TERRAN ORBITAL

CubeSat Proximity Operations Demonstration (CPOD) Mission Results

August 9, 2023

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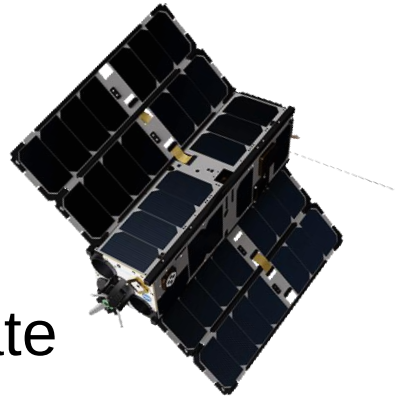
CPOD INTRODUCTION

Motivation: Advance technology for low-cost RPO missions, e.g.
- Space debris remediation
- Inspection/servicing/assembly of other systems

Mission: Develop a physical satellite platform and GNC framework for CubeSat rendezvous & formation flight

Vehicles: Two identical 3Us

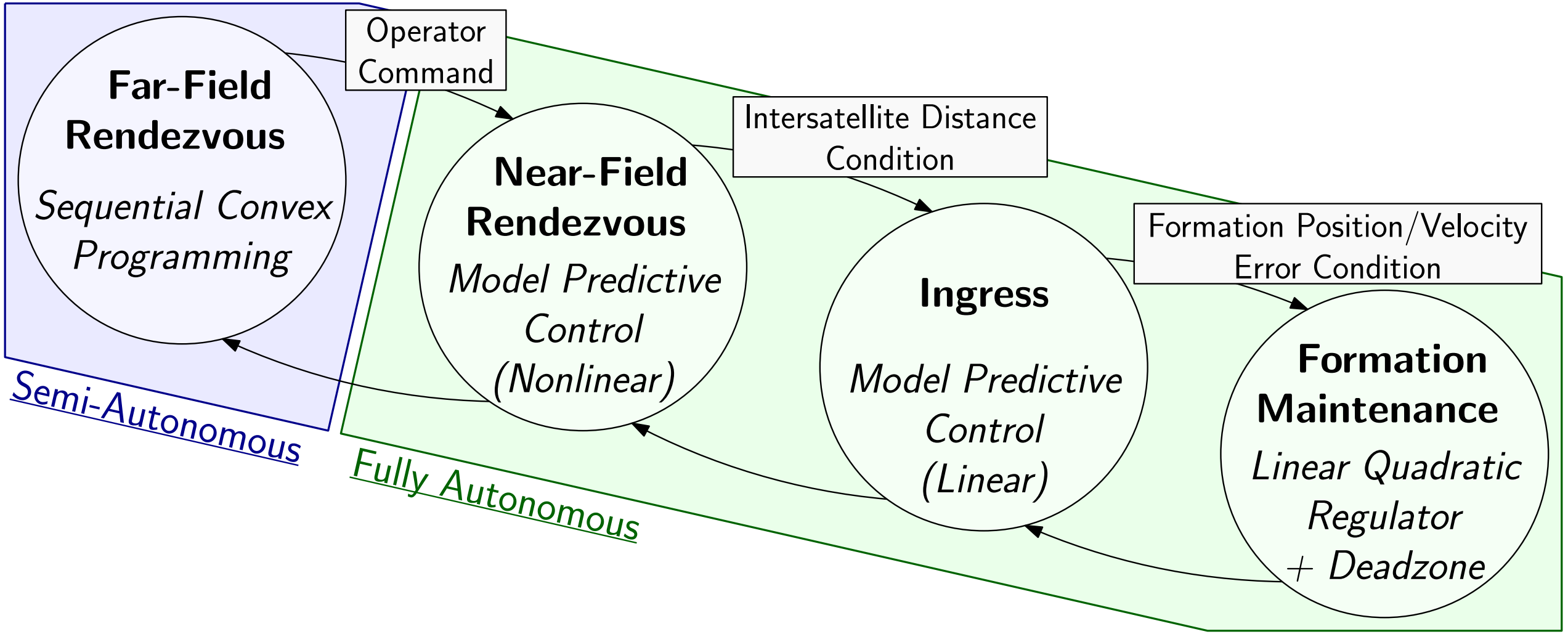
Presentation Focus: Optimization-based guidance for RPO emphasizing:
- Autonomy
- Safety
- Reference tracking performance
- Fuel economy



Funding: NASA Space Technology Mission Directorate

RPO ARCHITECTURE OVERVIEW

Automaton Representation



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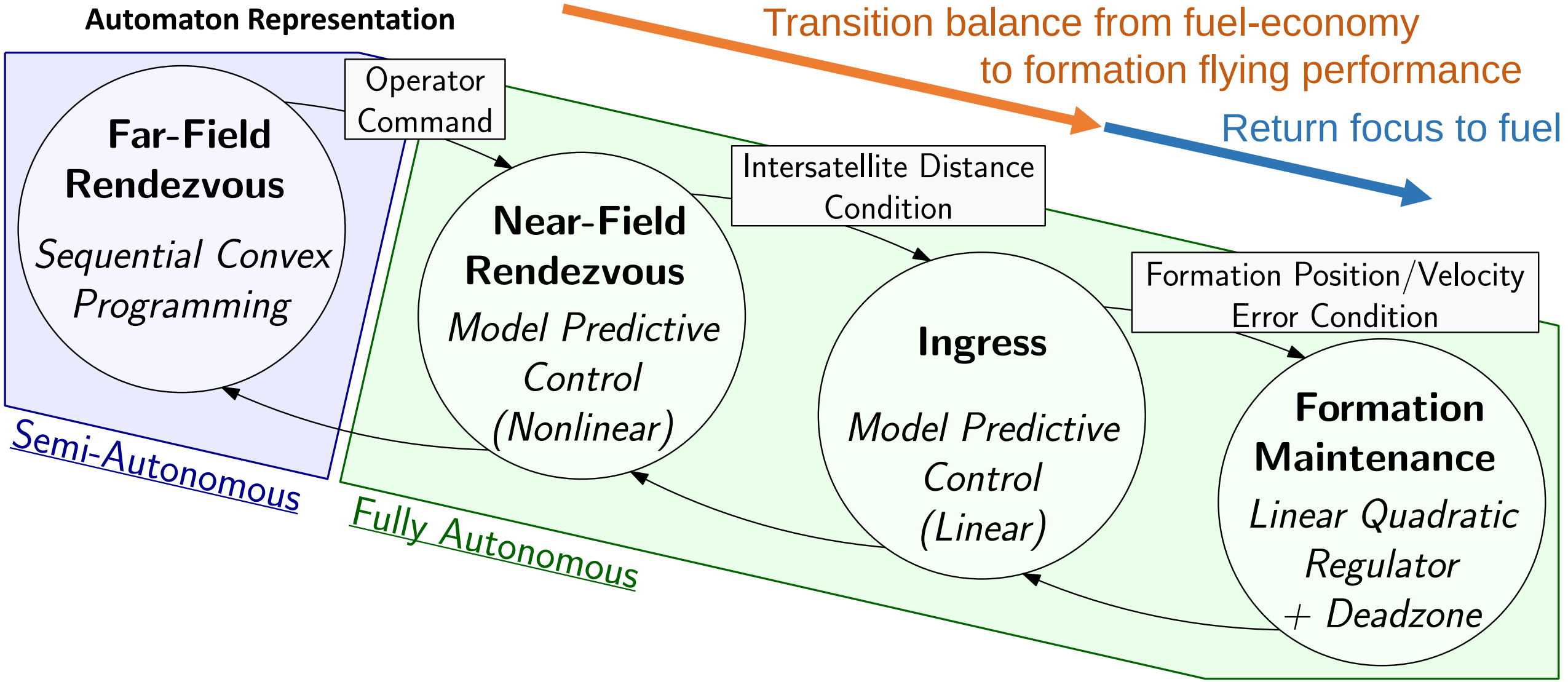
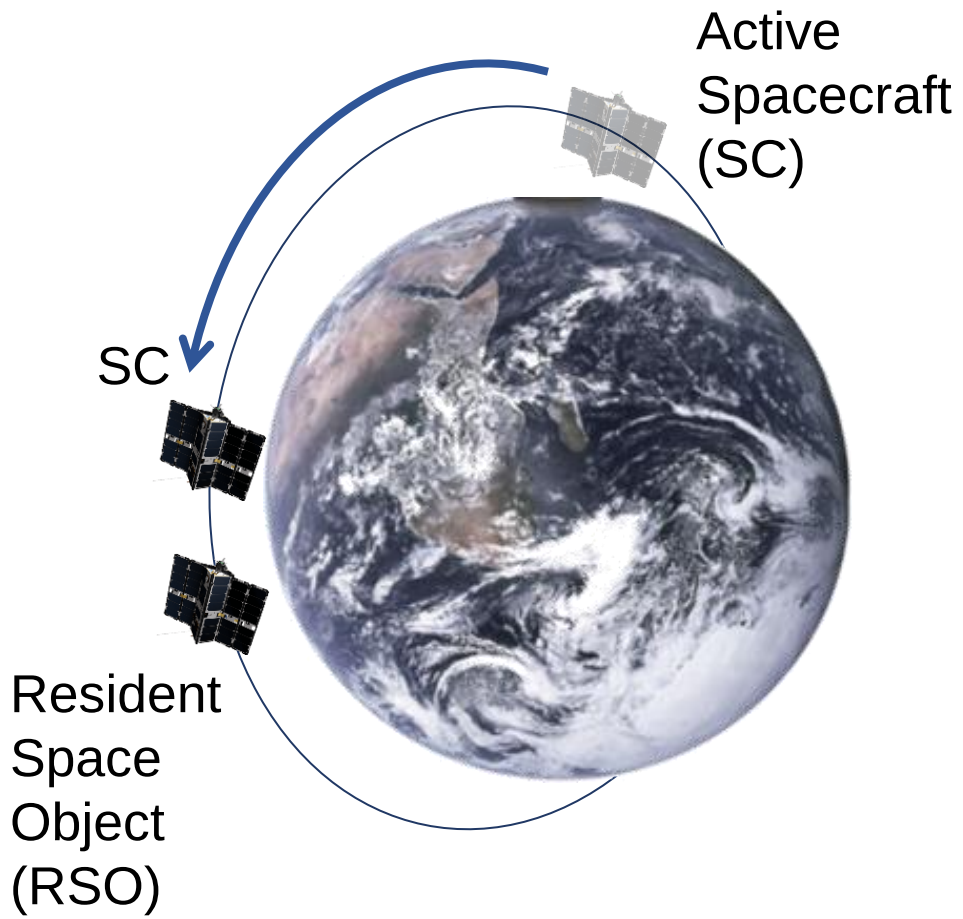


FAR-FIELD RENDEZVOUS

Close the Vast Majority of Intersatellite Distance



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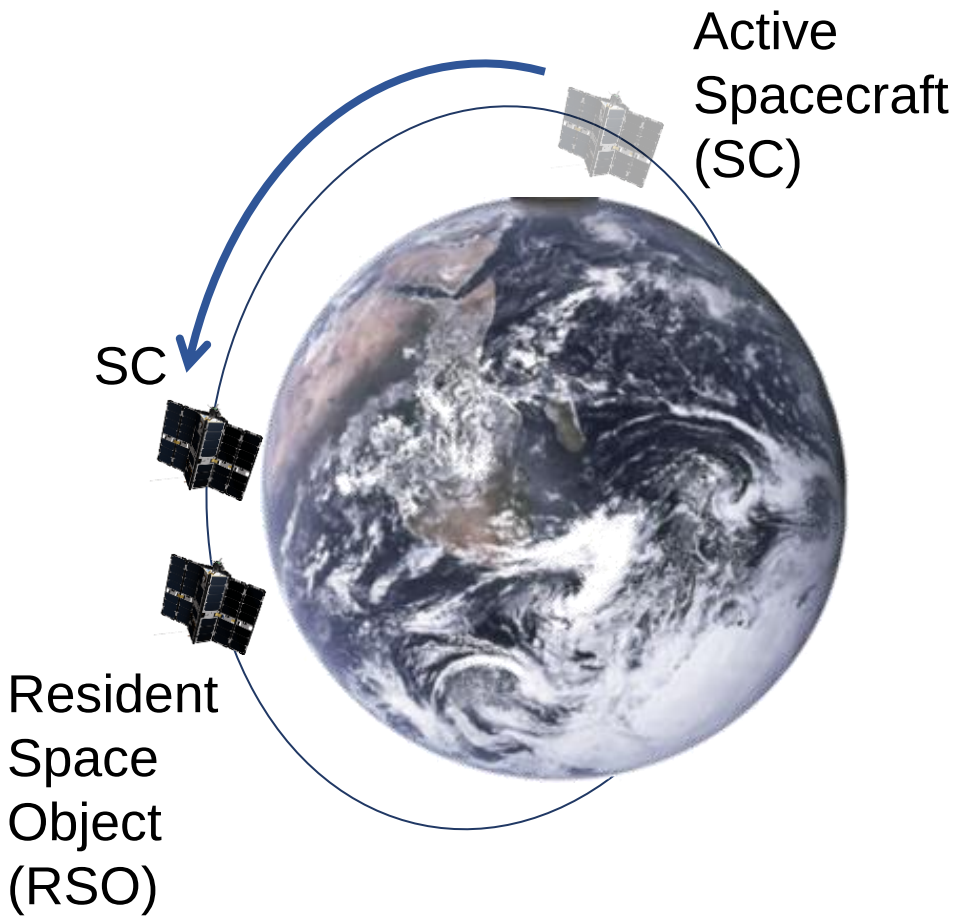
Optimization Structured for Fuel Economy

- Once terminal state error is “good enough”, exclusively focus on minimizing fuel use
- Cost function design yields more impulsive thrust trajectory than typical optimal controllers



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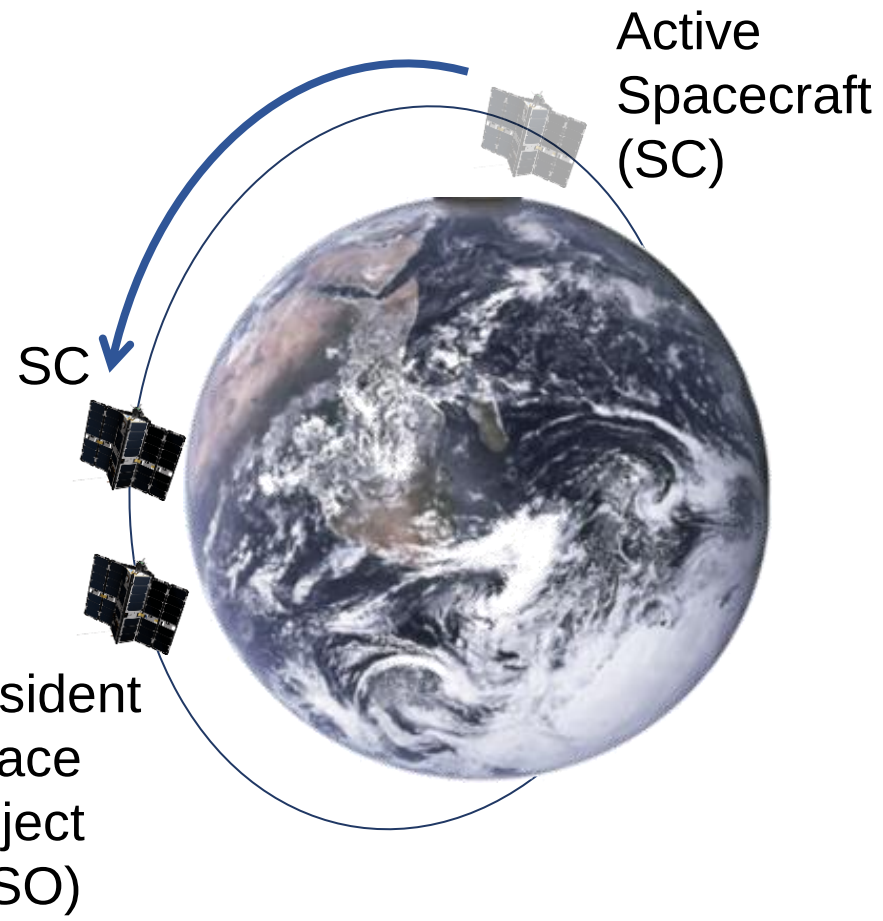
Optimal Feedforward Net Thrust Trajectory

Generated by Sequential Convex Programming

- Numerous optimizations with nonlinear models
- Optimization i informs optimization $i + 1$



NEAR-FIELD RENDEZVOUS

Compensate for Error Accumulation of Feedforward Guidance in Far-Field Rendezvous

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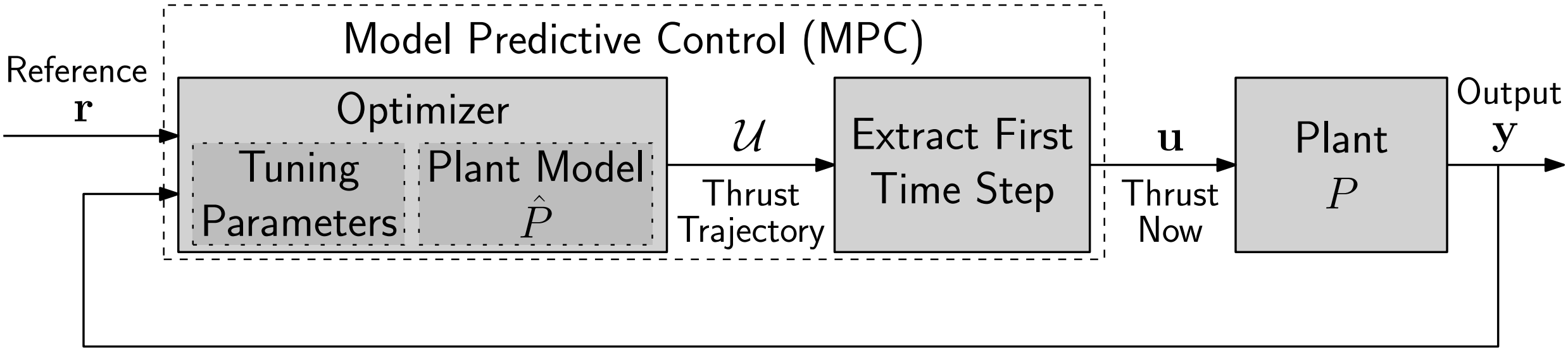
Model Predictive Control

Periodic reoptimization of thrust trajectory
+ Online measurement feedback
= Disturbance rejection



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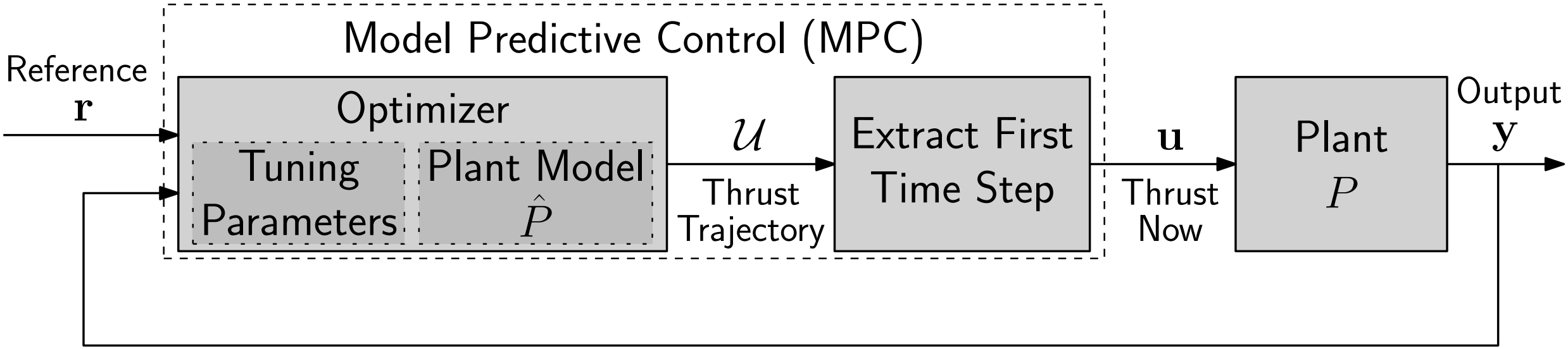
Full Autonomy & Onboard Optimization

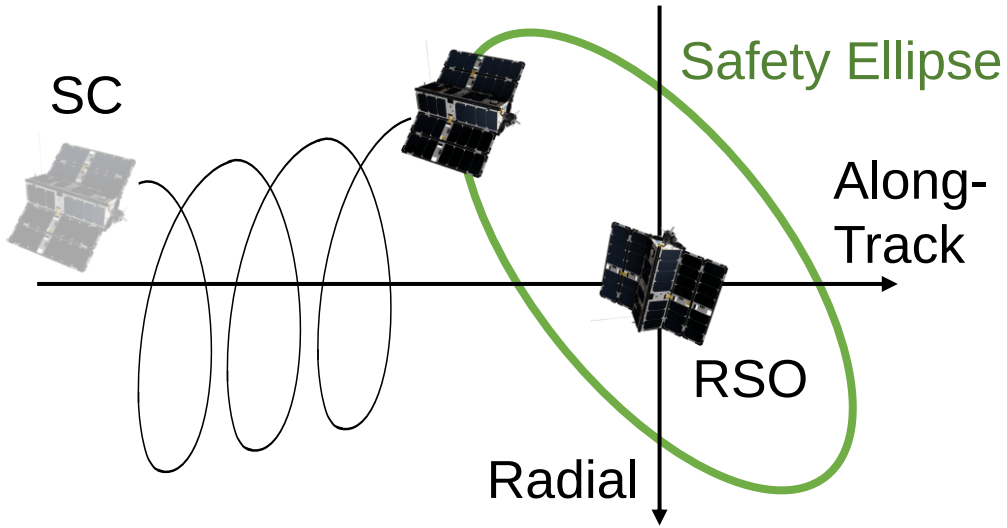
Enabled by switching to typical quadratic cost function

Feedback includes both SC & RSO states



INGRESS

Attain Desired Flying Formation



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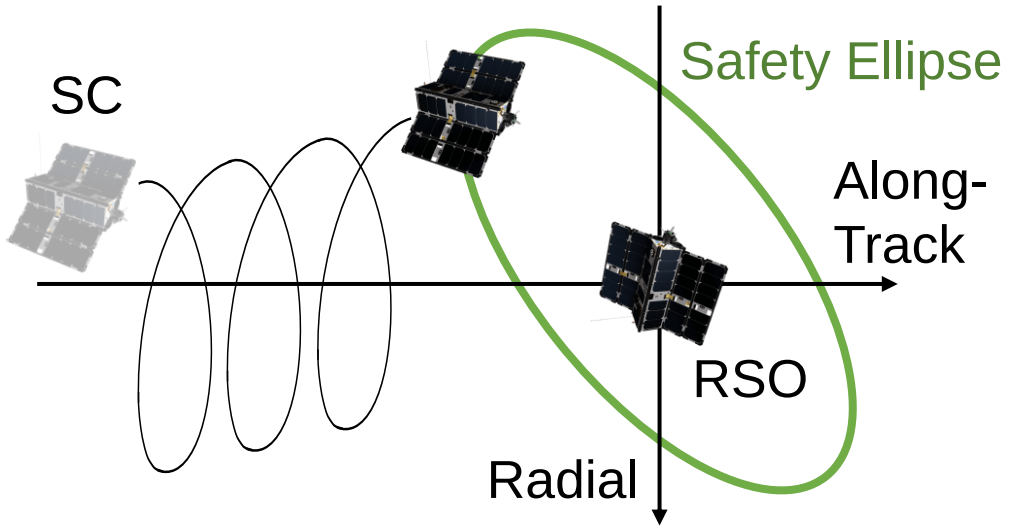
Attain Desired Flying Formation

“Safety Ellipse” Formations
⟹ Collision Avoidance & Fuel Economy

Safety Ellipse: unforced response of Clohessy-Wiltshire linearization of relative astrodynamics



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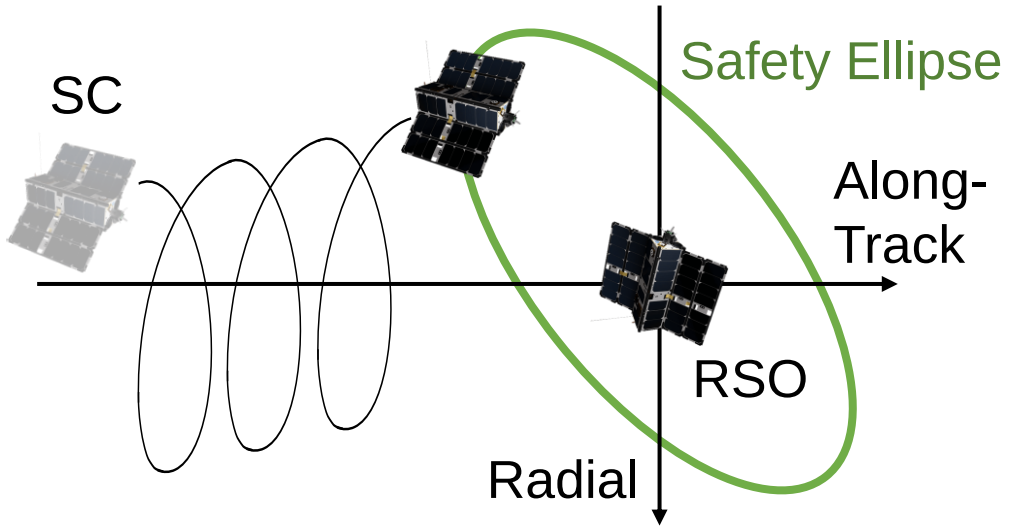

Passively Safe Ellipse Geometry:
SC position trajectory never crosses RSO along-track direction

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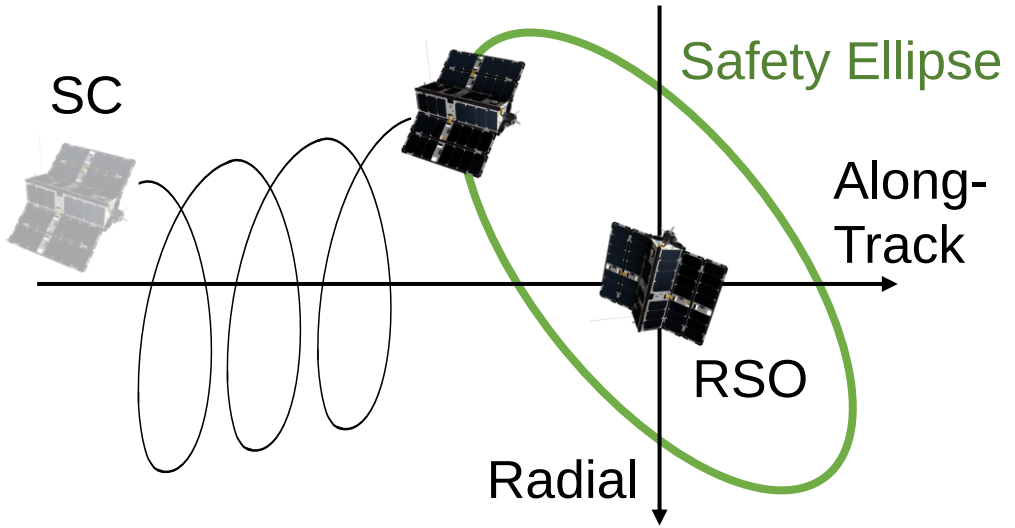

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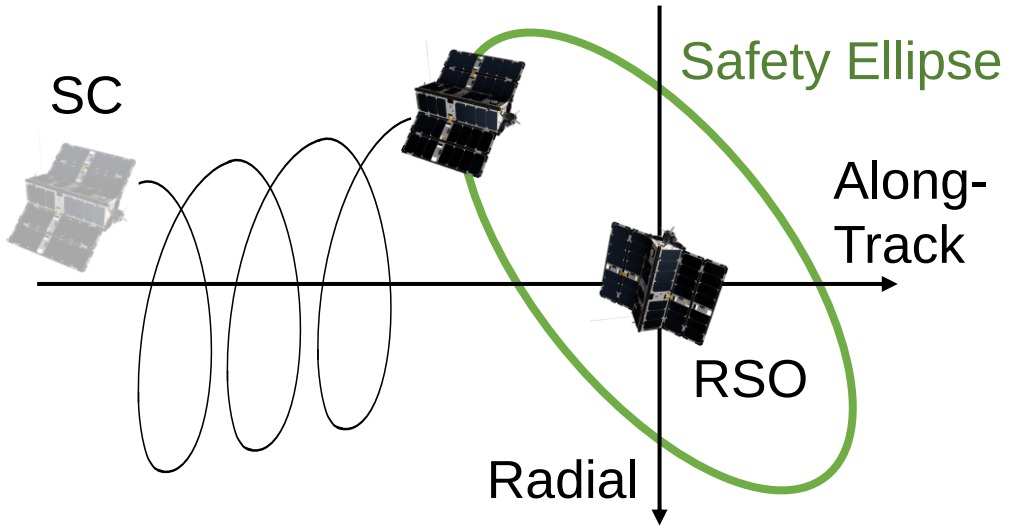
Enables switch from nonlinear to linear MPC



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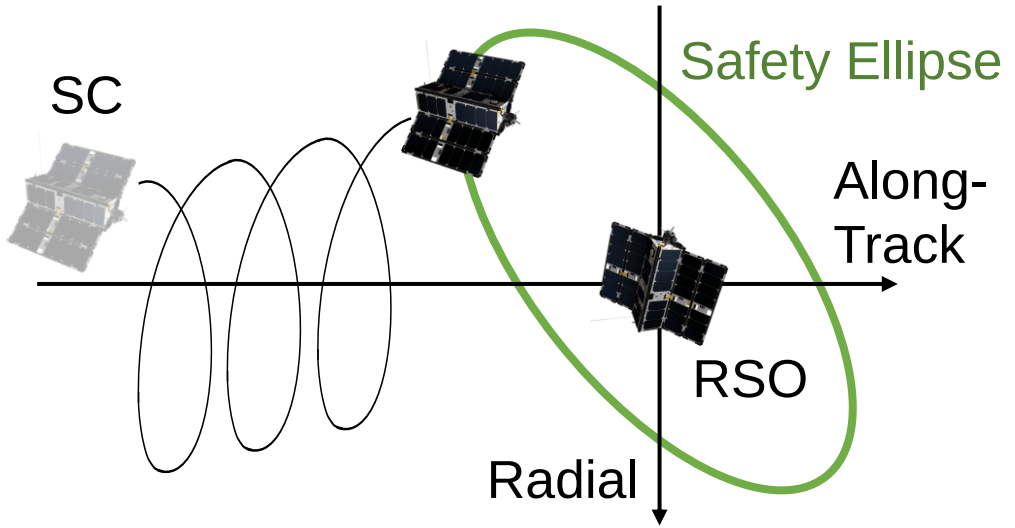

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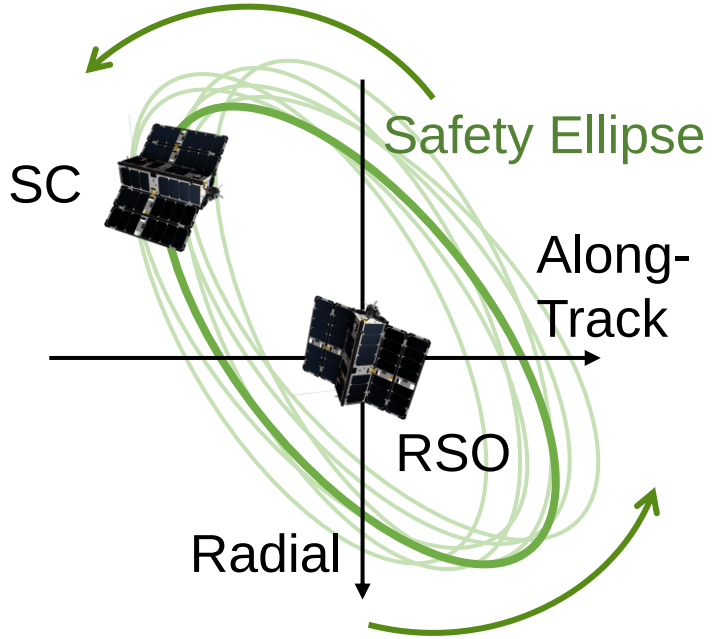
Ingress Requires More Accuracy than Other Stages

- MPC tuned for greater robustness & aggression
  - e.g. 75% shorter reoptimization period

FORMATION MAINTENANCE

Indefinite Compensation for Disturbances



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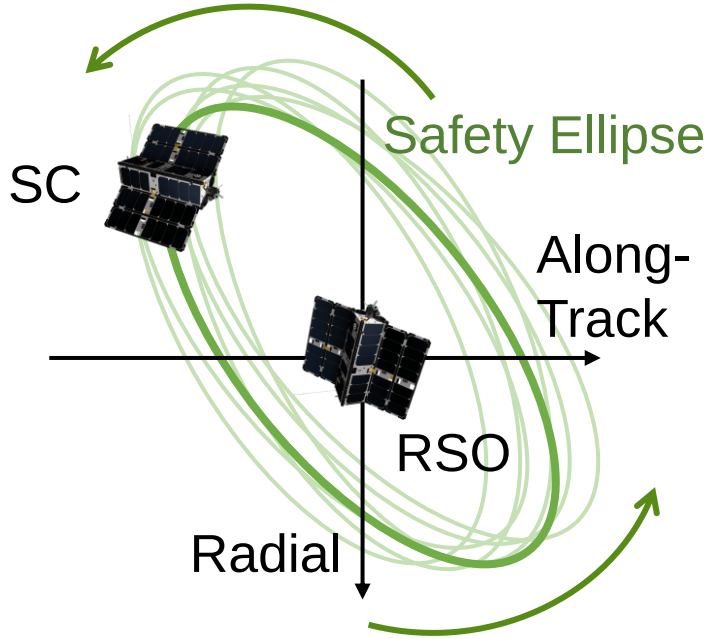
Disturbances Degrade Formation Over Time

Ingress error, linearization error, knowledge error, non-spherical gravitation, drag, etc.



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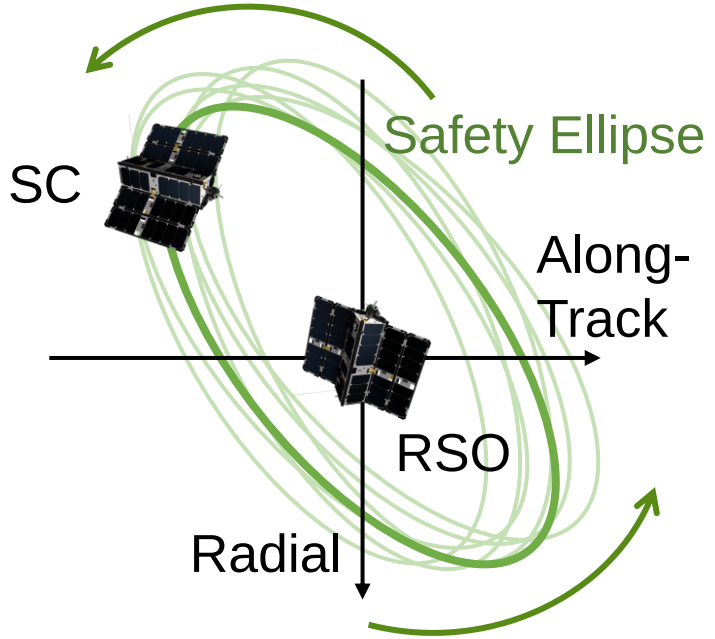
Reference Tracking is Relaxed to Reduce Fuel Use

- Formation is easier to hold than enter
- Deadzone: error below threshold is treated as zero



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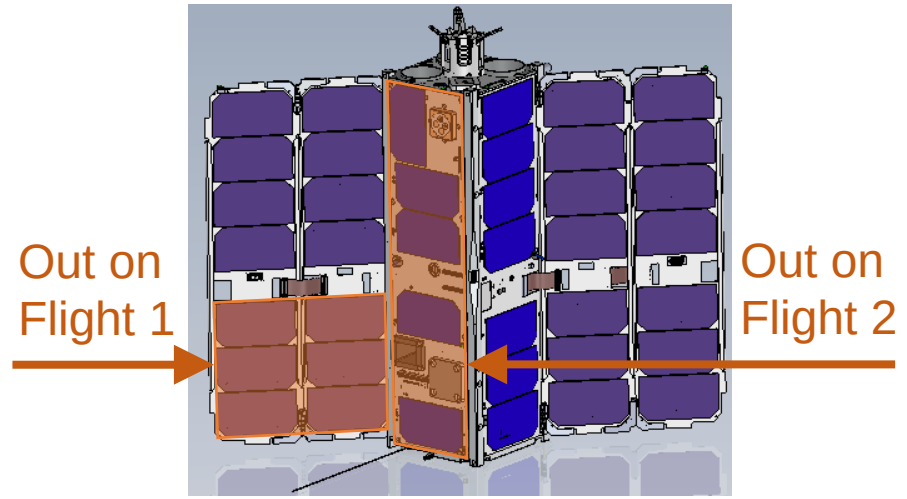
ON-ORBIT HARDWARE CHALLENGES

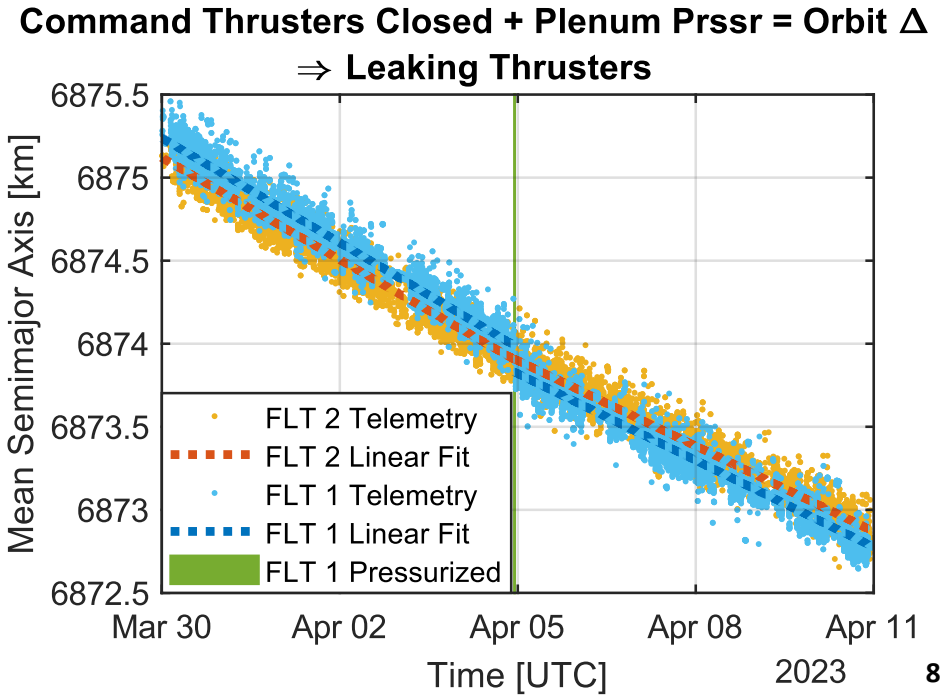
Reduced Solar Power Generation

- Both vehicles lost 5-10 W of generation capacity
- Likely due to an inaccurate integrated circuit spec
- Risk known before launch; redesigned MPPT rolled out to other vehicles, but did not fit in 3U CPOD bus



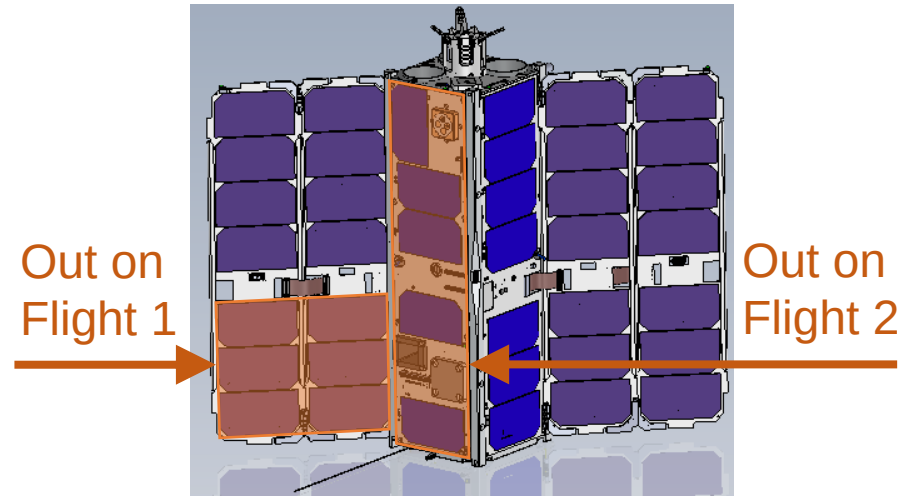
Disturbances from Cold Gas Prop System

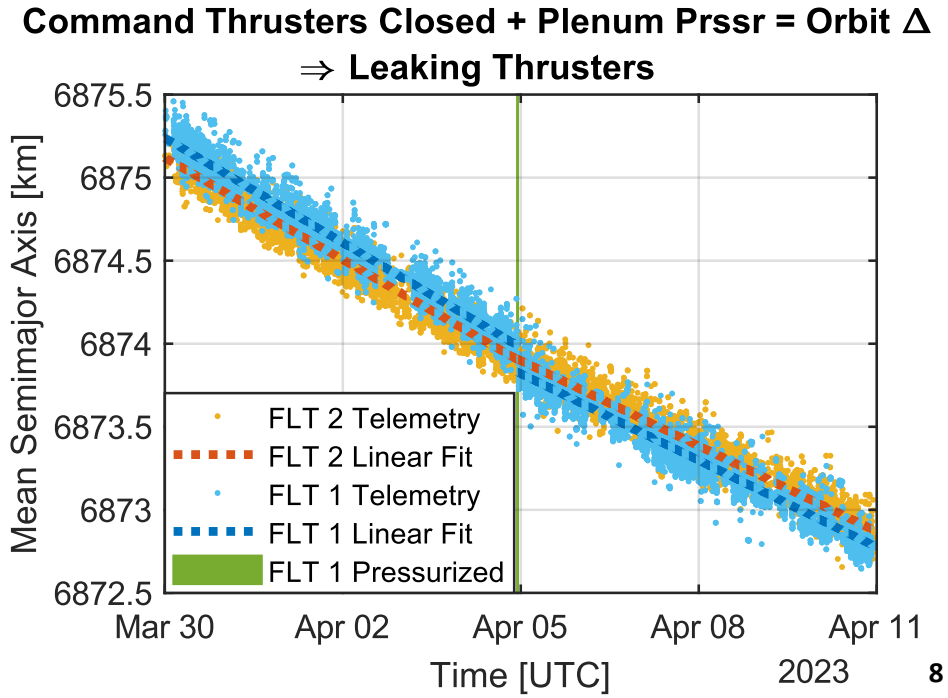
- Rebuilds by system vendor reduced total Δv
- 2 thrusters stuck open on one vehicle
- Plenum pressure varied widely (up to 75% error)
  ⟹ Thrust force likely varied widely



ON-ORBIT HARDWARE CHALLENGES

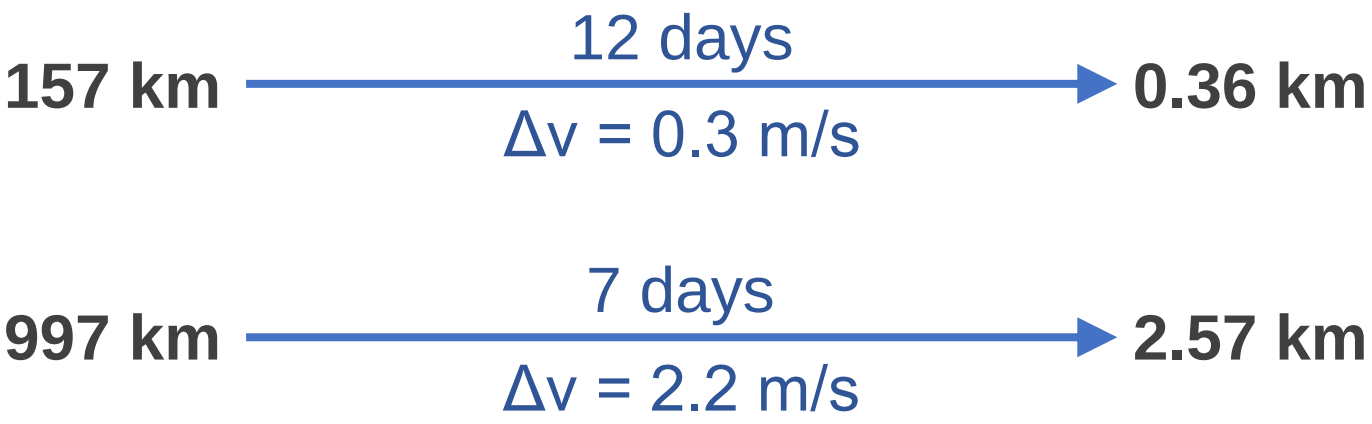
Challenges from external hardware limited the mission and stress-tested RPO capabilities





ON-ORBIT RPO RESULTS

Two major semi-autonomous experiments were performed



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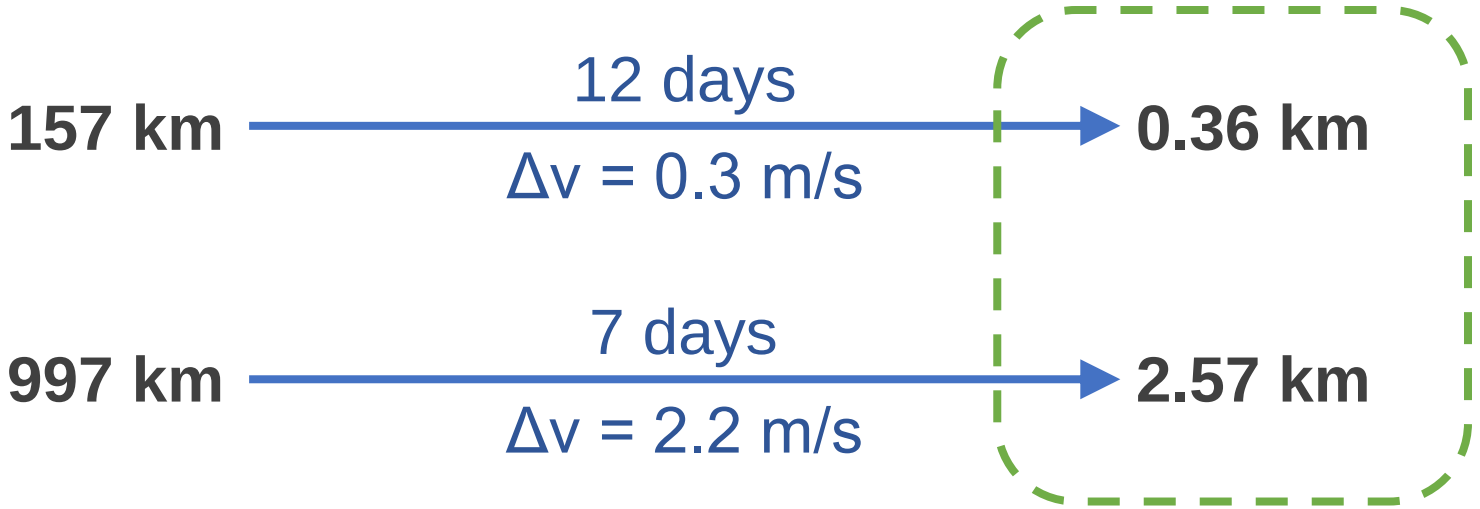
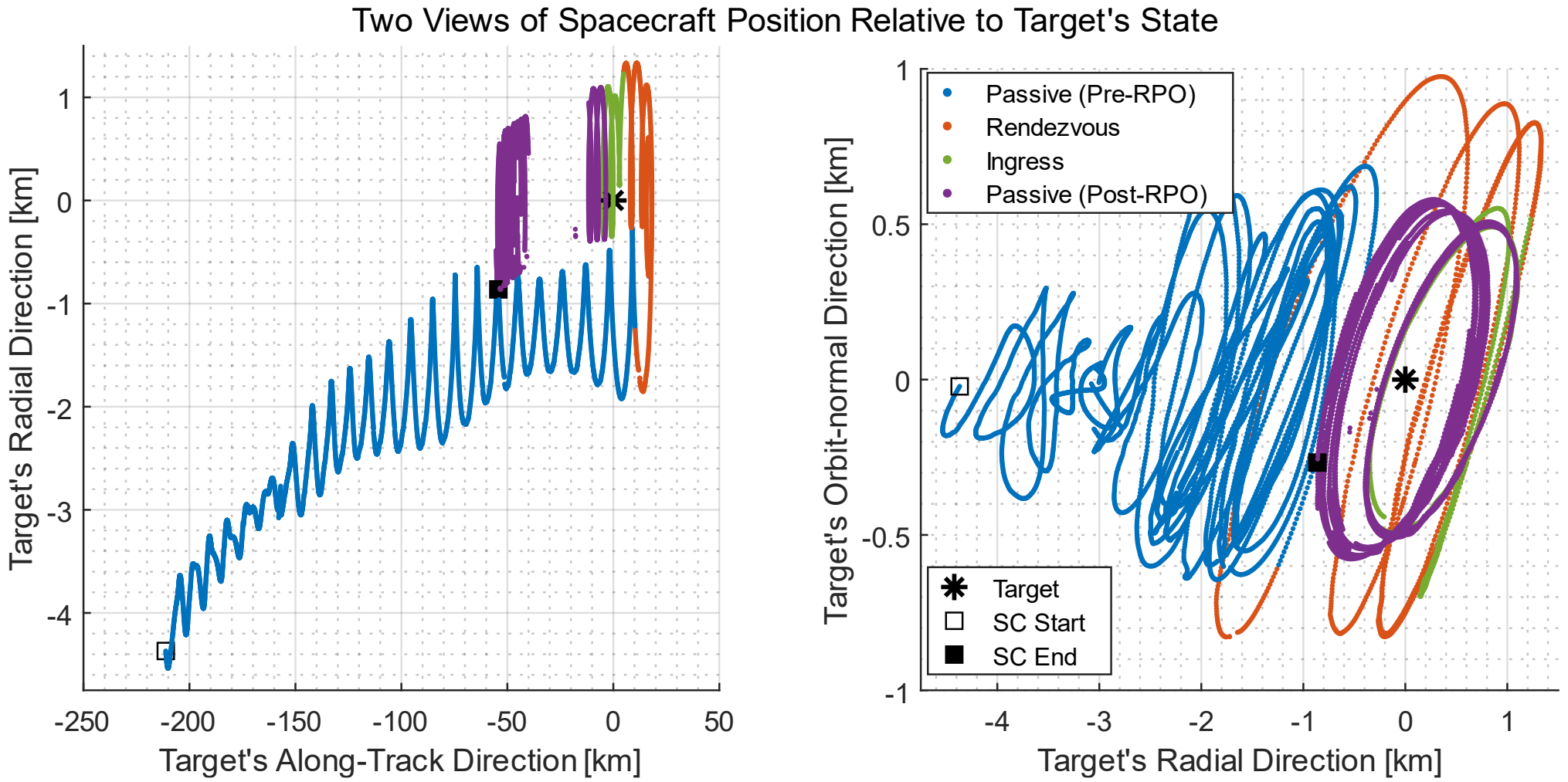


Substantially better than the closure desired to switch to full autonomy (5-50 km)

ON-ORBIT RPO RESULTS

Fully Autonomous Experiment Telemetry (All Thrusters Closeable)

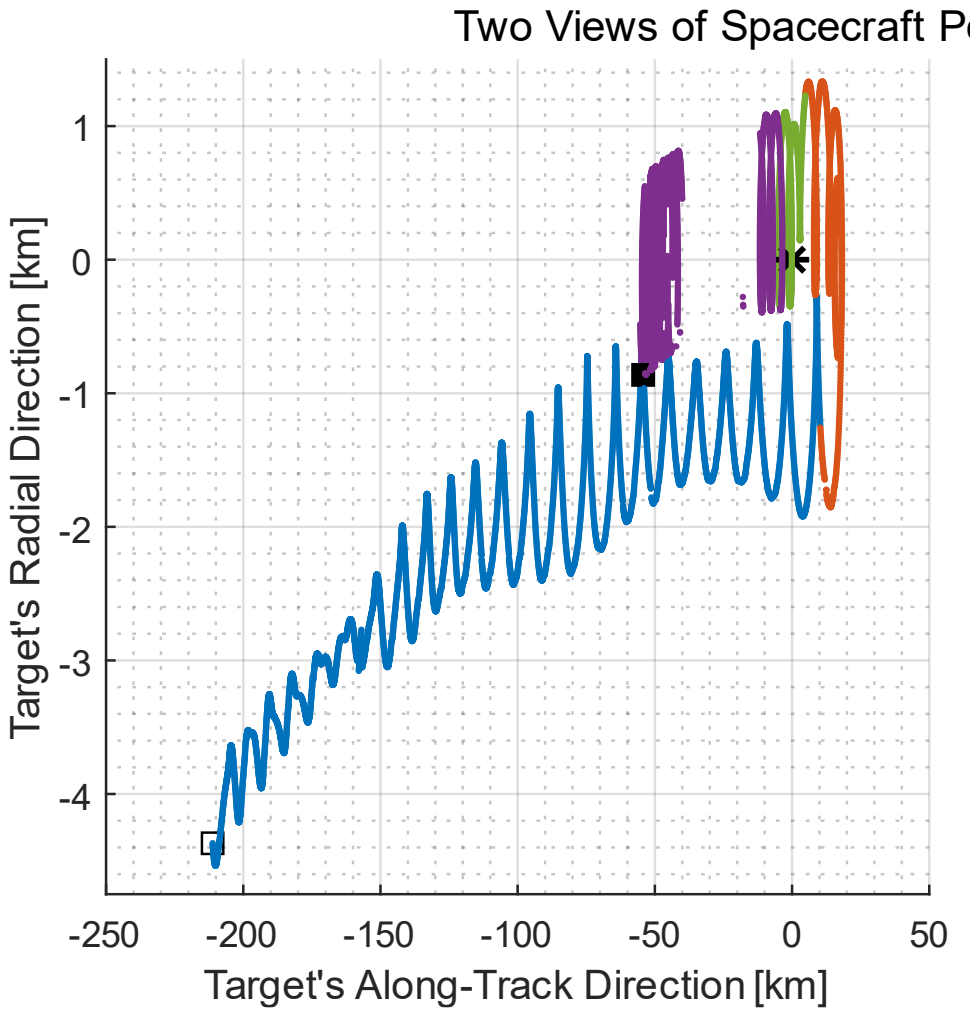


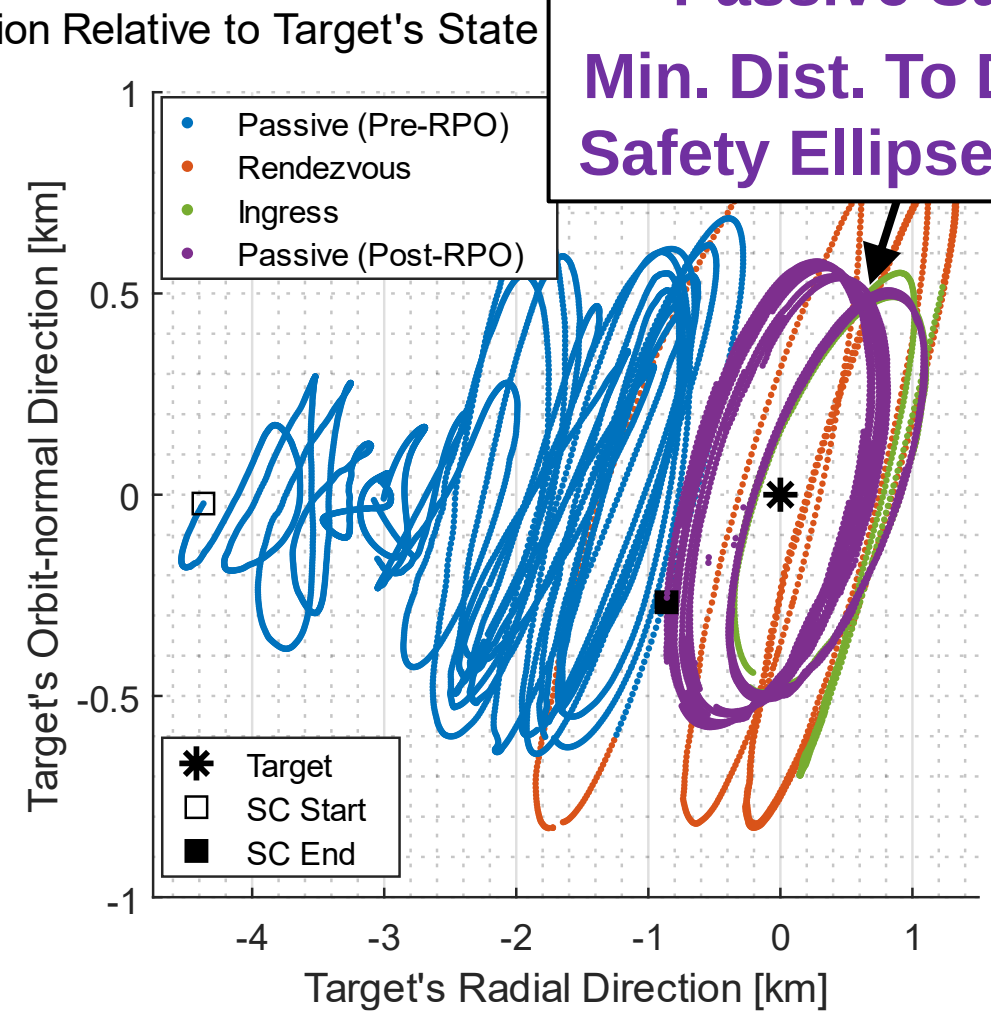
ON-ORBIT RPO RESULTS

Fully Autonomous Experiment Telemetry (All Thrusters Closeable)

Passive Safety

Min. Dist. To Desired Safety Ellipse: 473 m





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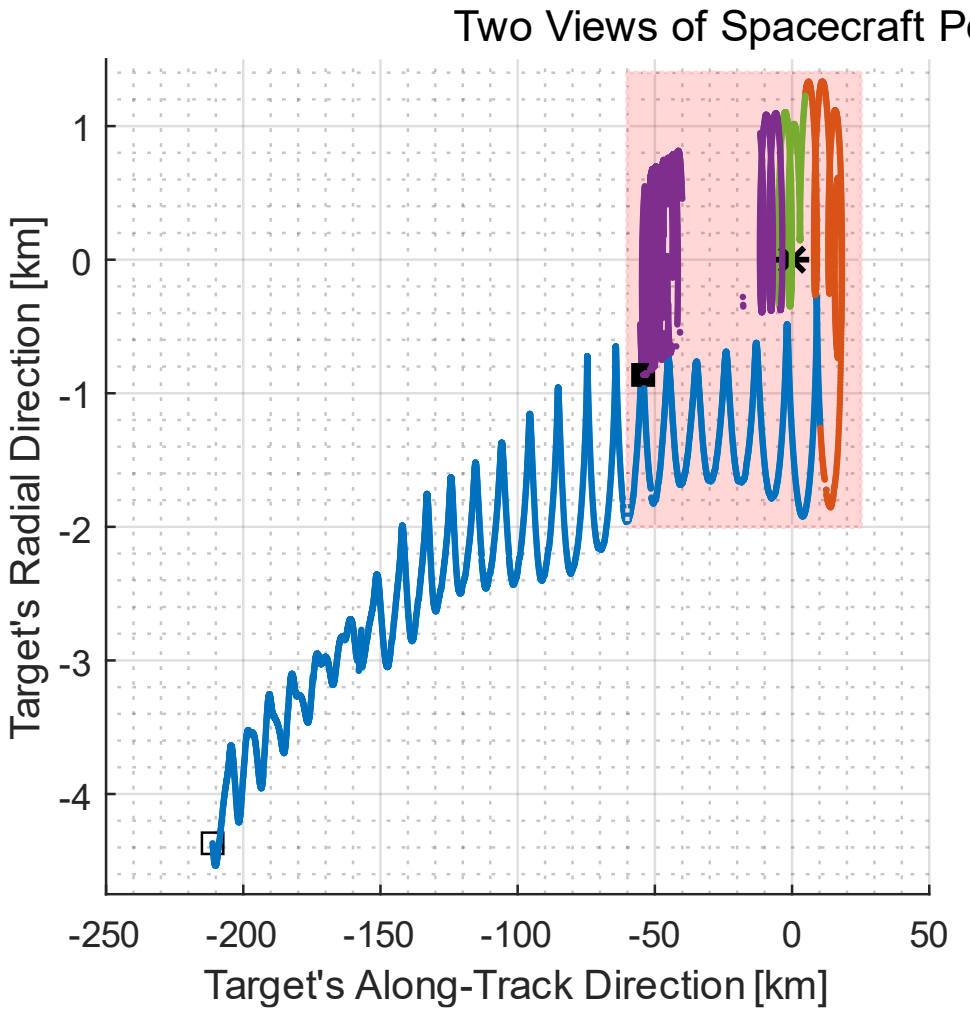

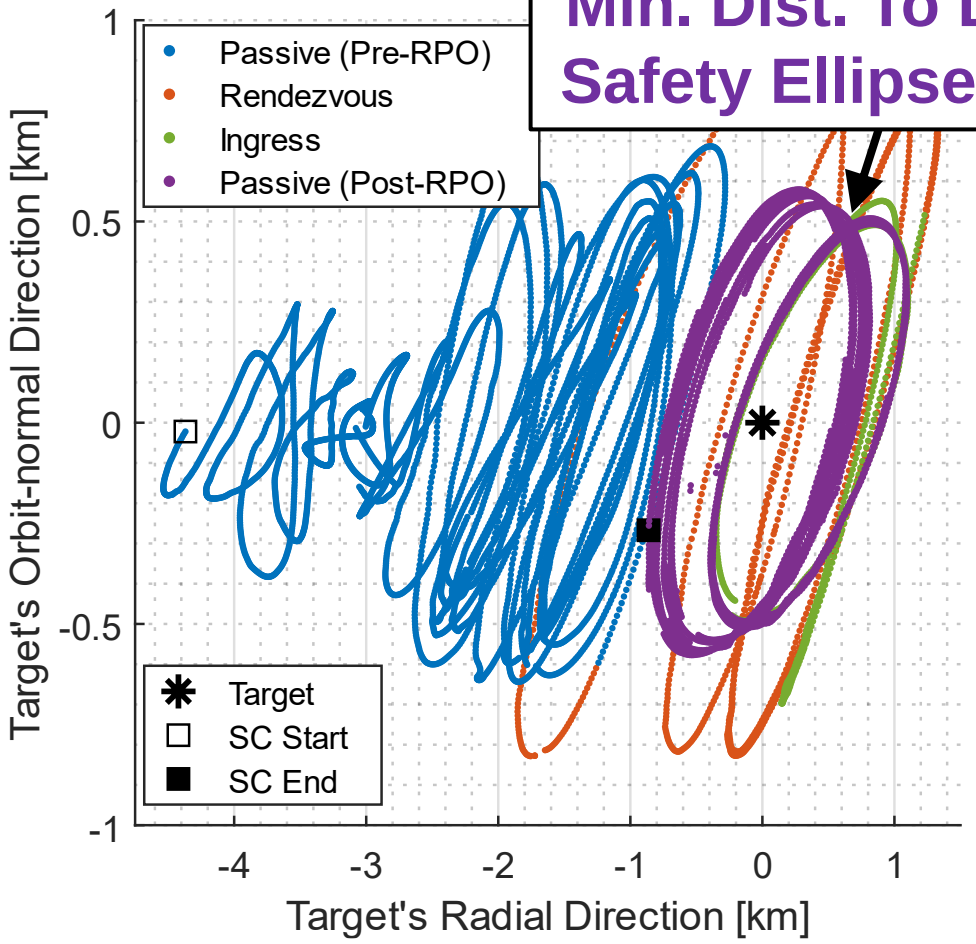

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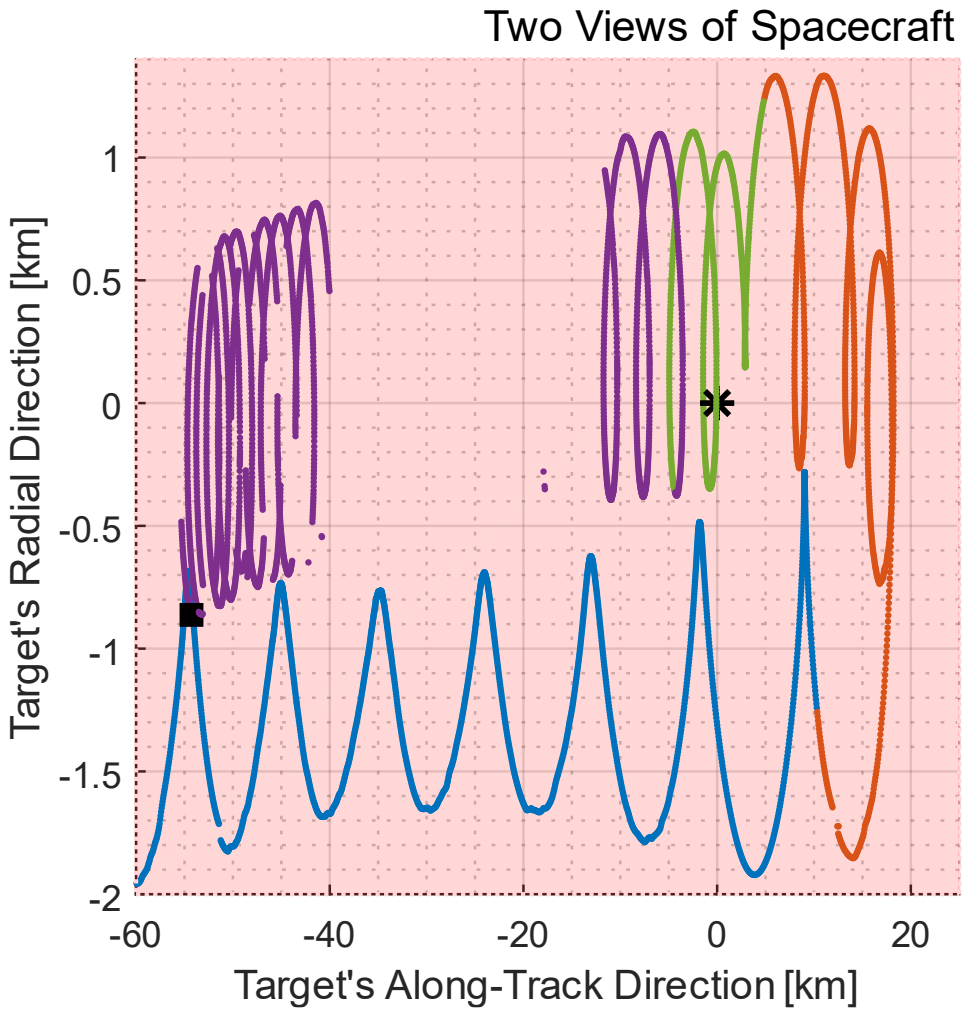

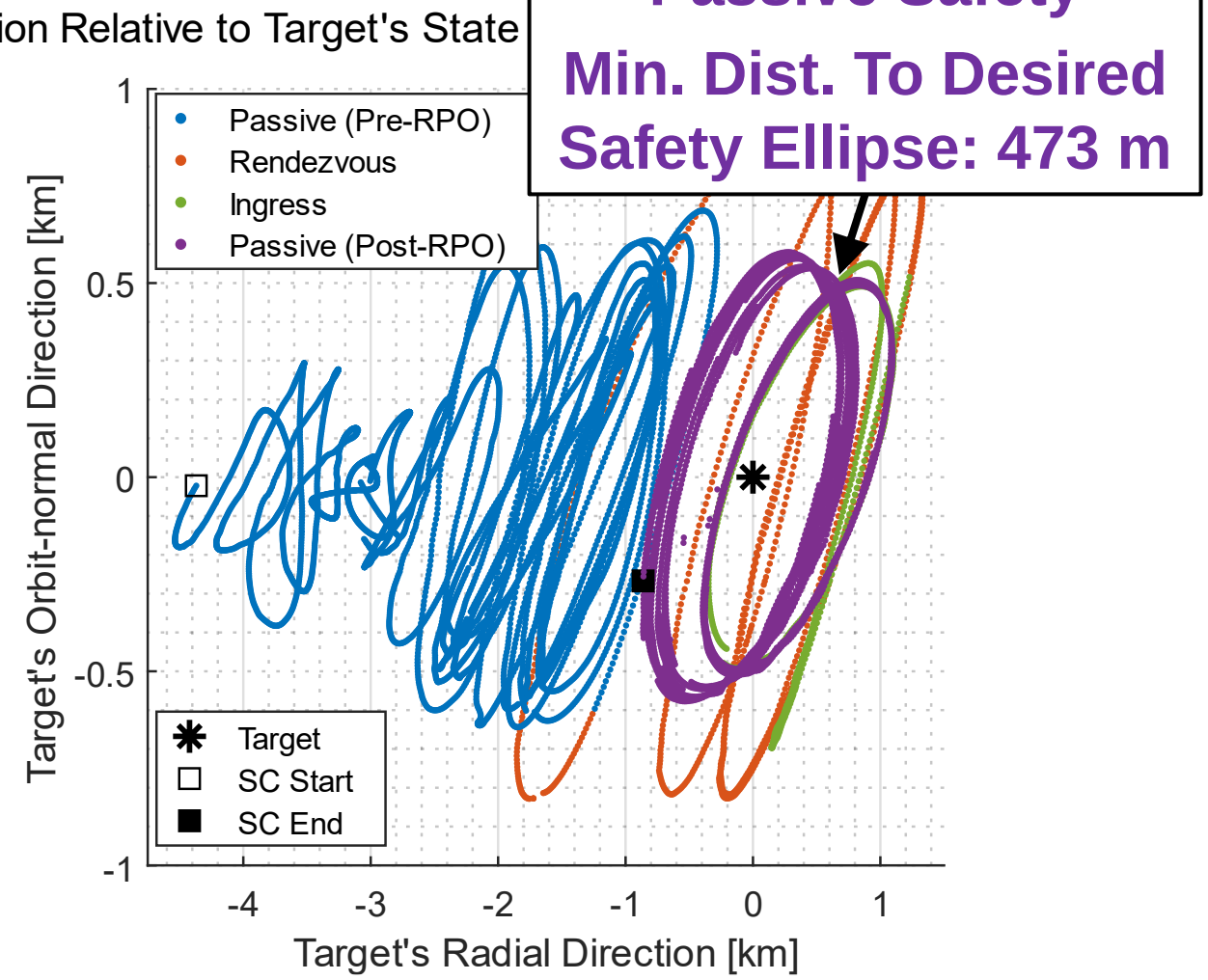

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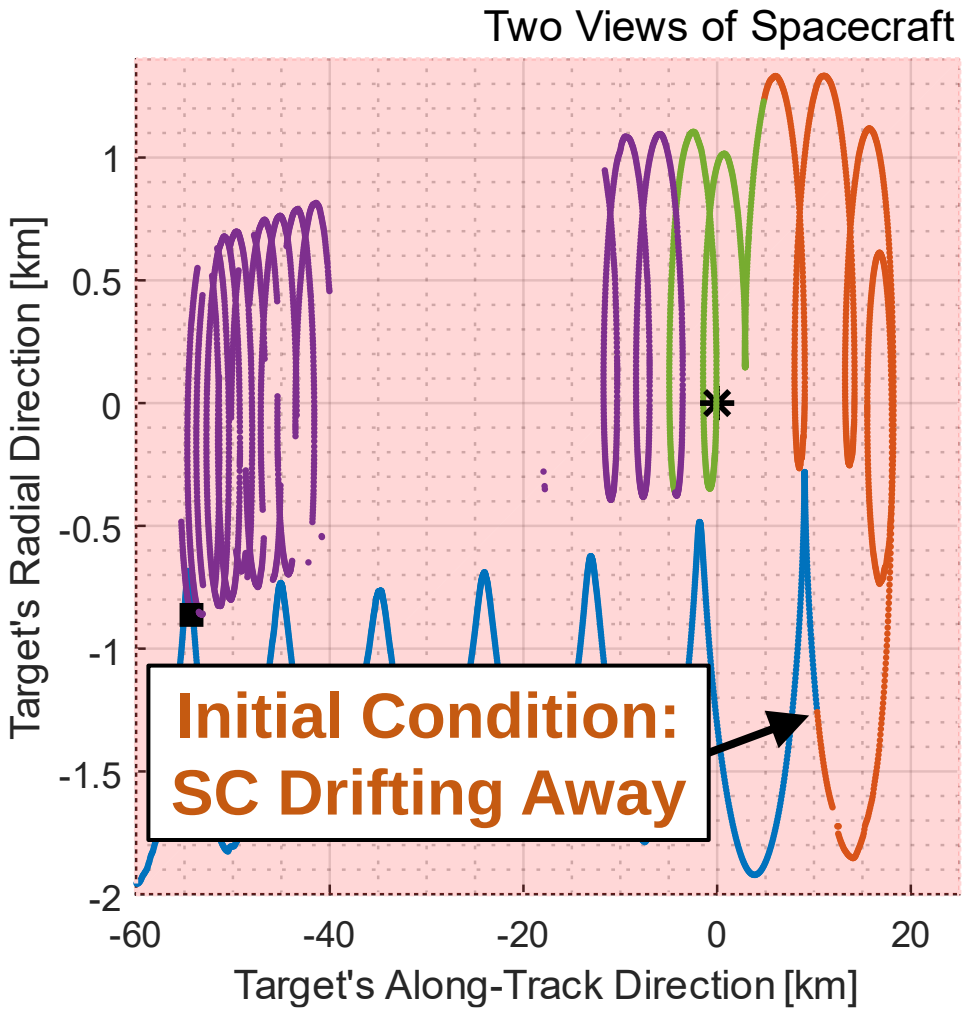

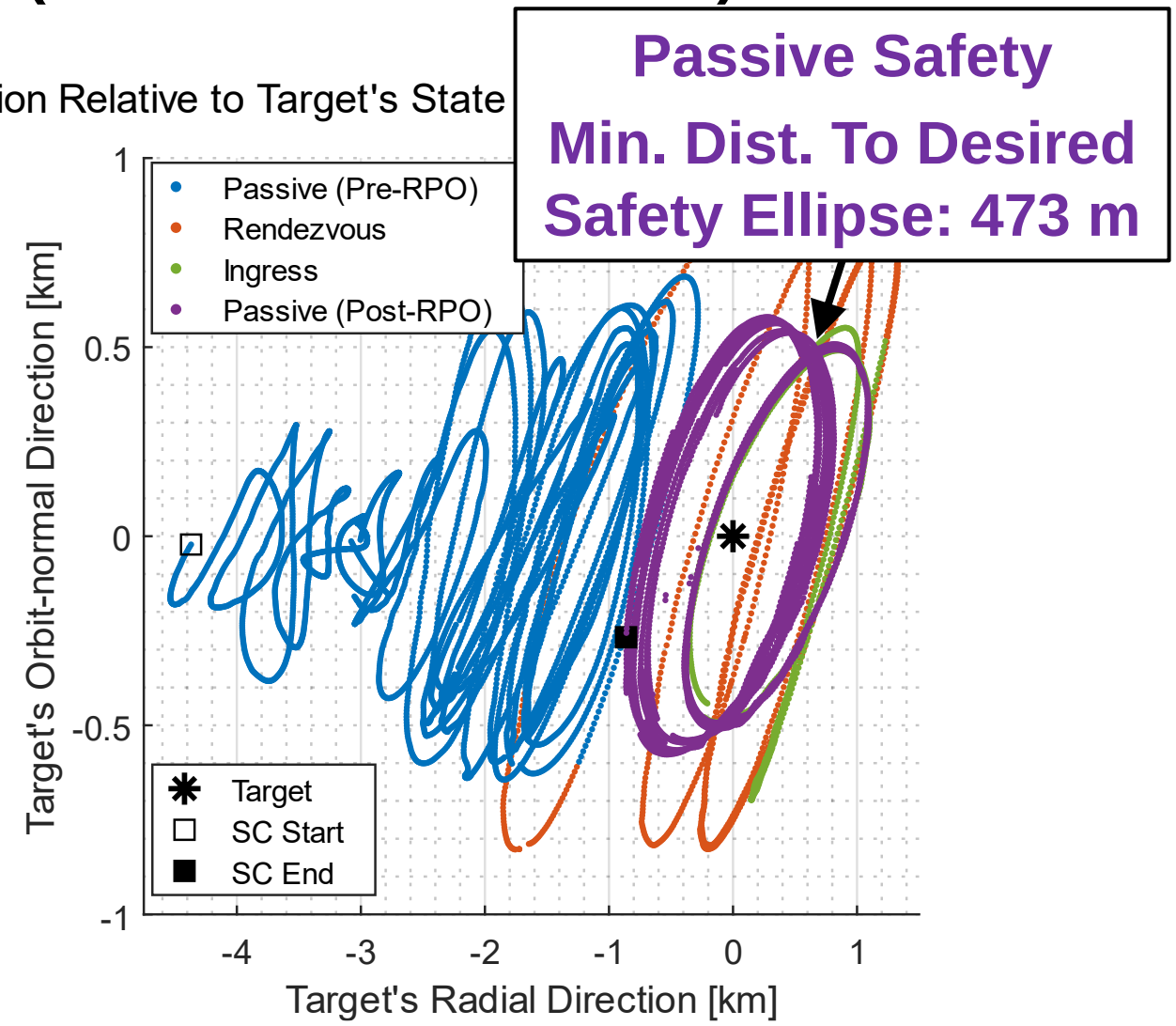

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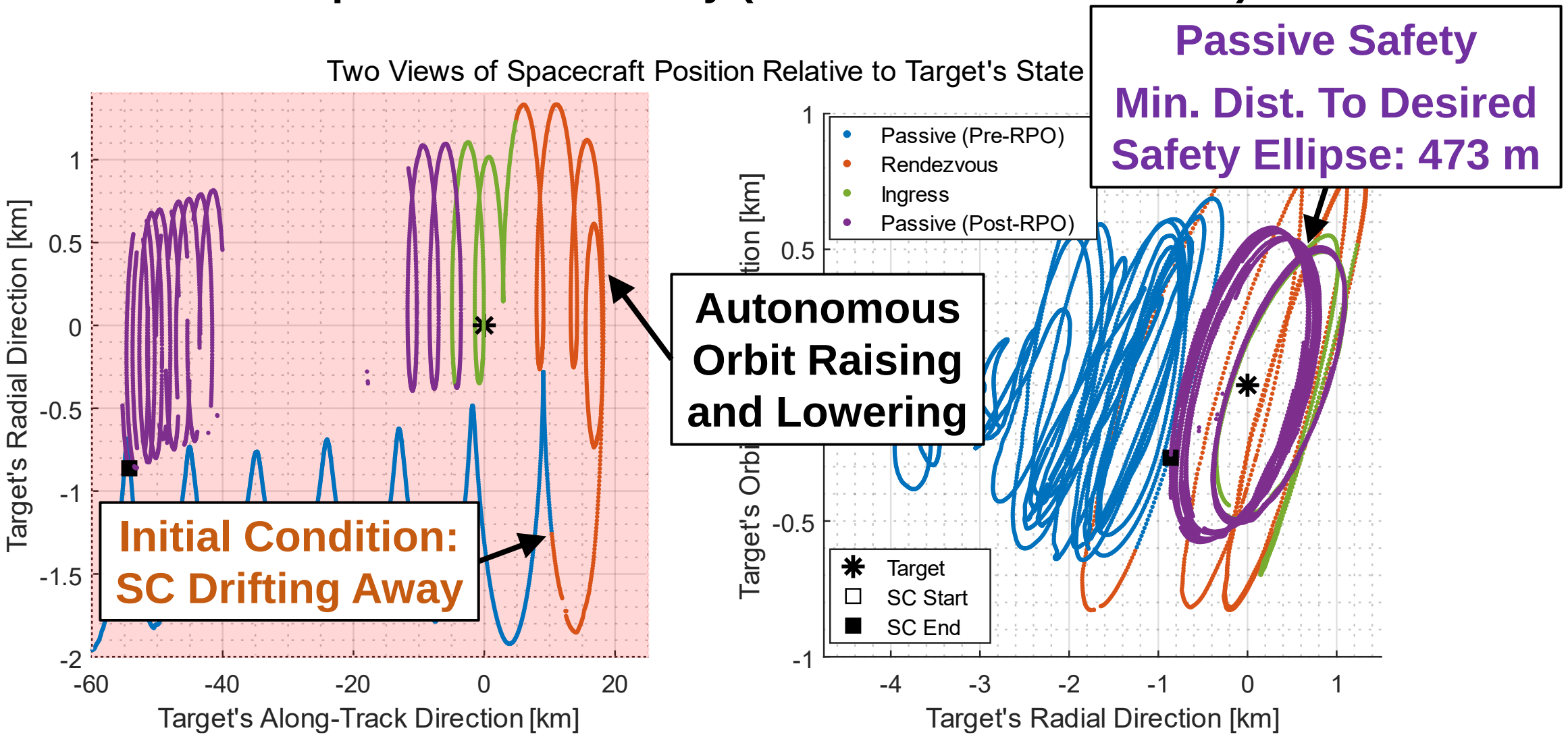

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Fully Autonomous Experiment Telemetry (All Thrusters Closeable)

Termination due to Solar Cell Outage

Initial Condition: SC Drifting Away

Autonomous Orbit Raising and Lowering

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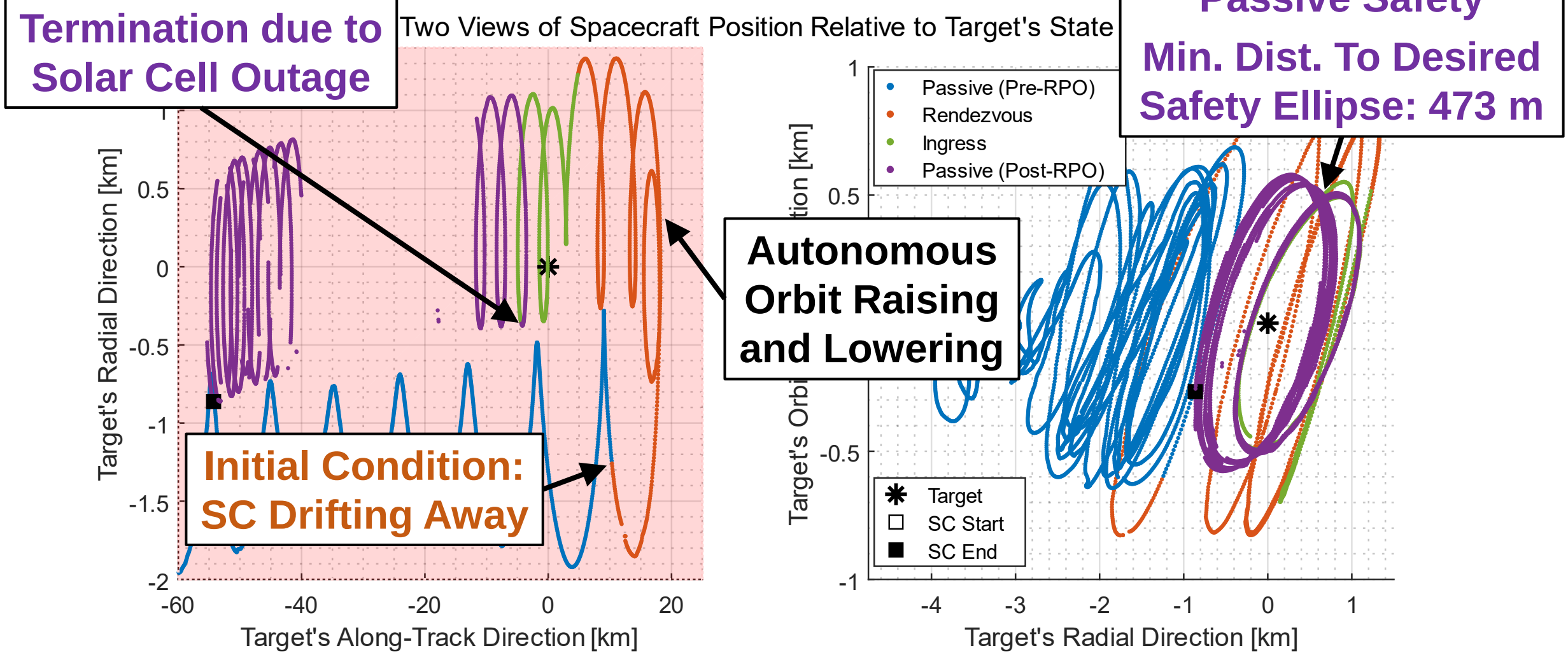

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Termination due to Solar Cell Outage

Countermeasure: Constrain Attitude to Maximize Power Gen

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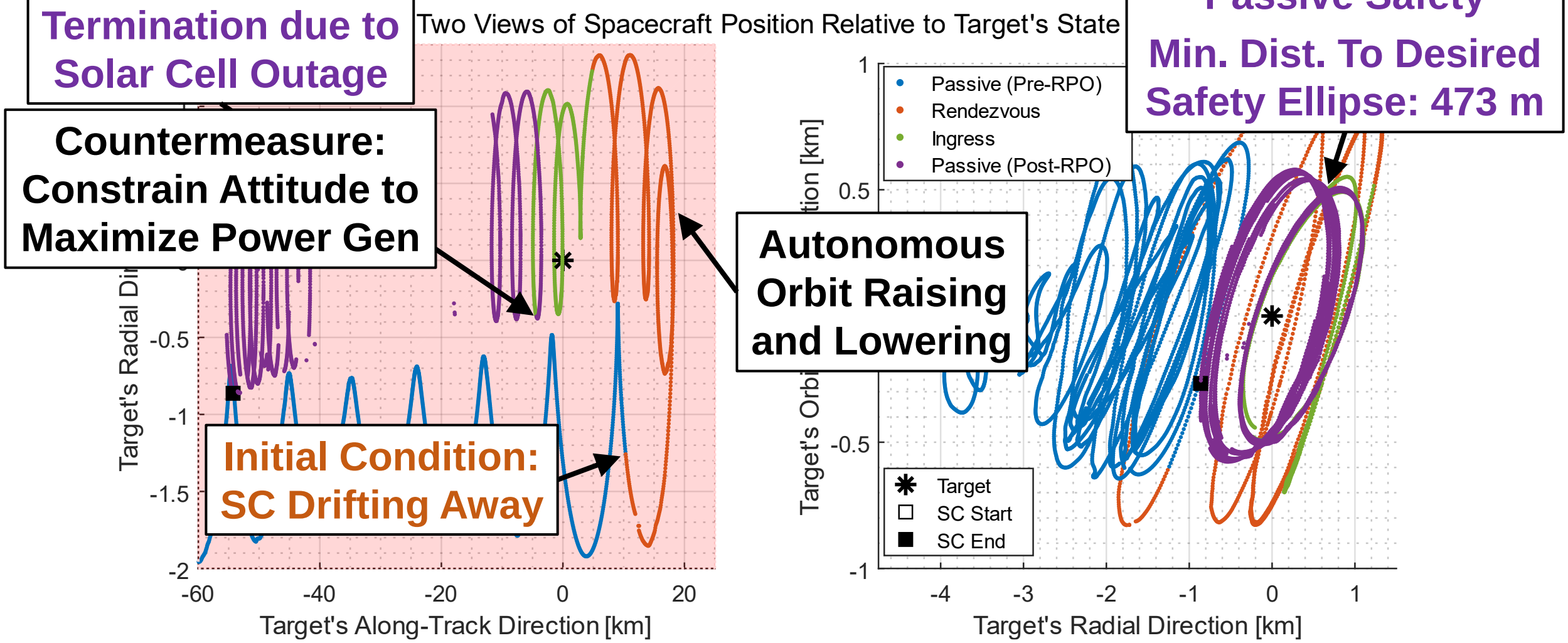

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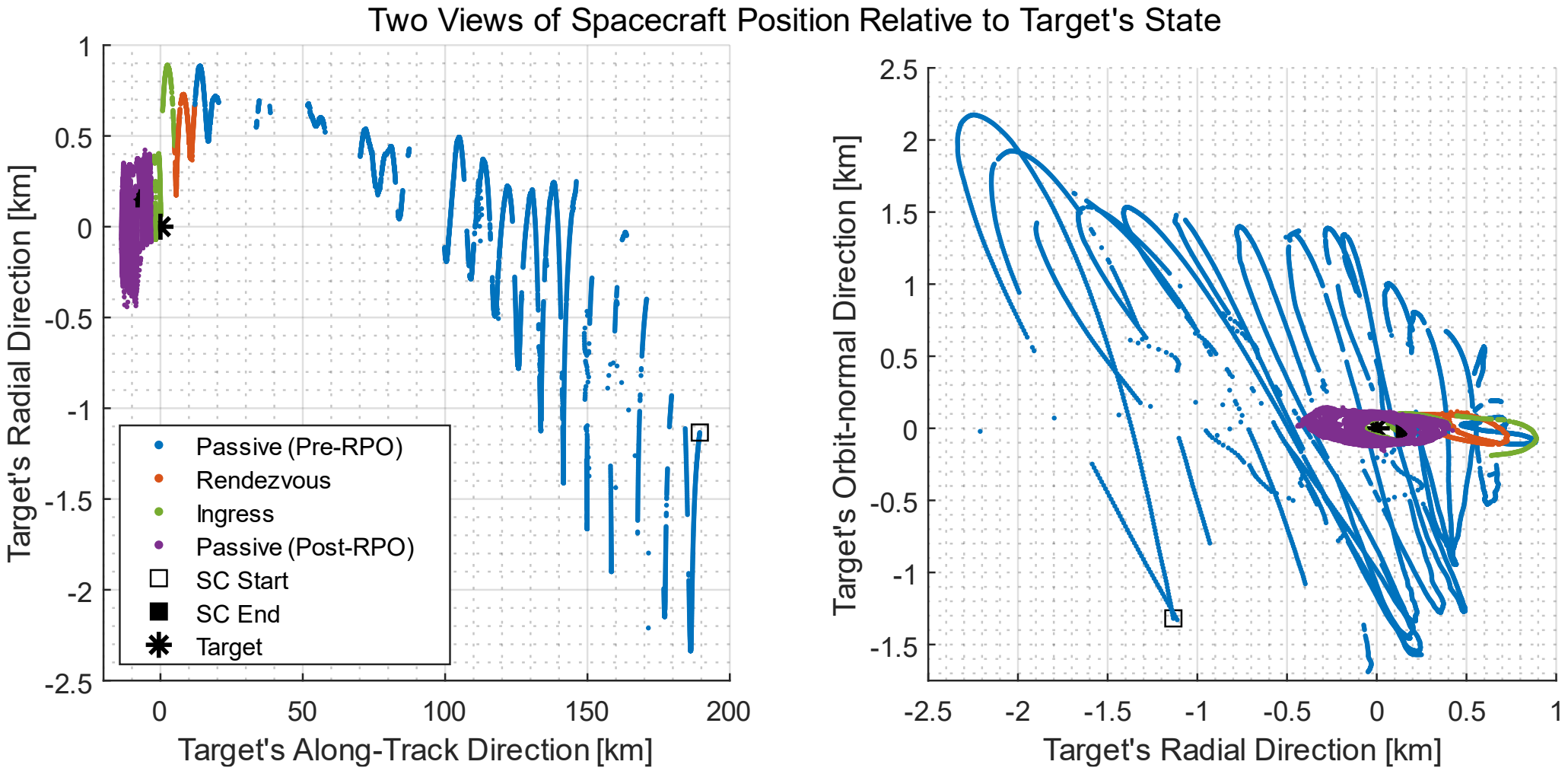

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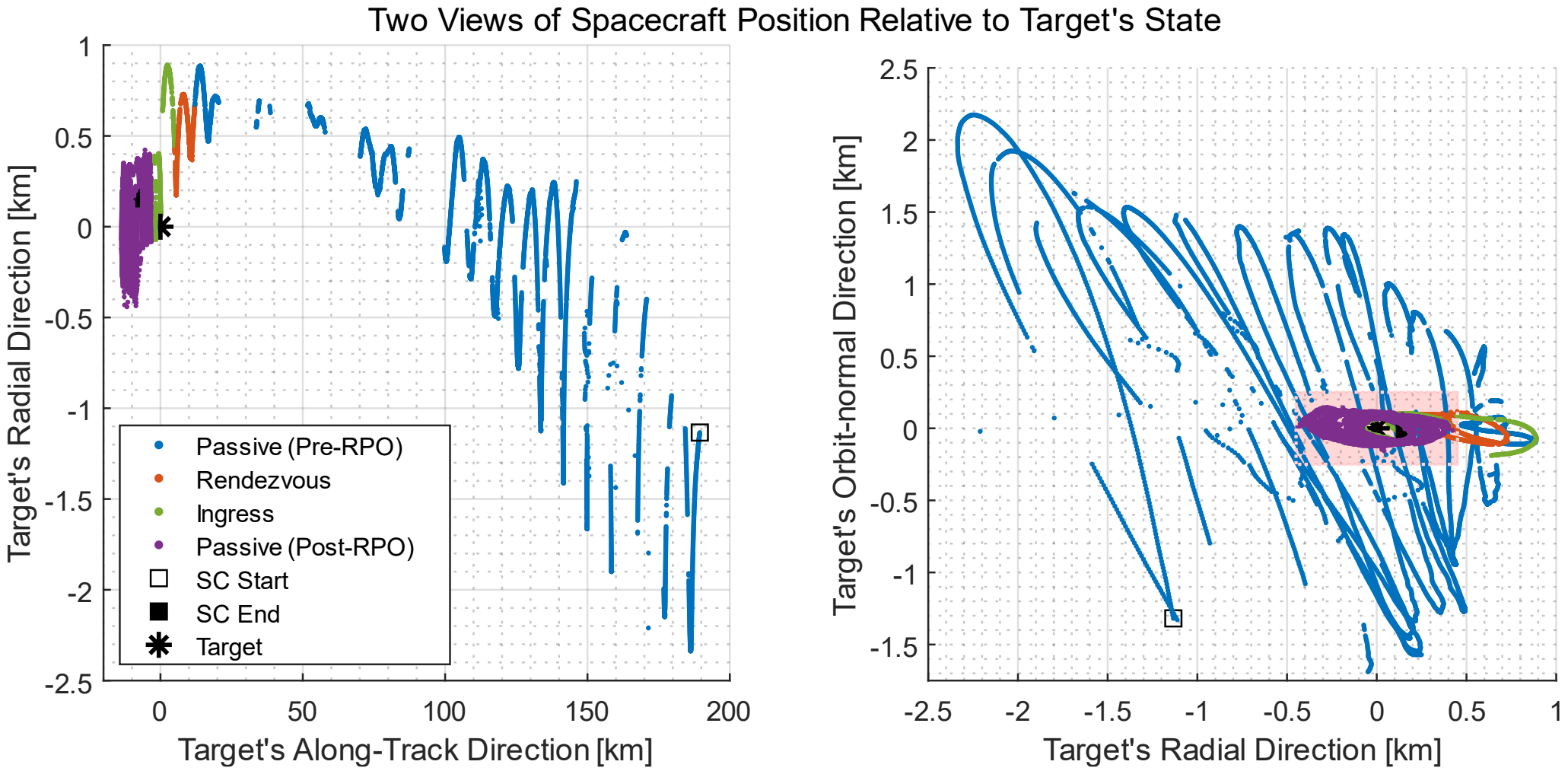

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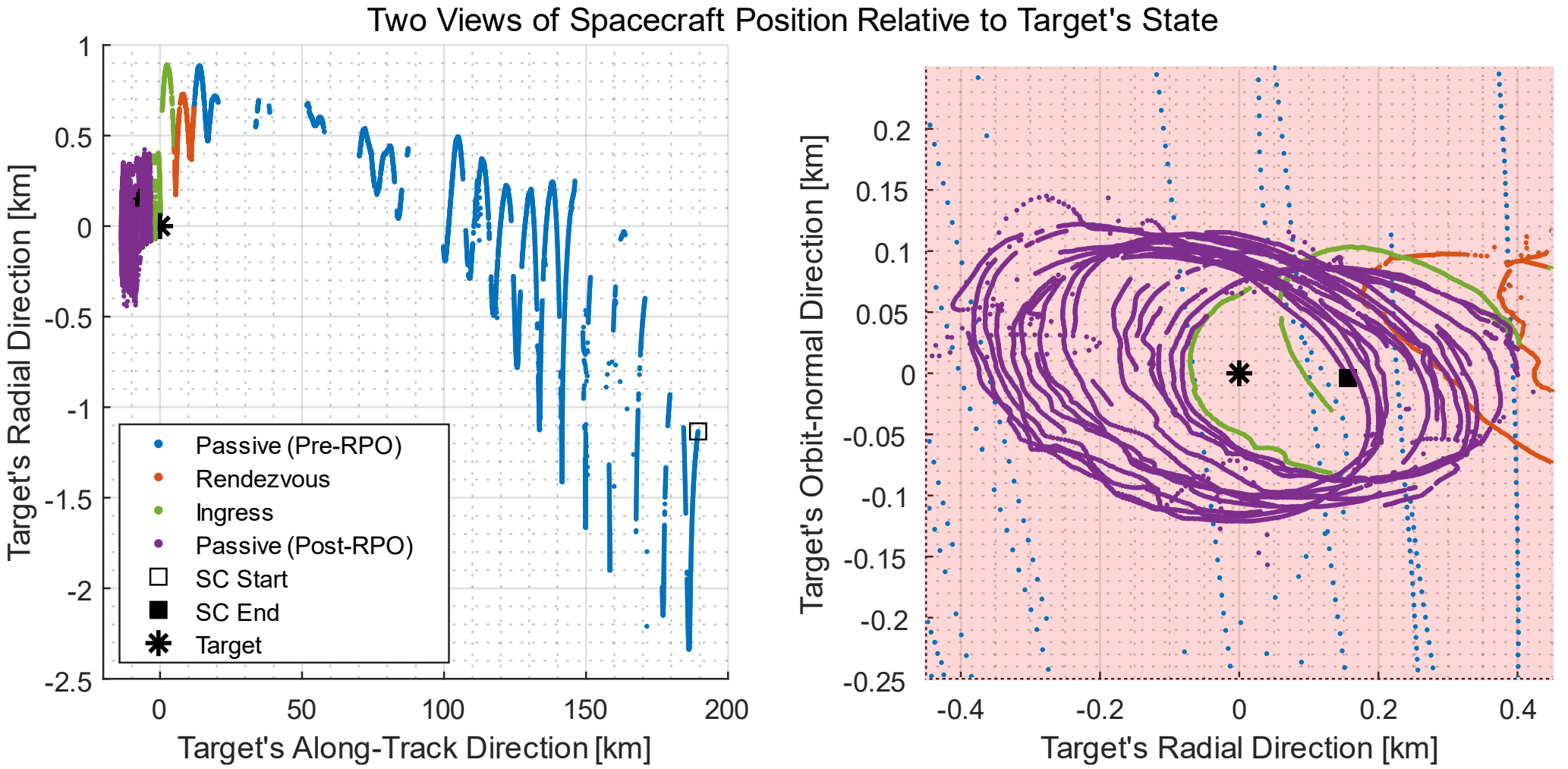

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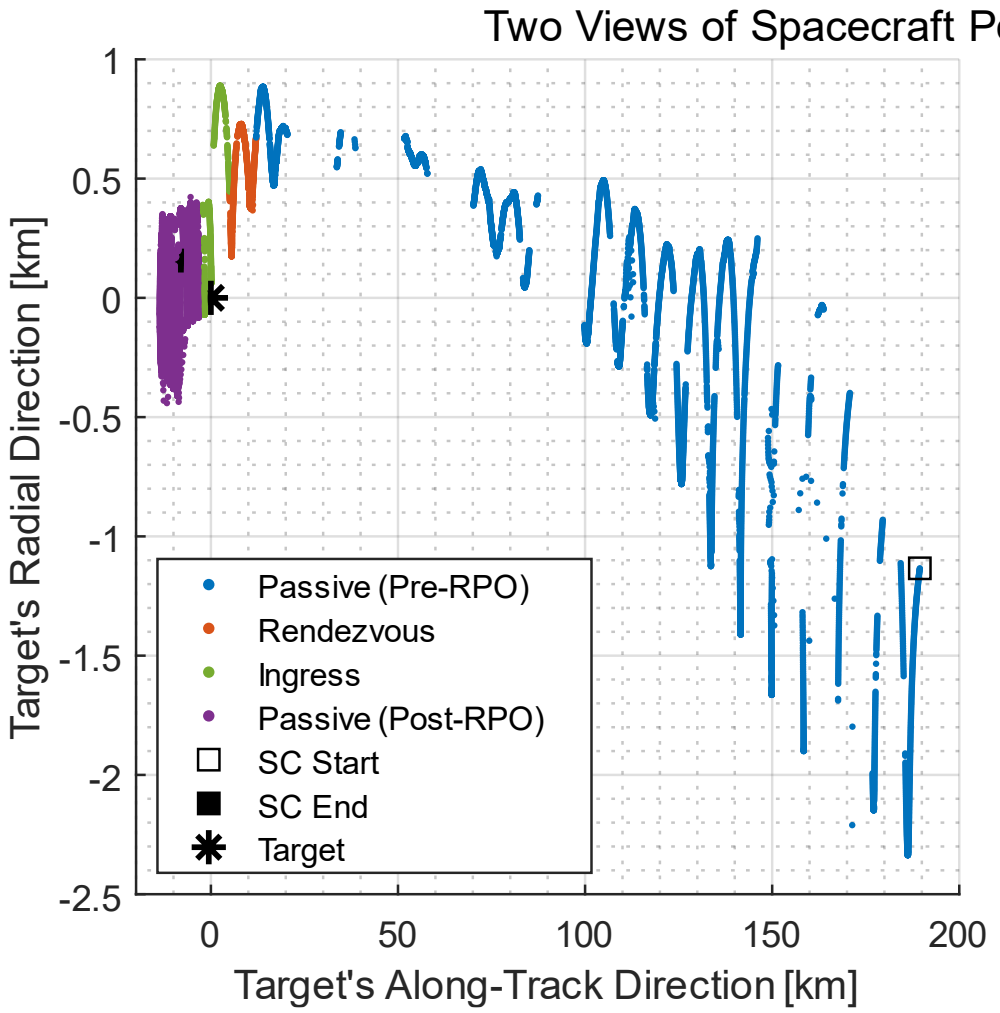

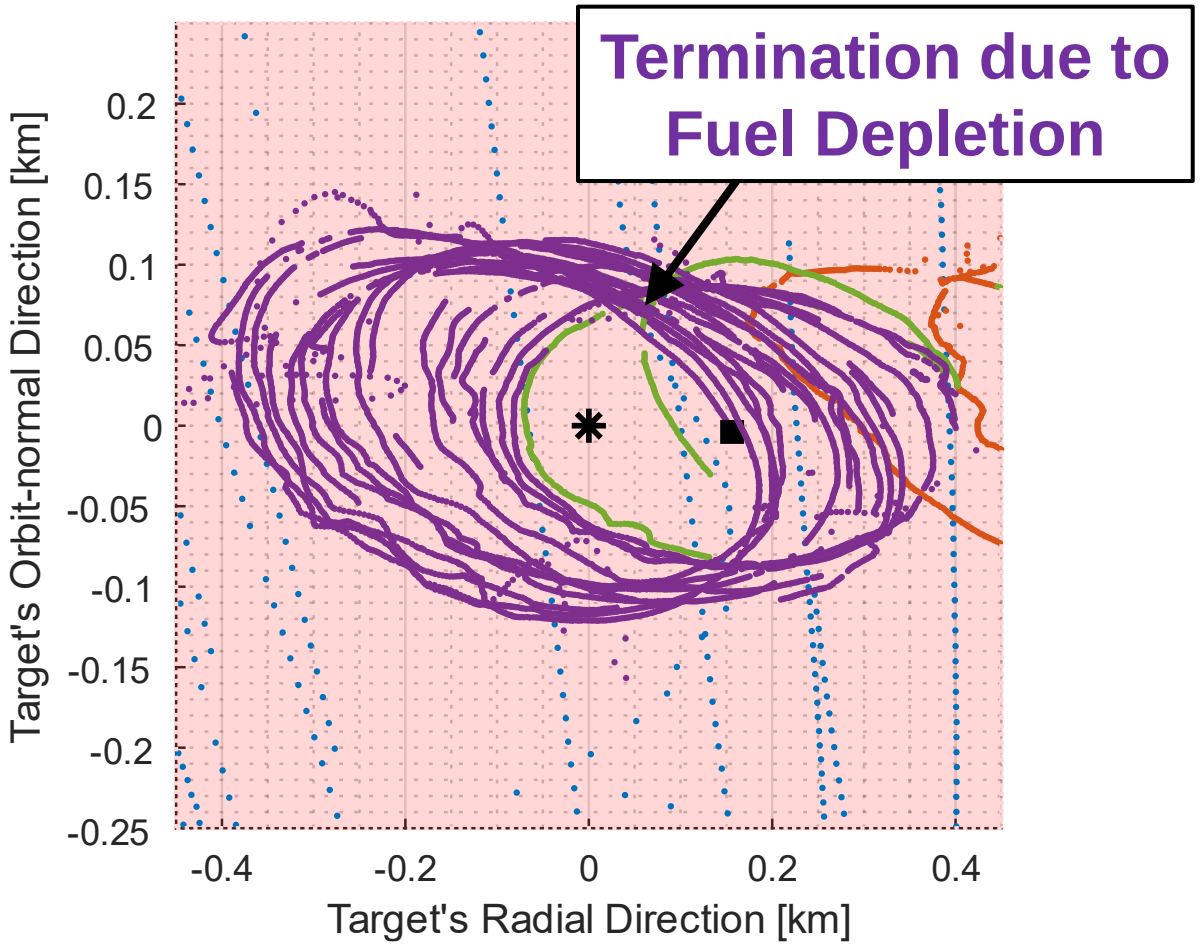

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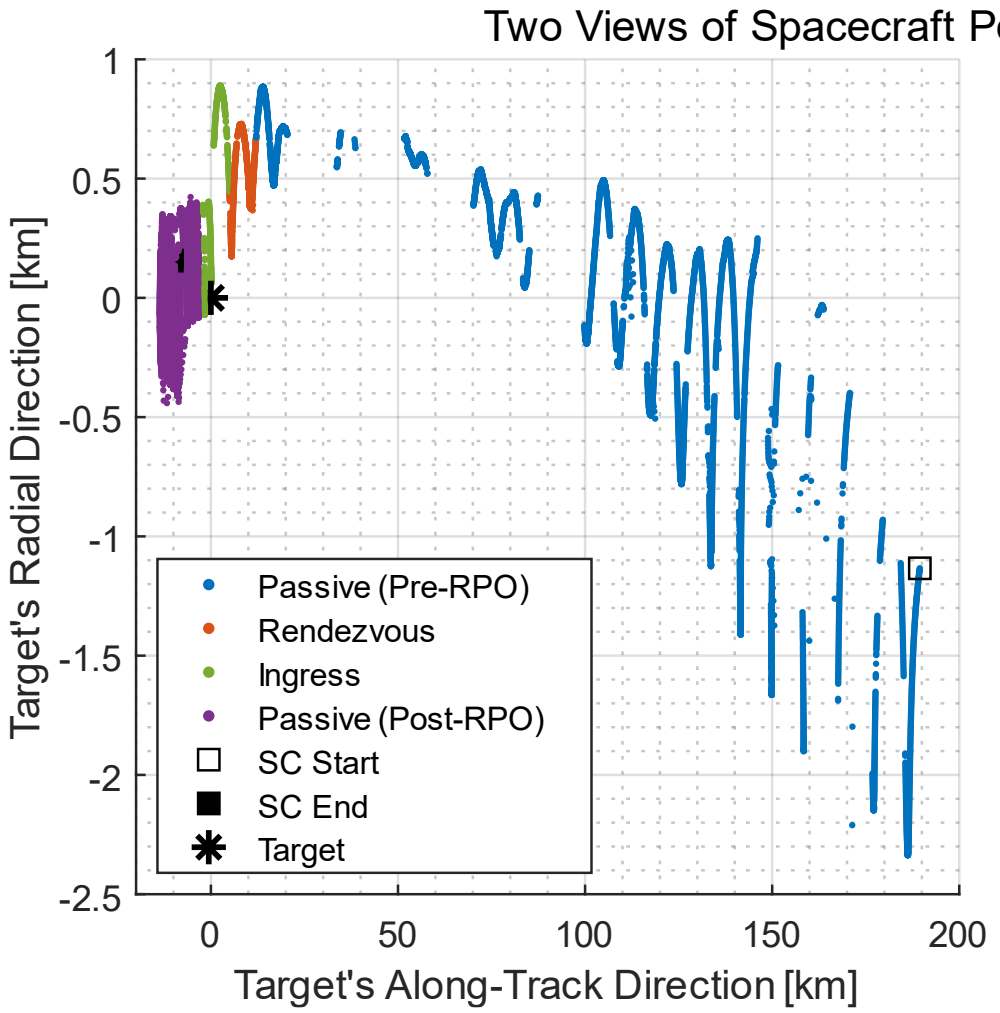
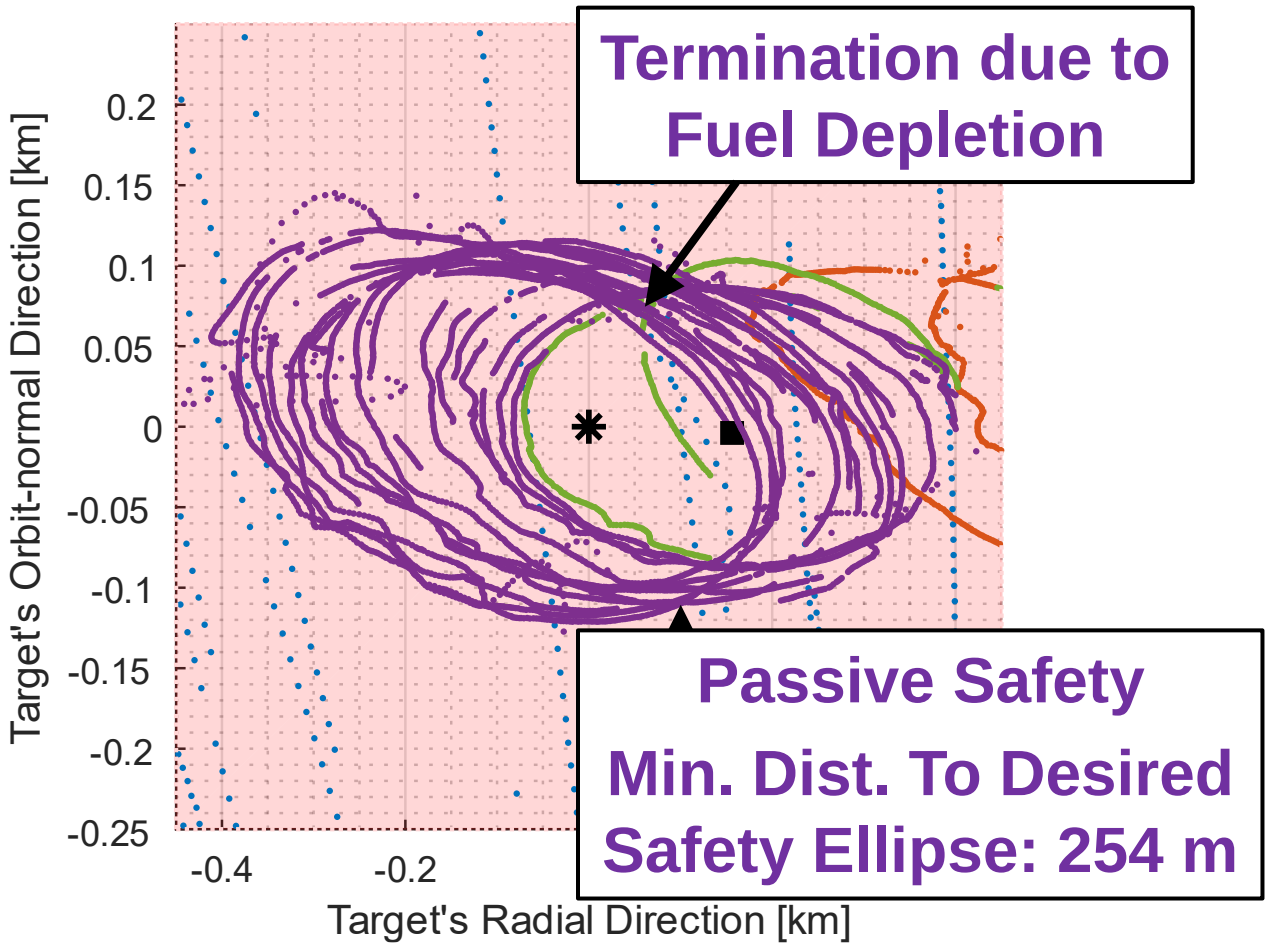


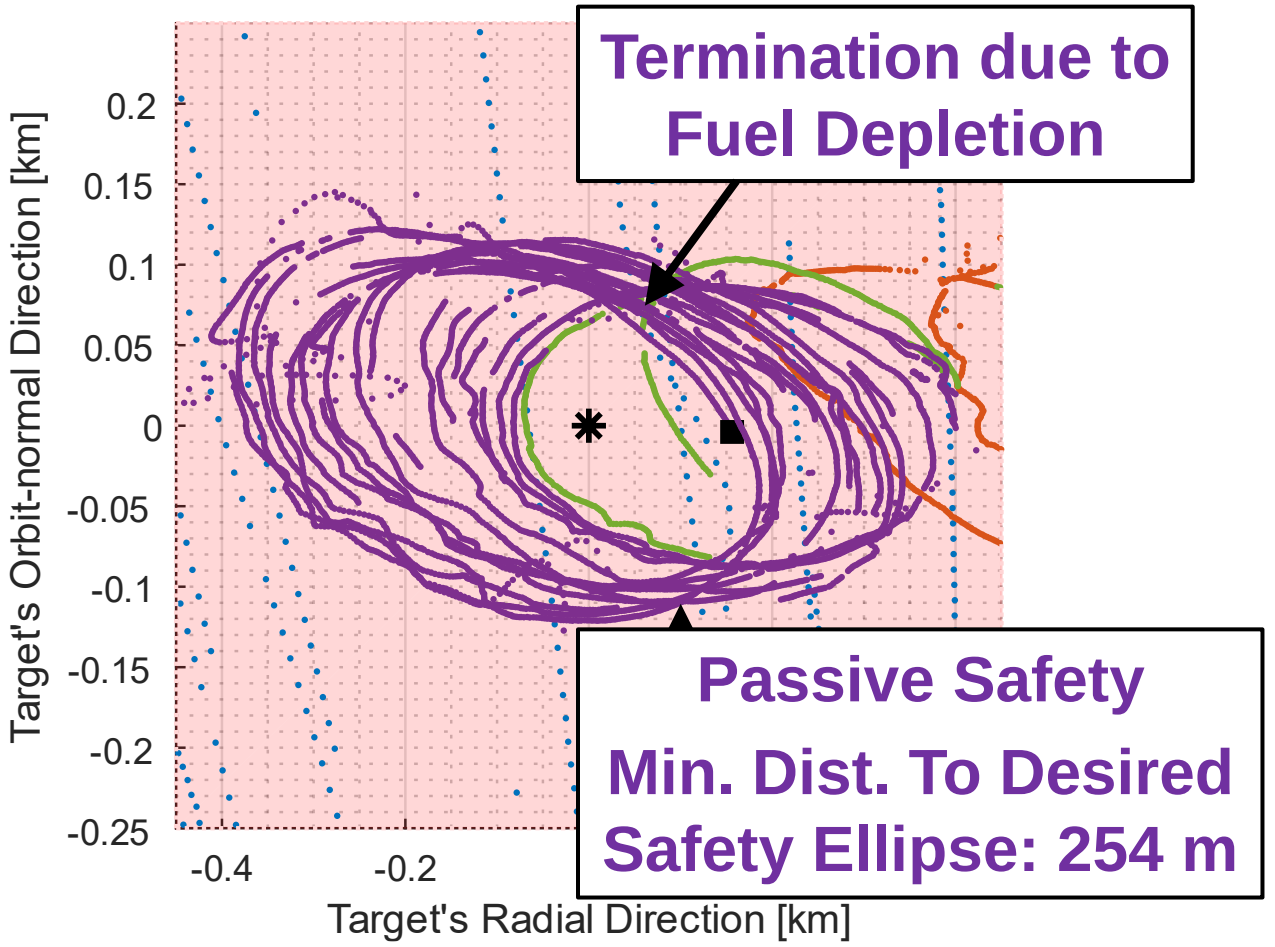


ON-ORBIT RPO RESULTS

Fully Autonomous Experiment Telemetry (2 Thrusters Stuck Open)

Two Views of Spacecraft Position Relative to Target's State

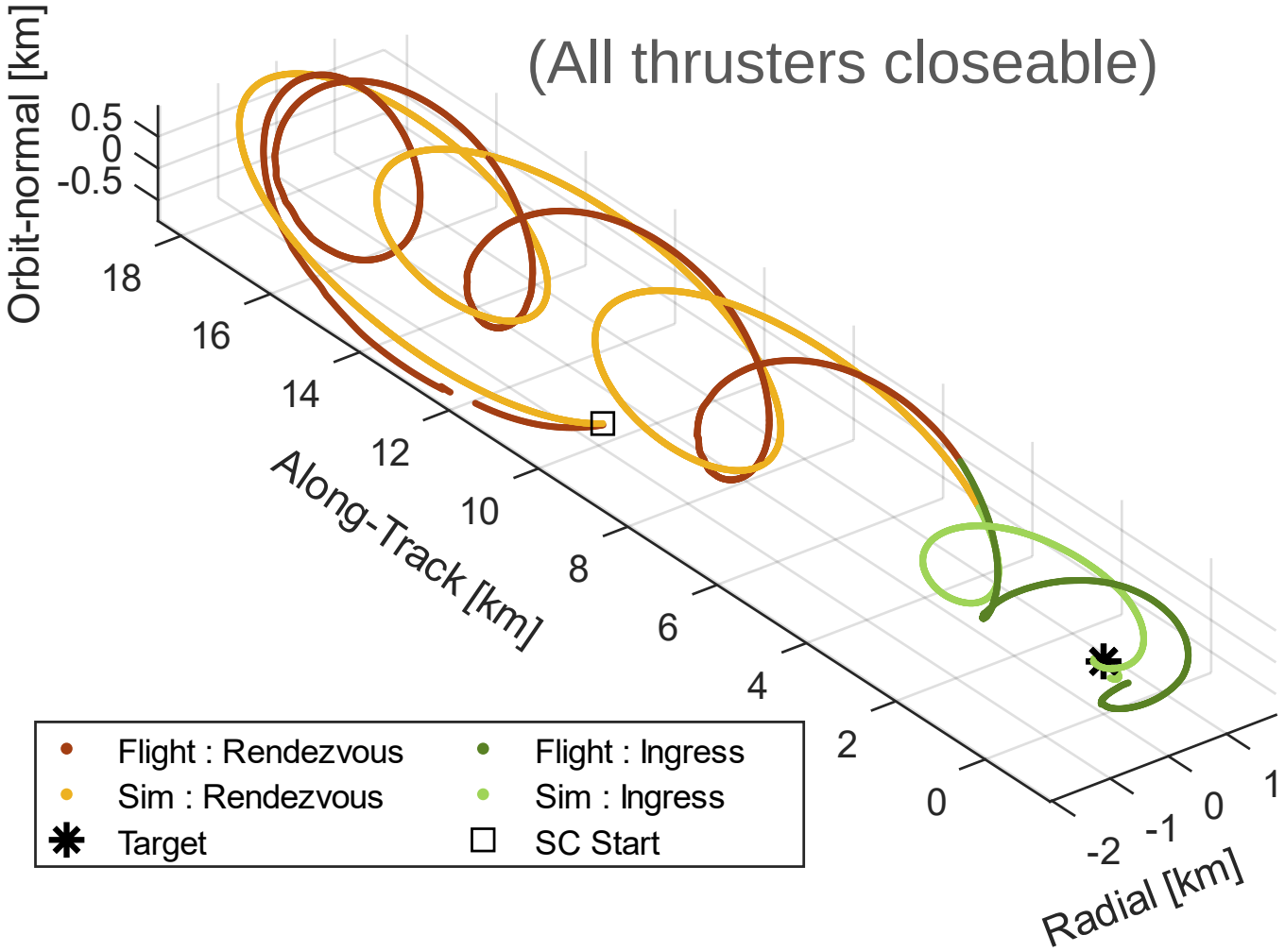
<u>Robustness</u>:
Rejection of Propulsion System Disturbances



ON-ORBIT RPO RESULTS

Flight Telemetry vs. Simulation With Constant Thruster Force

Plotted from RPO start time to time of minimum position error on-orbit



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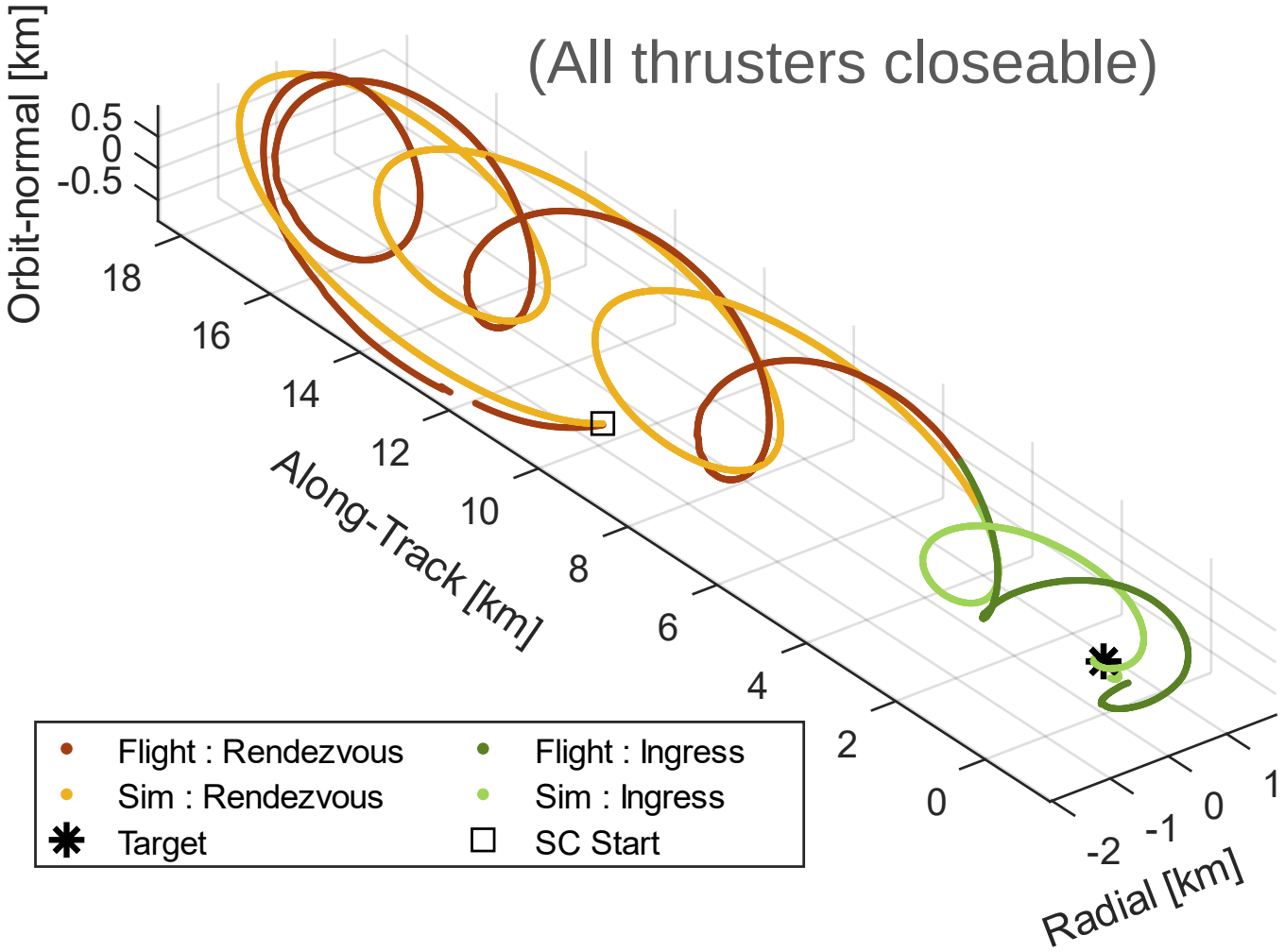

Largest Simulation Assumption:
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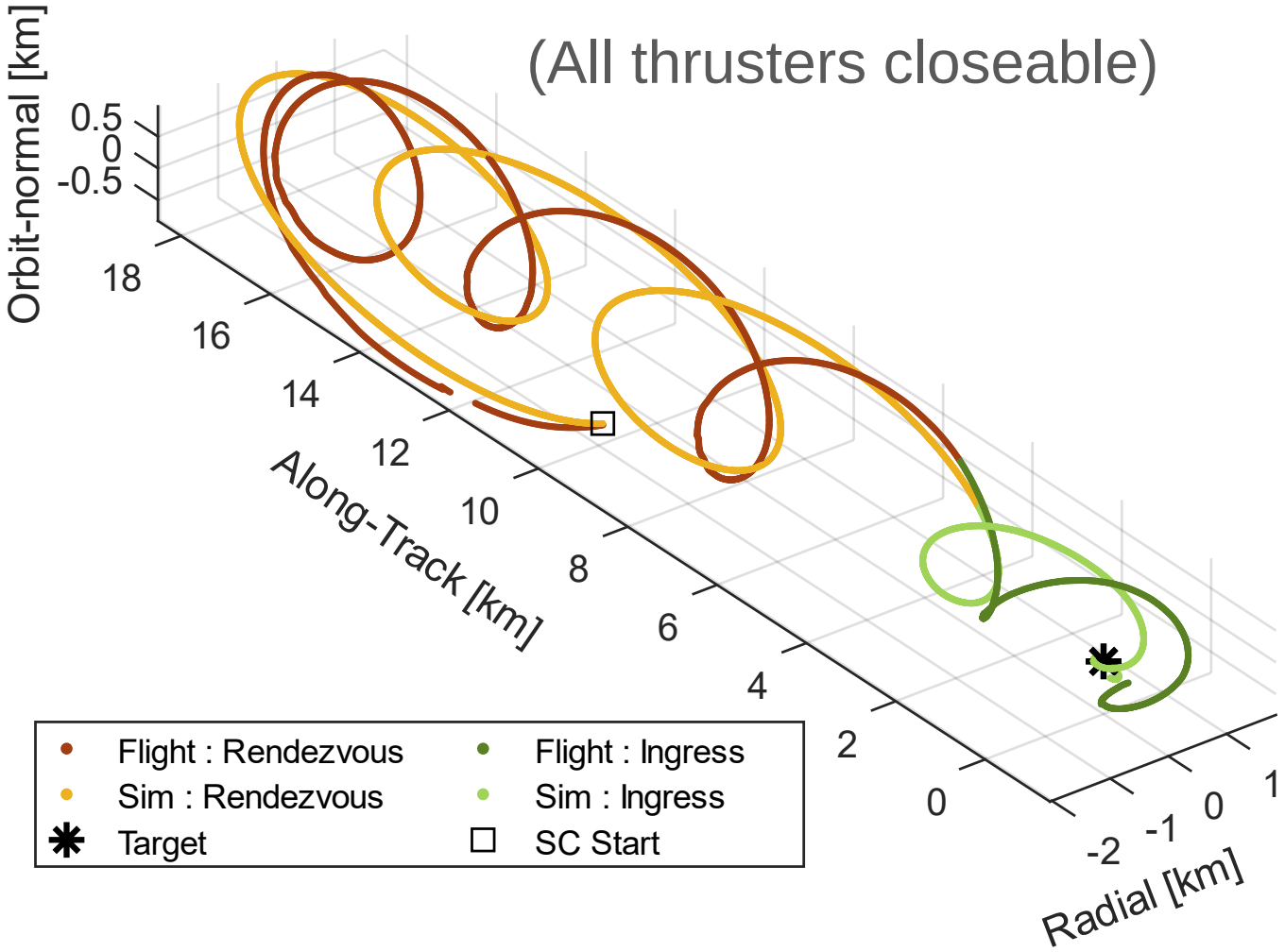

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  ⟹ assumption violated in reality

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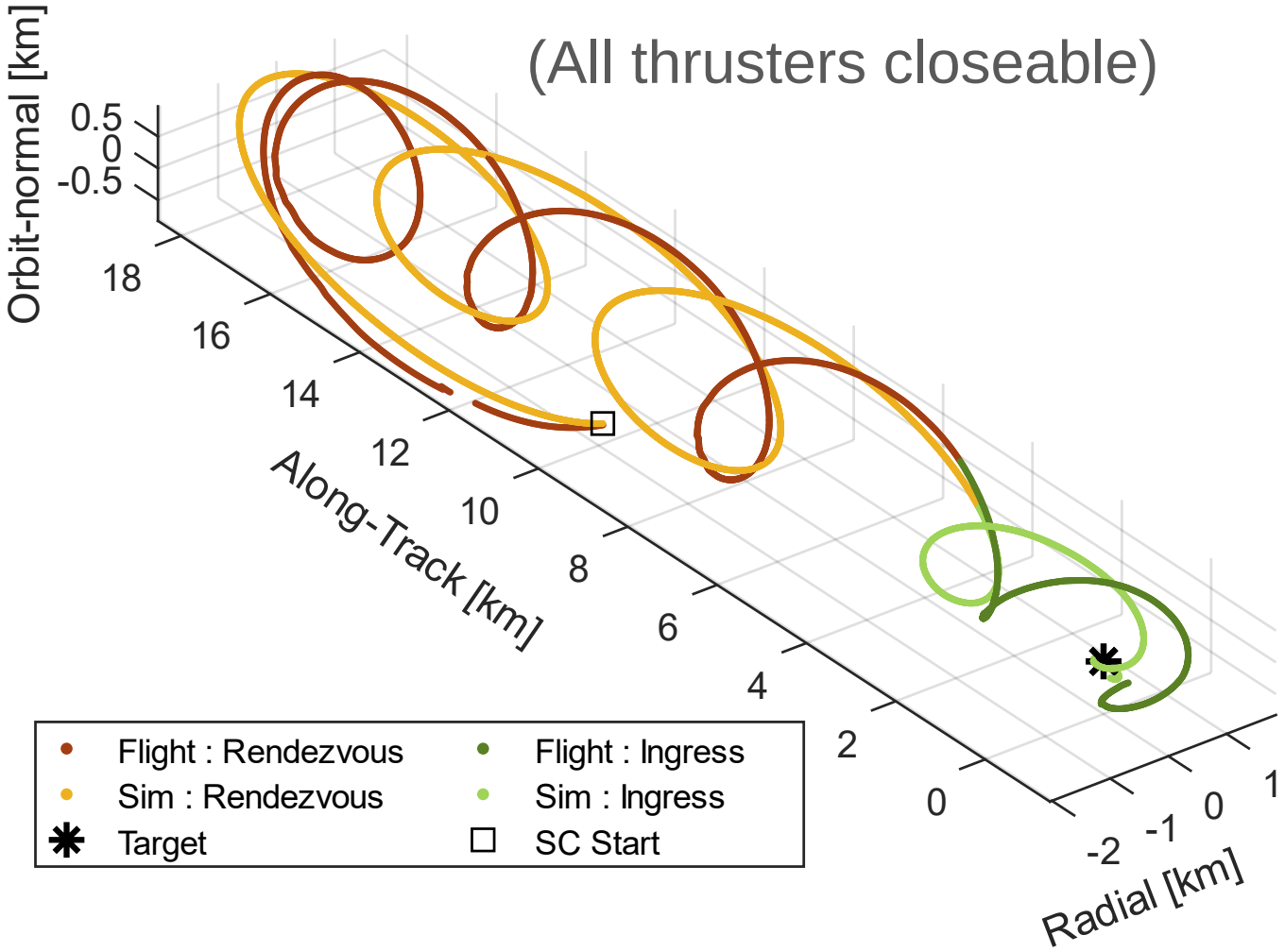

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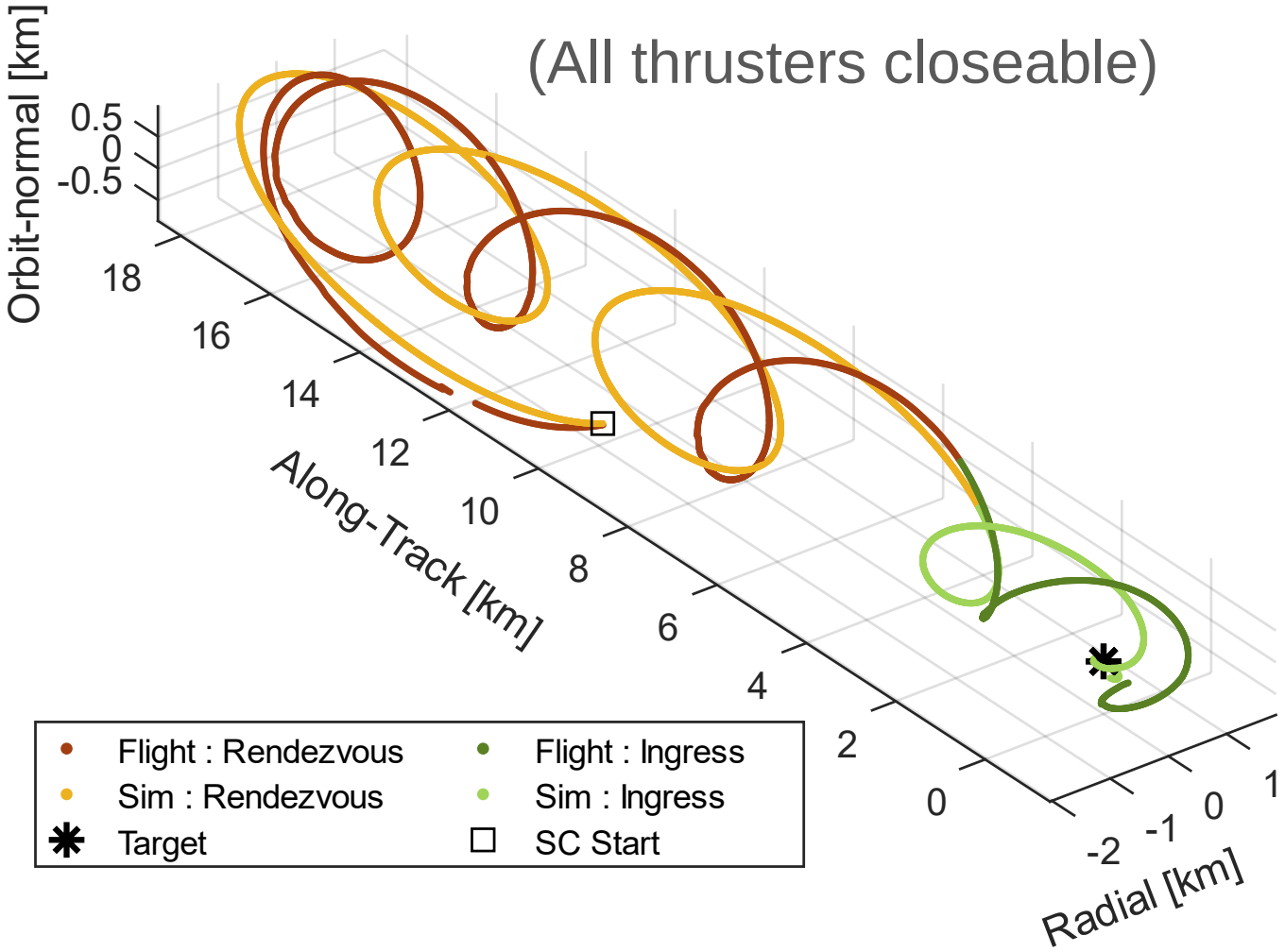

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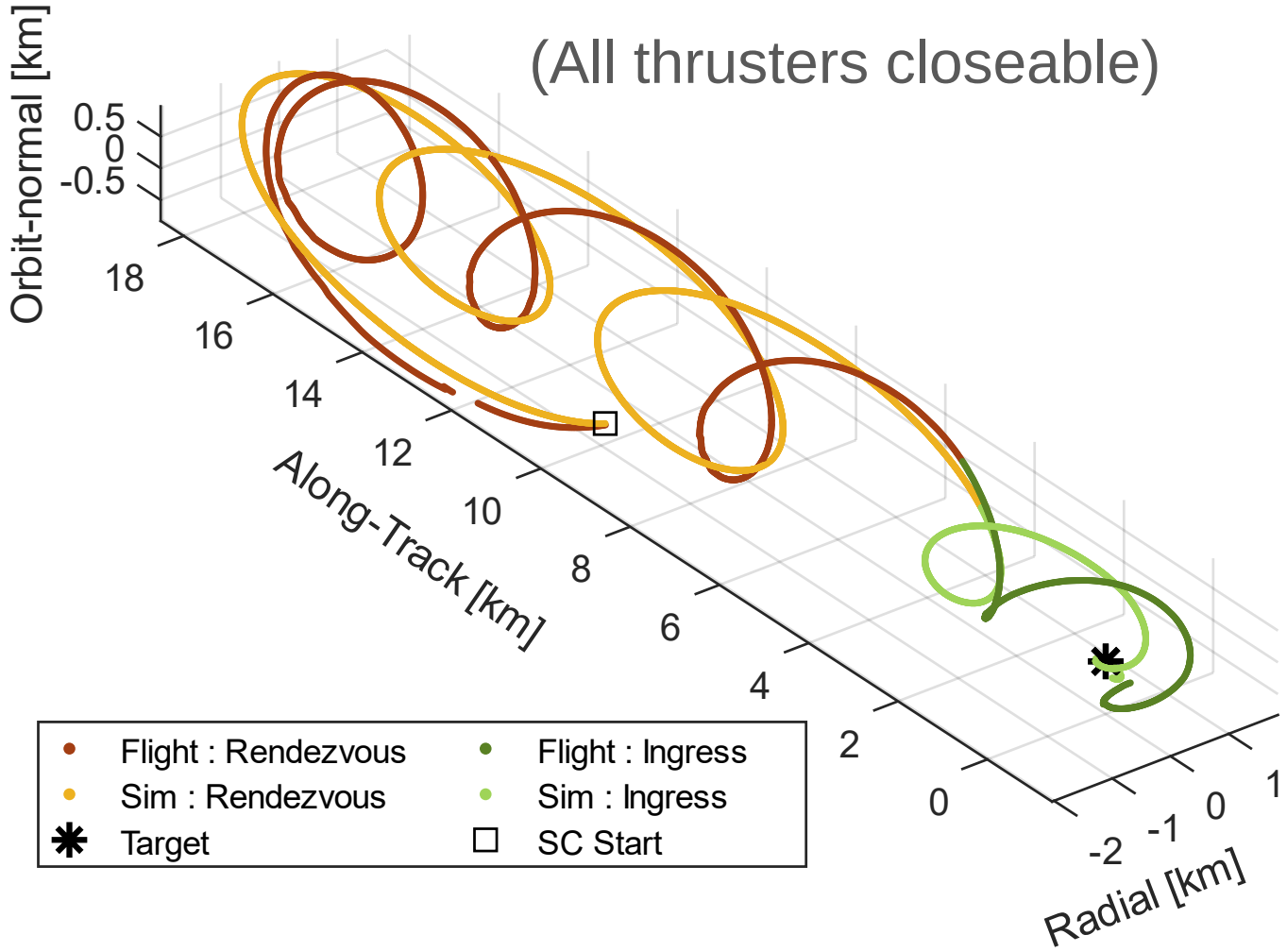

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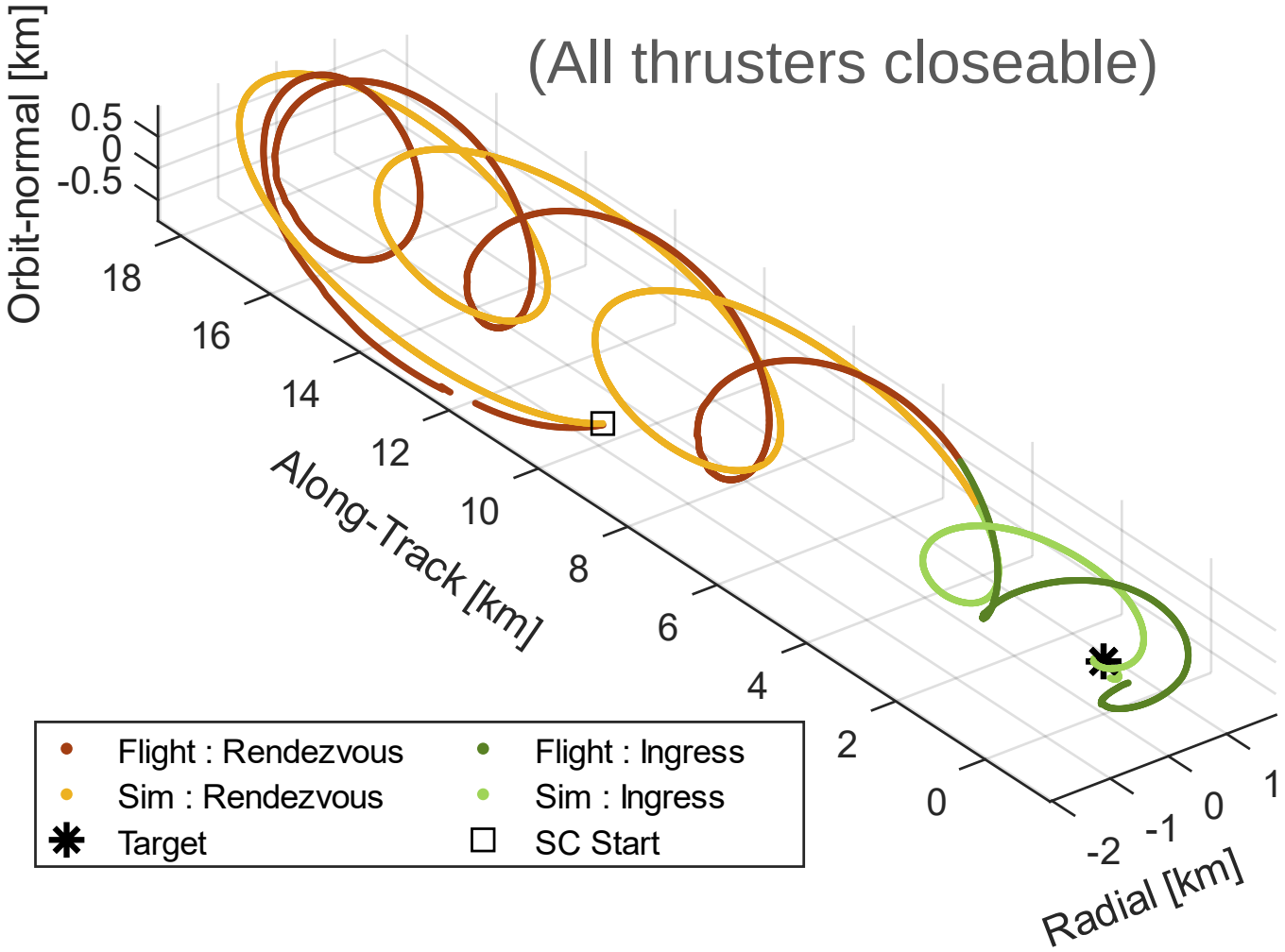

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Disturbances still impact outcome

- Simulation converges faster

CPOD CONCLUSION

Key Accomplishments

- 5 major experiments yielding rendezvous and passively safe formations
- 3 guidance algorithms validated on-orbit for autonomous RPO
- Exceptional robustness to disturbance forces

Key Lesson Learned

- Primary performance bottleneck: propulsion system reliability
  - Dynamic modeling will improve performance with existing hardware
  - Improved hardware will further increase performance and flexibility

Funding Acknowledgment

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