	**Hosted Payload Study**		BAA-12-02
	Retired Communications Satellite & Aperture	√	
10	**N-DOF based test support**	(√)	BAA-13-12
11	**Virtual ground station operations (Servicer/Tender & Robotics)**	(√)	BAA-13-12
12	**Commercial bus ridealong slot (to host PODs)**	(√)	BAA-13-12

Examples of proximity operations considerations that Phoenix is engaged in during Phase 1

Considerations in Servicer/Tender proximity operations:

- Notifications to interested parties
- Local obstacle avoidance inputs for tele-operators
- Variety of structural attach points
- Optimal location to dis-engage aperture from satellite
- Multi-arm grappling requirements and/or scenarios





Phase 1 is uncovering & investigating solutions to many technical challenges Phoenix may face.

Challenges

Environment

- Unknown static discharge state of the retired satellite and/or aperture.
- Very high radiation dosage on electronics.

Retired Satellite

- Unknown tumble rate(s).
- Unknown dynamics for extended structure(s).
- Unknown condition of metal or structures to be used for grappling.
- Unknown propellant load and associated dynamics.

Retired Aperture

- Non-consistent supports (e.g. material and different construction frames, i.e. tubular, square, I-Beam etc).
- Varying Feed collectors (center, offset, on satellite etc).
- Unknown state of the antenna collection mesh/substrate.

Operations in Space

- Delay time for Robotic tele-operations control.
- Local tele-operator situational awareness limitations.
- Limitations in degrees-of-freedom vs. manipulation needs.
- Mitigation of multiple RF emissions between different elements, simultaneously.

Early Investigations

- *Static discharge tests done in plasma.*
- *Commercial radiation dose estimated.*

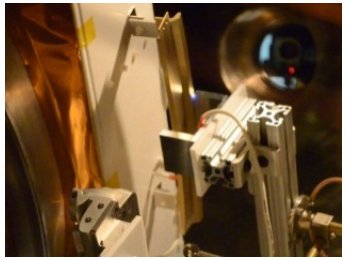
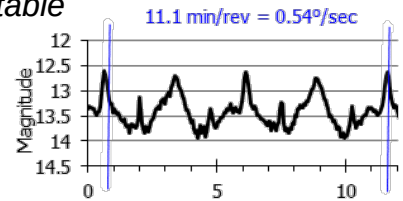


Photo courtesy of NRL

- *Study completed, suitable candidates identified.*

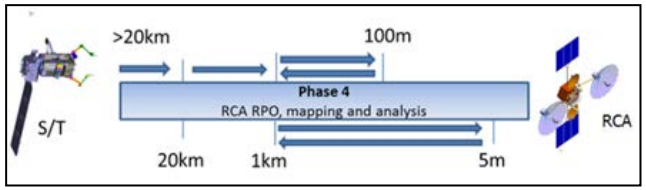


Results of optical survey of DirectTV1

- *As-built survey completed, models created to being to test.*

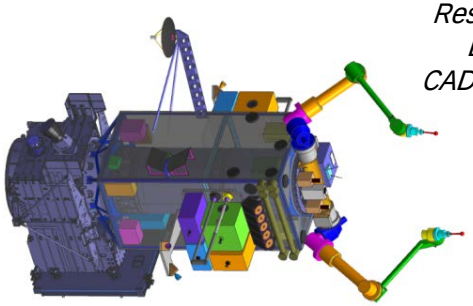
http://airandspace.si.edu/collections/artifact.cfm?id=A19860098000

- *Tele-operations system to support latency in work.*
- *Detailed POP concept of operations working through nodes of robotic operations anticipated.*
- *EMI tests completed on flight robotics Hardware.*



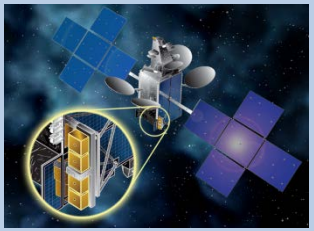
Representations of technical elements that flow from Phoenix concepts

Servicer / Tender



Naval Research Lab CAD Model

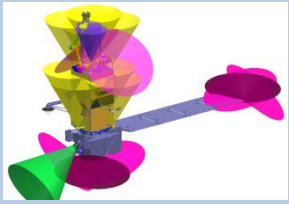
GEO Hosted Hardware



SS/L Artist Concept

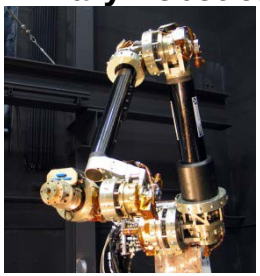
Example retired satellite with aperture

IPAS / RPO



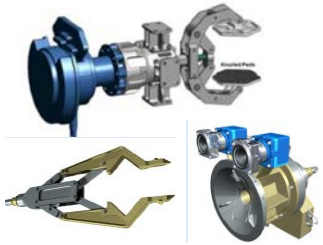
Naval Research Lab CAD Model

Primary Robotics



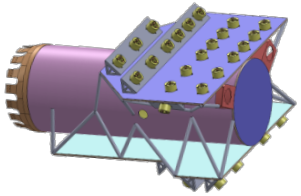
Naval Research Lab

Tools



MDA-CA, ATK CAD Models

Notional Toolbelt / Toolcaddy



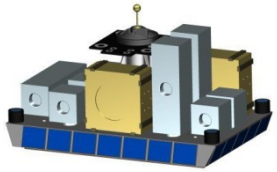
MDA-US CAD Model

High performance communications

Next generation hyper-dexterous manipulator

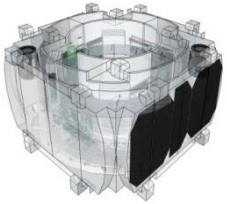
MDA-US CAD Model

POD



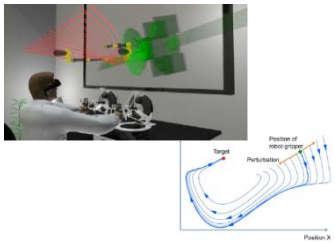
Artists conception CAD model

satlet



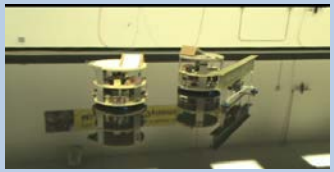
Novawurks CAD Model

Tele-operation control



HRL Concepts

N-DOF Facilities



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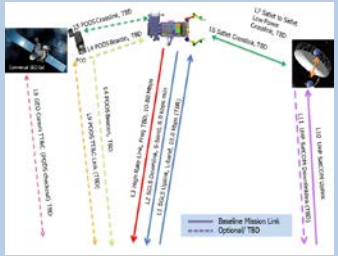
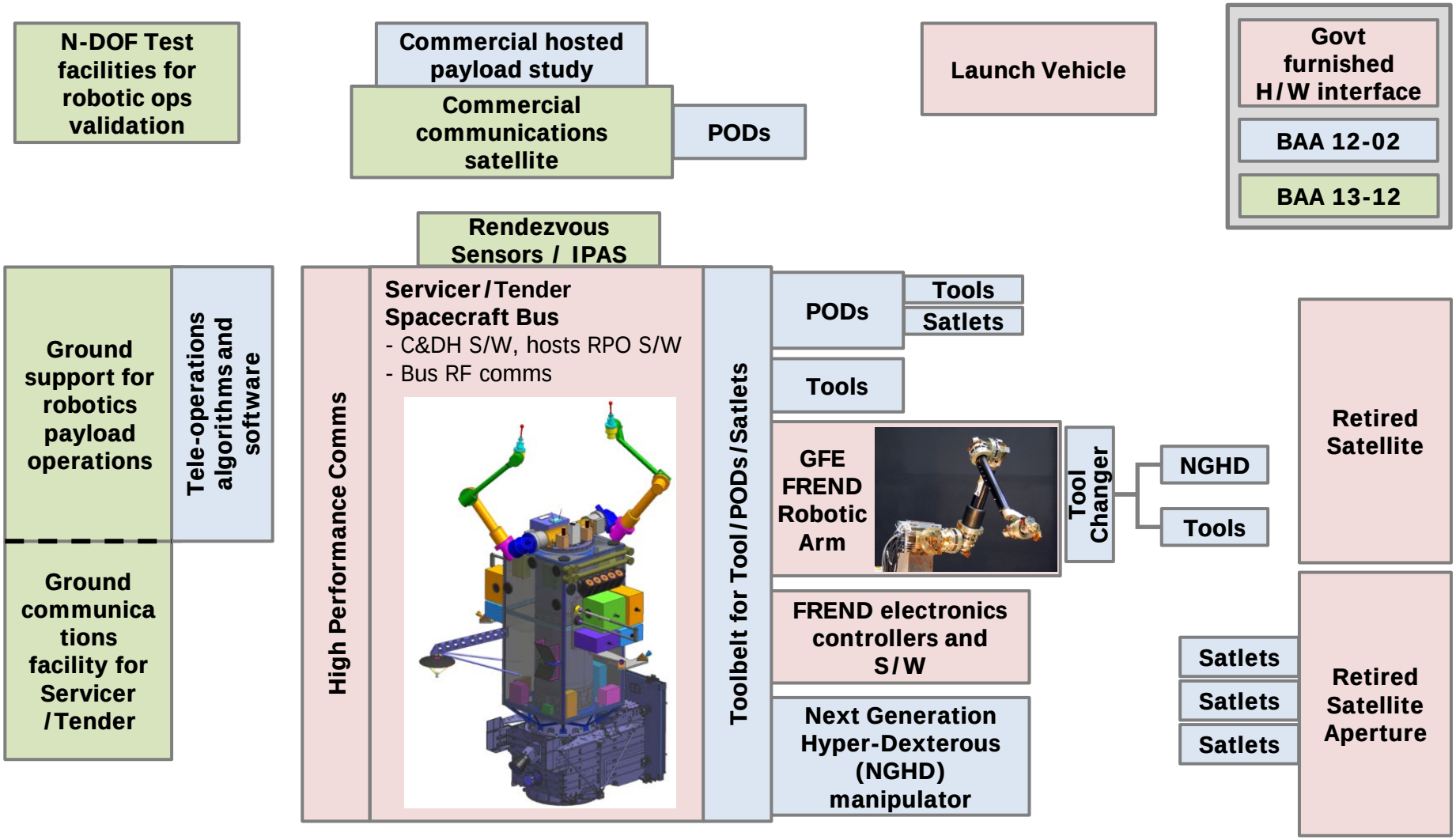
Ground Operations



Notional Technical Element Interfaces



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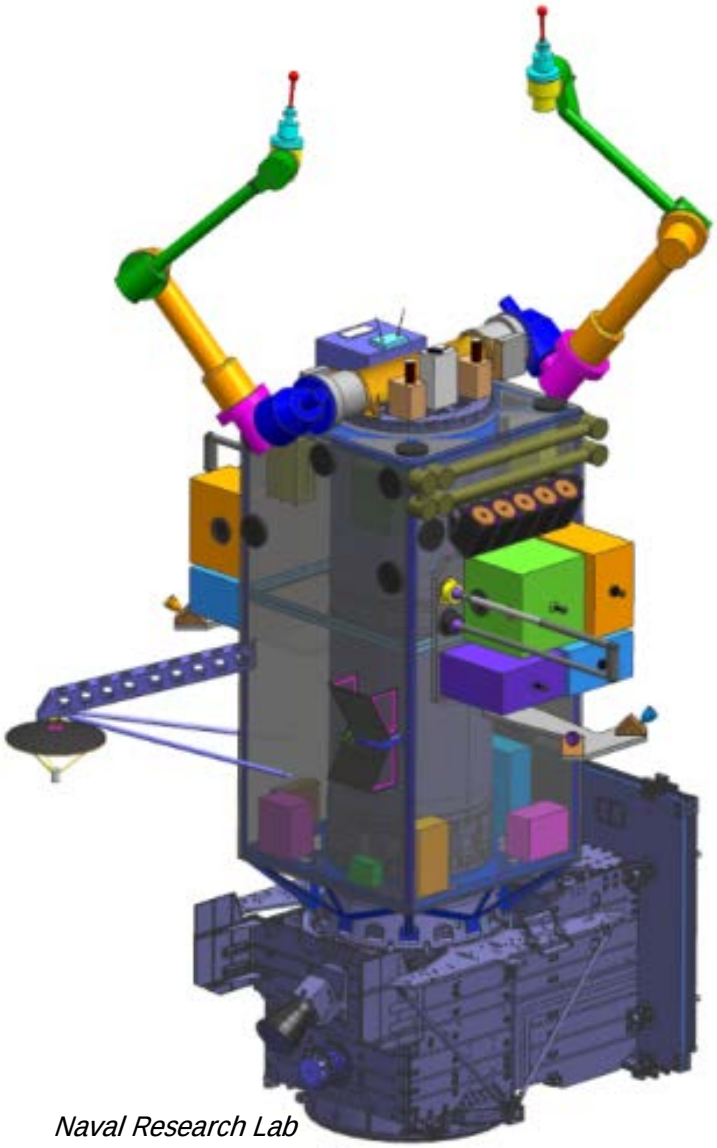
Servicer/Tender: Functions and nomenclature

"Servicer" refers to functions that the GEO spacecraft does to affect actions to another object. These include:

- Rendezvous and proximity operations.
- Transfer from GEO to Graveyard orbit.
- Robotic operations.
- Storing PODs and satlets and tools.

"Tender" refers to functions that the GEO spacecraft does after or beyond "servicing." These include:

- Stable standoff up to some distance (i.e. 1 km) from the repurposed aperture.
- RF collection and re-transmission from the repurposed aperture.
- Inspection of the re-purposed aperture after release.



Naval Research Lab CAD Model

Draft Phoenix expected environmental requirements characteristics

Phoenix Mission Environment:

- Launch in 2016 and 1 year mission life in Geosynchronous orbit
- Expected EELV launch vehicle environmental requirements

The Phoenix Environmental Requirements Documents (ERD) will include:

- Radiation Environments
  - Total Ionizing Dose (TID)
  - Displacement Damage (Optocouplers)
  - Electron and Proton Plasma Fluence (Charging/Materials Impacts)
  - Enhanced Low Dose Rate Sensitivity (ELDRS)
  - Single Events Effects (SEE) part restrictions
- Thermal Environment
  - Payload Component Operational Temperatures (0 to 40C TBR)
  - Payload Component Survival Temperatures (-30 to 70C TBR)
- Electromagnetic Interference and Compatibility (EMI/EMC) Environments
  - EMC design and test requirements for Phoenix Elements (S/T bus and payload components, PODs, satlets, etc.)
    - Derived from MIL-STD-461C and MIL-STD-461E
- Electrostatic Discharge (ESD) Environments
  - ESD and EMI characteristics for two objects in contact at GEO
    - 20kV worst case GEO charging potential v. 10kV lab testing

Dose Depth Curve Data for 1 year at GEO synchronous orbit

Radiation modeling in GEO based on:

- Jan 2016 Launch to 0° GEO, 35800km, RA=99°, 0° AOP, 0° TA
- Models – Based on Aerospace Corporation's "Space Environment Model Recommendations for GEO"
- ESP90 SPENVIS, Solar Proton
- IGE-2006 "Mean", Trapped Electrons
- AP-8 MAX, Trapped Protons
- Dose-depth from SHIELDOSE-2 Version 2.10

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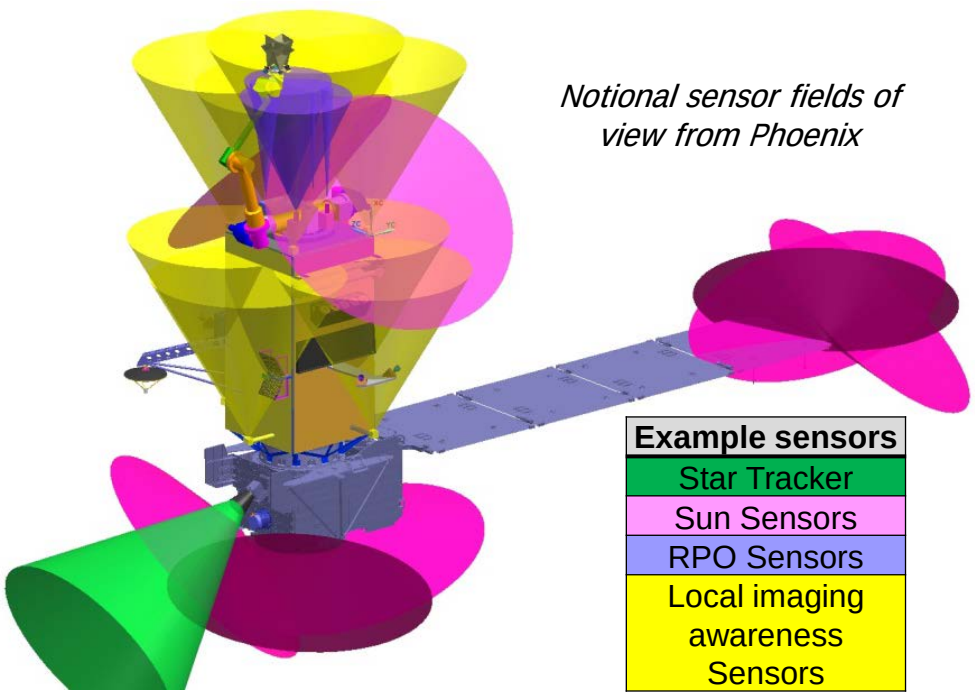
Technical Area #8: Integrated Proximity Awareness System (IPAS)

- IPAS to be capable of using every available Phoenix sensor and sensing modality to provide;
  - Constant estimates of collision hazards
  - Inputs for tele-operators in planning path maneuvers for the Phoenix vehicle and the onboard robotics.
- Provide local imaging awareness data to ground operators and to onboard autonomous systems
  - SLAM–like (Simultaneous Localization and Mapping) sensor fusion
  - Localization algorithms that are tailored specifically for orbital robotic servicing



- Utilize disaggregated sensors located non-linearly around Phoenix vehicle to create various on-demand situational and proximity-based information streams.
- Sensors may be mounted in non-orthogonal locations
  - On FREND robotic arm tools, on satlets, static mounts on the Phoenix vehicle
  - Even remotely on the retired satellite, as examples
- Handle a constantly evolving set of information to support collision avoidance and path planning optimization for maneuvering.

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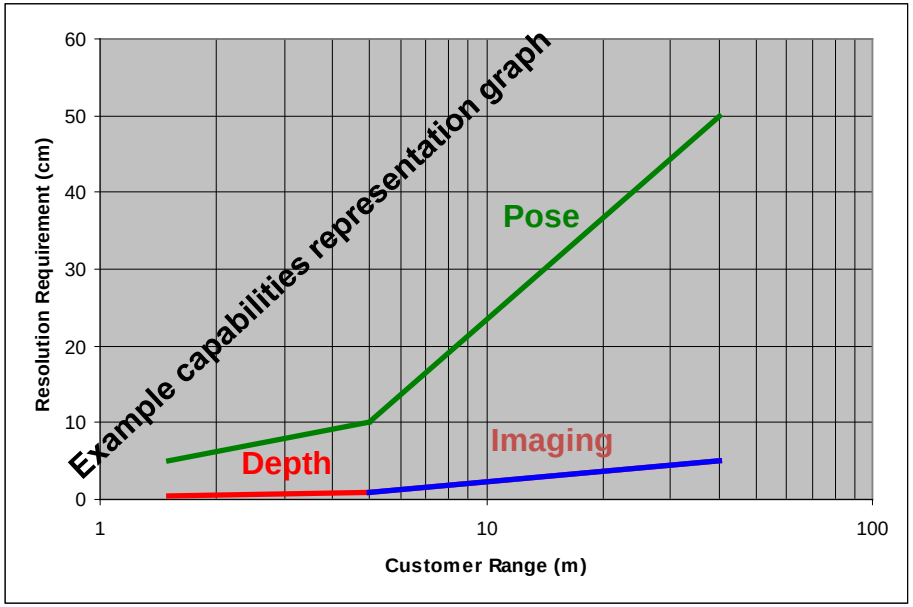
Technical Area #9: Rendezvous and proximity operations (RPO) sensors and/or suite

- Description: Provide relative navigation data during various ranges of proximity between Servicer/Tender, PODs, retired satellite and aperture(s):
  - RPO info should consider development of pose, fidelity of image generated (i.e. feature recognition), depth mapping, variable frame rate for pose tracking of tumble or non-static object, etc. over a range of lighting conditions.



Notional Attributes
Power required by RPO sensors
Navigation Data from RPO Sensor
Mechanical Interface to Servicer/Tender Bus
Software Interfaces for Autonomous Control
Volume
Control methodology
Life at GEO
Etc.

RPO Sensor Suite Performance Values expected for Phoenix

	Range boundary	Error Knowledge (3-sigma)	Sensor Modality	Notional goals during Phase
Far Rendezvous Phase	From 100km to 20km	<1 degree bearing after on-board acquisition	Relative bearing (angles only)	Open loop navigation and GEO Host satellite, RCA acquisition
Near Rendezvous Phase	From 20km to 1km	• < 1 degree bearing • < 5% range error after range acquisition	Relative bearing to relative position (bearing & range)	Transition from open-loop to closed-loop navigation with ranging knowledge, POD/RCA ranging, POD release station or phase staging standoff
Proximity Phase	From 1km to 50m	<1% relative position error	Relative 3D position	RCA 3D survey, coarse feature imaging (cm level)
Grapple or contact Phase	From 50m to 2m	• Position Accuracy: <= +/- 0.02 meters (from 2m to 5m); can linearly degrade to 0.2 meters at 50m • Attitude Accuracy: <= +/- 0.5 degrees (from 2m to 5m); can linearly degrade to 2 degrees at 50m • 6DOF Pose Rate: Not less than 5 Hz	Relative 6-DOF pose (position and attitude)	RCA grapple region inspection, fine feature imaging (mm level) and POD/RCA grapple

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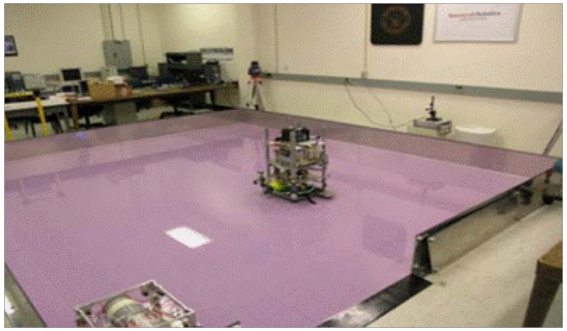
Technical Area #10: N-DOF based test support

- Challenge: Interlink multiple N-DOF facility(ies) and infrastructure(s) that can support various tests and validations for all aspects of the Phoenix demonstration mission scenarios, at significantly lower cost
- Consideration of Capabilities: Internet connectivity to other sites, capability and interoperability of N-DOF simulation (interaction internal to existing facility and to external facilities), # of DOF, test articles for facility, # of nominal and off-nominal scenarios that can be supported in facility, levels of hardware integration available (for Phoenix prototype and flight hardware), ability to act as proxy payload robotic control or validation center, etc.

Source: Naval Postgraduate School

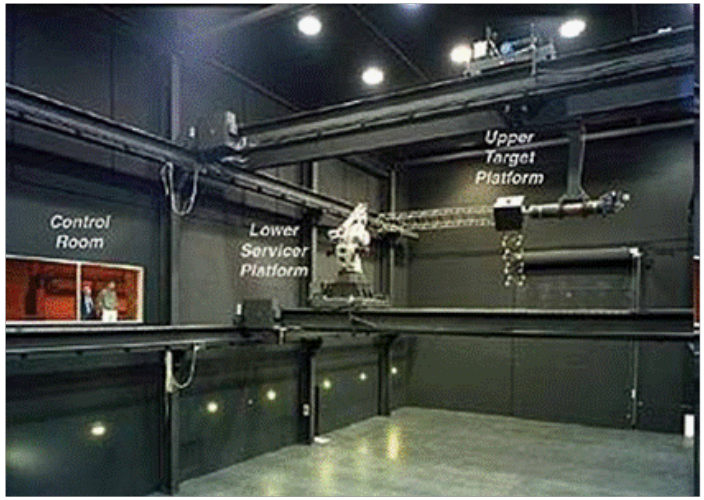


NPS- 12'x 12'

Source: Georgia Institute of Technology

GT 8'-12'

Source: Naval Research Laboratory



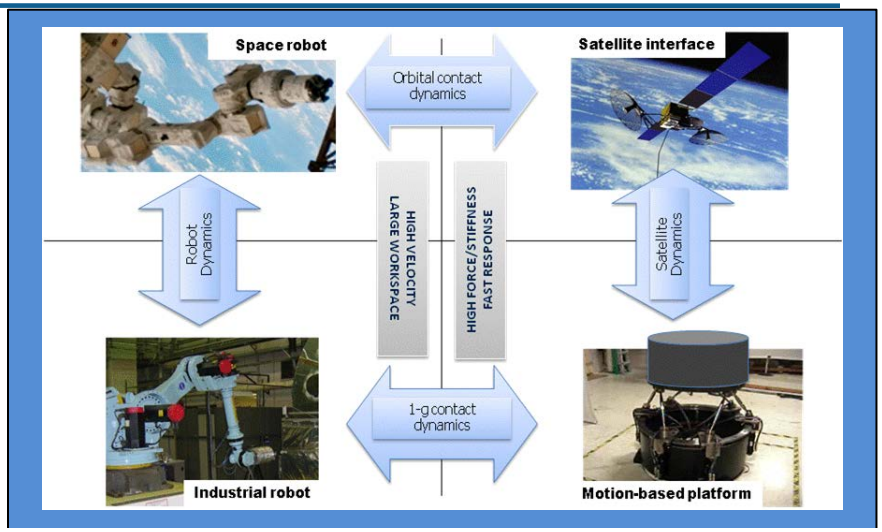
NRL – 30 m long x 13 m wide x 5 m high

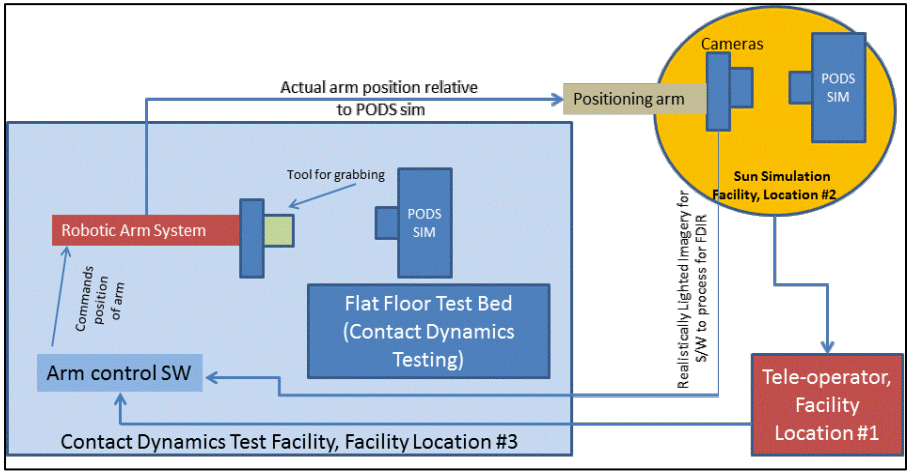
Limited examples of existing N-DOF facilities shown for reference only.

Phoenix expected to provide GFE software to support linking multiple N-DOF testbeds

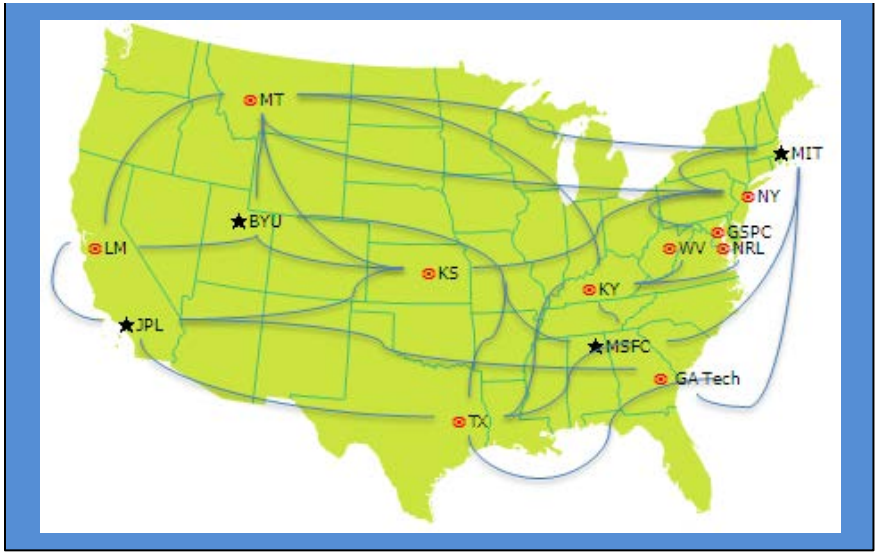
DARPA SBIR123-004: Realtime interlinked software for distributed Non-latent N-DOF operations *

- OBJECTIVE: Create and link a nationally distributed network of very low cost space-simulated N-degree of freedom (DOF) test beds using a common open source set of real-time software.





Goal is to link existing 2,3,4,5-DOF testbeds to provide real-time (non-latent) **virtual enhanced 6-DOF simulation capability.**

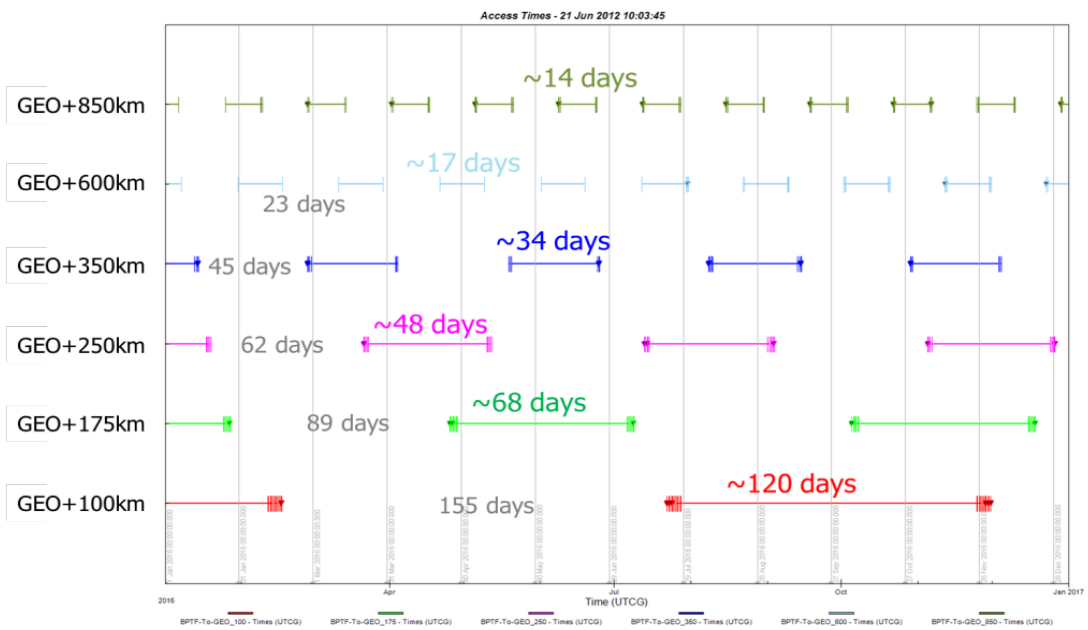


* http://www.acq.osd.mil/osbp/sbir/solicitations/sbir20123/darpa123.pdf

Technical Area #11: Virtual ground station operations

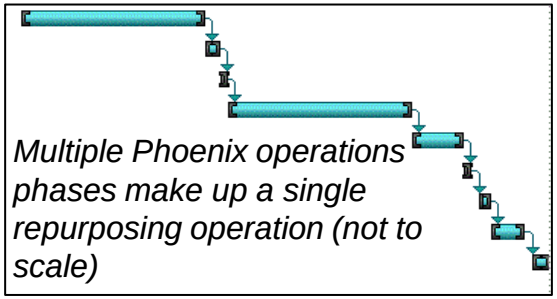
- Challenge: Provide flexible ground architecture at lowest possible cost for Phoenix operations

Multiple methods:
- **Use of Multiple World-Wide Sites**
- **Use a Single Site + AFSCN(e.g.)**
- **Use combination of methods and sites/facilities etc.**



Example of Direct Coverage Over a Single Ground Site at various altitudes
(All at 5° Inclination)

- Phoenix Servicer/Tender is expected to operate above GEO altitude
  - Specific altitude depends upon the RCA's selected
- Notional Phoenix ConOps are being developed for each repurposing operation



- Phoenix mission operations must balance the potential drift rate around the GEO belt versus ground communication contact points and operations centers relative to the expected ConOps.

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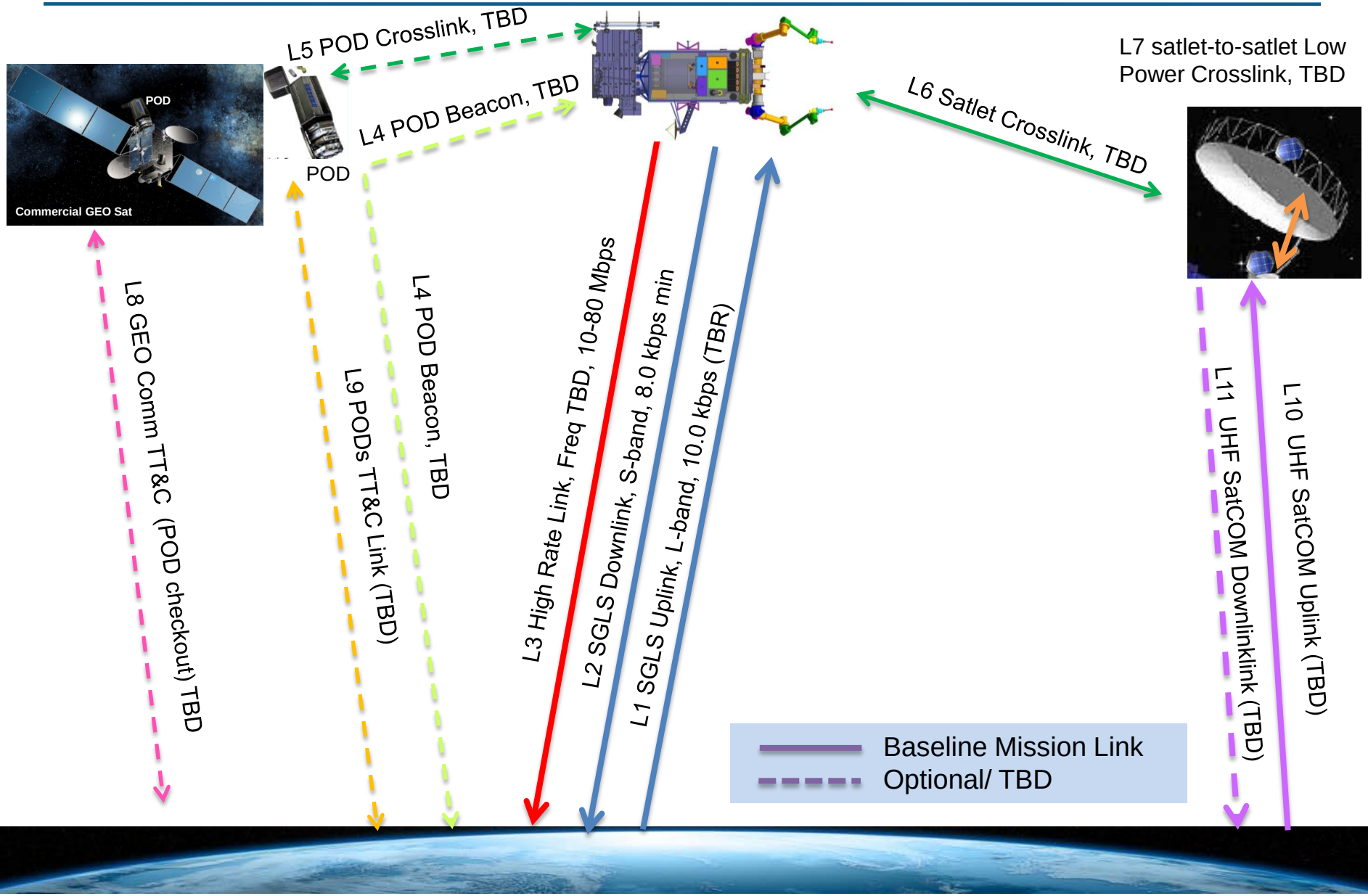
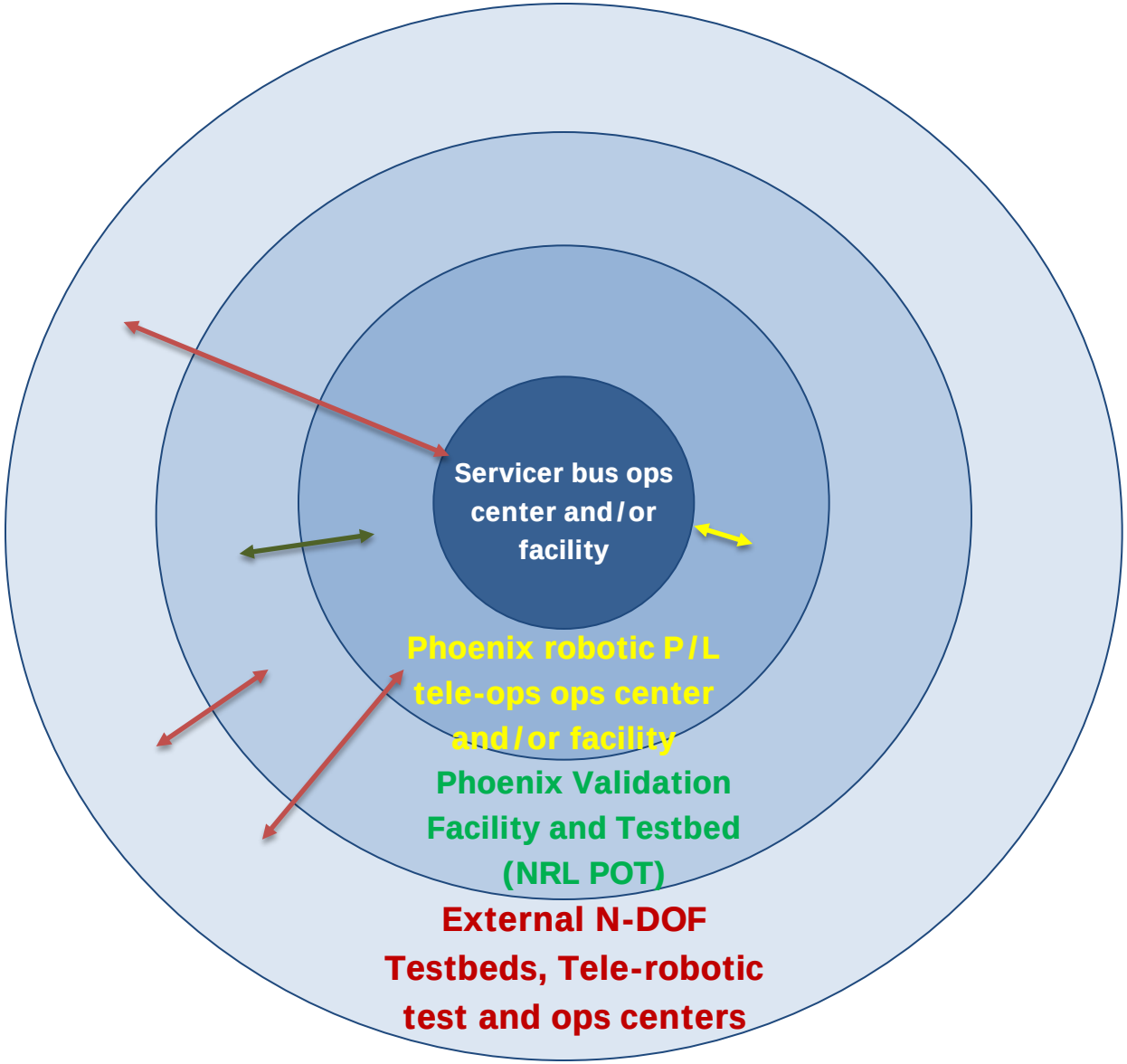
Notional communication link considerations for Phoenix Ground architecture development



Interaction considerations between various operations centers for test, training and on-orbit operations

Goals:

- Develop simple and supportable interface between the Phoenix robotic control systems and various testbeds and operations centers, worldwide.
- Provide flexibility for virtual operations between robotic control systems and various testbeds and operations centers, worldwide.



DARPA seeks flexible and lowest cost approach for achieving required coverage to support Phoenix operations.

- <u>Consideration of Capabilities:</u>
  - Interfacing with a variety of ground communication networks (commercial or US Govt.)
  - Communicating with each other over voice, data, and video links
  - Hosting and/or integrating tele-operations and interactive displays to support rendezvous operations with host spacecraft and with retired spacecraft
  - Providing or hosting displays to support state-of-health monitoring, navigation, situational awareness for the Servicer/Tender
  - Providing reliable continued operations during critical mission phases
  - Supporting pre-flight simulations and rehearsals to support all operational phases of the mission profile
  - Flexible to accommodate various elements of ground operations that are in work on Phoenix today by variety of suppliers
  - Include disparately developed satellite command and control software and scripts, mission planning software, mission execution software, etc.

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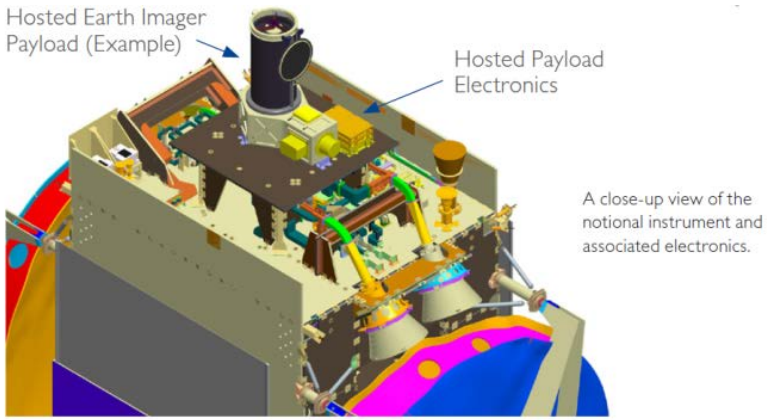
Technical Area #12: GEO communications satellite host and launch for POD(s)

- Goal: Commercial satellite that provides hosted payload mass and volume that could support Phoenix POD(s).
- Consideration of capabilities: Control of ejection of PODs (upon receipt of dispense request from Phoenix ground control station, or from Servicer/Tender or from Arm), velocity of ejection, location in GEO belt for ejection, RF frequency assignment for active obstacle avoidance, etc.



Core Features

Payload Mass Capability:	Approx. 60 kg, dependent on size of primary payload (STAR Bus can carry 430 kg total payload mass)
Avail. Payload Vol.:	Approx. 25" x 30" x 28"; can be tailored as necessary based on payload and specific host spacecraft
Orbit:	Geosynchronous
Launch Vehicle:	Ariane, Soyuz, Land Launch, Proton, and similar
Typical Mission Life:	1 to 4 years
Program Schedule:	24 months from ATP to launch

Example of Hosted Payload accommodations
(Orbital Sciences hosted payload fact sheet)

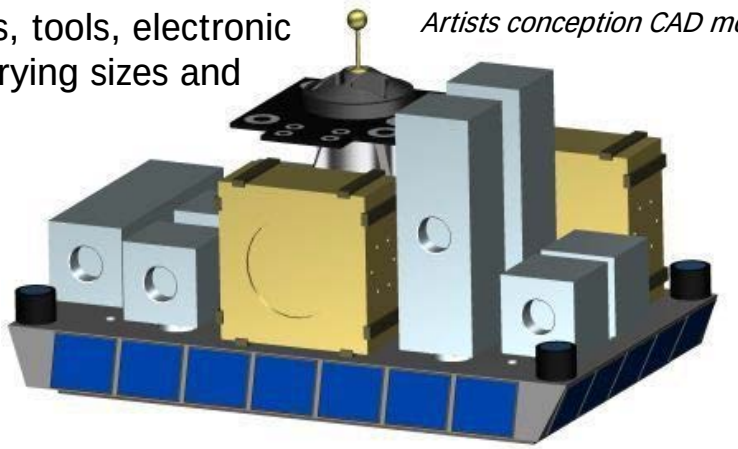
POD: Function and Nomenclature

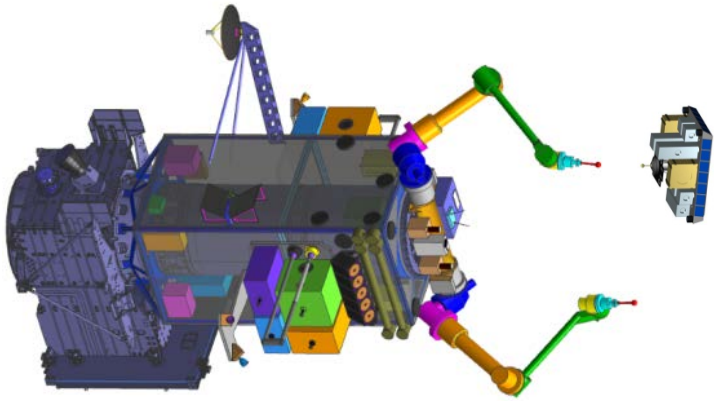
POD (Payload Orbital Delivery) system

- Structural container that supports satlets, tools, electronics, etc. during launch on a host communications satellite.
- Can be dispensed into space by a host satellite to be picked up by the Servicer/Tender.

POD(s) are meant to contain multiple satlets, tools, electronic boxes all of varying sizes and shapes.

Artists conception CAD model





Naval Research Lab CAD Model

PODs Configuration (DRAFT)

- Modular form factor derived from key available volume and Phoenix hardware dimensions
- Intended to fly singly or in assemblies of 2 or more (est.)
- Designed to contend with multiple interfaces: i.e. host communications satellite, grapple tools on Servicer/Tender, toolbelt on Servicer/Tender, etc.

Draft POD Characteristics

	Draft POD Characteristics	
Parameters for each POD Module Type (Draft)	**Hardware POD (i.e. satlets/tools/etc.)**	**Fuel POD**
Mass (empty, single POD)	From 10kg to ~ 20kg (TBD)	From 15kg to ~ 30kg (TBD)
Mass (loaded, single POD)	From 50 to 150 kg (TBD)	From 100 to 300 kg (TBD)
Notional Envelope (LxWxD, max estimated in aggregated form, i.e. multiple PODs)	Variable based on size of GEO host payload capability (assume ~ 1000kg/m^3 for density and sizing).	Variable based on size of GEO host payload capability (assume ~ 1000kg/m^3 for density and sizing).
Survival Power (thermal control)	< 35 W (assumed thermally isolated from spacecraft) Heater power dependent on mounting configuration.	Heater power dependent on mounting configuration.
Checkout Power (max estimated prior to ejection, if required)	30 W (sporadic and only if required)	30 W (sporadic and only if required)
POD assemblies	Modules can be flown singly or aggregated in groups of multiple units.	Modules can be flown singly or aggregated in groups of multiple units.
Parameters common to aggregates of Multiple POD Modules		
Release Mechanism	Per normal industry standard	Per normal industry standard
Data interface (if needed at all)	MIL-STD-1553 or RS-485 preferred (low duty cycle)	MIL-STD-1553 or RS-485 preferred (low duty cycle)
Temperature Capability (non-operating, includes internal hardware)	-25C to +70C	(+10C to +50C)

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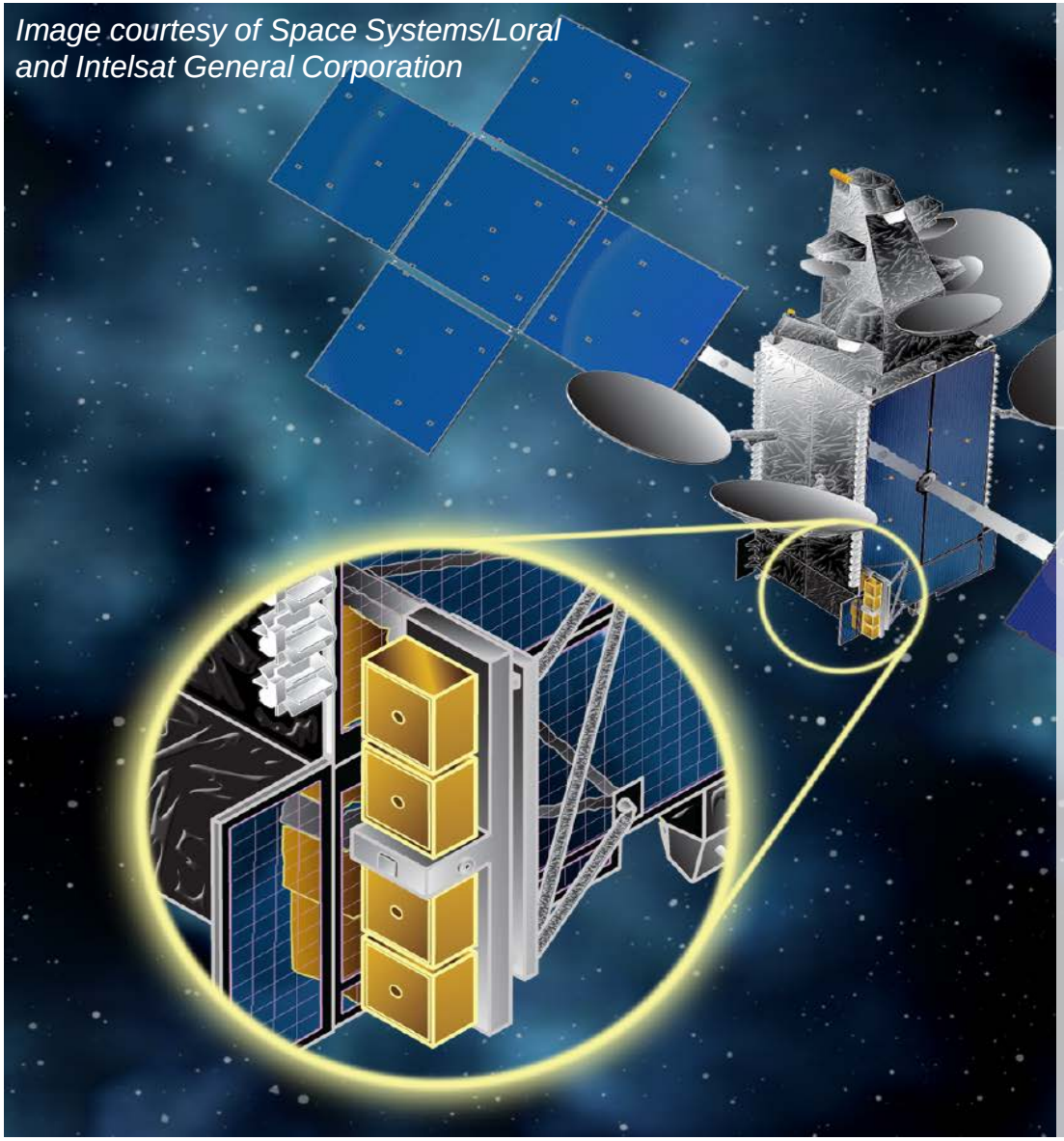
GFE report on hosted payload study (TA#7) to be provided at Phase 2 K/O in support of TA#12



- **Study Goal:**
  - **Provide Rideshare hosting of PODs/satlets on commercial GEO spacecraft**
- **Survey of physical accommodation matrix**
- **Recommendation for safe holddown and release**
- **ConOps for release recommendations**
- **Recommendations to minimize adverse impacts on host mission**
- **Cost & risk assessment**
- **Contractual, regulatory, and insurance issues**

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Phoenix Performers

TA	Name	Technical Concept
1	ATK	Satellite Capture Tool (SCT) for marmon band capture; option for the Aperture Grasp/Severing Tool (AGST) for grabbing and severing aperture attachment structure
1	Honeybee	Universal Gripper/Anchor (UGA); Satlet Grasper Tool (SGT)
1	JPL	Gecko Gripper tool
1	MDA Canada	Flight-ready MultiPurpose Gripper (MPG); PODs Capture Tool (PCT); and MicroCam Vision Tool
1	Oceaneering	Tool changer with a common interface based on the u-conical fitting that incorporates electrical and data fittings
2	Energid	3D visual/kinematic/dynamic integrated simulation and control system for tele-operations
2	HRL	Sensor processing/model and flow field/path generation integrated into tele-operators hardware in the loop
2	MEI	Integrated Telerobotics and Telepresence System (ITTS)
3	Altius	Single Storable Tubular Extensible Member (STEM) module/element (fixed orientation; deployable and retractable) to be used as (a) a camera mount and/or (b) a damping point
3	MDA USA	Next Generation Hyper-Dexterous Manipulator system using SuperBots from the Polymorphic Robotics Lab
4	MDA USA	S/T Toolbelt concept
5	Aurora	Modularized, Aggregatable Satlets for Repurposing Retired Assets
5	Busek	Electrospray propulsion for Satlets; Power Processing Unit; Digital Control Interface Unit; integrated testing
5	Draper	ADCS and P-management employing ZPM (Zero Propellant Maneuvers) technology
5	Intentional Software	Integrated Systems Health Management (ISHM) for satlets
5	NovaWurks	Hyper-Integrated Satlet (HISat) System
5	SRI	Electrostatic adhesion for inter-satlet contact interfaces
6	MDA Canada	SRR level PODs design
7	Intelsat	Provision of inputs and conceptual precepts to answer various industry-related technical questions on safety, legal, regulatory and insurance issues associated with hosted payload deployments
7	SS/L	Study of dispensing commercially hosted payloads: Identification of technical operational challenges that need to be addressed for operators/builders and development of a set of standard approaches for interfaces and testing methodologies
	ATK	Servicer/Tender spacecraft bus
	MDA USA	FREND primary robotics arm

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Questions?

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