USC Viterbi Information Sciences Institute

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USC Space Engineering Research Center (SERC)

Design-Based Safe Operable Metrics for Earth Regime RPO

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USC VITERBI SCHOOL OF ENGINEERING

The (Good) Problem:
"Non-traditional" Space Applications are here!

Rapid expansion in the number & types of commercial space applications is creating new opportunities for advanced space missions

Image Source: NASA

Image Source: Planetary Resources

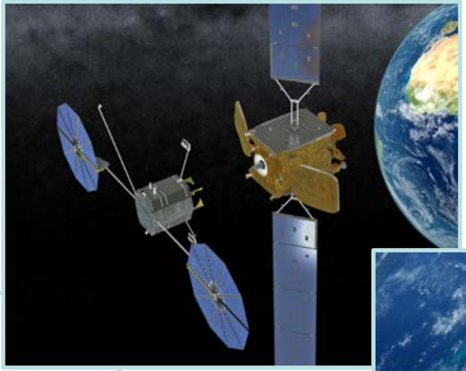


Image Source: Orbital ATK

Image Source: UNOOSA / Sierra Nevada Corp

Challenge? How can governments/private sector work together to avoid more risk to the "global commons of space" for these emerging applications?

How is it done today? Through "Norms"

Much of the existing space governance framework is based on norms

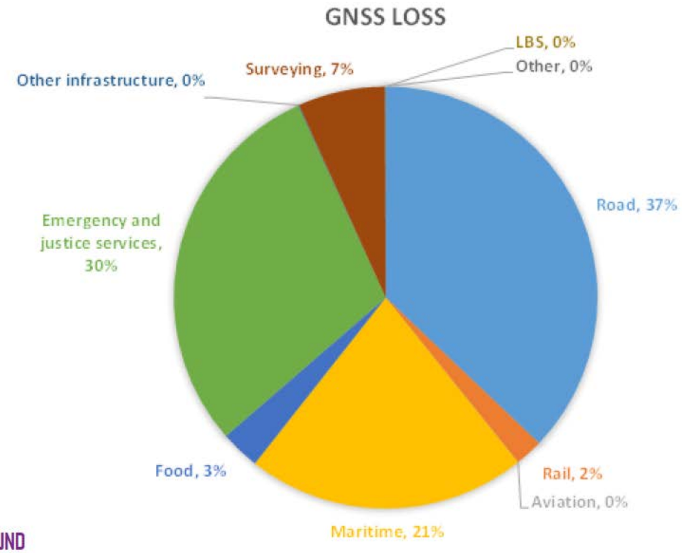
- **Example: Freedom of overflight for satellite reconnaissance**
  - ***Launch of Sputnik in 1957 helped set the norm that satellite overflight did not breach territorial sovereignty***
  - ***By mid-1960s, freedom of overflight was a generally accepted norm***
  - ***Was not codified into "hard law" until Outer Space Treaty of 1967***

Quick example of Economic Impact analysis on loss of space assets that affect people/every day life…

- **Economic loss of GNSS for 5 days from any cause…**

Impact of Loss of GNSS (for 5 days)

- The economic impact to the UK of a five day disruption to GNSS has been estimated at £5.2bn.



Consider this a LOWER BOUND

"Economic Impact of the loss of GNSS to the UK", Andy Proctor, UK Government PNT Group, Delegate to ESA Board of Navigation, Nov 2017

Critical Applications

Infrastructure	Aspect	RAG	Loss of GVA (direct+secondary) (five days)	Loss of utility benefits (five days)
Space	Satellite communications		£22.5m	*See Maritime transport infrastructure*
Transport infrastructure	Maritime transport infrastructure		£1,069.3m	*See Maritime usage applications*
Application	**Aspect**	**RAG**	**Loss of GVA (direct+secondary) (five days)**	**Loss of utility benefits (five days)**
Surveying	All applications		£344.8m	£-
Rail	Automatic train doors			£2.8m
	Train cancellations		£77.7m	£12.7m
Road	Navigation		£-	£1,869.7m

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Proposed Solution:

Consortium for Execution of Rendezvous and Servicing Operations (CONFERS)

Goal: Develop and introduce industry-consensus standards for new emerging applications for cooperative rendezvous and proximity operations and on-orbit servicing (RPO & OOS)

ATI Advanced Technology International

Secure World Foundation

USC University of Southern California

Space Infrastructure Foundation

USC Charter: Survey current RPO & OOS Operations & Recommend Changes/Inputs

"Rendezvous and Proximity Operations (RPO)": Timelines, actions, maneuvers between two different space platforms from distance (>100km) to within several meters

First year tech focus: *Complete*

"On-Orbit Servicing (OOS)": Timelines, actions, maneuvers, interactions, manipulations, between two different space platforms within several meters to contact/dock/grapple/connect etc.

Second year tech focus*: In Progress*

1. Database survey of past RPO missions revealed no specific "standard" on rendezvous schema (distance, velocity, gates, phases, etc)
    1. No concurrence on use of specific nomenclature or lexicon to describe rendezvous
    2. No concurrence on graphical representation or depiction of "rendezvous"
2. First set of RPO safety metrics created to begin discussions with industry
3. Initial survey with first industry members candidates
4. RPO survey results and metrics presented in Bremen Germany at IAC

Results of 1st year: Three initial RPO Metrics created for discussion

#1: Contact Velocity

#2: Remote Influence

#3: Control Accuracy

Metric value $x = \frac{v_{projected}}{v_{max}}$

Metric value $x = \frac{\omega_{projected}}{\omega_{max}}$

Metric value $x = \frac{MCO}{ECD}$

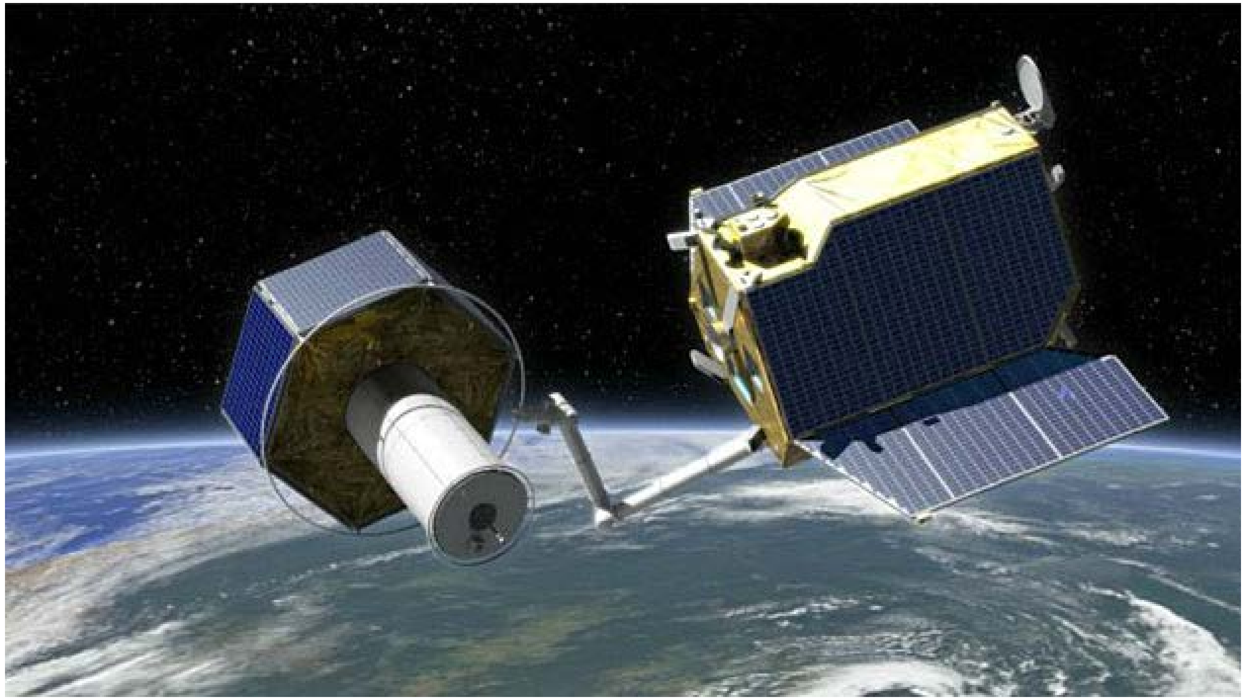
- **Inputs:** Physical values of Servicer and Client Spacecraft, desired performance
- **Outputs:** Unitless ratios; <1 : safe, >1 : risky

Metrics applied to past (and current) missions appear to follow ratio of "low riskiness"…

Mission Details				Metrics		
Name	**Primary Organization**	**Target**	**Date**	**Contact Velocity**	**Remote Influence**	**Control Accuracy**
STS-41C	NASA	Solar Max	4/9/84	0.1523	0.154	0.245
Dragon	SpaceX	ISS	5/22/12	0.0295	0.00585	0.0198
Apollo 11 (LEM)	NASA	CSM	7/21/69	0.8119	0	6.45
MEV-1	Northrop Grumman	Intelsat-901	2020	0.3221		
RESTORE-L	SSL	Landsat-7	2022	0.2909		
O.CUBED	Airbus	TBD (GEO)	2023	0.393		

Second Year Initiative

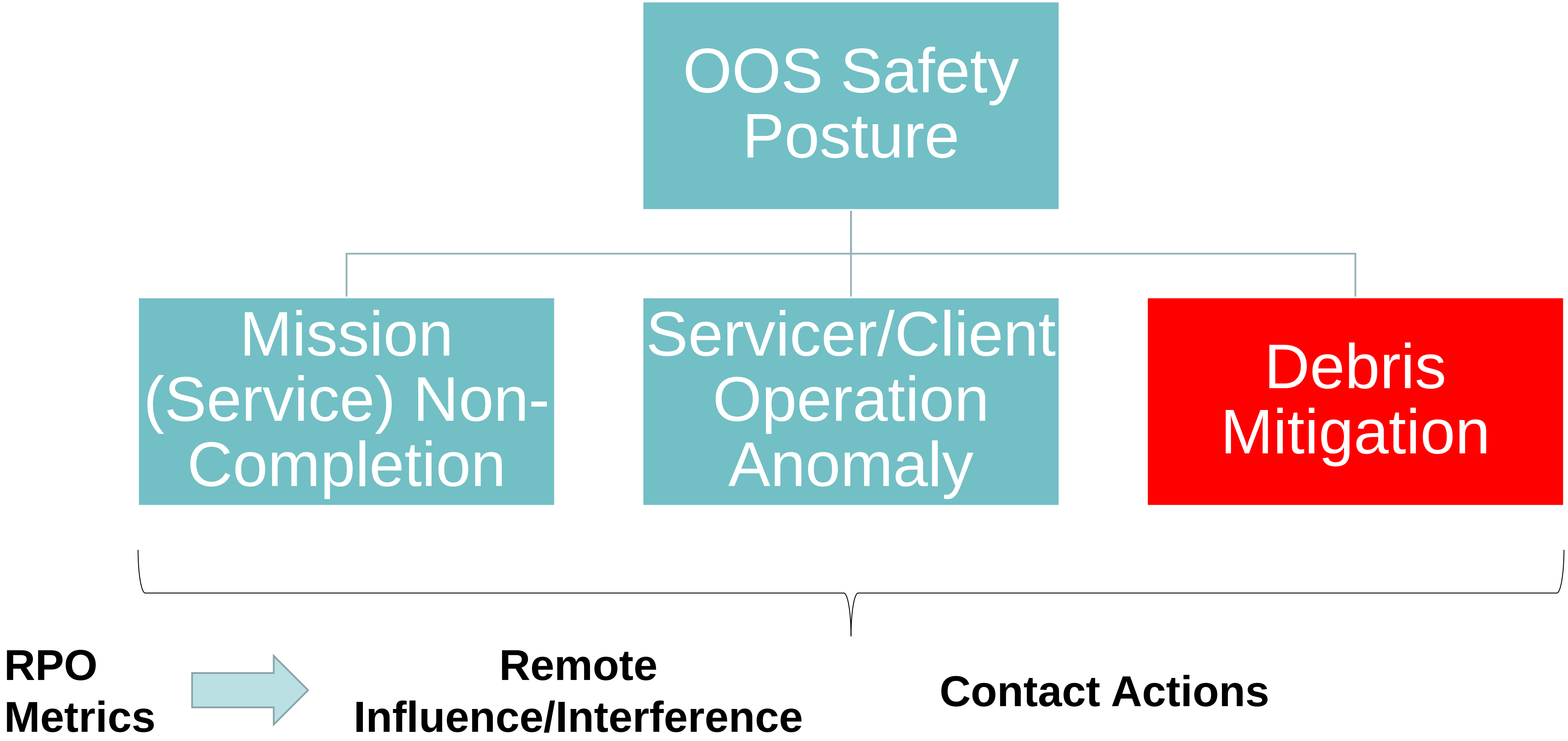
- **Develop background on OOS “Safety” and “Interfaces”**
- **Develop OOS Topology of Functions/Attributes from the initial Mission architecture**
- **Assess existing Standards (domain agnostic) against Topology**
- **Initially Populate Quantitative values for topology attributes**
- **Develop process to Identify most relevant Functions:Attributes suitable for Standards**
- **Initial look at transit orbit optimization for RPO missions from projected spatial density plots**



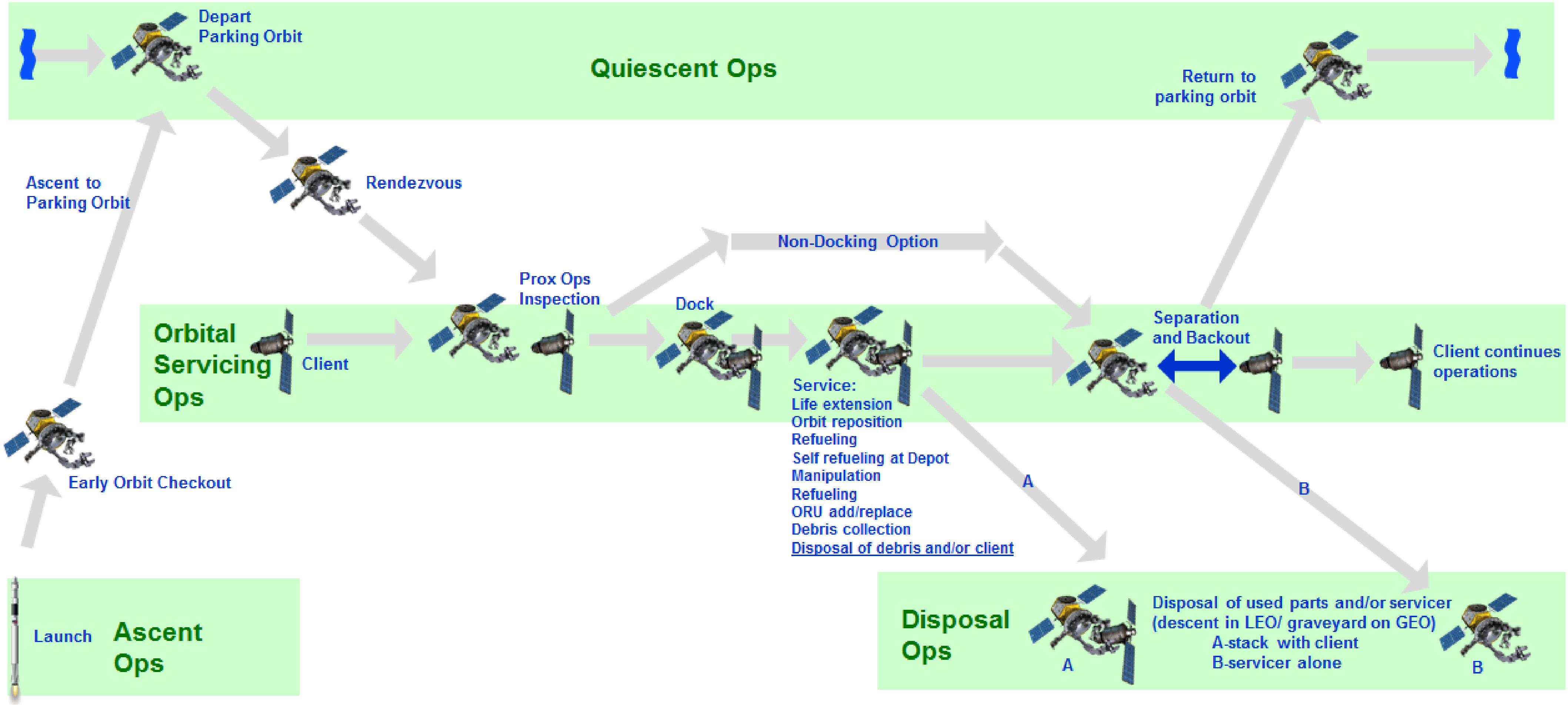
On-Orbit Servicing Example

Credit: Astrium Services

Initial OOS Safety Posture drivers



CONFERS draft initial architecture describes various OOS mission "elements"



Each of the Mission Elements translates to more detailed "Execution Functions" that translate into hardware or software to enable the Mission Element to succeed

Decomposition of OV-1 Mission Element into Initial "OOS Topology"

- An initial Topology was created to attempt to capture the various functions and attributes that could contribute to a Mission Element
- The elements of the Topology were defined as "functions" and "attributes"
- "Function" defined as an activity required to affect a particular OV-1 OOS element
  - There can be multiple functions required for each element
  - Functions are defined as actions that are either primary or secondary activities that correspond to a particular event in the OV-1 for a particular Service
- "Attribute" defined as the quantitative metric or characteristic to enable a function to be executed or satisfied
  - *Depicted as "Function:Attribute" in our internal nomenclature*
- Finding Attributes in many cases are straightforward
  - Many have measurable value metrics that can be logically assigned or estimated or calculated
- What is not straightforward is identifying attributes that affect "Safety" as defined in our OOS analysis context at the beginning…
  - Subject of next 6 months of analysis

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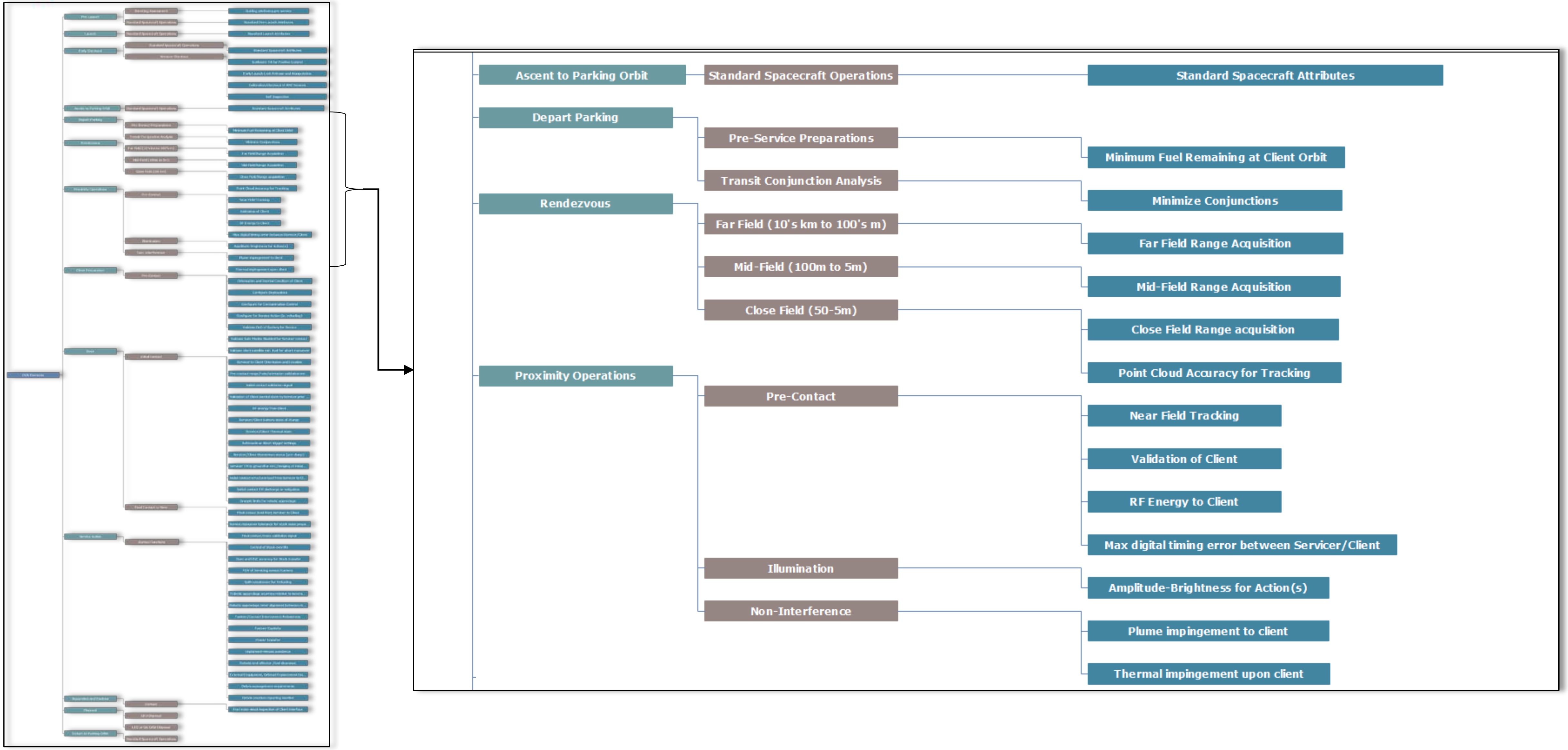
Initial OOS Topology



Inspirations to Draw From

- Automotive Industry - 225 million licensed drivers in US with 268.8 million registered cars [4,5]
- Nuclear Industry - Activities not just local impact but global in reach [1]

Terrestrial Servicing Platforms and their "safety protocols" may provide valid communicable analogies for OOS industry to consider…

Resilient operation of engine ("propulsion") system to avoid collision

Clear control for "Robotic arm" to avoid service failure

Clear View for arriving ("Rendezvousing") at servicing location

Clear communication for locating servicing item

Mining of initial Space standards list for quantitative information*

Type	Standard	Identifier	Intended Use	Quantitative Values?	Applicable to RPO in Space?	Applicable to OOS?
Physical	Spacecraft Identification Feild Code Assignment Procedures	CCSDS 320.0-M-7	Requesting, assigning, and relinquishing SCID field codes	Y	Y	Y
	Mitigation of Impacts	ISO 11227:2012	Sizing surface materials under debris/micrometeroid impacts	Y	Y	Y
	Proton Flux at GEO	ISO 12208:2015	Solar cell degradation	Y	Y	Y
	Electromagnetic Compatibility	ISO 14302:2002	EM compatibility		Y	Y
		ISO 24637:2009	EM interference (system level)		Y	Y
		ISO 24637:2009	EM interference (equipment level)		Y	Y
		AIAA S-121A-2017	Design practices for EM compatibility	Y	Y	Y
	Launch Vehicle Interface to Spacecraft	ISO 14303:2002	Format for specifying interface (does not limit design)			
	Structural Design	ISO 14622:2000	Determine loads during launch and operations			
	Launch Vehicle Loading Test	ISO 14953:2000	Loading level qualification test of LV			
	Exchange of Mathematical Models for Dynamic and Static Analysis	ISO 14954:2005	exchange of models between contractors and launch providers. Standard modeling behavior. DOES NOT INCLUDE VALIDATION STANDARDS			
	Pressurized Structures	ISO 14623:2003	best practices for metallic and COPV vessels	Y		
		ISO 24638:2008	All pressure components other than pressure vessels (lines, fittings, valves, etc)	Y		
		ANSI/AIAA S-081B-	baseline requirements for COPV			
		ANSI/AIAA S-080A-	baseline requirements for components other than PVs			
	Compatibility of Materials	ISO 14624	Testing for safety of materials (flammability, outgassing, permeability, etc)			
	Surface Cleanliness of Fluid Systems	ISO 14952	cleanliness of fluid systems for GSE, LV, and SC	Y		
	Contamination and Cleanliness Control	ISO 15388:2012	Baseline preferred program elements recommeded for contamination control			
	Stress Analysis	ISO 16454:2007	Determination of stress/strain distribution and margins under loading. Static failures: rupture, collapse, yield. DOES NOT COVER FATIGUE			
	Simulation	ISO 16781:2013	Guidance for system engineers on what to simulate and how to incorporate results. Minimum set of reqs. VERY GENERAL			
	Connectors for Serviceability	AIAA G-072-1995	Technical info on development of spacecraft utility connectors (power, dataa, fluid, etc). Divided into 3 classes (Manual/EVA, Robotic, and Automatic)		Y	Y
	Grasping, Berthing, Docking Interfaces	AIAA G-056-1992	Technical info on design of 3 mechanical interfaces required for servicing: grapshing by telerobotic/visual manipulation, berthing of payloads or spacecraft, and docking of spacecraft		Y	Y
Servicing						
Communications	On-board Communication	CCSDS SOIS	Sharing of instruments between two spacecraft while docked		Y	Y
Information	Orbit Data Messages	CCSDS 502.0-B-2	Message format for transferring orbit information between space agencies and commercial or governmental spacecraft operators	Y		
	Tracking Data Message	CCSDS 503.0-B-1	Message format for use in exchanging spacecraft tracking data between space agencies	Y		
	Attitude Data Messages	CCSDS 504.0-B-1	Message format for use in transferring spacecraft attitude data between space agencies	Y		
	Cojunction Data Message	?	Message format for use in exchanging spacecraft conjunction information between originators of assessment and satellite owner/operators			
	Exchange of Orbit Information	ISO/TR 11233:2014	How to describe orbit determination and estimation techniques			
		ISO 26900:2012	Standard message formats for use in transferring spacecraft orbit information between space agencies and commercial or governmental SC operators (OPM, OMM, OEM)	Y		
	Telerobotics Lexicon	AIAA S-066-1995	Vocabulary for space automation and robotics to aid in mutual understanding of robotic automation systems (~200 terms)			Y
Operations	Concept of Operations	ISO 14711:2003	Guidelines of areas to address and products to be generated to develop a space systems mission operations concept.			
	Operability	ISO 14950:2004	Define essential properties of operation of unmanned SC, guidelines for SC functions in order to enable a ground segment to operate in nominal situations			
	Documentation	ISO 23041:2018	Define guidelines to minimize duplication of effort between cooperating parties. Documentation, support, and information sharing.			
	Space Debris Mitigation	ISO/TR 18146:2015	Minimize creation of debris by ensuring SC and LV stages are desgned, operated, and disposed of in safe manner		Y	Y
		ISO/TR 20590:2017	Reduce the growth of space debris by ensuring that LV orbital stages are disposed of safely		Y	
		ISO/CD 20893	IN DEVELOPMENT. Detailed debris mitigation requirements for LV orbital stages		Y	
		ISO 24113:2011	primary space debris mitigation requirements applicable to all elements of unmanned systems launched into or passing through near-Earth space (LV stages included)	Y	Y	Y
	Ground Testing (General)	ISO 15864:2004	baseline on testing of system and subsystems. Documentation requirements	Y		
	Ground Testing (Fluids)	ISO 15859:2004	Sampling requirements for fluid entering LV or SC (check limits)	Y		
	Safety of Launch Site Operations	ISO 14620:2011	Requirements for safety liabilities of countries undertaking space activities on or from their territory under the UN Outer Space Treaty. Defines safety responsibilities of operators			
	Flight Safety During Launch	ISO 14620-3:2005	Minimum requirements for flight safety systems: flight termination systems, tracking systems, and telemetry data transmitting systems			
	Launch Integration Practices	AIAA R-099-2001	Recommended practices for LV integration			
	Early Operations	ISO 10784-1:2011	Common language and form to document early operations (SC startup after LV separation)			
	Space Solar Panels - ESD testing	ISO 11221:2011	Qualification and characterization testing for plasma interactions and electrostatic discharges on solar array panels in space			
Debris Avoidance	Prevention of Break-Up of Unmanned Vehicles	ISO 16127:2014	Reduce risk of in-obrit breakup of unmanned SC, during and after operational life (deplete energy sources safely, shutdown systems)		Y	
		ISO 21347:2005	General requirements for fracture control technology	Y	Y	Y
	Avoiding Collisions	ISO/TR 16158:2013	techniques for perceiving close approaches, estimating collision probability, probability of survival, maneuvers to avoid collision	Y	Y	Y
OOS	Measuring Residual Fuel	ISO 23339:2010	Estimate the mass of remaining usuable propellant (LEO or GEO)			Y
	Disposal of GEO satellites	ISO 26872:2010	Requirements to safely dispose of GEO satellites s.t. they will not re-enter op. region for 100 yrs, deplete energy sources	Y		Y
	Telerobotics	CCSDS 540.0-G-1	PROPOSED STANDARD			Y

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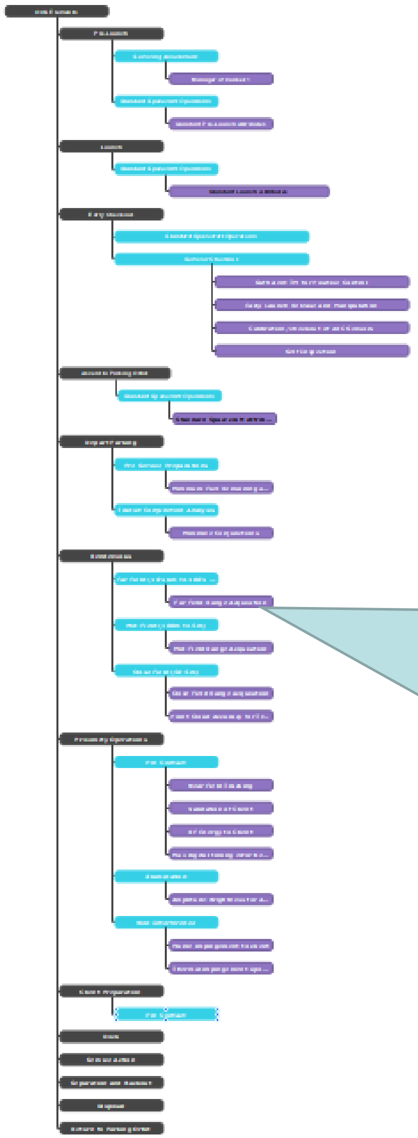
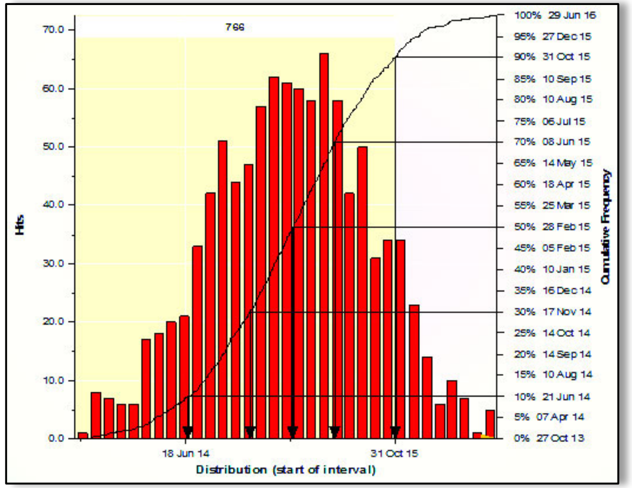
* List from CONFERS TWG March 2019

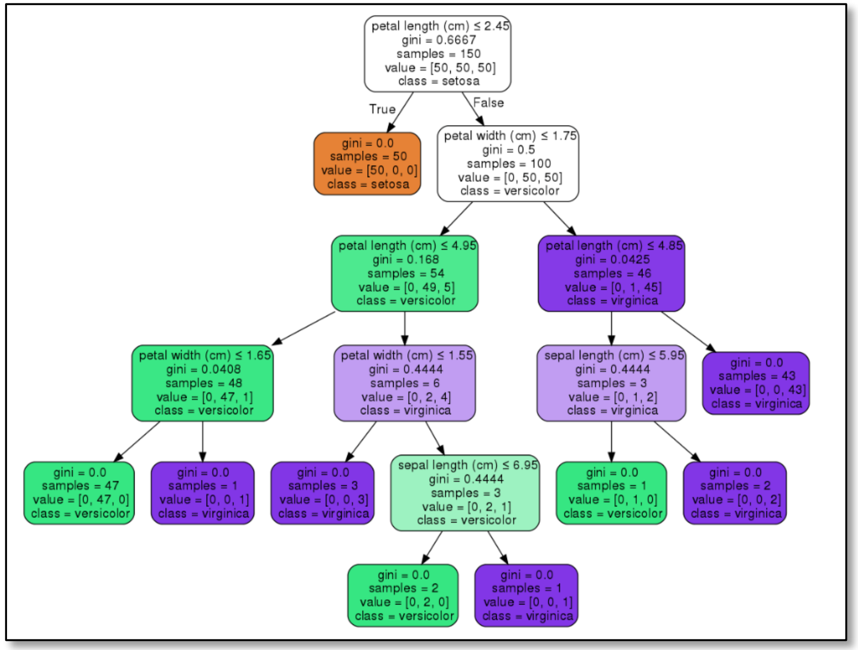
Proposed process to identify most relevant attributes for OOS uses data decision trees for sensitivity analysis



Pick single attribute, create analysis based on quantitative metric with bounds



Run monte carlo analysis based on the bounds, with worst case inputs that create a database of results



Apply the data base to a dynamic data decision tree to uncover sensitivity to the performance of the attribute based on the bounds

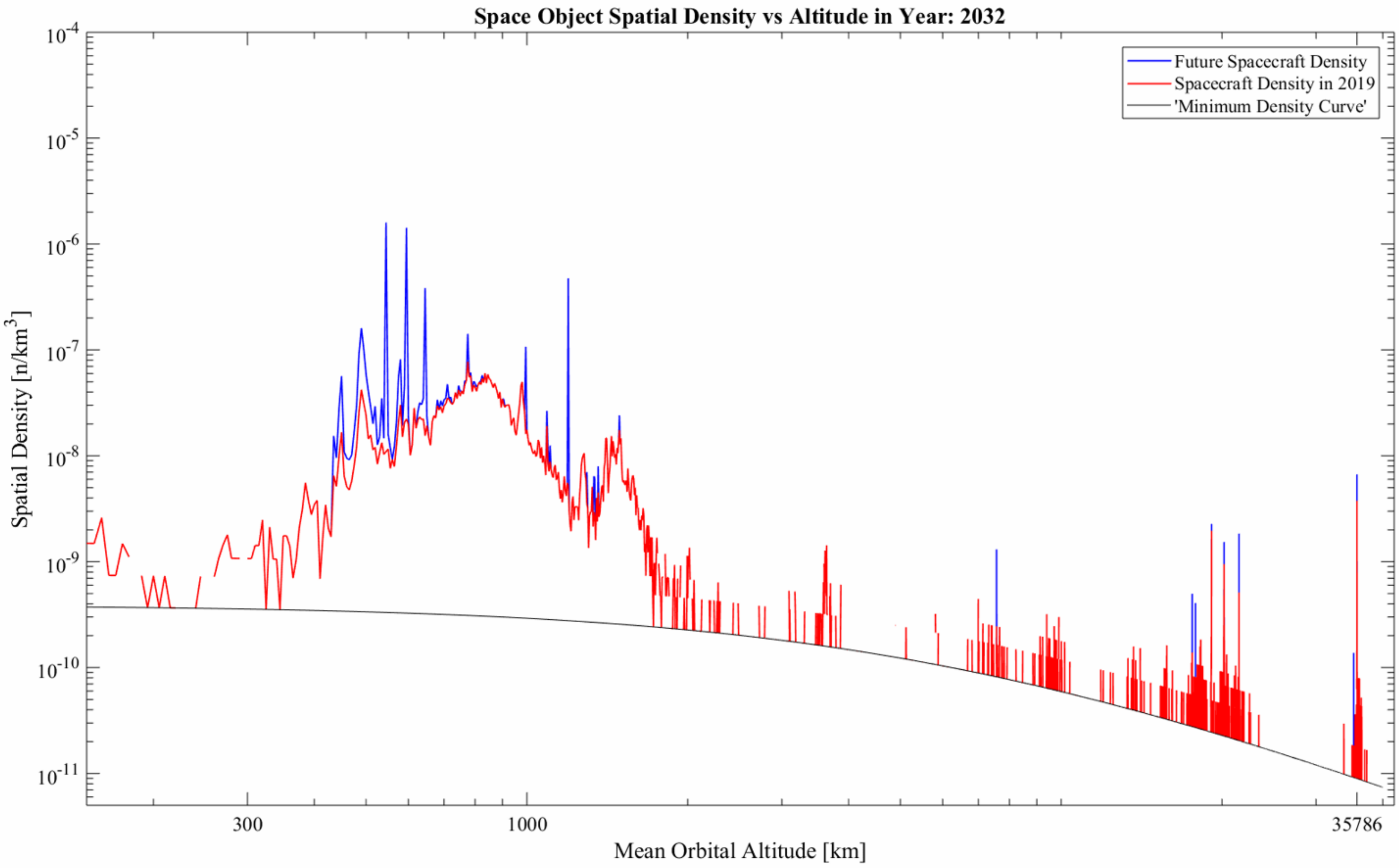
Increasing Spatial Density in Orbit

- **Upcoming space servicing companies are proposing first operations outside of high value and heavy spatial density orbits**
- **An unprecedented surge in new constellations with not just hundreds but thousands of new satellites are in progress.**
- **As servicing satellites transit high density zones, the risk of collisions becomes greater**

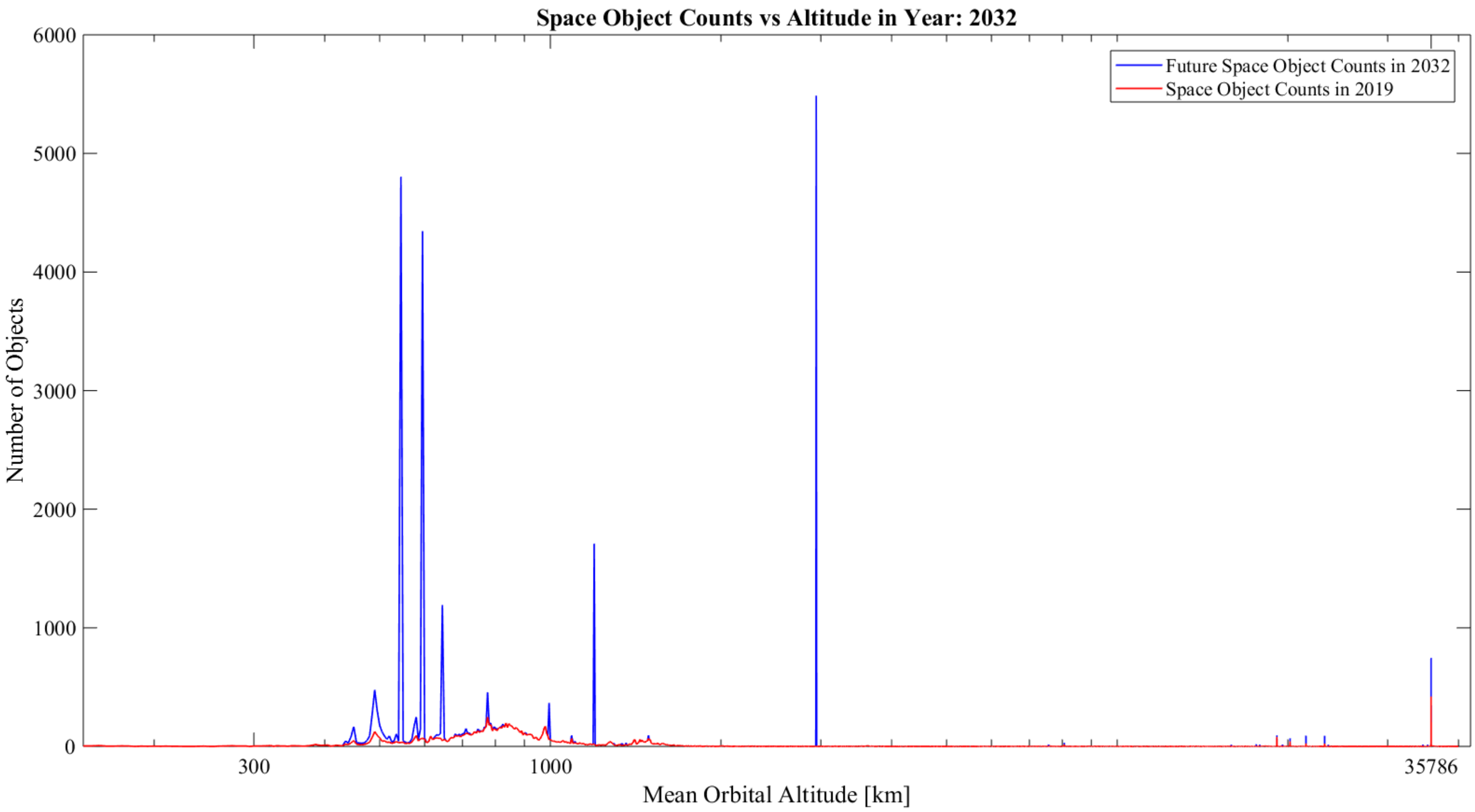
Satellites & Debris in Orbit (2013)

Credit: Michael Najjar

Historical/Projected Spatial Density

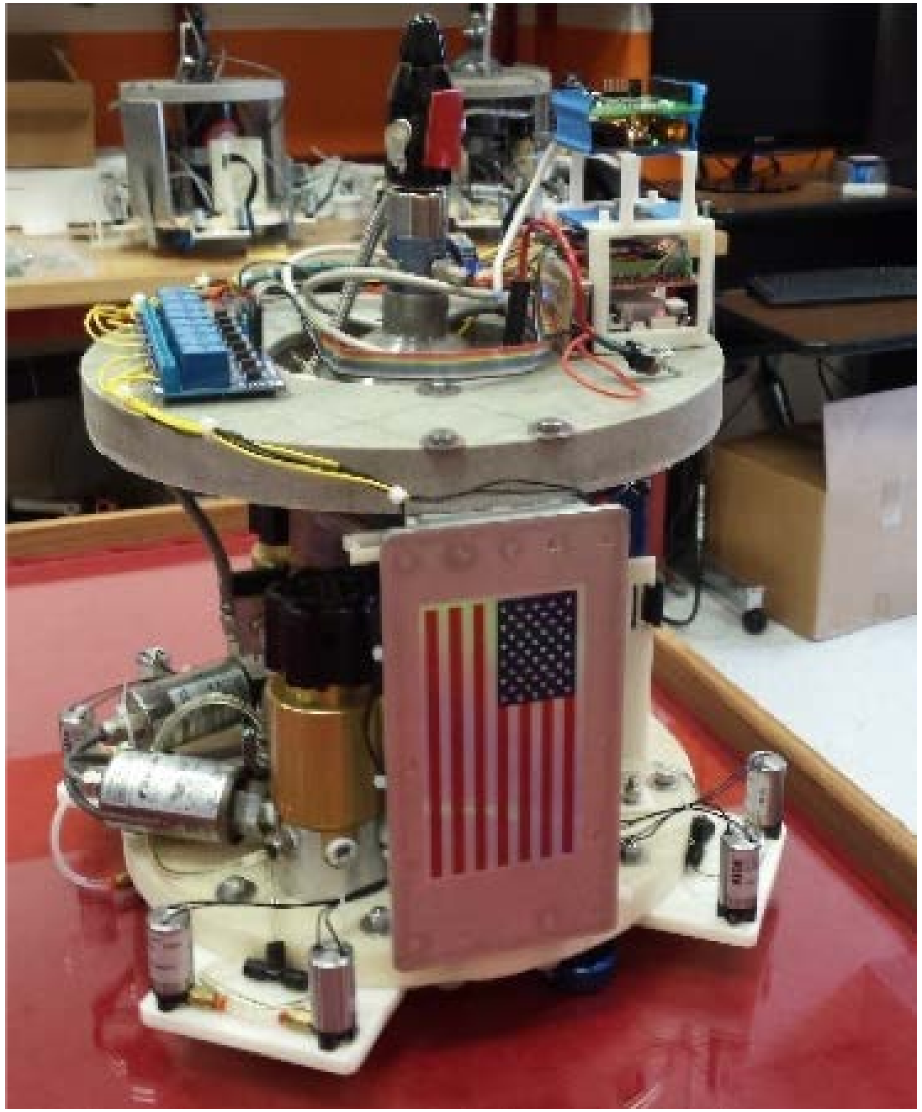


Historical/Projected Spacecraft Numbers/Altitude



Summary

- 1st Year RPO metrics proposed appear to still hold up to contemporary missions
- Initial creation of topology out of OOS "OV-1" completed
- Creation of "function:attribute" mapping provides for first look at quantitative values
- Looking at standards from multiple domains provides informed approach to "space standard" analysis
- Initial consideration for determining what is critical "safety" attribute will continue
- Initial data for transit orbit optimization/consideration for RPO missions created
- Possible functional tests of defined metrics on hardware testbeds in the future



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[6] National Highway Transportation Safety Administration (NHTSA). 49 cfr part 571, docket no. nhtsa-2010-0162. Federal Register, 79(66), 2014.

[7] David A Barnhart, Rahul Rughani, Jeremy J Allam, Brian Weeden, Frederick A Slane, and Ian Christensen. Using historical practices to develop safety standards for cooperative on-orbit rendezvous and proximity operations. In 69th International Astronautical Congress (IAC), Bremen , Germany, 1-5 October 2018, 2018.