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USC Space Engineering Research Center (SERC)
Design-Based Safe Operable Metrics for Earth Regime RPO

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http://serc.usc.edu
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.

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/everyday life…

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

```
<table>
<thead>
<tr>
<th>Infrastructure</th>
<th>Aspect</th>
<th>Loss of GVA (direct+secondary) (five days)</th>
<th>Loss of utility benefits (five days)</th>
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<td>Space</td>
<td>Satellite communications</td>
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<td>See Maritime transport infrastructure</td>
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<tr>
<td>Transport</td>
<td>Maritime transport infrastructure</td>
<td>£1,069.3m</td>
<td>See Maritime usage applications</td>
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<td>Aspect</td>
<td>RAG</td>
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<td></td>
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<td>£12.7m</td>
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<tr>
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<td>Navigation</td>
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“Economic Impact of the loss of GNSS to the UK”, Andy Proctor, UK Government PNT Group, Delegate to ESA Board of Navigation, Nov 2017
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)
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
Metric value $x = \frac{v_{projected}}{v_{max}}$

#2: Remote Influence
Metric value $x = \frac{\omega_{projected}}{\omega_{max}}$

#3: Control Accuracy
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”…

<table>
<thead>
<tr>
<th>Mission Details</th>
<th>Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Contact Velocity</td>
</tr>
<tr>
<td>STS-41C</td>
<td>0.1523</td>
</tr>
<tr>
<td>Dragon</td>
<td>0.0295</td>
</tr>
<tr>
<td>Apollo 11 (LEM)</td>
<td>0.8119</td>
</tr>
<tr>
<td>MEV-1</td>
<td>0.3221</td>
</tr>
<tr>
<td>RESTORE-L</td>
<td>0.2909</td>
</tr>
<tr>
<td>O.CUBED</td>
<td>0.393</td>
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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

OOS Safety Posture

- Mission (Service) Non-Completion
- Servicer/Client Operation Anomaly
- Debris Mitigation

RPO Metrics ➔ Remote Influence/Interference ➔ Contact Actions
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.
Initial OOS Topology

Ascent to Parking Orbit
- Standard Spacecraft Operations
- Standard Spacecraft Attributes

Depart Parking
- Pre-Service Preparations
- Transit Conjunction Analysis
- Minimum Fuel Remaining at Client Orbit
- Minimize Conjunctions

Rendezvous
- Far Field (10's km to 100's m)
- Mid-Field (1000m to 5m)
- Close Field (50-5m)
- Far Field Range Acquisition
- Mid Field Range Acquisition
- Close Field Range Acquisition

Proximally Operations
- Pre-Contact
- Point Cloud Accuracy for Tracking
- Near Field Tracking
- Validation of Client
- RF Energy to Client
- Max digital timing error between Servicer/Client

- Illumination
- Amplitude-brightness for Action(s)
- Non-Interference

- Plume impingement to client
- Thermal impingement upon client
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

*List from CONFERS TWG March 2019*

<table>
<thead>
<tr>
<th>Type</th>
<th>Standard Identification Field Code</th>
<th>Identifier</th>
<th>Identued Use</th>
<th>Quantitative Data?</th>
<th>Applicability to GEO in Space?</th>
<th>Applicability to NGCS in Space?</th>
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<tr>
<td>Physical</td>
<td>CCON-3 2019-5.7</td>
<td>5005.6.7</td>
<td>1300.2.03</td>
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<td>ISO 24357:2009</td>
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<td>Y</td>
<td>Y</td>
<td>Y</td>
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**Sensing**

- **On-board Communication**
  - CCON-3 2019-5.7
- **Tracking Data Message**
  - CCON-3 2019-5.7
- **Attitude Data Message**
  - CCON-3 2019-5.7
- **Communication System Information**
  - CCON-3 2019-5.7

**Telecomatix**

- **Telecommunications**
  - AAAS 3-121A-2017
- **Satellite Design**
  - AAAS 3-121A-2017
- **Spacecraft Systems**
  - AAAS 3-121A-2017

**Orbit**

- **Orbit Determination**
  - AAAS 3-121A-2017
- **Orbit Determination**
  - AAAS 3-121A-2017

**Celestial Navigation**

- **Celestial Navigation**
  - AAAS 3-121A-2017
- **Celestial Navigation**
  - AAAS 3-121A-2017

**Disposal of Debris**

- **Disposal of Debris**
  - ESO 24357:2009
- **Disposal of Debris**
  - ESO 24357:2009

**Terrestrial**

- **Terrestrial**
  - ESO 24357:2009
- **Terrestrial**
  - ESO 24357:2009

**Aerospace**

- **Aerospace**
  - ESO 24357:2009
- **Aerospace**
  - ESO 24357:2009

**Spacecraft**

- **Spacecraft**
  - ESO 24357:2009
- **Spacecraft**
  - ESO 24357:2009

**Satellite**

- **Satellite**
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- **Satellite**
  - ESO 24357:2009

**Orbit**

- **Orbit**
  - ESO 24357:2009
- **Orbit**
  - ESO 24357:2009

**Disposal of Debris**

- **Disposal of Debris**
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- **Disposal of Debris**
  - ESO 24357:2009
Proposed process to identify most relevant attributes for OOS uses data decision trees for sensitivity analysis.

1. Pick single attribute, create analysis based on quantitative metric with bounds.
2. Run Monte Carlo analysis based on the bounds, with worst case inputs that create a database of results.
3. 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

Space Object Spatial Density vs Altitude in Year: 2032

- Future Spacecraft Density
- Spacecraft Density in 2019
- 'Minimum Density Curve'

Spatial Density [n/km^3] vs Mean Orbital Altitude [km]
Space Object Counts vs Altitude in Year: 2032

- Future Space Object Counts in 2032
- Space Object Counts in 2019

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
References


