SPAC 6405

Justin Lin

APS: Protecting Space Stations in LEO

Master's Thesis
Fall 2020

OUTLINE

- Problem Definition
- Proposed System
- Mission Architecture
- Laser Performance Analysis
- Implementation on ISS
- Conclusions

Why is the APS Needed?

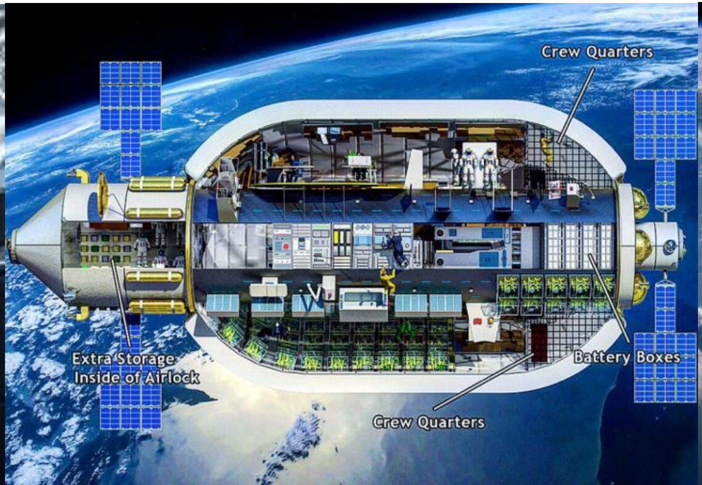
ADDRESSING RISK TO SPACE STATIONS (IN LEO)

Large structures with long orbital lifespans

- Carry important cargo: Humans!

LEO environment is filled with Resident Space Objects (RSOs)

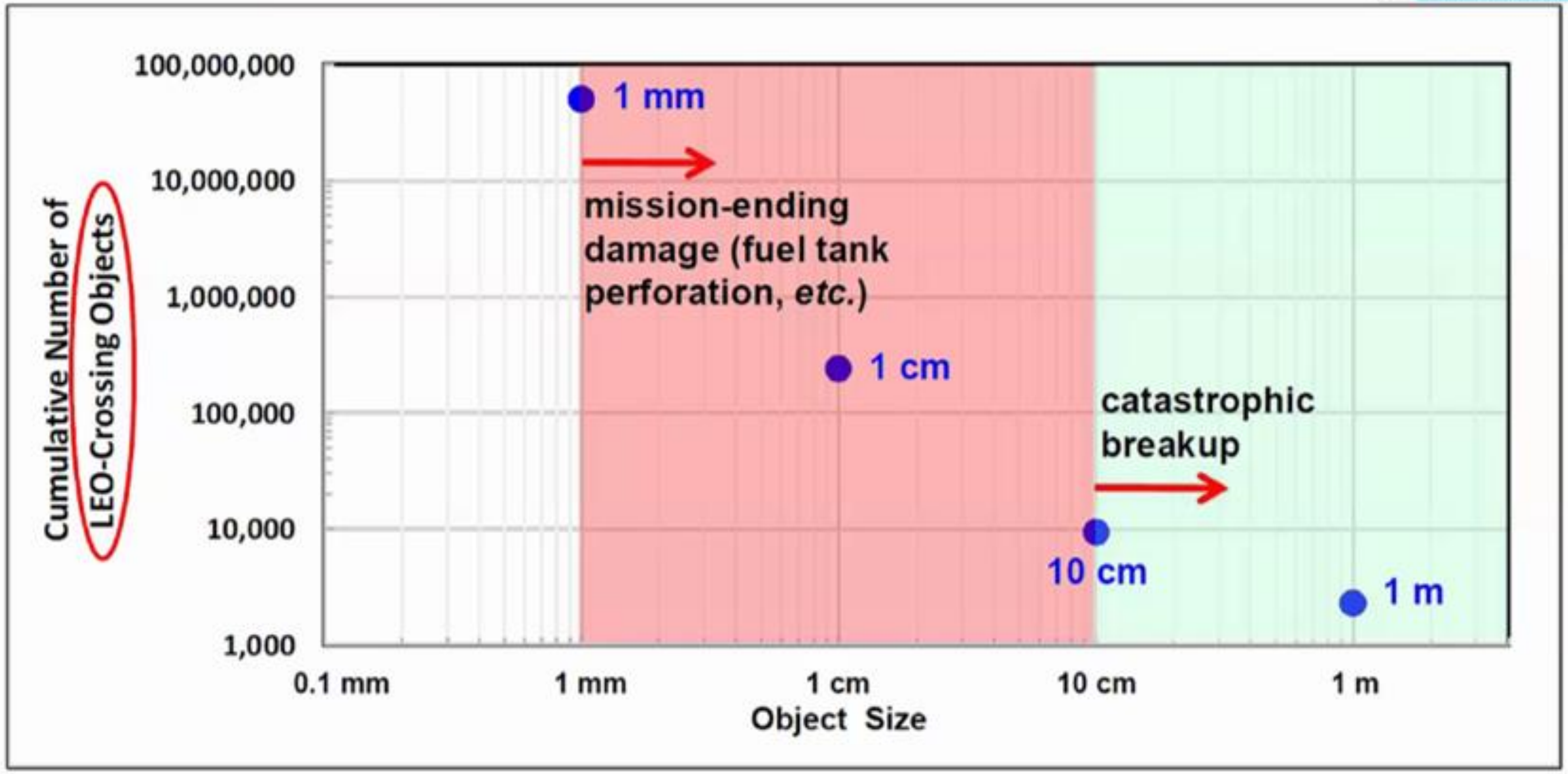
- Source of mission risk
- High relative velocities lead to fatal collisions



The Short-Term Orbital Debris Problem

- **There is far more small debris than large debris**
  - Mission-ending risk is driven by millimeter-sized OD in LEO, and sub-centimeter-sized debris in GEO, but there is a lack of data on such small debris
  - Conjunction assessments and collision avoidance against the large (≥10 cm) tracked objects only address <1% of the debris impact risk

Speaking: J.-C. Liou



Source:
Orbital Debris Panel
ANSI, Dec 2020

THE ISSUE WITH CM-SIZED DEBRIS

Too big to be practically shielded against

- ISS shielding limit: 1.3 cm @ 9 km/s, 45°

Too difficult to avoid using typical collision avoidance procedures

"If operators were to have a truly comprehensive set of conjunctions against all objects larger than 1 cm, they would likely be continuously conducting avoidance maneuvers at the risk of running out of fuel"

- The technical challenges of better Space Situational Awareness and Space Traffic Management

A Station Based
Active Protection System (APS)

APS HIGH LEVEL REQUIREMENTS

1. Enable the station to respond effectively to RSO threats in the cm size range
2. Reduce mission risk for the station regarding RSOs
3. Respond to RSO threats without creating more debris
4. Operate in a manner that does not pose a danger to other spacecraft
5. Complement future space situational awareness frameworks if possible
6. Aid in active debris removal if possible

DEVELOPING THE PROPOSAL

The APS needs to perform:

1. Detection of RSOs
2. Tracking
3. Threat Remediation

→ Trade studies and analysis of needs

- Optical Methods
- Radars
- Lasers
- Active debris removal

⋮

Results:

- Close approaches screened by ground radars and targets relayed to APS
- Cued detection, tracking, and ablation using **pulsed laser optical system**
- RSOs engaged for deorbiting* at least one orbit cycle before conjunction

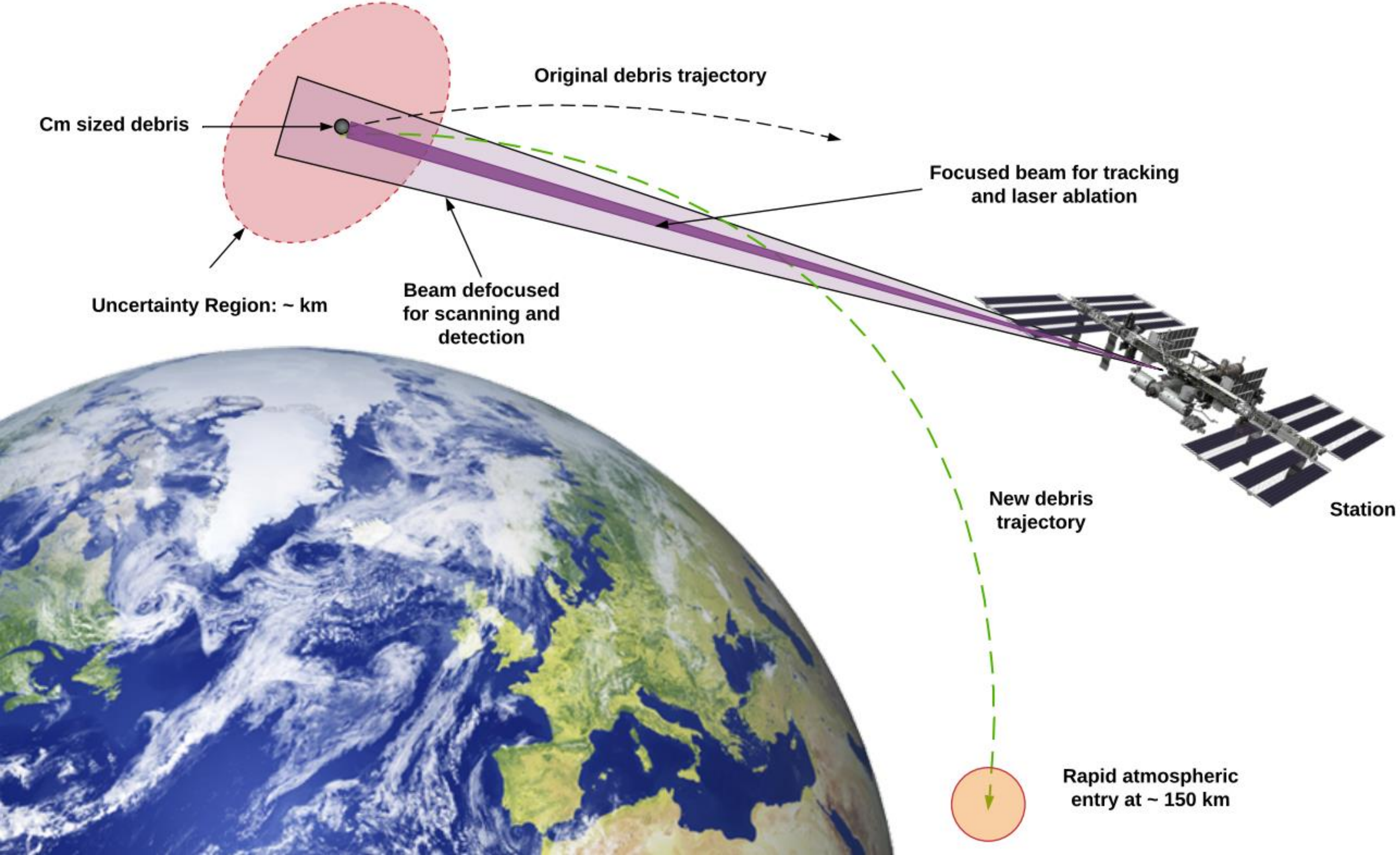
* Nominal case

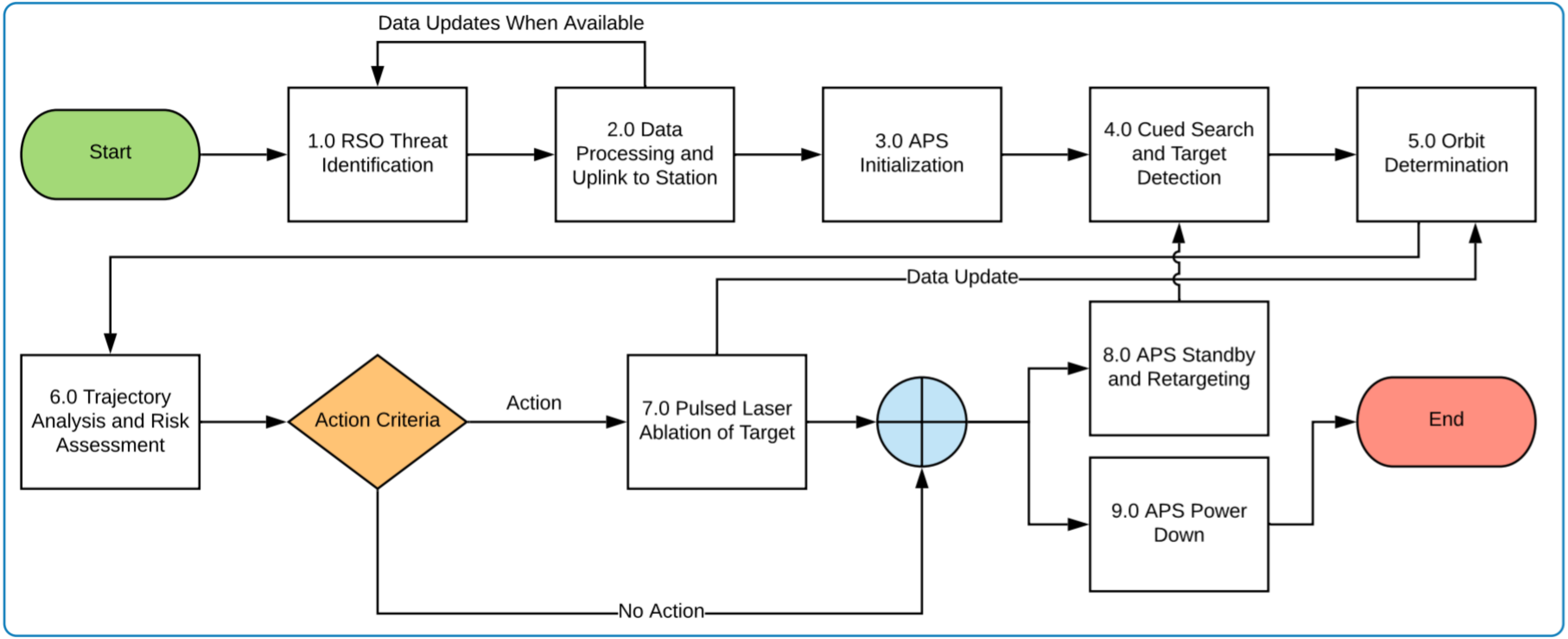
Proposed System

BENEFITS

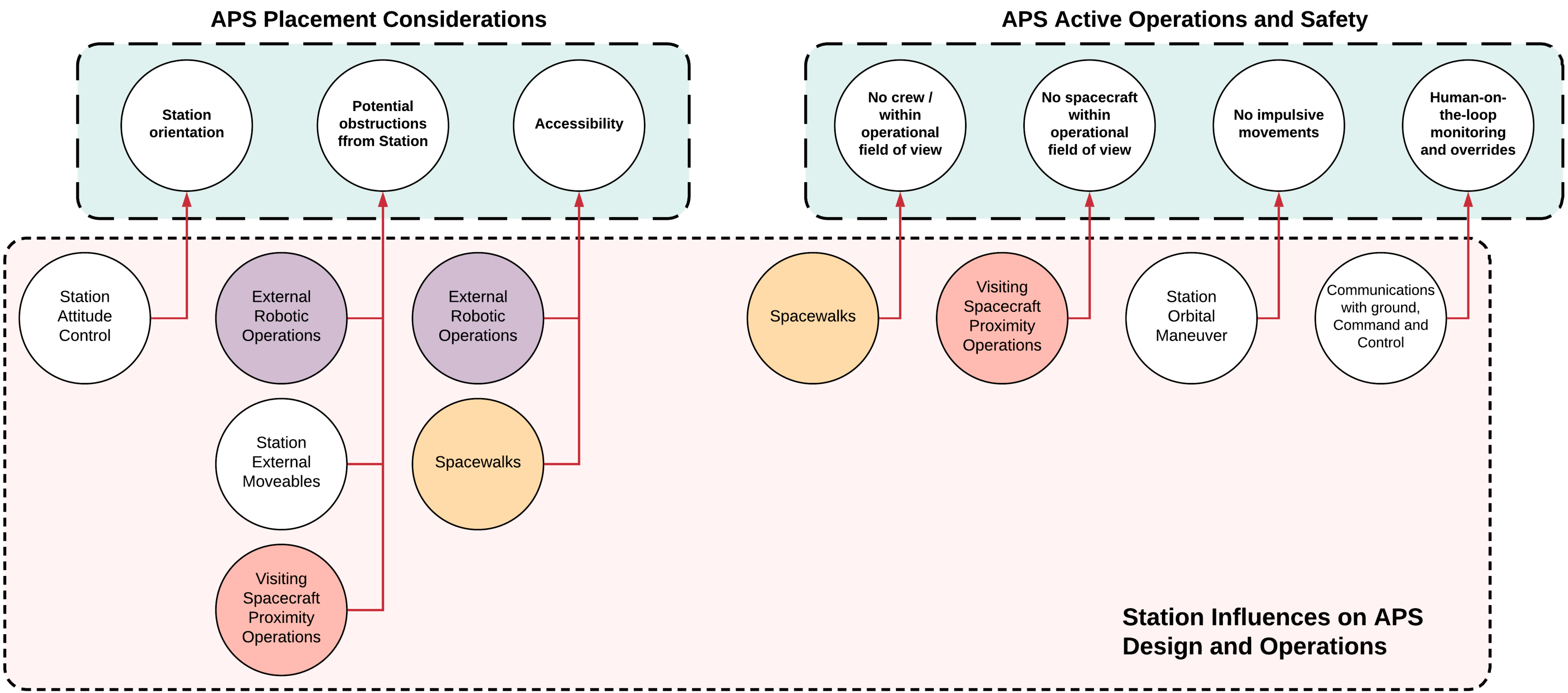
- Leverages existing space surveillance frameworks (ie: Space Fence)
- No collision avoidance planning needed
- Target information can be uplinked to APS just **hours** before conjunction
- Only high-threat RSO trajectories are considered (minimal false alarms)
- Approach is suitable for any station in LEO

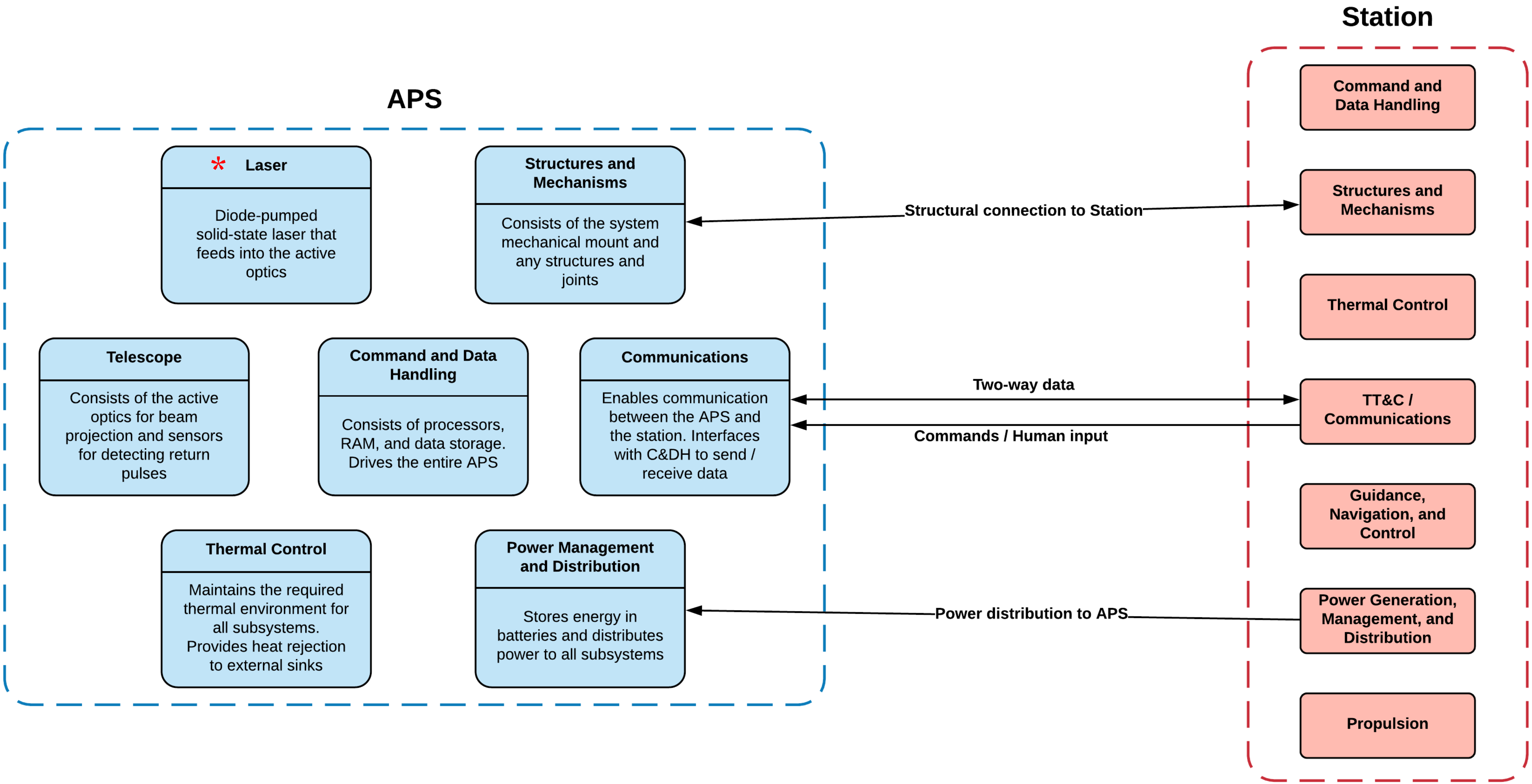
Mission Architecture


Original debris trajectory
Cm sized debris
Focused beam for tracking and laser ablation
Uncertainty Region: ~ km
Beam defocused for scanning and detection
New debris trajectory
Station
Rapid atmospheric entry at ~ 150 km



Mission Architecture


APS Placement Considerations
Station orientation
Potential obstructions ffrom Station
Accessibility
APS Active Operations and Safety
No crew / within operational field of view
No spacecraft within operational field of view
No impulsive movements
Human-on-the-loop monitoring and overrides
Station Attitude Control
External Robotic Operations
External Robotic Operations
Station External Moveables
Spacewalks
Visiting Spacecraft Proximity Operations
Spacewalks
Visiting Spacecraft Proximity Operations
Station Orbital Maneuver
Communications with ground, Command and Control
Station Influences on APS Design and Operations



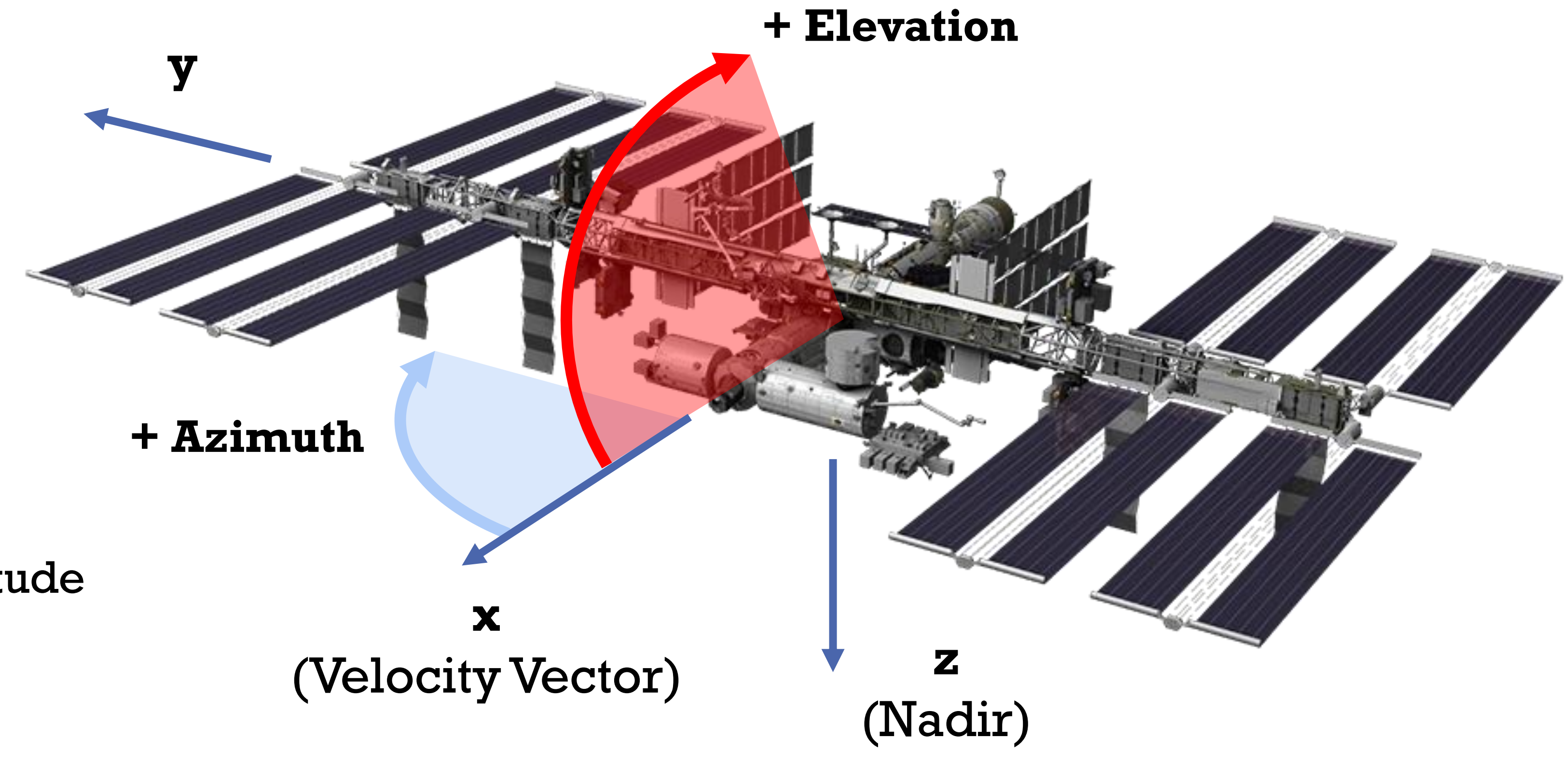
* DPSSL at TRL 6

Laser Performance Analysis

DEBRIS THREATS

Want to address **primary source** of RSO threats for the ISS trajectory

- 400 km altitude, 51.6° inclination



+ XVV flight attitude

Laser Performance Analysis

OFF-NOMINAL RSO TRAJECTORIES

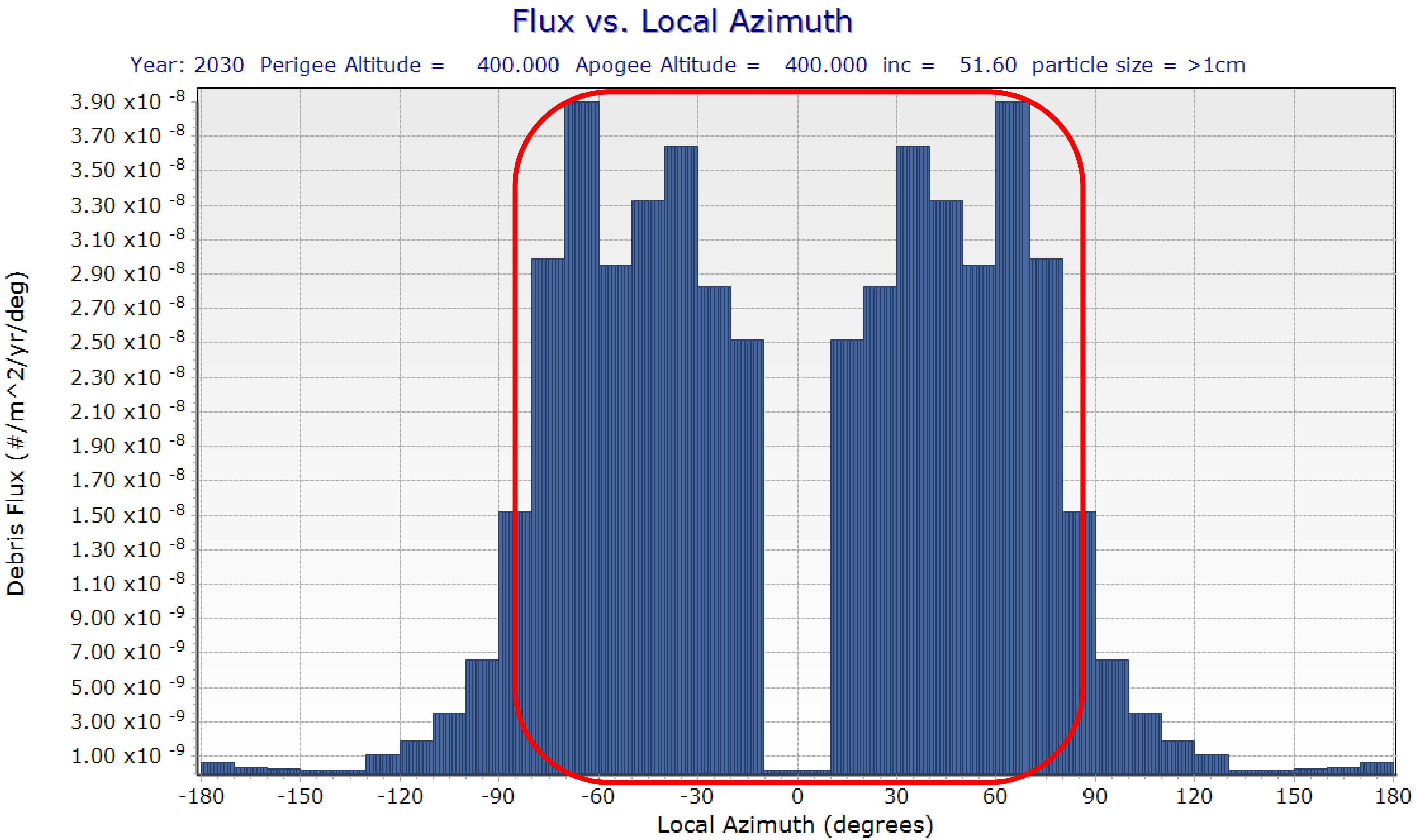
Nominal case: Deorbit RSOs

- Majority of expected debris flux in LEO

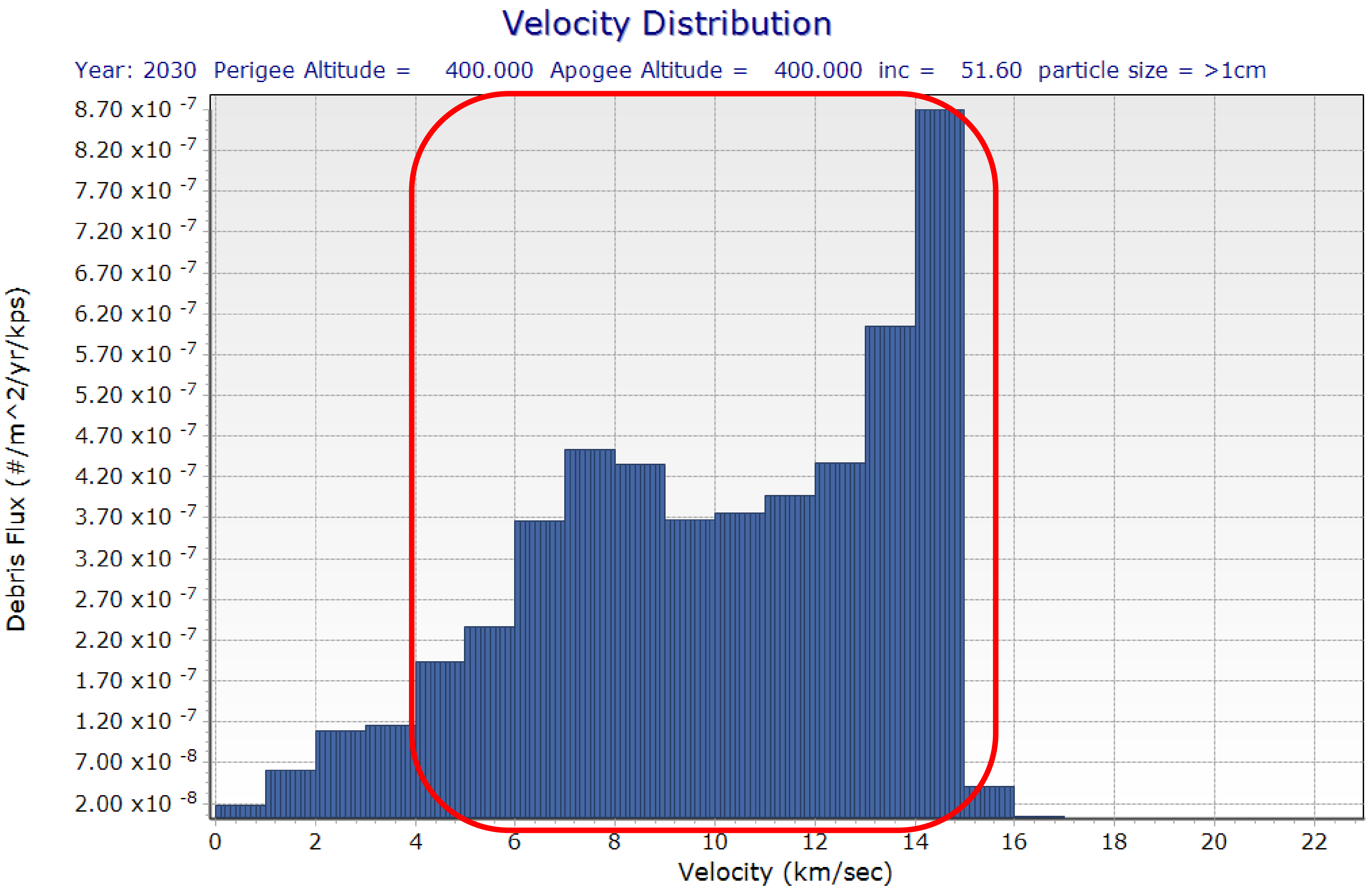
Focus of the analysis

Off-nominal cases: Orbit modification only (cannot reliably deorbit)

- Highly elliptical RSO orbits
- RSOs approaching near ±90° in azimuth
- **Still enables conjunctions to be avoided** → Satisfies high level requirements



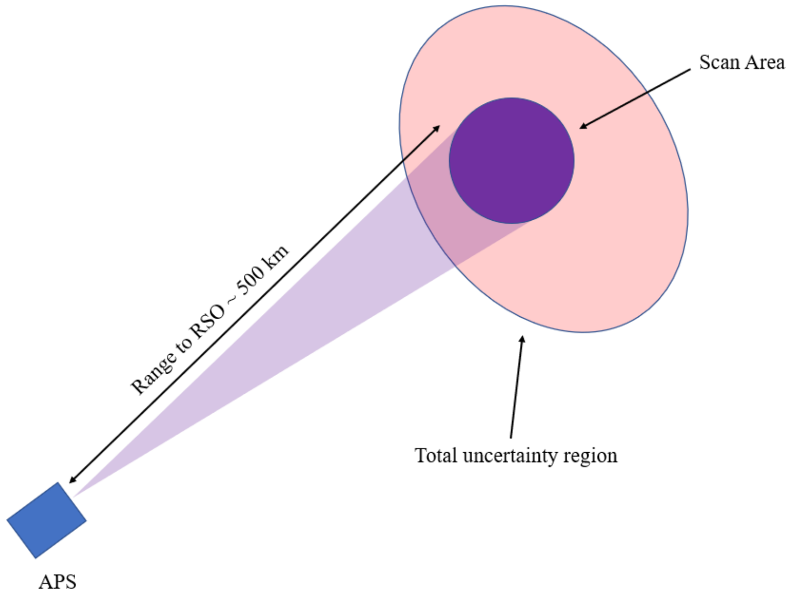
Flux vs. Local Azimuth
Year: 2030 Perigee Altitude = 400.000 Apogee Altitude = 400.000 inc = 51.60 particle size = >1cm
Debris Flux (#/m^2/yr/deg)
3.90 x10 -8
3.70 x10 -8
3.50 x10 -8
3.30 x10 -8
3.10 x10 -8
2.90 x10 -8
2.70 x10 -8
2.50 x10 -8
2.30 x10 -8
2.10 x10 -8
1.90 x10 -8
1.70 x10 -8
1.50 x10 -8
1.30 x10 -8
1.10 x10 -8
9.00 x10 -9
7.00 x10 -9
5.00 x10 -9
3.00 x10 -9
1.00 x10 -9
-180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180
Local Azimuth (degrees)


Velocity Distribution
Year: 2030 Perigee Altitude = 400.000 Apogee Altitude = 400.000 inc = 51.60 particle size = >1cm
Debris Flux (#/m^2/yr/kps)
8.70 x10 -7
8.20 x10 -7
7.70 x10 -7
7.20 x10 -7
6.70 x10 -7
6.20 x10 -7
5.70 x10 -7
5.20 x10 -7
4.70 x10 -7
4.20 x10 -7
3.70 x10 -7
3.20 x10 -7
2.70 x10 -7
2.20 x10 -7
1.70 x10 -7
1.20 x10 -7
7.00 x10 -8
2.00 x10 -8
0
2
4
6
8
10
12
14
16
18
20
22
Velocity (km/sec)

ESTIMATING LASER OUTPUT ENERGY

Broken down into three phases:

1. **Cued Detection**
   - Scanning uncertainty region for RSO
2. **Tracking**
   - Beam focused onto RSO for tracking
3. **Laser Ablation**
   - Ablate RSO until perigee lowered sufficiently (~ 150km altitude)



Each phase can be mathematically modelled…

$$E_{phase} = \int_{\mathrm{t_{phase}}} W(t)PRF(t)dt$$

* Pulse energy (W) depends on many factors (including range)

Laser Performance Analysis

TRACKING ANGLES AND RATES

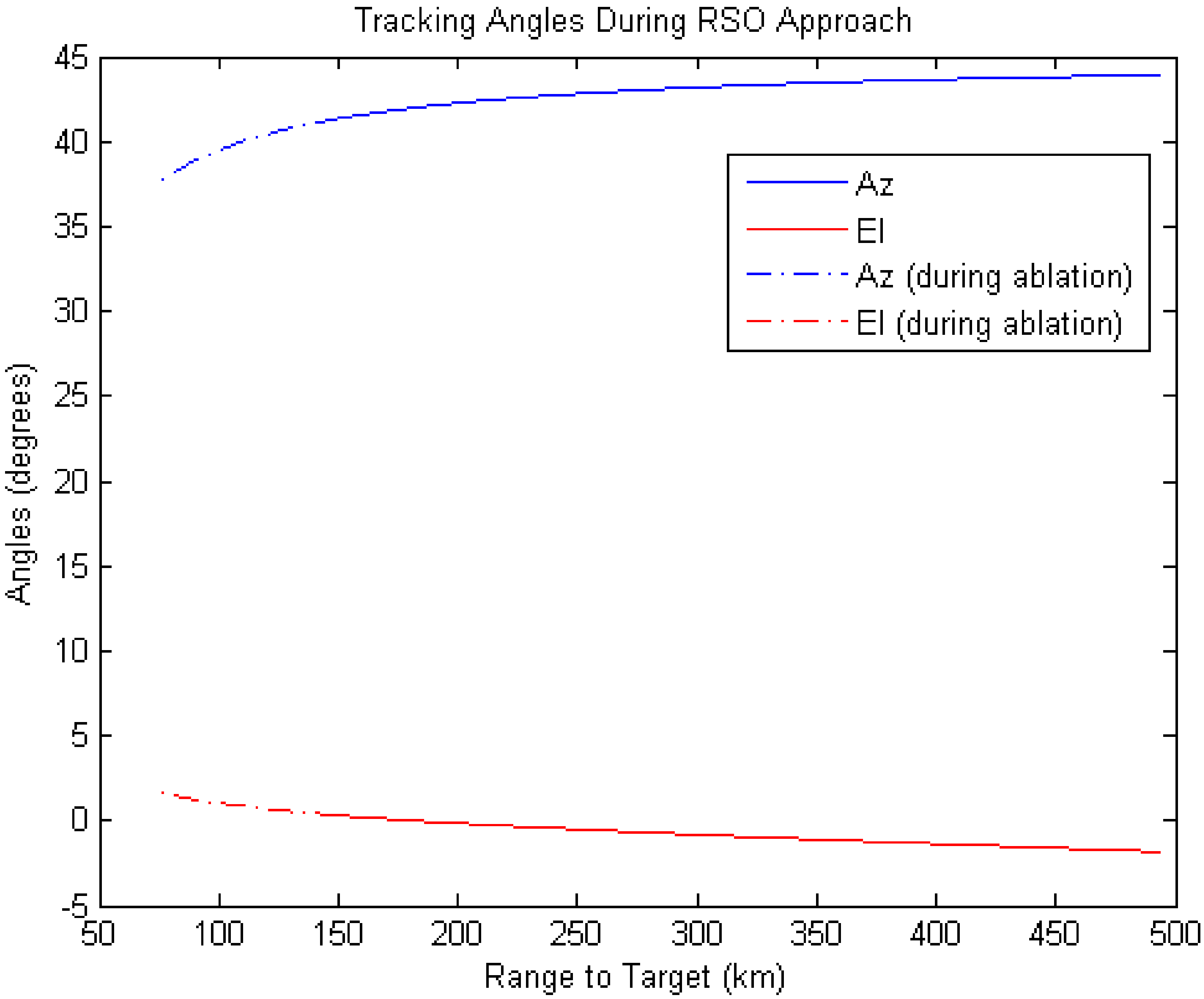
- As a RSO approaches, the pointing angles and angular rates will vary
- Can obtain angles (Az, El) and rates ($\dot{Az}, \dot{El}$) during approach
- Want to limit rates to ≤ 1.5°/s

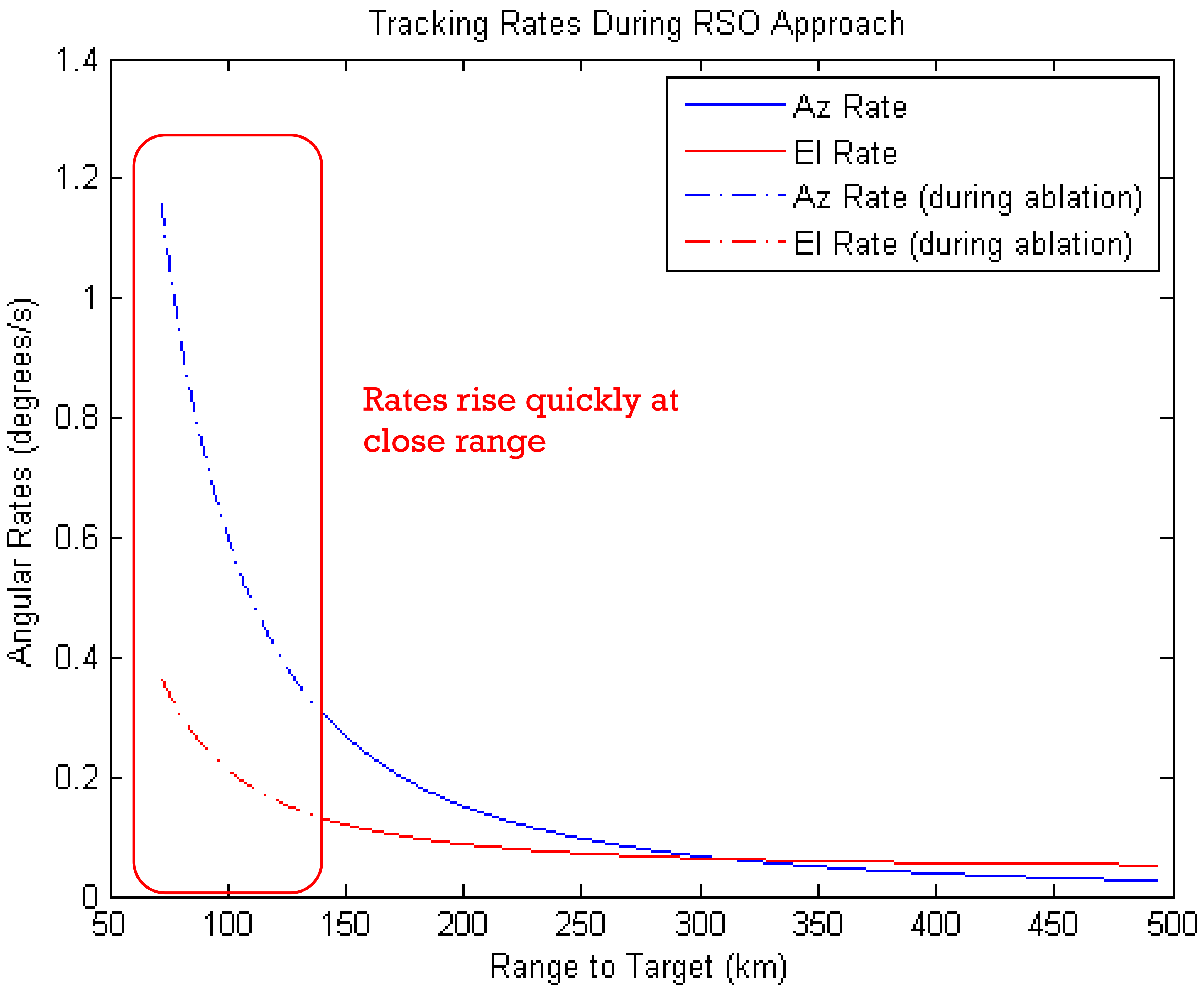
Example debris scenario

Closest approach to station: 12 km
Relative velocity: 11 km/s
Az: 45°
El: 0°
Perigee altitude: 397 km
Apogee altitude: 782 km

Values for initial debris orbit

Laser PRF: 90 Hz
Maximum ablation range: 150 km


Tracking Angles During RSO Approach
Angles (degrees)
Range to Target (km)
Az
El
Az (during ablation)
El (during ablation)
45
40
35
30
25
20
15
10
5
0
-5
50
100
150
200
250
300
350
400
450
500



Tracking Rates During RSO Approach
Angular Rates (degrees/s)
Range to Target (km)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
50
100
150
200
250
300
350
400
450
500
Az Rate
El Rate
Az Rate (during ablation)
El Rate (during ablation)
Rates rise quickly at
close range

RESULTS: PERFORMANCE

Phase	Laser Output Energy (kJ)	Typical Operating Time (s)	Average Laser Power (kW)
Cued Detection	≤ 70	5 – 10	7 – 14
Tracking	2 – 9	20 – 90	≤ 0.1
Ablation	30 – 130	3 – 20	7 – 9

Maximum of ~ 120 s

Laser Performance Analysis

RESULTS: PARAMETERS

Station and RSO Parameters	
Reference Station Orbit	ISS; Near-circular, 400 km, 51.6°
RSO Approach Angles	±75° in Az; ~ 0° El
Laser Parameters	
Laser Wavelength	355 nm
PRF	90 – 100 Hz
Maximum Detection Range	500 km
Maximum Ablation Range	150 km
Azimuth Range	±80°
Elevation Range	±20°
Angular Rate Limits	< 1.5°/s

Addresses majority of debris flux

Line of sight requirements

Laser Performance Analysis

Implementation on ISS

SYSTEM SIZING AND DESIGN CONSIDERATIONS

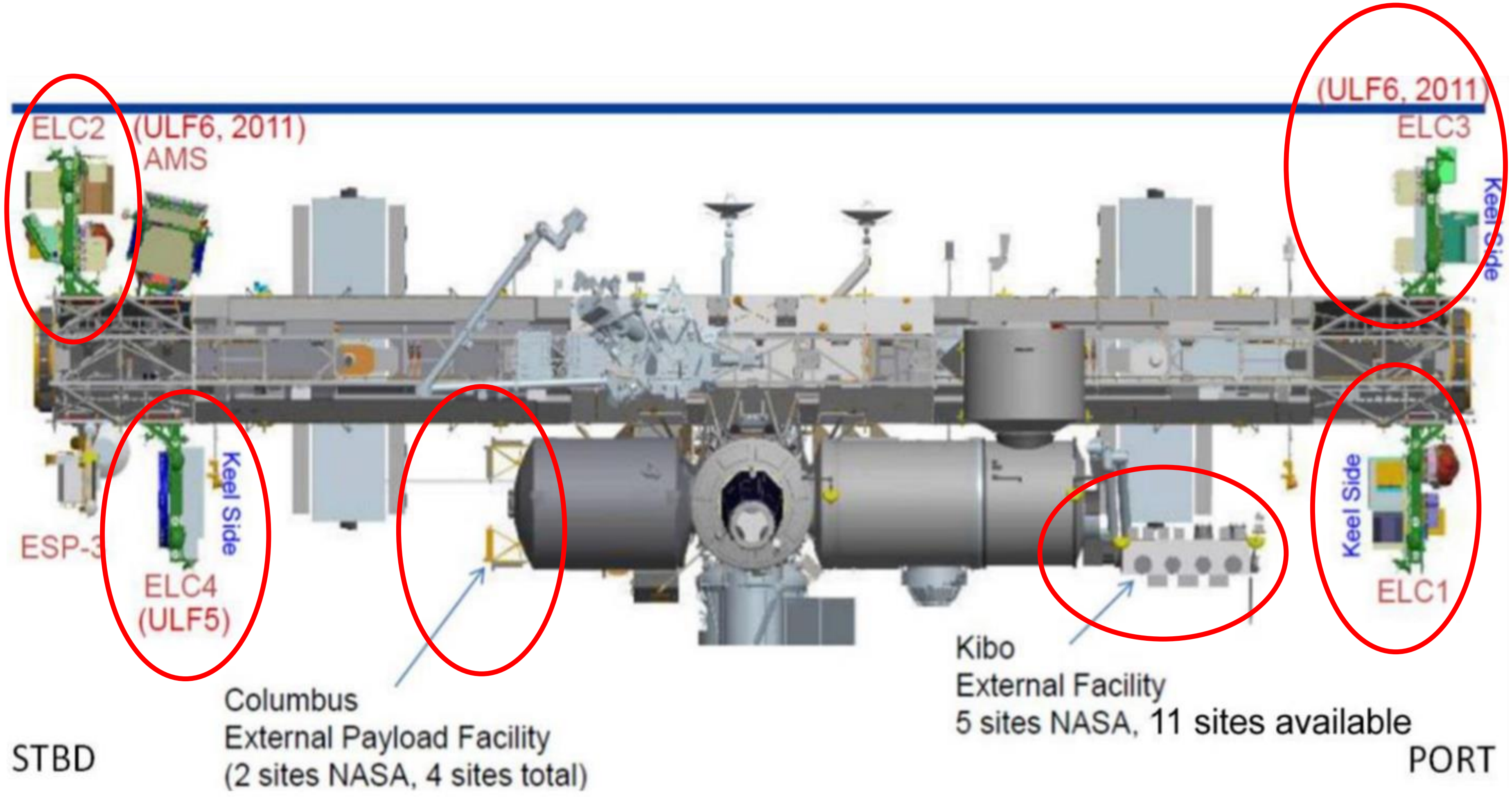
- ROM Mass, Volume, Power
  - Several tons
  - Primary mirror 1.5 m in diameter
  - Burst power in the tens of kW → Energy storage in Li-Ion batteries, charged by station power system

- Structural, Power, Data connections
- Unobstructed line of sight to RSOs during approach
- Flexible mounting system design for adaptability across stations

} System Conceptual Design Mounting Location

ISS EXTERNAL PAYLOAD LOCATIONS

- ELC / ExPRESS Payload Adapters
- Columbus External Payload Facility
- JEM External Facility



Implementation on ISS

ISS EXTERNAL PAYLOAD LOCATIONS

	ELC / ExPRESS Sites	Columbus EPF	JEM - EF
Payload Mass Limit	227 kg	230 kg	500 kg standard 2500 kg heavy
Payload Envelope	34 in x 46 in x 49 in ($1\ m^3$)	34 in x 46 in x 49 in ($1\ m^3$)	73 in x 32 in x 39 in ($1.5\ m^3$)
Available Power	750 W	2.5 kW (shared)	3 – 6 kW

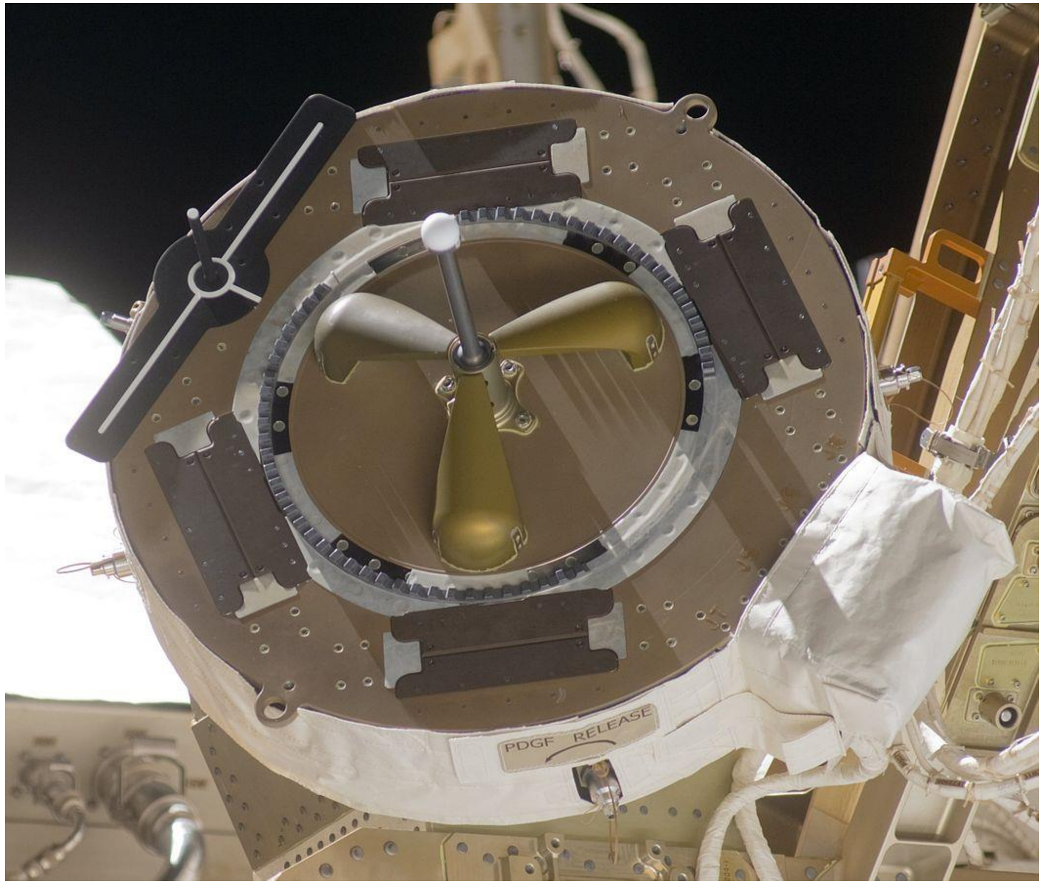
Too light

Very restrictive envelope

Additional problem: Poor viewing angles

INTERFACING TO ISS

- Utilize a Power Data Grapple Fixture (PDGF) for system mounting
  - Can supply power (~ 2kW), integrated data connection, **extensive use on ISS**
- Provides an easy, flexible interface between APS and station
- Installed at suitable location on ISS Integrated Truss Structure (ITS) to facilitate line-of-sight requirements



Implementation on ISS

POWER ANALYSIS

- Based off laser performance results
  - Laser electrical to optical efficiency: 32%

Phase	Maximum Laser Input Power (kW)	Waste Heat (kW)	Active Thermal Control (kW)	Battery Output Power (kW)
Cued Detection	44	30	14	58
Tracking	0.3	0.2	0.1	0.4
Ablation	28	19	9	37

Reasonable for Li-ion cell configurations

Implementation on ISS

BATTERY SIZING AND RECHARGING

- For each RSO interaction

Laser Input Energy	653 kJ
Active Thermal Control Energy	209 kJ
Total Energy Discharged Per RSO Interaction (30% margin)	1121 kJ
Total Battery Mass (Li-ion)	8.3 kg
Recharge Time (at 1.2 kW)	16 minutes

Remaining 800 W for keep-alive activities

VL 51ES 5p10s battery

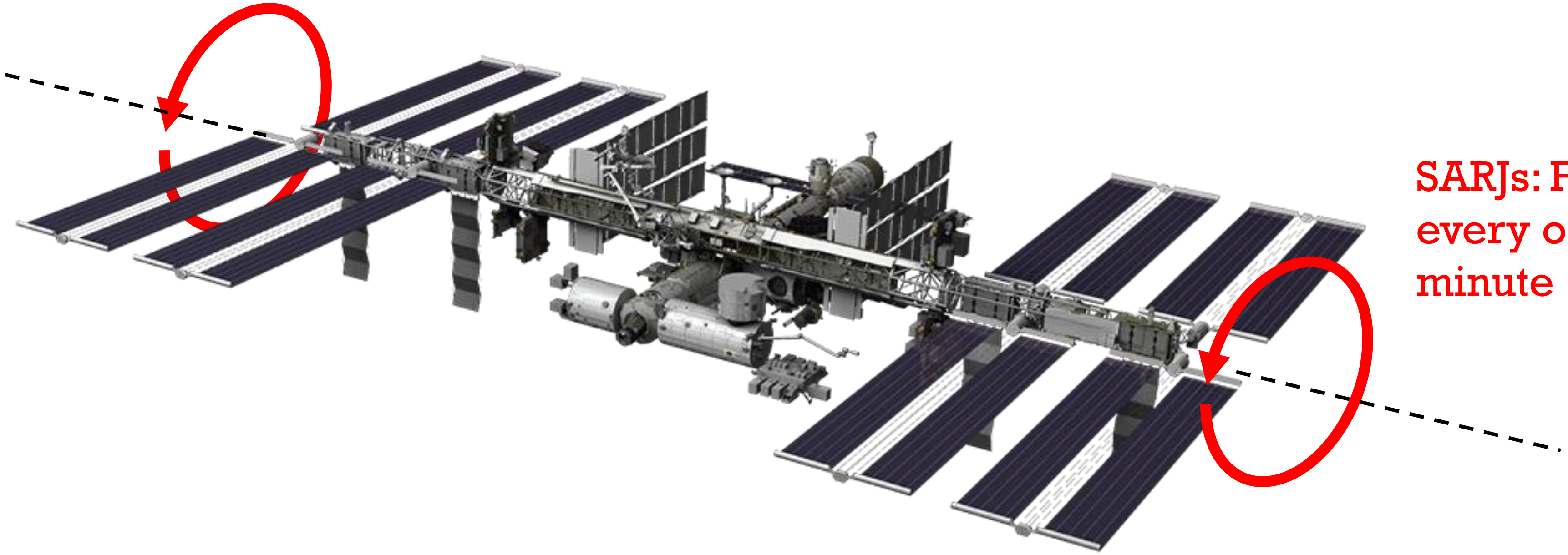
VL 51ES cell

Using commercial Li-ion cells: 125 WHr/kg

Implementation on ISS

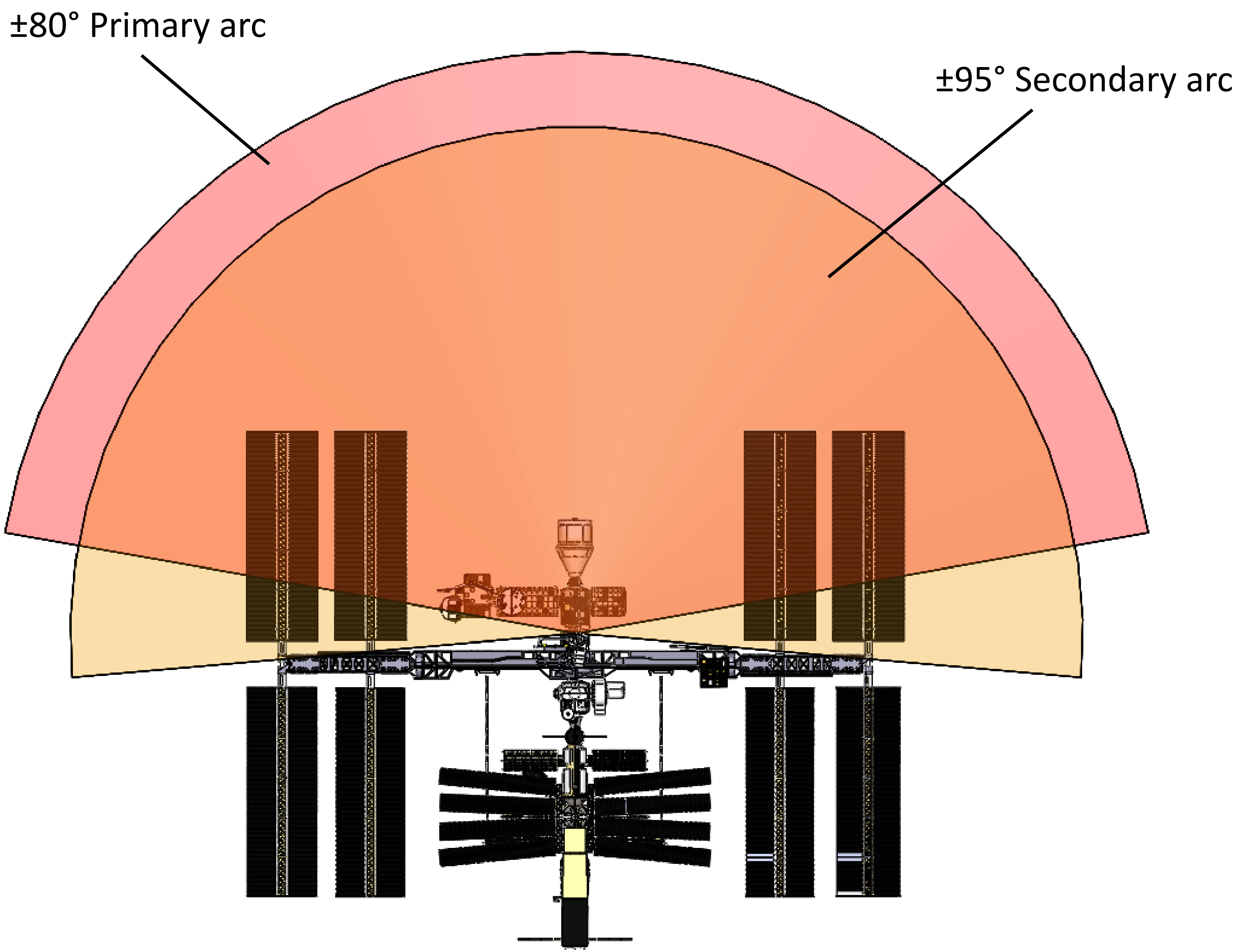
CONCEPTUAL DESIGN

- Optics mount requires rotation about two axes (Az and El) for precision pointing
- To avoid line of sight obstructions, APS positioning should be flexible
  - A robotic arm enables optimal positioning for **every unique encounter**
  - Longer arm permits more flexible response for every scenario (including off-nominal cases) but increases mass and system complexity



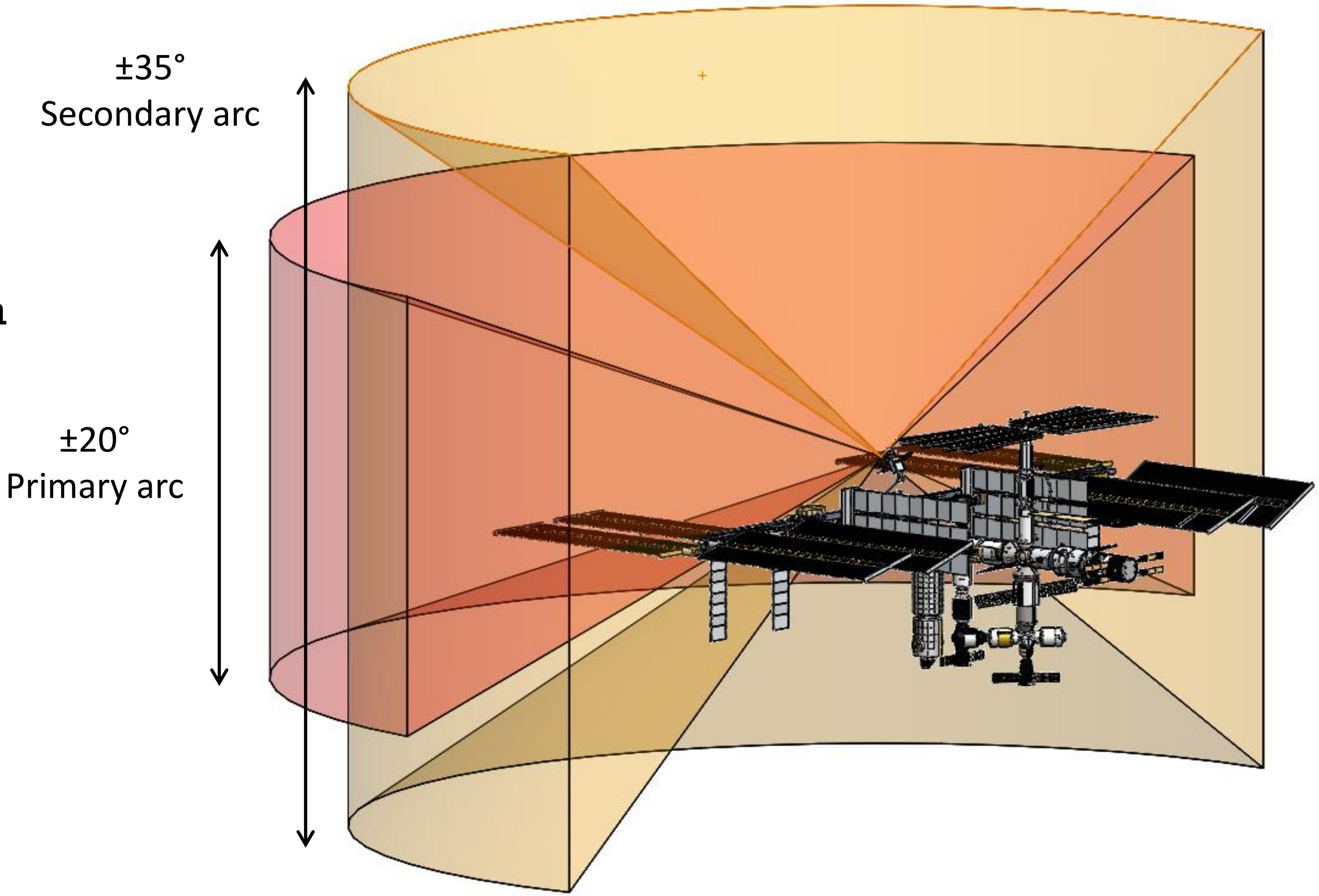
SARJs: Full rotation every orbit; 3.9° per minute

Line of sight requirements (with ±15° ISS attitude variations)

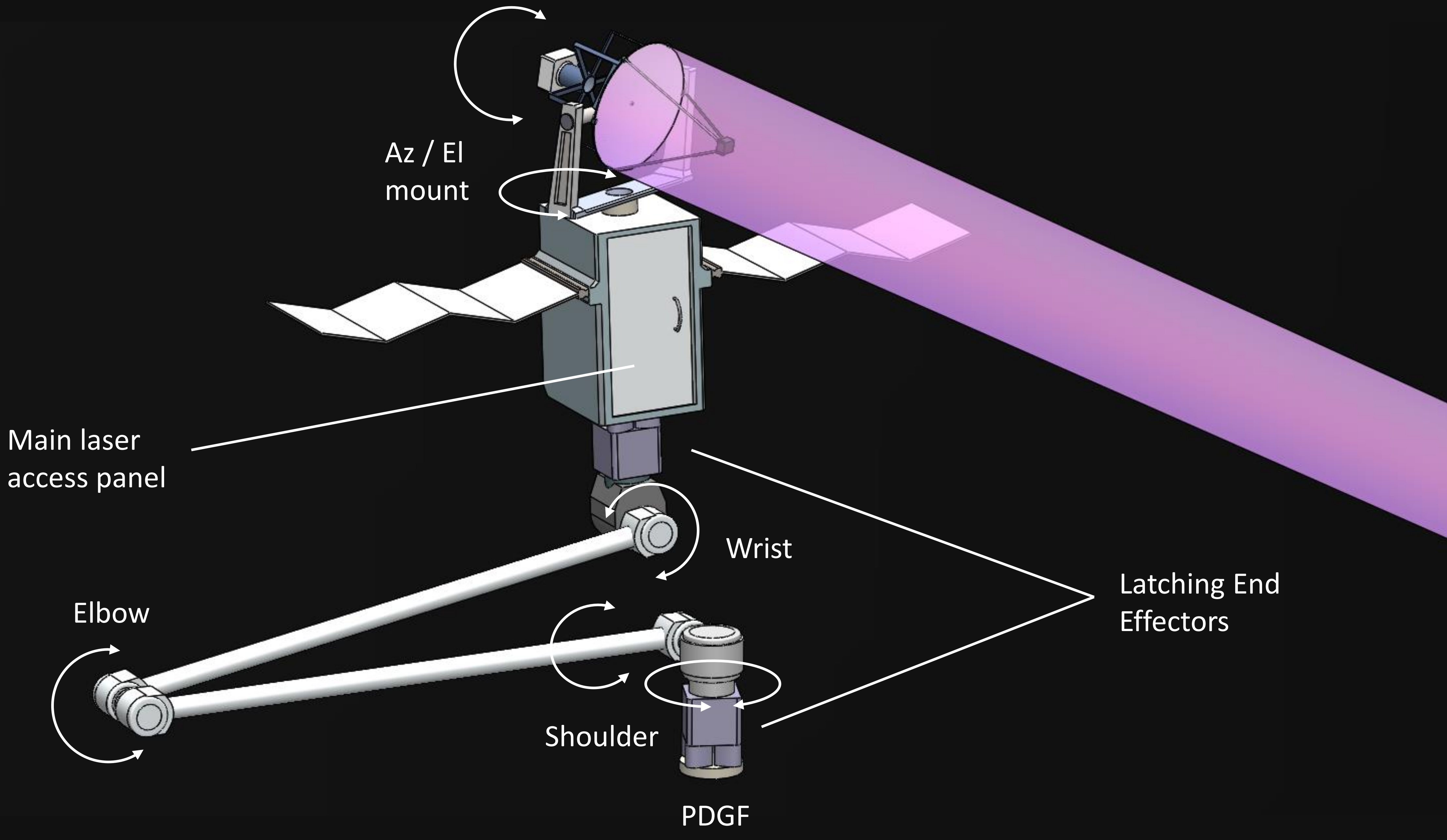


Implementation on ISS

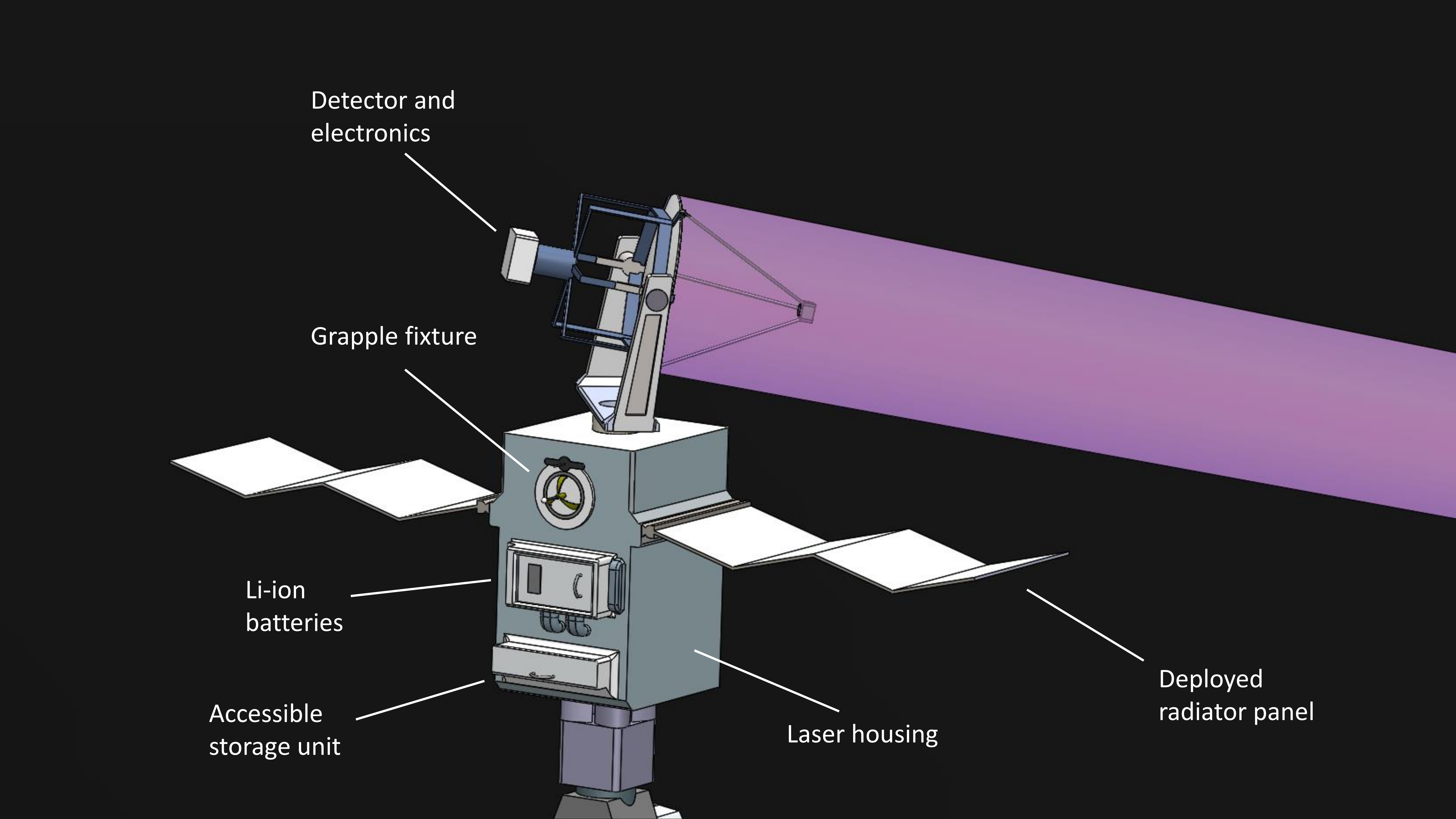
Line of sight requirements (with ±15° ISS attitude variations)

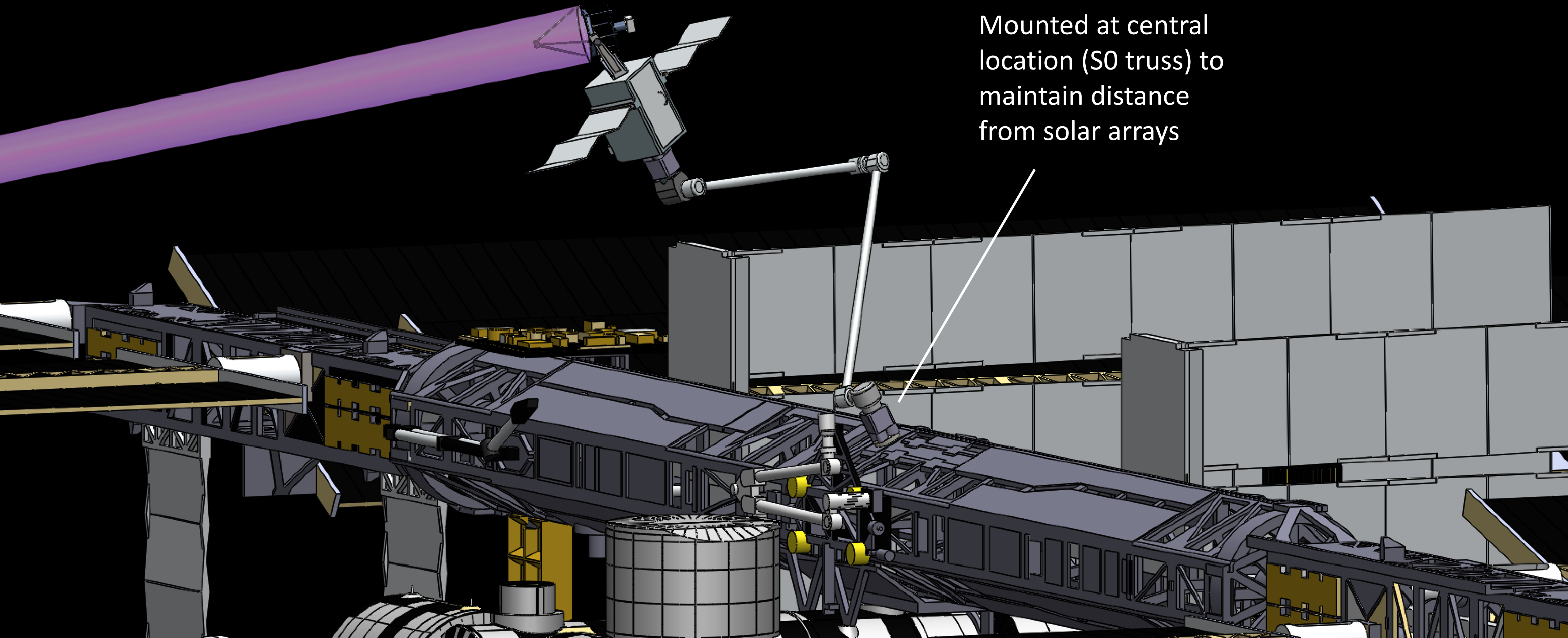


Implementation on ISS



Az / El
mount
Main laser
access panel
Wrist
Latching End
Effectors
Elbow
Shoulder
PDGF


Detector and
electronics
Grapple fixture
Li-ion
batteries
Accessible
storage unit
Laser housing
Deployed
radiator panel


Mounted at central location (S0 truss) to maintain distance from solar arrays

PRELIMINARY MASS BUDGET

* Values are ROM

Subsystem	Mass (kg)	Margin (%)	Totals (kg)
Structures and Mechanisms	1200	25	1500
Laser	1100	25	1375
Optics	35	15	41
C&DH	10	15	12
Thermal Control	1000	25	1250
Communications	30	15	35
PMAD	500	25	625
Total			4840
Uncertainty Factor (15%)			726
Final Mass			**5565**

Implementation on ISS

OPS TIMELINE

> 1 hr before engagement

- Calculate target vectors and APS positioning → Check for conflicts with ISS Ops timeline

< 30 min before engagement

- Prepare for real-time ground monitoring → Initialize APS and point to search direction → Place ISS in quiescent mode / enact thruster inhibit → Enable laser operation

During engagement

- Human-on-the-loop monitoring of APS activity

After engagement

- Place APS on standby / power down sequence → Systems check and return APS to keep-alive activities → Take ISS out of quiescent mode / remove thruster inhibit

Implementation on ISS

CONTINGENCY SCENARIOS

Scenario	Possible Actions
RSO on possible impact trajectory upon detection	1. Provide crew with advance warning (tens of seconds) 2. Estimate most likely location of impact
ISS in attitude other than +XVV / Obstructed line of sight	1. Change APS positioning 2. Engage at different times in RSO trajectory (previous orbit cycles) 3. Relocate APS onto MBS and translate to different position on truss
Off-nominal RSO trajectories	1. Use APS for orbit modification instead of deorbiting 2. Conduct collision avoidance maneuvers
Expected APS operational time conflicts with ISS Ops timeline	1. Determine if relocating APS (via MBS) enables conflict to be resolved 2. Engage at different times in RSO trajectory (previous orbit cycles) 3. Revise ISS Ops timeline

Summary

- Cm-sized debris present an evolving issue not properly addressed today
- APS is a pulsed laser optical system that can be used to defend space stations from these threats
- Applicable to different stations / orbits in LEO

Future Research...

- Assessing system parameters for off-nominal RSO trajectories
- Maturing high energy lasers for use in space environment
- Commercial usage (ie: GEO satellite tracking service)
- Political / legal implications

Pentagon Wants to Test A Space-Based Weapon in 2023

Defense officials have asked for $304 million to fund research into space-based lasers, particle beams, and other new forms of missile defense next year.

Thank You! Questions?

Backup Slides

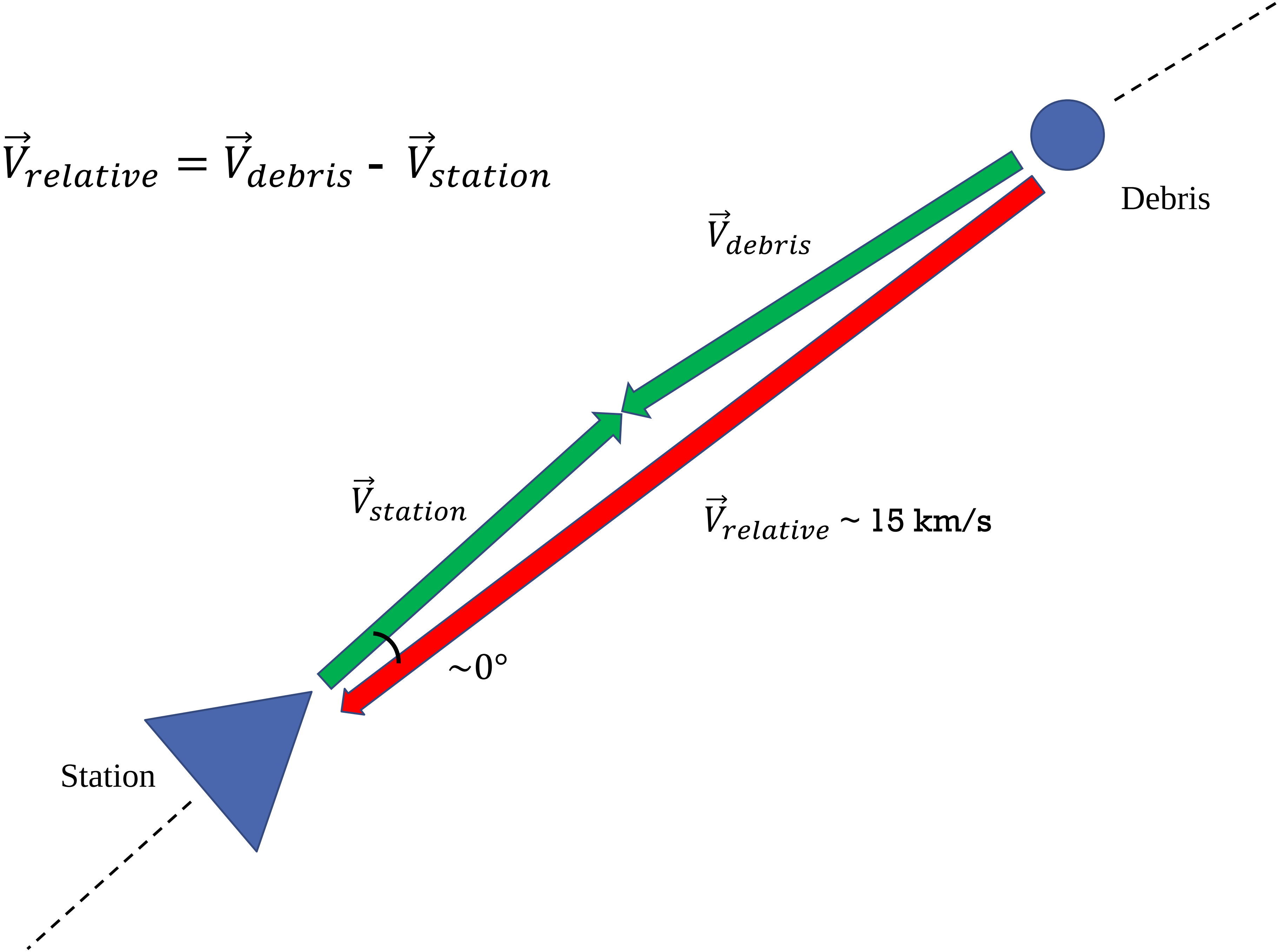
THE LEO ENVIRONMENT

- Over **900,000** Resident Space Objects (RSOs) >1 cm (~ 2000 active satellites)
- Highest RSO spatial density in LEO
- RSO population will continue to rise
  - Increased LEO usage (mega-constellations)
  - Increased collisions: "Kessler Syndrome"
- Impact with RSOs >1 cm is typically **fatal**

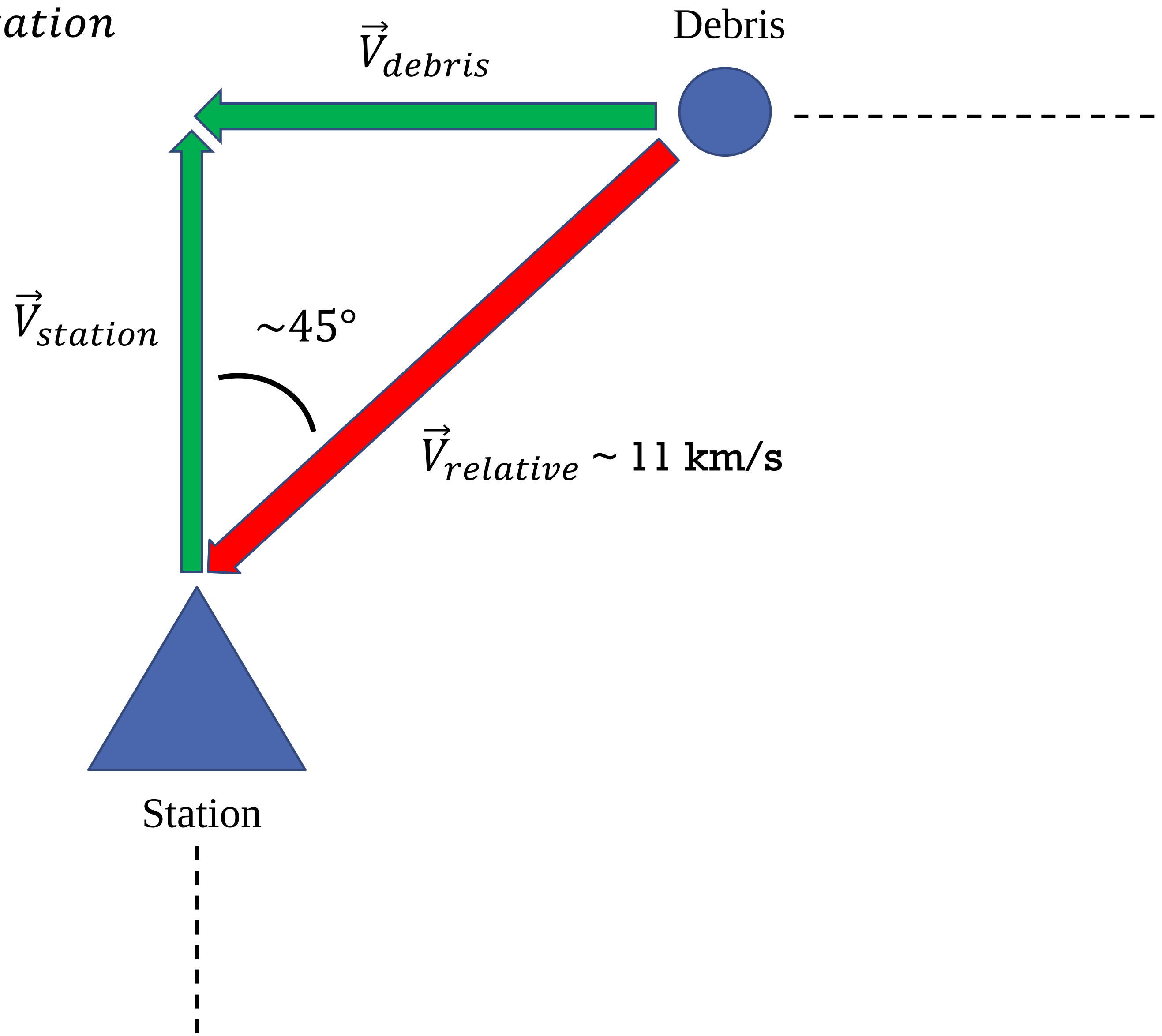
SPACE SURVEILLANCE

- Approx. **4%** of LEO RSO population tracked by U.S. Space Surveillance Network (SSN)
- For LEO coverage, Phased Array Radars used:
  - Current capabilities: RSOs down to **~10 cm**
  - U.S. SSN public catalog: **~23 000 tracked objects**
- Future SSA capabilities:
  - RSO tracking down to **~2 cm**
  - Expected catalogue growth: **>250 000 tracked objects**

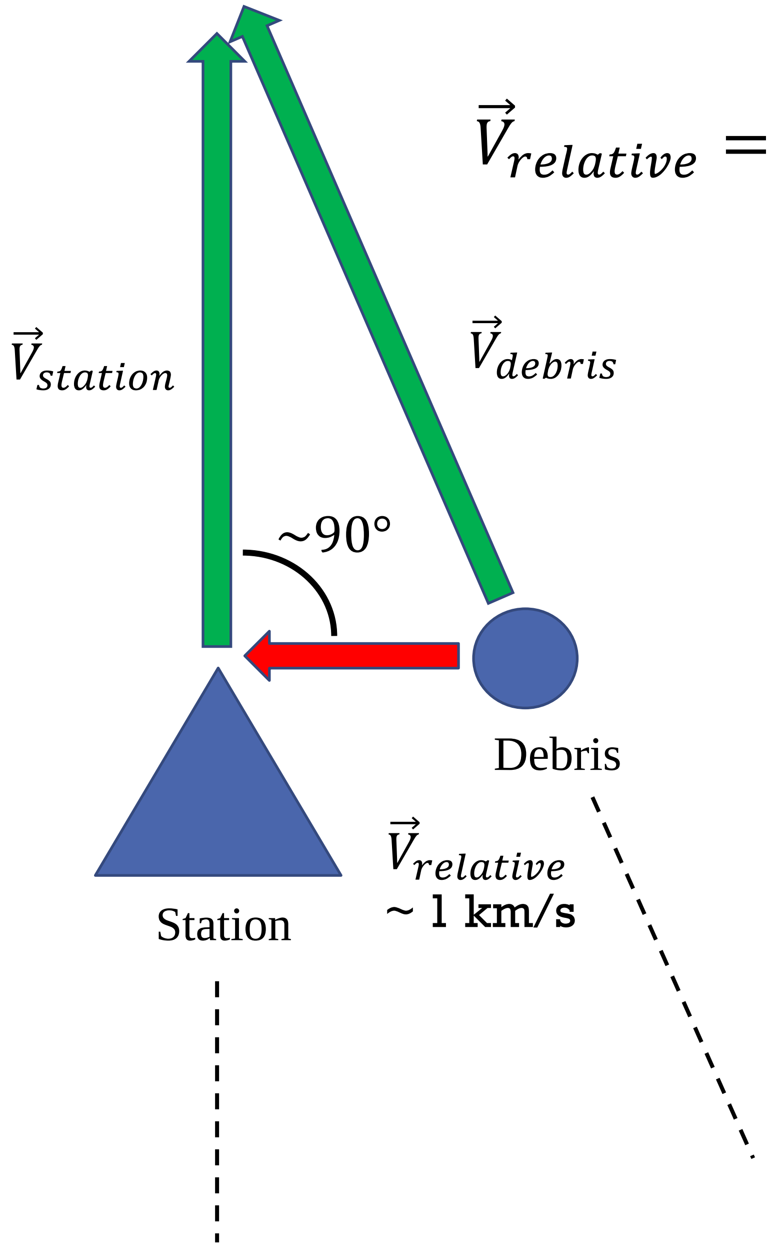
$$\vec{V}_{relative} = \vec{V}_{debris} - \vec{V}_{station}$$

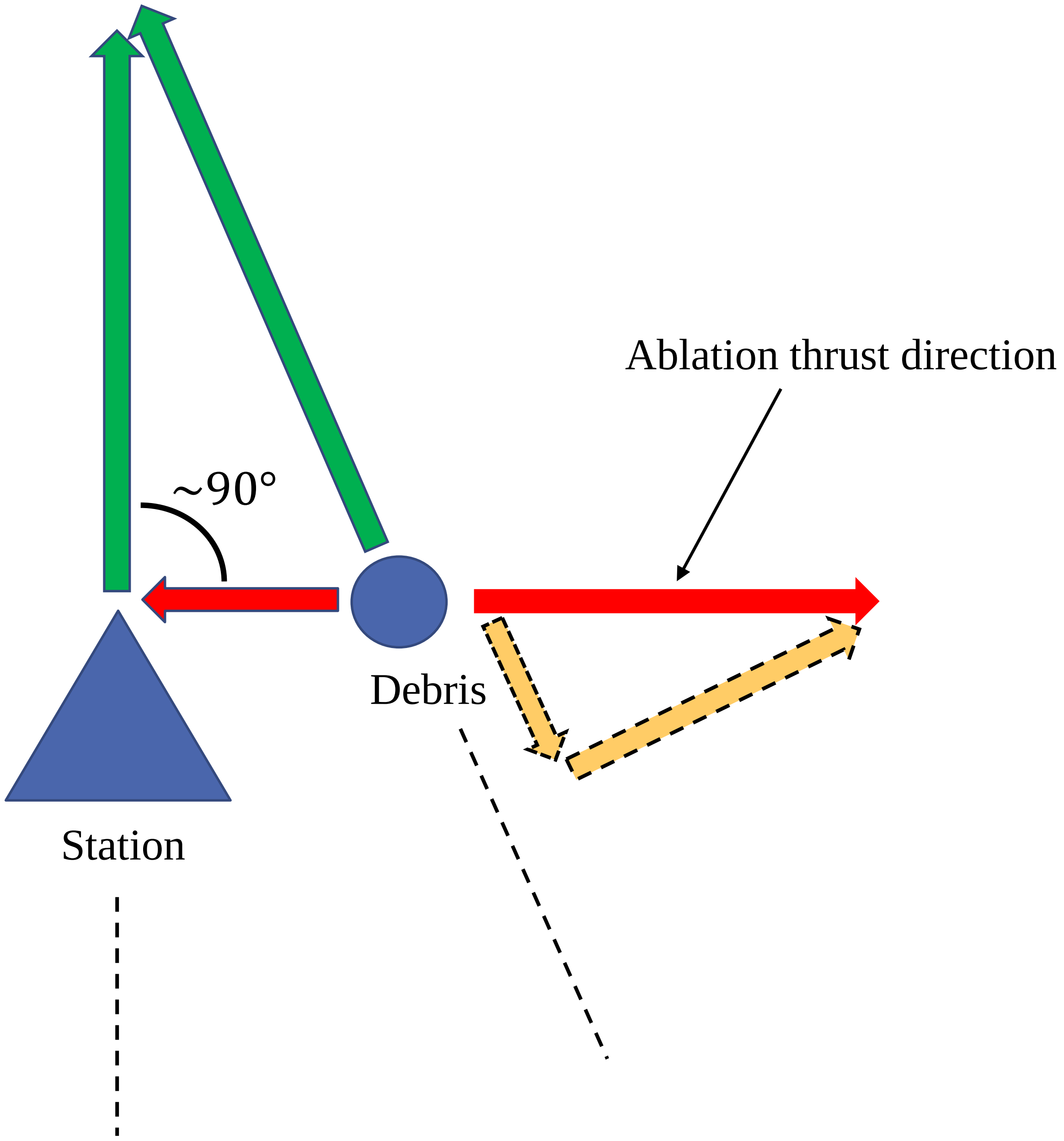


$$\vec{V}_{relative} = \vec{V}_{debris} - \vec{V}_{station}$$



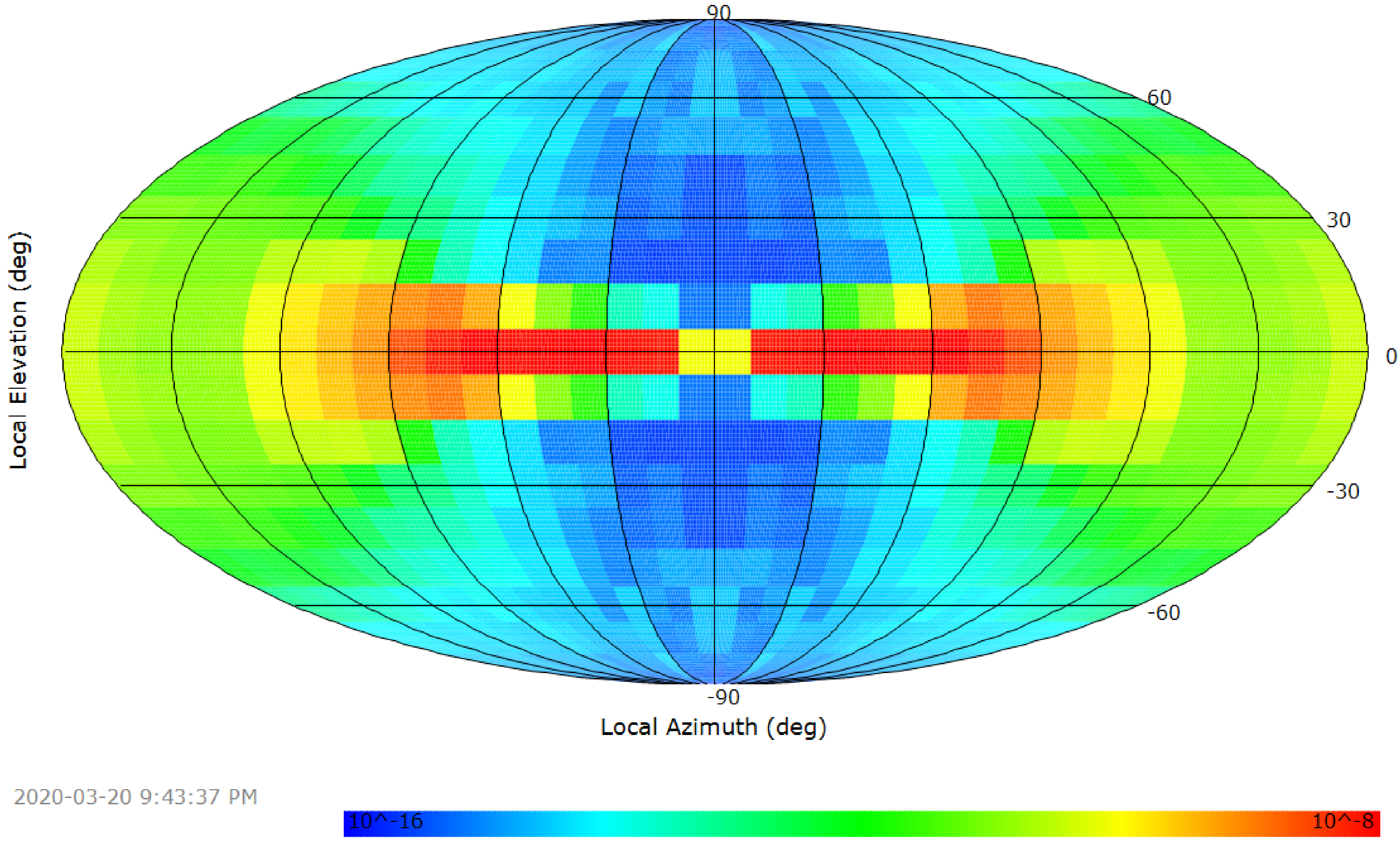
$$\vec{V}_{relative} = \vec{V}_{debris} - \vec{V}_{station}$$



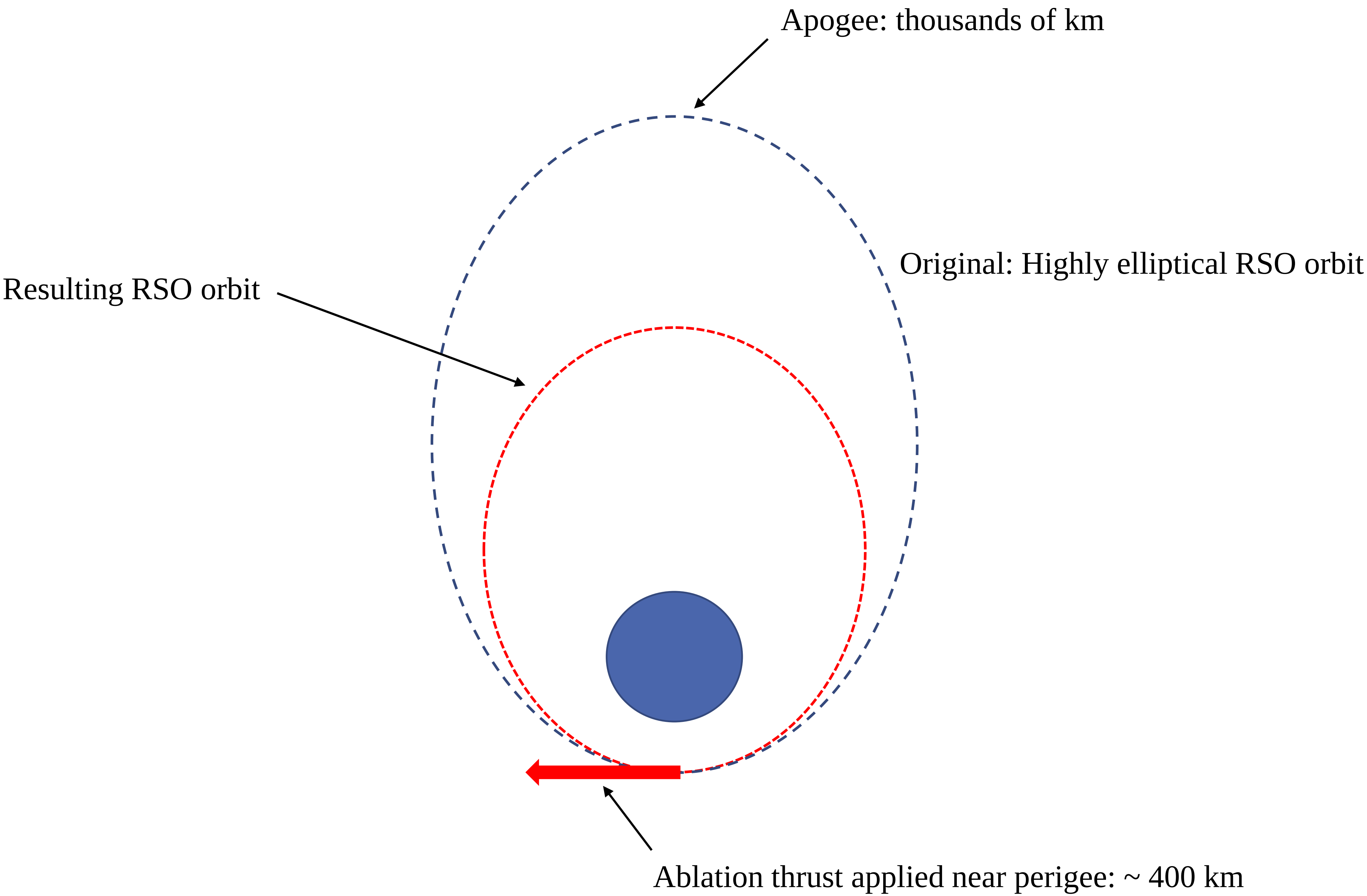

Ablation thrust direction
~90°
Debris
Station

2-D Directional Flux

Year: 2030 Perigee Altitude = 400.000 Apogee Altitude = 400.000 inc = 51.60 particle size = >1cm



2020-03-20 9:43:37 PM


Apogee: thousands of km
Original: Highly elliptical RSO orbit
Resulting RSO orbit
Ablation thrust applied near perigee: ~ 400 km

TRADE STUDIES: DETECTION AND TRACKING

- Continuous uncued detection
- Scanning through all RSO approach angles
- Sensitivity to detect cm sized RSOs at hundreds of km

Criteria too difficult to meet practically

Candidate Methods (Space-based)	Optical	Radar	Laser Optical
Type	Passive	Active	Active
Characteristics	Wide FoV camera	Phased array radar; mmWave bands	Scanning LiDAR; Flash LiDAR; Hybrid
Mass	Hundreds of kg	Thousands of kg	Thousands of kg
Power	Minimal	>> kW	≥ kW
Limitations	System dependent on solar illumination	Heavy phased array antenna; Very high power requirements	Heavy laser and optics system; Complex mechanical design

Too much power required for continuous operations

Restricted operational times

Proposed System

TRADE STUDIES: RSO REMEDIATION

- Eliminate or deflect incoming RSOs
- Act on small RSOs at long range (hundreds of km)
- Act over short timescales (seconds)

Only laser-based methods are feasible

Candidate Methods (Laser-based)	Laser Photon Pressure	Continuous Wave (CW) Laser Ablation	Pulsed Laser Ablation
Action	Orbit Modification	Vaporization / Orbit Modification	Orbit Modification
Acting timescale	Long; Days – Months	Short	Short
Comments	Applied forces too small; only useful for long term orbit perturbation	Requires too much energy; Messy ablation process creating debris; Unreliable impulse generation	Good momentum coupling; No generation of new debris; Moderate energy requirements

Long timescales only

Messy and unreliable

Only suitable choice

Proposed System

RSO INPUT PARAMETERS

Local Azimuth (Az)	Local Elevation (El)	Relative Velocity (km/s)
0°	0°	15.4
15°	0°	14.9
30°	0°	13.4
45°	0°	11
60°	0°	7.9
75°	0°	4.4