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Using Historical Practices to Develop Safety Standards for Cooperative On-Orbit Rendezvous and Proximity Operations

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Background: Contemporary Development of OOS and RPO Capabilities

- On-orbit servicing (OOS) and Rendezvous and Proximity Operations (RPO) are key to enabling future of on-orbit activities
- Benefits and challenges
- OOS and RPO are not new, and are already international
- How to develop norms and standards to enable cooperative OOS/RPO and mitigate challenges?


Image Source: NASA


Image Source: Planetary Resources

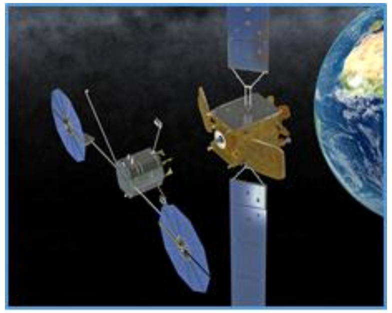
Image Source: Orbital ATK


Image Source: UNOOSA / Sierra Nevada Corp

Norms in Space Governance for "non traditional" applications

- 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
- Norms are likely going to be the main mechanism to address future challenges
  - "Congested, contested, competitive"
  - Far more space actors than ever before, with diverse interests and goals
  - Increasingly challenging to get global consensus on new "hard law"

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Consortium for Execution of Rendezvous and Servicing Operations (CONFERS)

Goal: Develop and introduce industry-consensus standards for cooperative OOS & RPO

ATI Advanced Technology International | Secure World Foundation | USC University of Southern California | Space Infrastructure Foundation

USC Activity: Characterize the On Orbit Servicing arena for input to the Standards process

"RPO": Timelines, actions, maneuvers between two different space platforms from great distance (>100km) to within several meters	**"OOS": Timelines, actions, maneuvers, interactions, manipulations, between two different space platforms within several meters to contact/dock/grapple/connect**
First year	**Second year**

USC Survey and Metric Formulation Steps

1. Look at Past/Existing RPO Practices for "Standards, Metrics or Best Practices" that stand out
2. Survey current/existing industry participants for "best practices"
3. Survey current metrics related to Safety, Operability for RPO
4. Formulate potential operable metrics for Industry consideration for RPO

Step 1 create an initial database of Past RPO Events

- Early review of 65+ references indicated that only a handful of "events" contributed so far, and those events were from a small set of organizations

- These were then focused on as the principle contributing constituents
  - Apollo 11 (Lunar Orbit Rendezvous)
    - Early Gemini/Apollo followed same process
  - JAXA ETS-VII
  - NASA DART
  - Space Shuttle (14 missions)
  - ISS Missions (multiple vehicles)
    - NASA/ESA Automated Transfer Vehicle
    - SpaceX Dragon
  - DARPA Orbital Express

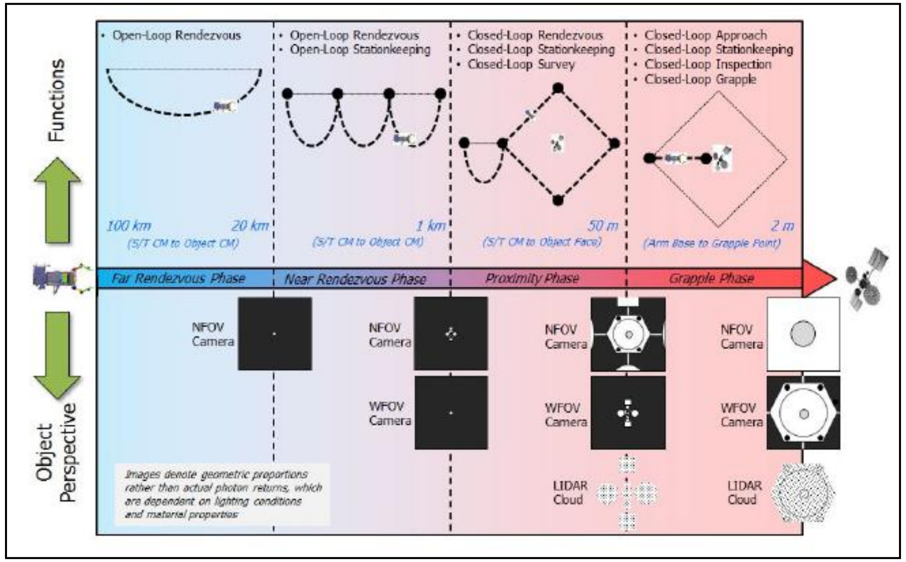
			Orbital Parameters			Phasing Metrics	1st Hold or Gate (Distance from Target)			1st Gate Metrics				
Mission Name	Primary Organization	Date	Altitude (km)	Inclination (deg)	RAAN (deg)	(1-Tc/Tt)	rbar (km)	vbar (km)	Mission Time	dV of transition [m/s]	ground comm [0,1]	rel comm [0,1]	lighting [0,1, -1]	dt bef hol [hr]
STS-41C	NASA	April 1984	560	28.5	?	0.0040013	18.52	?	?	?	?	?	?	?
STS-88	NASA	December 1998	408	51.7	?	?	0.55	-0.24	?	?	1	1	?	?
STS-97	NASA	November 2000	408	51.7	?	?	0.55	-0.24	?	?	1	1	?	?
STS-102	NASA	March 2001	408	51.7	?	?	0.55	-0.24	?	?	1	1	?	?
STS-114	NASA	July 2005	408	51.7	?	?	0.55	-0.24	?	?	1	1	?	?
STS-71,74	NASA	1995	359	51.6	?	?	0.853	-0.061	?	?	0	?	1	?
STS-76,79,81,84	NASA	1997	359	51.6	?	?	0.853	-0.061	?	?	0	?	1	?
STS-86,91	NASA	1998	359	51.6	?	?	0.609	-0.305	?	?	0	?	1	?
STS-89	NASA	1998	359	51.6	?	?	0.609	-0.305	?	?	0	?	1	?
Dragon	SpaceX	05/22/2012	408	51.7	?	?	10	?	2/23:16	?	1	1	?	?
ETS-VII	JAXA	1997	550	35	?	?	9		?	?	0	1	0	?
Apollo 11 (lunar orbit)	NASA	1969	83.34	?	?	?	27.78	-137.98	0:00	?	1	1	1	?
Automated Transfer Vehicle	ESA/NASA	1997	350	51.6	?	?	2	-20	?	?	?	?	?	?
GNC Strategy for RPO with noncooperative S/C [STUDY]	NASA Study	2011*	35768	0		0.0010675	30	-300	0/00:00	5.49	?	?	1	?
Orbital Express	DARPA	2007	492	46	?	?	0	-4	?	?	?	?	-1	?
DART	NASA	2005	765	90	?	0.0015745	7.5	-40	0/8:00	33.59	?	?	?	?

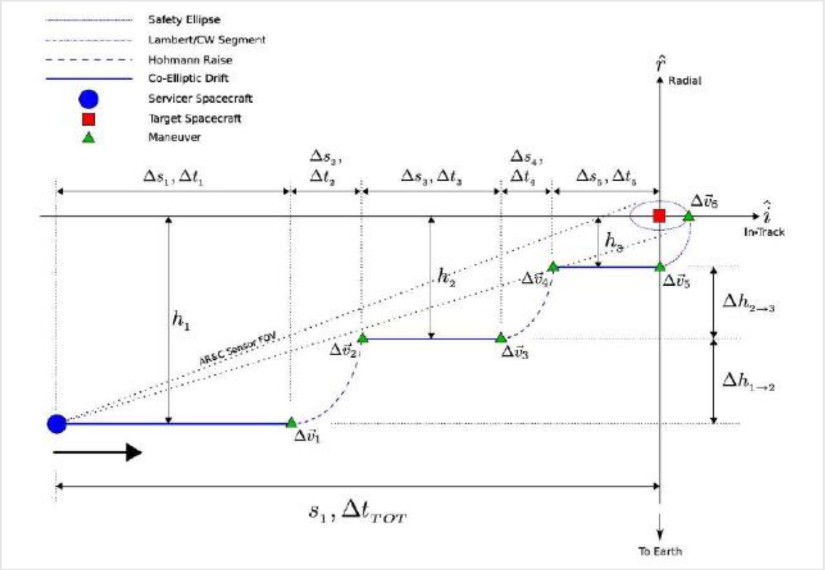
Note: No past missions identified in GEO

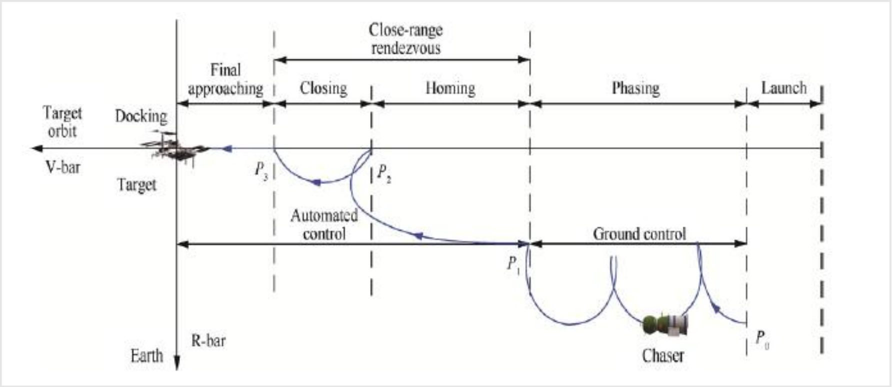
Step 1 Past Survey Initial Results

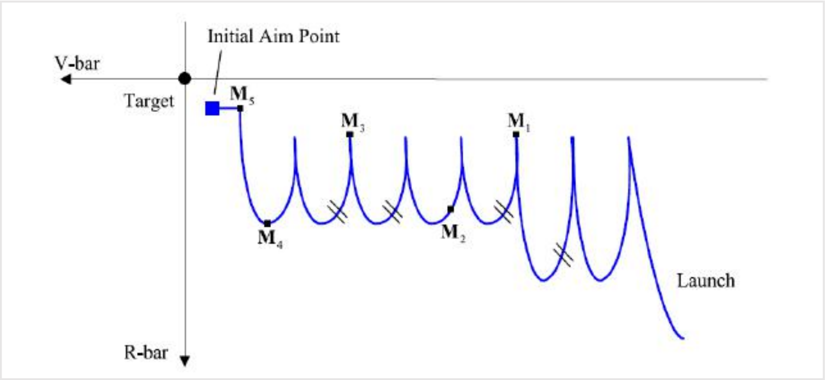
- 1. From 100km to close in, there are as many ways to execute "rendezvous" as there are orbits in the sky…
- 2. There was some concurrence on levels of safety applied to "approach velocity on final burn"
- 3. There was no concurrence on use of specific nomenclature
- Initial Conclusion and Way Ahead:
  - A. Hard to put a standard/metric on "rendezvous" dynamics from afar, focus may need to be on design or testing of "servicer" to get close to the initial "stand off point"
  - B. Results pointed to trajectory safety for "Final Approach to …", where "…" would be focus as possible investigative vector on possible metrics
  - C. Useful to start an ontological lexicon focused on RPO (OOS)…

Interesting observation: No international agreement on “RPO” representations



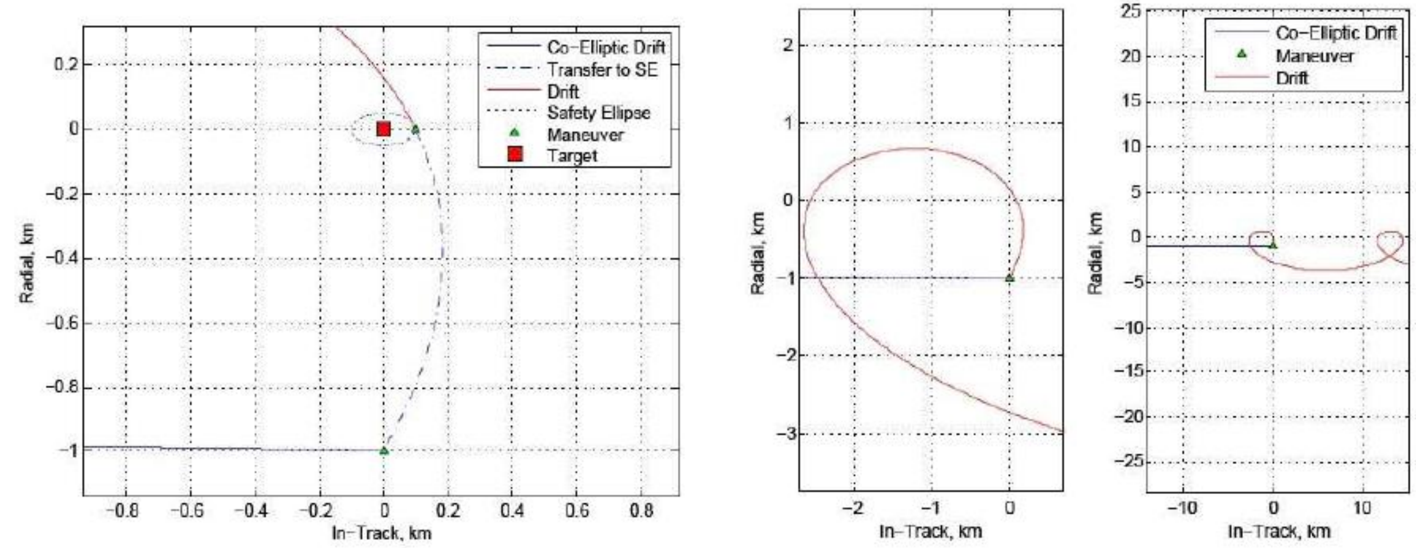






Different regimes, different nomenclature, different layouts on the page….

No agreement on Graphical Illustrations depicting the approach(es)



(a) Simulated Proximity Operations Trajectories

(b) Safe Natural Drift After Missed Safety Ellipse Insertion Maneuver

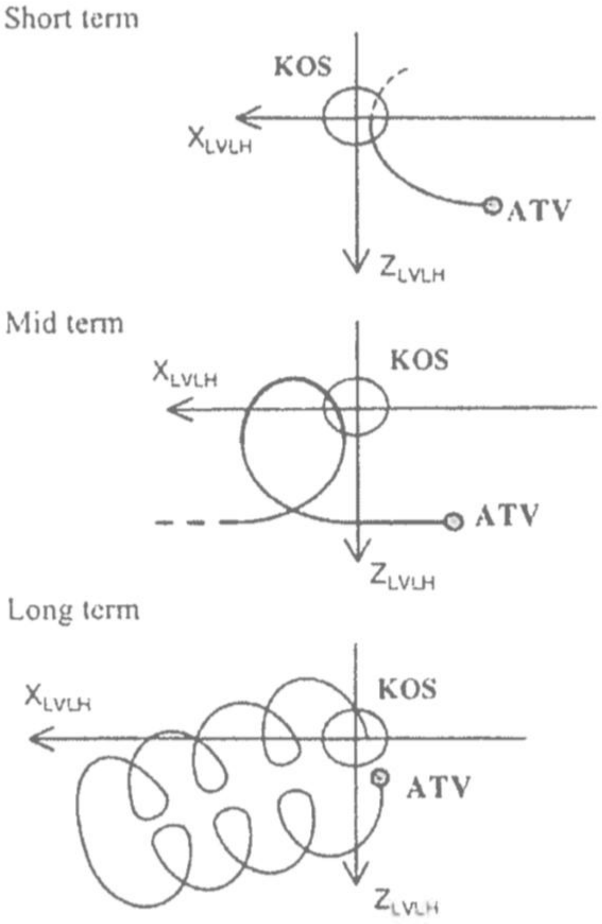
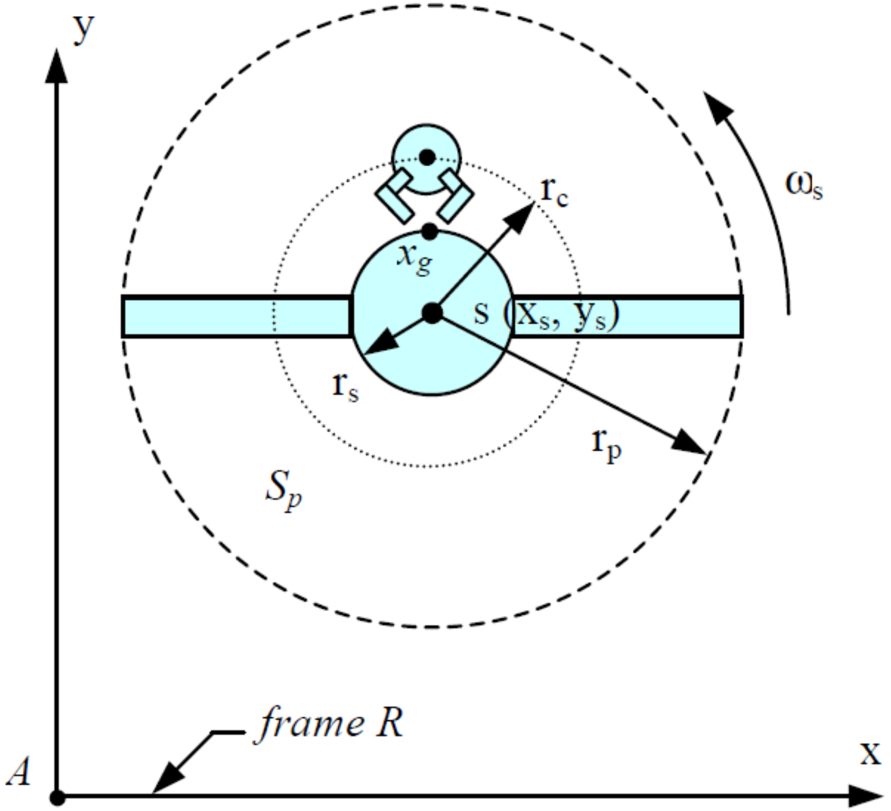
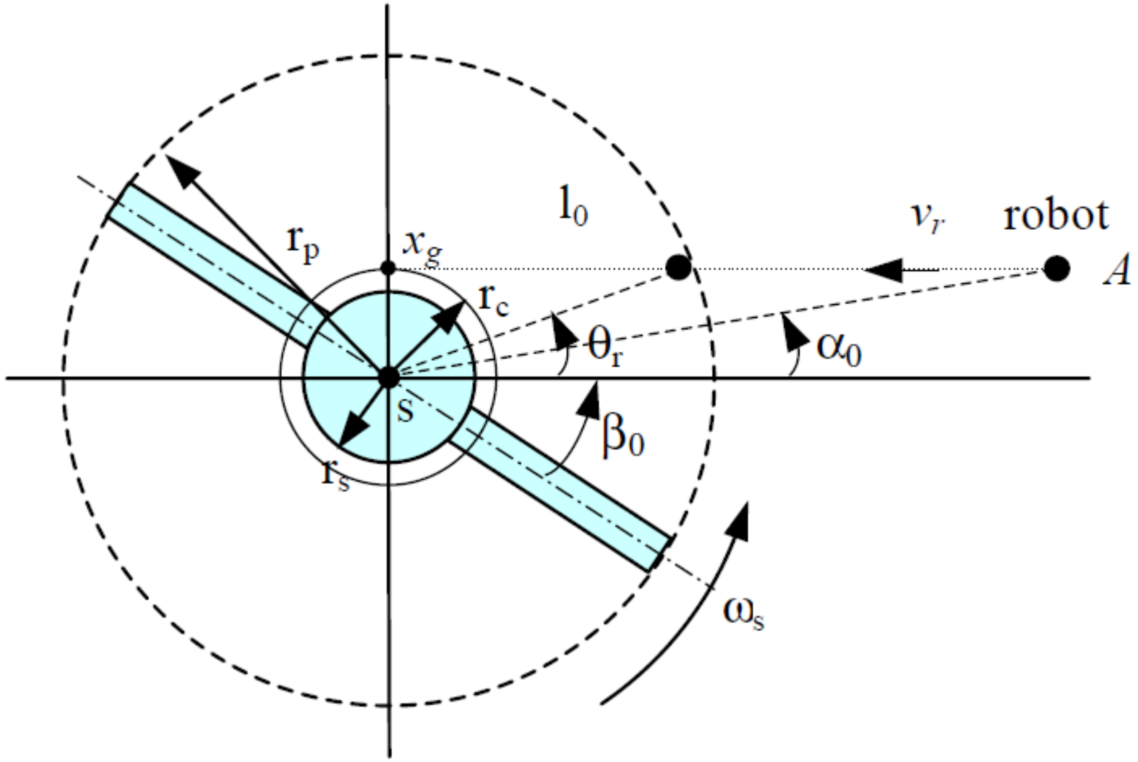


Fig. 3. Illustration of unsafe trajectories

Many use traditional Rbar and Vbar, yet some identify a specific reference plane; did not find a common or standard designation

Very limited robotic approach depictions after rendezvous begins…





Very rare to find details or operational examples… same problem with reference frame, is it spacecraft or robot centric?

Step 2, Survey Industry participants

- USC reached out to existing commercial parties in RPO/OOS
- A questionnaire was provided to help bound/uncover possible areas for evaluation
- *Any/all information was anonymized*

- **Detailed RPO Schema**
- **Nomenclature**
  - “Rendezvous”, “rendezvouser”, “rendezvousee”, “target”, “gate”, “Phase”, “stage”, etc.
- **Safety**
  - Zero probability of collision
  - Min Probability of rendezvousee power systems eclipse
  - Min probability of rendezvouser propulsion impingement
  - Min probability of freq interference (or loss of control)
  - etc
- **Transparency**
  - Time before RPO announcement
  - Audience for RPO announcement
  - Detail within announcement
  - Coordination between Rendezvouser/ee
  - Etc.
- **Government Regulation Affect**
  - Secondary affects only? (ie fuel, power, time etc)
  - Safety Issues?

Step 2: Initial Results of Industry Discussions

1. **General concern over undue (additional) regulations**
2. **Different nomenclature for different events were common in each companies RPO/OOS Architecture**
3. **“Transparency” versus “Safety” was a distinct issue**

Step 3, Survey Metrics related to Safety, Operability for RPO

- **Focus on "trajectory safety" during RPO approach**
- **Review representations of RPO maneuvers or depictions for comparisons**

Initial standard definition considerations:

- Likelihood of application to real operations
- Applicability to all types of mission sets that utilize RPO
- Consideration of multiple mass/size of potential spacecraft and space objects
- Focus on measurable elements or variables during an approach
- Have sequence of verifiable tests and analysis that can be applied prior to launch for hardware that drives a metric
- Dimensionless ratio accounts for any size objects
- Assumption in safe ops that the "final burn was made", and then failure occurs…

Two principle safety categories identified specific to RPO Actions:

1. Contact Actions

2. Remote Influence/Interference Actions

Step 3, Initial list of Safety Methodologies Surveyed

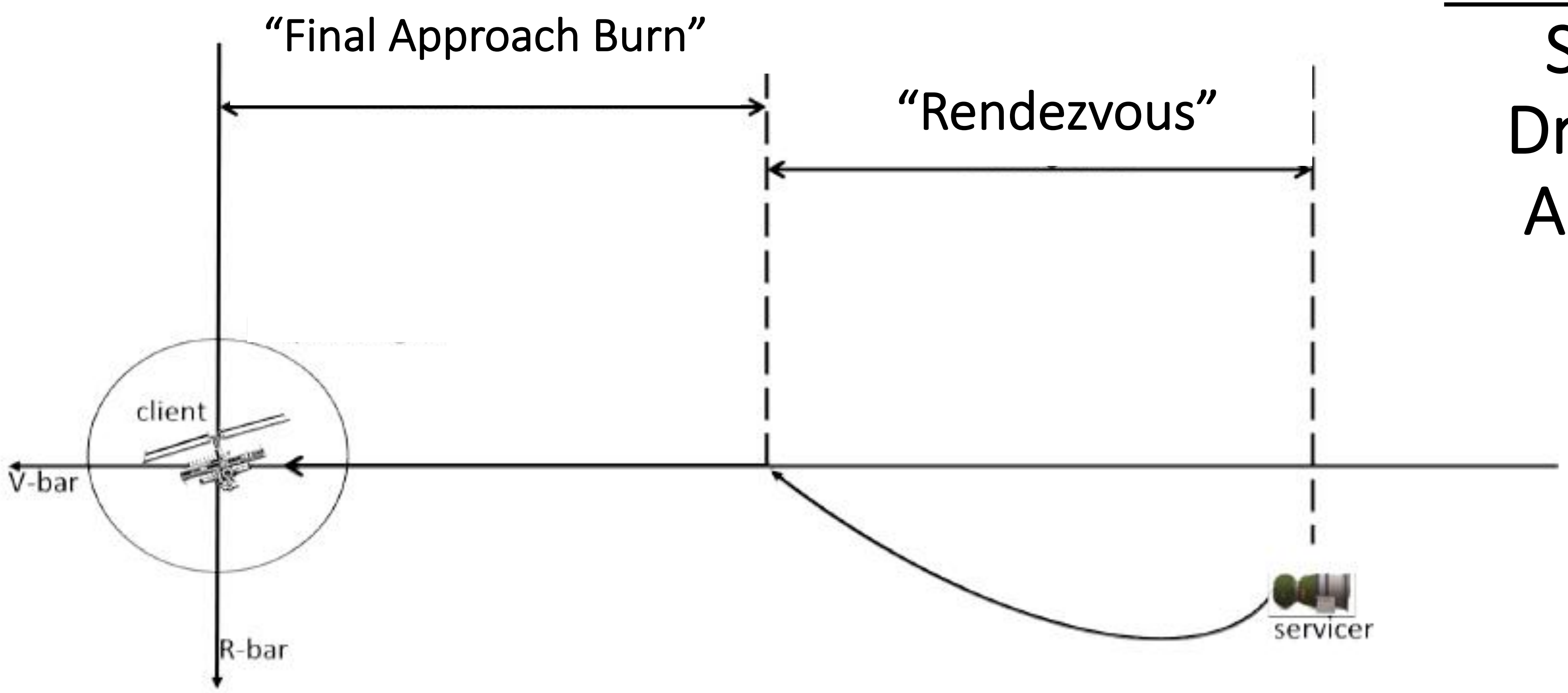
Safety Control Zone Methodology	• ISS External Control Zone (Approach Ellipsoid) at 4km x 2 km x 2km [64] • ISS Inside Control Zone (Keep out Sphere) radius of 200 m [64]
Passive Trajectory Safety Models	• Fehse (rules of rendezvous control zones) [65]; Yamanaka (safety velocity equations for V-Bar approach with cuboid control zone) [66]; and Zhu (safety velocities of cuboid, spheroid and cone zones) [67]
Active Trajectory Safety Models with Colli-sion Avoidance Maneuver	• Fehse (impulse in opposite direction to the velocity as CAM) [65]; and Zhu (method to calculate CAM based on safety boundary) [67]
Collision Probability	• Patera et al [68] • Wang safety analysis method using collision probability [69] • Luo proposed safety performance index based on collision probability [38]
Trajectory Safety Optimization	• Matsumoto and Jacobsen used reciprocal time of flight from "out of control" point to collision points as the flyby safety index, genetic algorithm optimized mixed index combining safety and propellant consumption [70] • Roger and McInnes used Laplace potential function to express safety control zone [71] • Richards added 0-1 variables to express constraints of the collision avoidance and plumes impact [72] • Breger and How accumulated probability of collisions from different failures in different trajectory points, formulated passive and active safety indexes, then proposed on-line method for optimal trajectory [12] • Luo defined min distance between chaser and target in chasers free flight path as trajectory safety performance index, then multi-objective optimization for impulsive rendezvous that included min velocity/flight duration and max safety index [38]

Step 4: Translation of operational considerations to New proposed Metrics for RPO

- Development of operational metrics apply only to the final rendezvous, defined from multiple meters to "contact" between a Servicer and Client, that addresses the scope for the standard to "do no harm" for RPO actions. The proposed metrics are

- Contact Velocity Metric (for Contact Action)
- Control Accuracy Metric (for Contact Action)
- Remote Influence Metric (for Remote Influence)

Basic Schema and specific examples used for comparison



RPO Examples:

STS-41C
Dragon ISS
Apollo 11

Rendezvous and Proximity schema roughly defined as >100km to “meters”

Metric #1 - Contact Velocity

Impact velocity was derived from an alternative perspective that the Servicer <u>WILL</u> in-advertantly contact the Client; goal to prevent critical damage

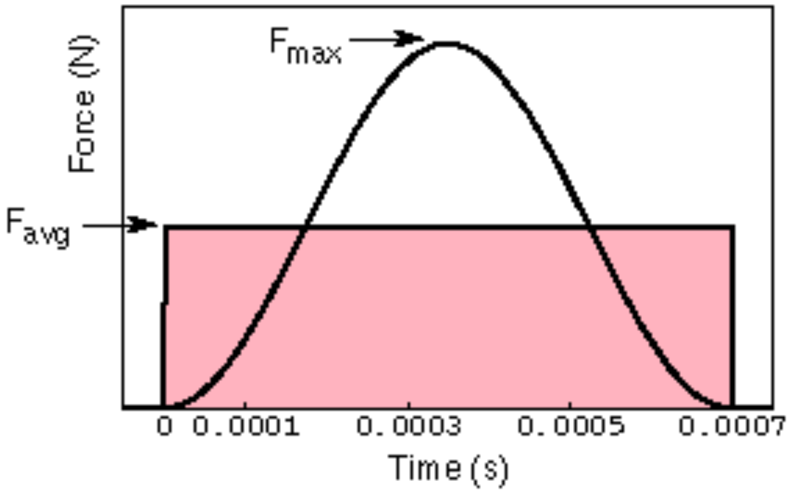
- Pragmatic viewpoint to account for (hopefully) high numbers of RPO operations
- Realistic, considering we have already experienced inadvertent impact(s)

Assumptions:

- Nominal trajectory, velocity is variable
- Contact assumed between planned contactable structures (i.e. not solar array, camera, etc)

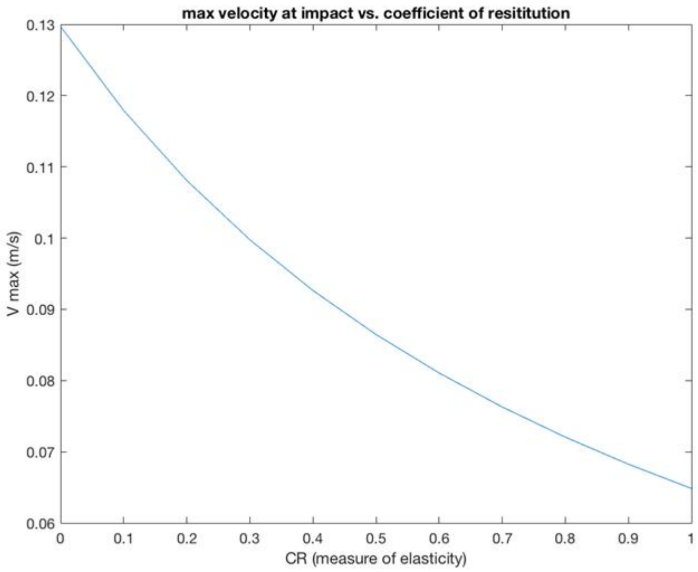
Metric created based on inelastic collisions and Coefficient of Restitution for any two surfaces

- Used in idealization of impact/contact between any S/C surface(s)
- Assumes constant force over the impulse time
- Used 5ms for impact force-time
    - Similar to automotive vehicle impact analysis



Representative profile figure only, scale does not match input. Used for illustration.

- Amount of momentum transferred depends on coefficient of restitution (CR)
    - Depends on how much imparted momentum causes deformation
- Measure of elasticity of collision
    - CR= 0: perfectly inelastic, both objects fuse
    - CR=1: perfectly elastic, all mom. transferred
- Max vel is inversely proportional to CR
    - CR = 0.4 – 0.6 deemed realistic values



Metric #1 - Contact Velocity Formulation

Input	STS-41C	Dragon ISS	Apollo 11
Mass of Client	2,315 kg	419,455 kg	5,560 kg
Mass of Servicer	94,050 kg	10,200 kg	2,613 kg
Material properties of Client	Al, Ti	Al, Ti	Al, Ti
Contact area on Servicer	0.4242 m^2	0.0314 m^2	0.4242 m^2
Estimated impulse time	5 ms	5 ms	5 ms
Safety factor	2	2	2
Coefficient of Restitution	0.6	0.6	0.6
Projected velocity of approach (i.e. final burn)	0.15 m/s	0.089 m/s	13.72 m/s

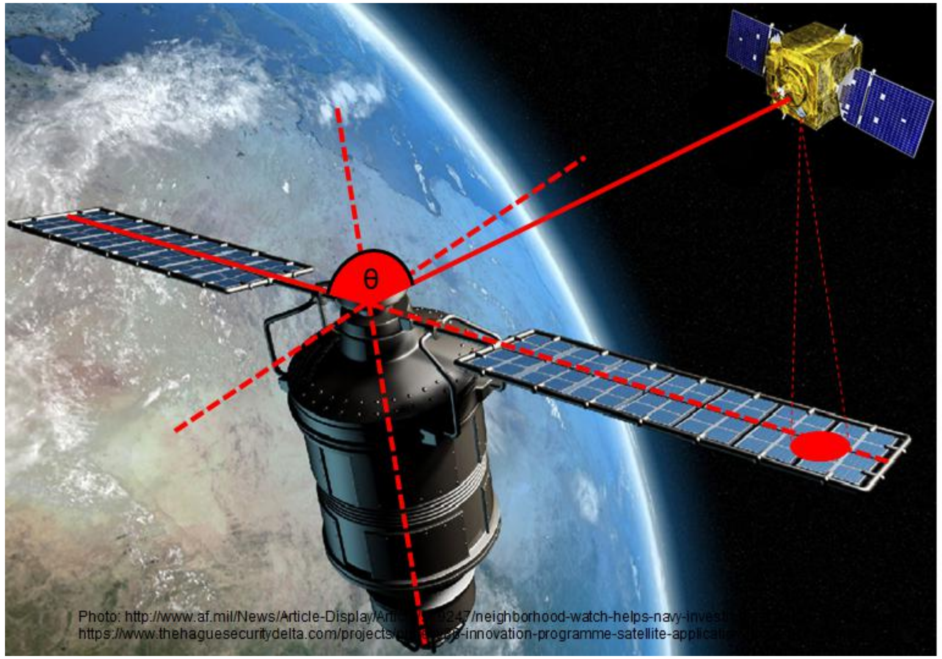
Values in yellow are estimates, could not find published values

Output

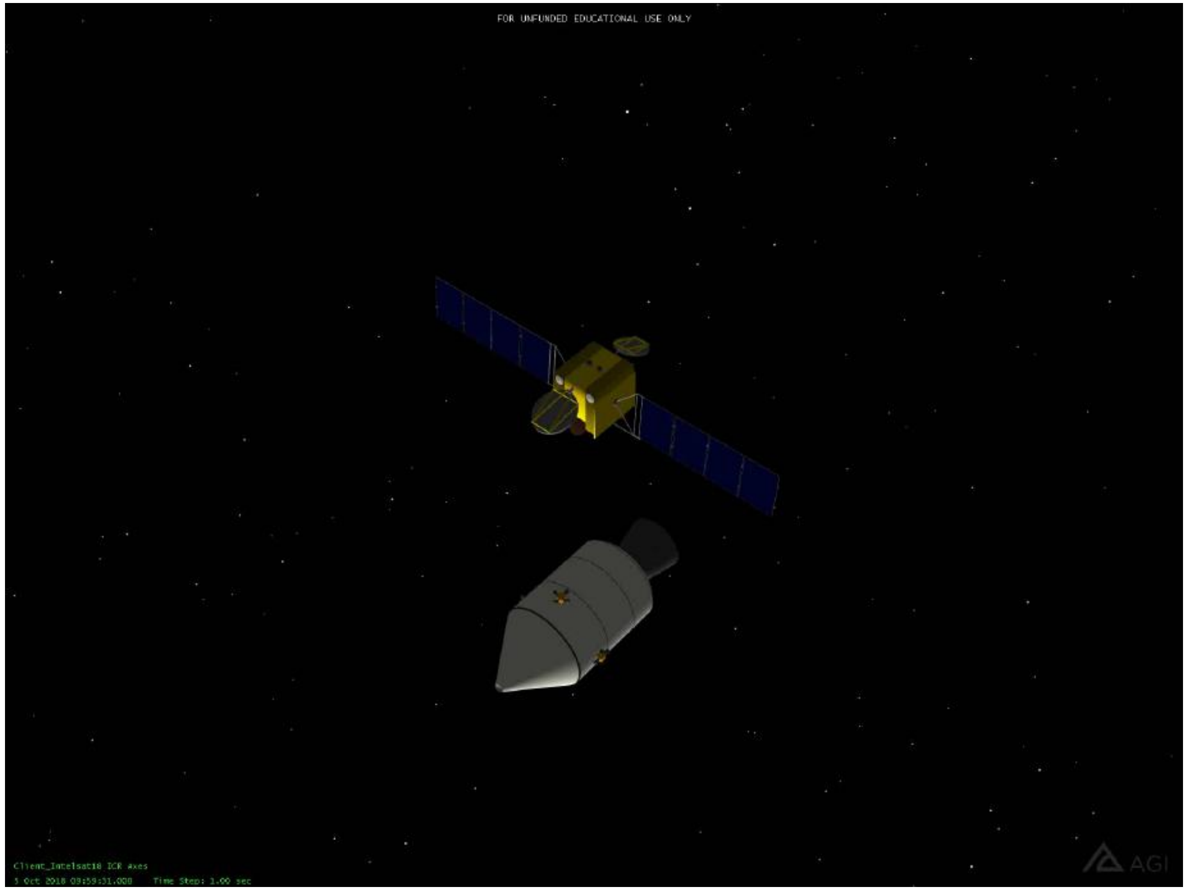
$$\textbf{Metric value } x = \frac{v_{projected}}{v_{max}}$$

$$if\ x < 1, maneuver\ is\ safe$$
$$if\ x \geq 1, maneuver\ is\ unsafe$$

Metric #2 – Remote Influence:
Plume Impingement used as 1st remote influence



- Theta is the angle from the servicer to the next object that can impact it under rotation
- $\omega_{max} = \dfrac{\theta}{retreat\ time}$
- The chosen servicer retreat time defines ω_{max}
- Long retreat time necessitates small $\omega_{projected}$
- Inertial control on client is passive



Note: Client depicted is full sized GEO satellite bus, rotation speed shown is ~30x real time

Metric #2 – Remote Influence Formulation

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

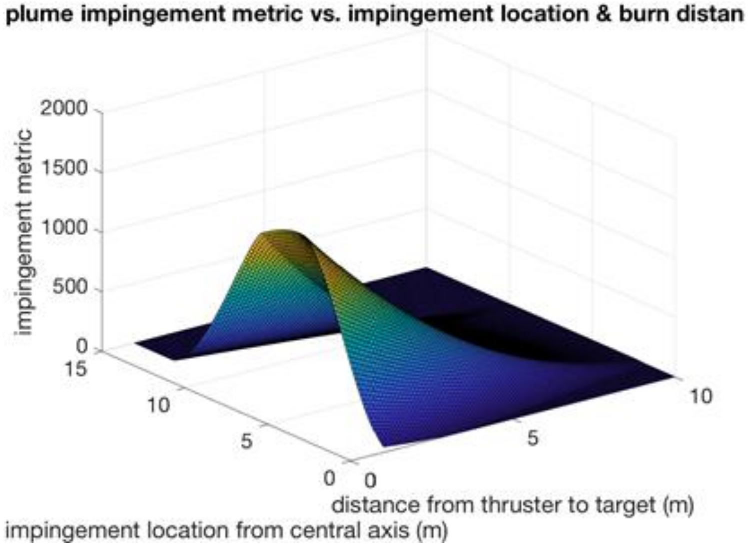
$$\omega_{max} = \frac{\theta}{retreat\ time}$$

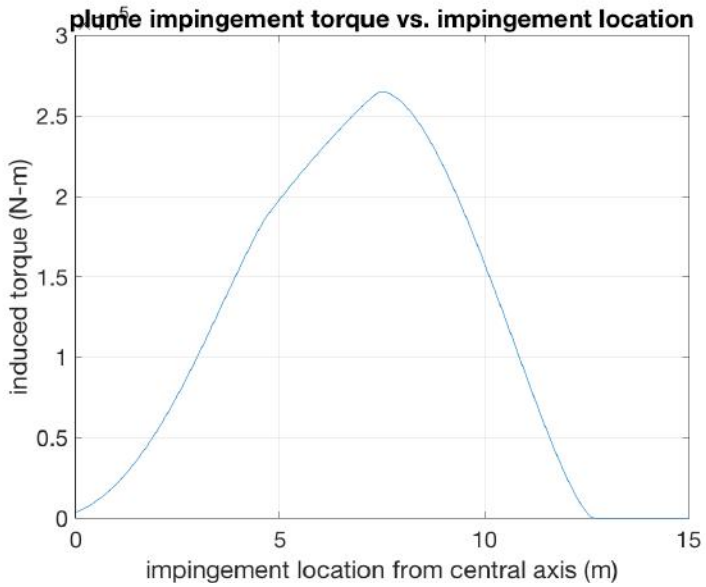
$$if\ x < 1, maneuver\ is\ safe$$
$$if\ x \geq 1, maneuver\ is\ unsafe$$

Input	STS-41C	Dragon ISS	Apollo 11
Mass of Client	2,315 kg	419,455 kg	5,560 kg
Mass of Servicer	94,050 kg	10,200 kg	2,613 kg
Servicer to Client separation	106.8 m	10 m	1850 m
Thrust of motor	53,400 N	1600 N	440 N
ISP of motor	316 s	300 s	290 s
Nozzle cone half-angle	20 deg	20 deg	20 deg
Nozzle exit area	1.108 m^2	0.393 m^2	7.85e-3 m^2
Projected velocity of approach	0.15 m/s	0.089 m/s	13.72 m/s
Retreat time	60 s	300 s	300 s

Values in yellow are estimates, could not find published values

Output





Metric #3 – Control Accuracy Metric

Pointing error was derived from desire to be within range of a robotic appendage to "capture/grab/hold" the Client

- Realistic, considering multiple contact mech. proposed and variations in GNC/ADACS

Possible Max. capture distance hardware dependent on scenario

- Reach of robotic arm
- Range of RCS thrusters
- Reel of harpoon
- Tether distance of net
- Electrostatic blanket size
- Etc.

Tradeoff between control accuracy and ECD

- Need higher pointing accuracy for lower effective capture distance

Photo: https://sspd.gsfc.nasa.gov/robotic_servicing_arm.html

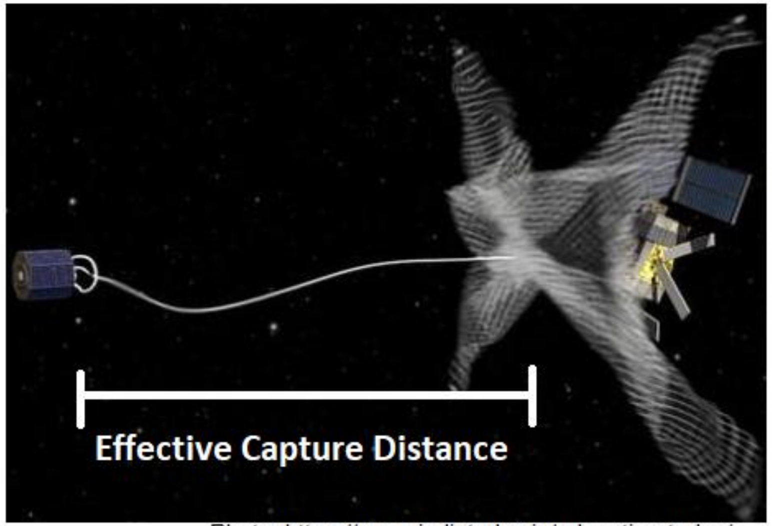
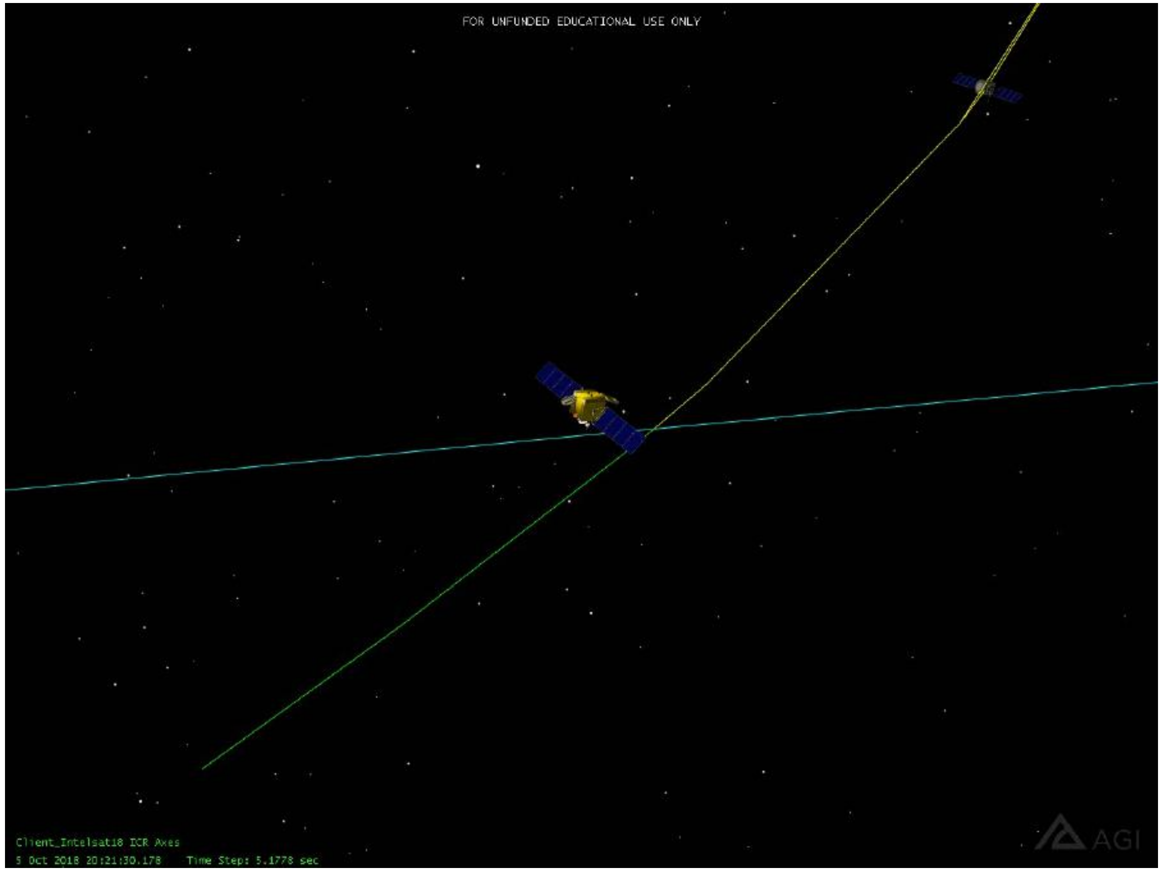
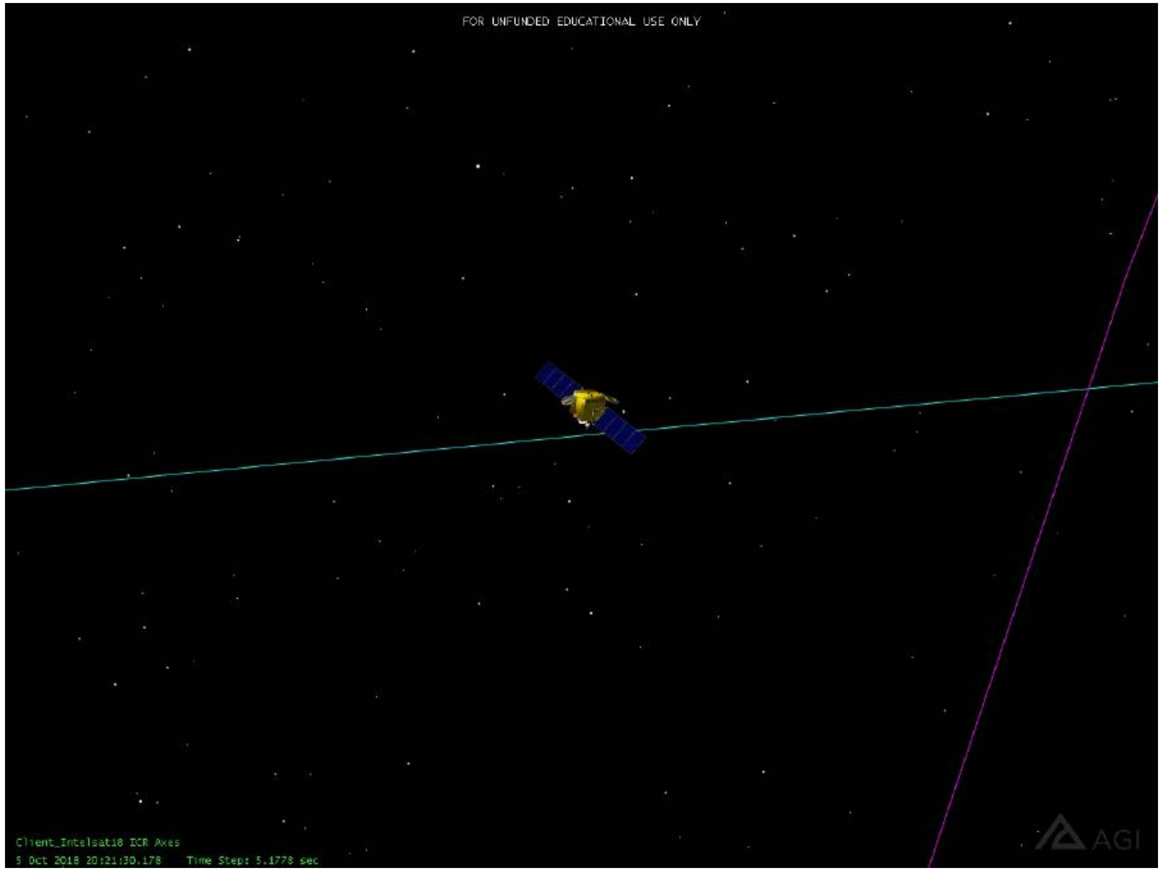


Photo: https://www.indiatoday.in/education-today/

Control Accuracy Depiction – Virtual "range sphere of contact"

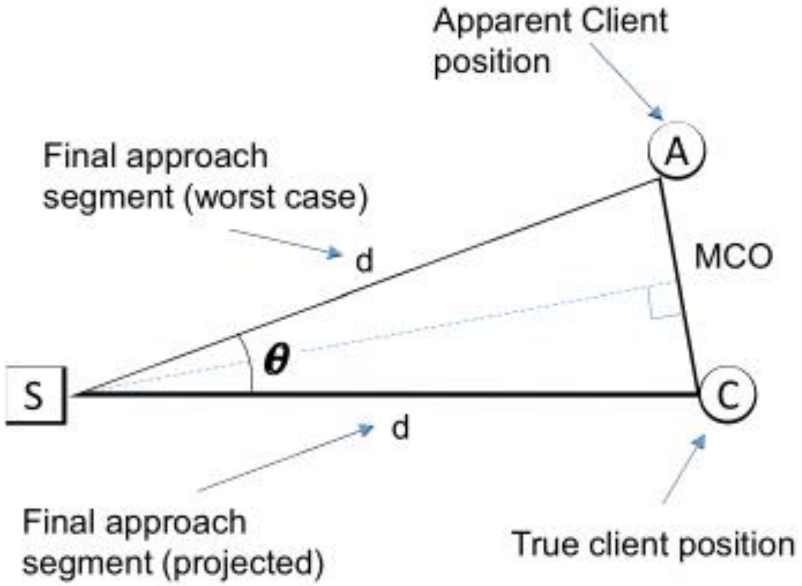


Nominal control accuracy



1 deg off from nominal

Metric #3 – Control Accuracy Metric Formulation



$$\theta = knowledge\ error + control\ pointing\ error$$

$$MCO = 2d \sin\frac{\theta}{2}$$

Output

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

Input	STS-41C	Dragon ISS	Apollo 11
ADACS knowledge error	1 deg	0.1 deg	5 deg
ADACS pointing error	1 deg	1 deg	5 deg
Effective Capture Distance	15.2 m	17.6 m	50 m
Standoff distance from Client	106.8 m	10 m	1850 m

Values in yellow are estimates, could not find published values

MCO: Max Capture Offset
ECD: Effective Capture Distance

$$if\ x < 1, maneuver\ is\ achievable$$
$$if\ x \geq 1, maneuver\ is\ not\ achievable$$

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Quick Results for examples: Application of Metrics to Survey Data

Mission Details				Metrics		
Name	Primary Organization	Client	Date	Contact Vel	Plume Impingement	Control Acc.
STS-41C	NASA	Solar Max	4/9/1984	0.1523	0.154	0.245
Dragon	SpaceX	ISS	5/22/2012	0.0295	0.00585	0.0198
Apollo 11 (LEM)	NASA	CSM	7/21/1969	0.8119	0	6.45

Caveats:

- **Best Guesses provided where information was lacking**
- **Only subset of primary agency groups evaluated**

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RPO Survey Summary

1. No real correlation in the approach distance or specific orbitology of any disparate platform RPO events
2. Correlation between most RPO events appeared to identify velocity as an important factor for the final approach maneuver prior to braking
3. No real correlation between presentation methodologies on what an RPO schema should be represented as
4. No International standard lexicon that applies to the RPO event scenario appears to be agreed upon
5. No existing RPO risk metric or standard relative to satellite to satellite platforms were readily identified (excluding ISS)
6. Commercial firms by and large prefer not to have external regulation, but do recognize the important of “do no harm” as a safety precept for RPO events