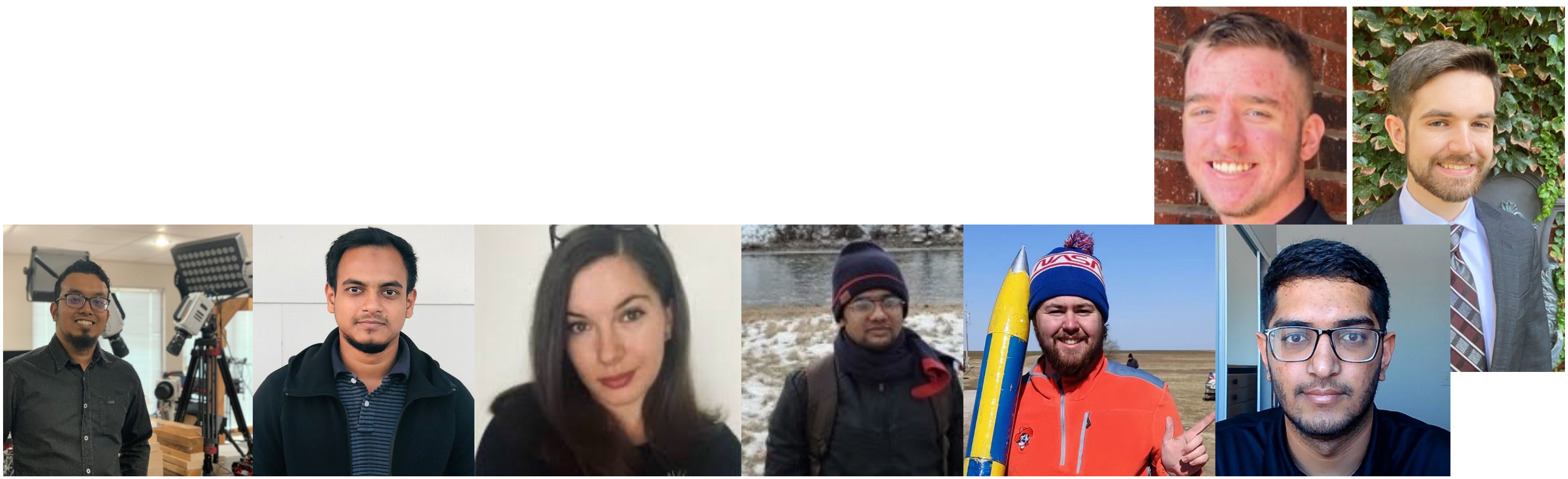
Active debris removal: perception, remediation, and quantification

Imraan A. Faruque (Oklahoma State University)



UAS R&D at OSU: 1997, 2011

2011
Pylon
Racer

2012
Vertical TO

2013
Fast Mover, Payload
Delivery

2014
Glider Insertion

2015
Autonomous Rover
Deployment

2016
Jet Powered Trainer

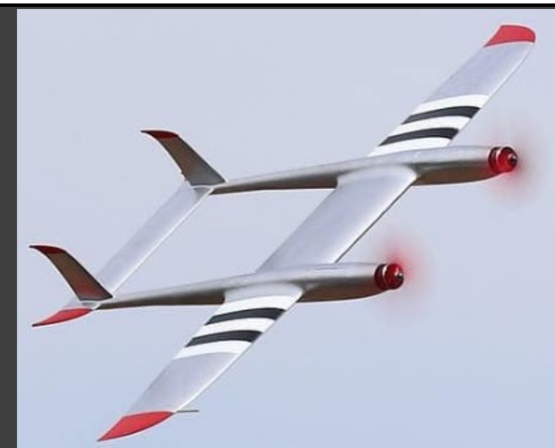
2017
Jet Powered Low
Observable Fast Mover

2018
Jet Powered, Low Observable,
Payload Deployment

2019
Jet Powered, Fast Attack,
Sensor Deployment

2020
Jet Powered, High Speed,
Fuel Efficient

2021
Jet Powered, Fast Mover,
High G



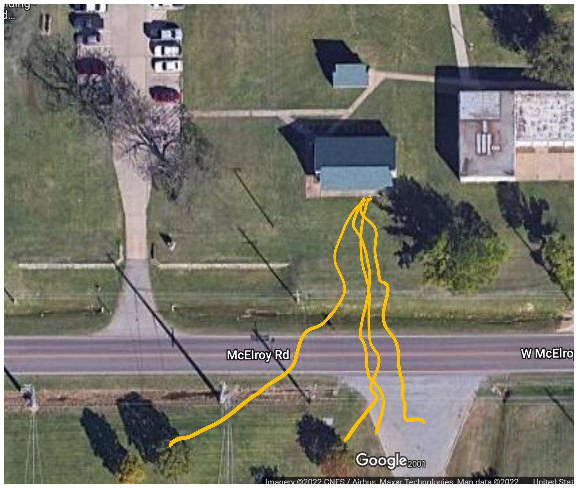
2022
Drag Racer, Short TO & Land

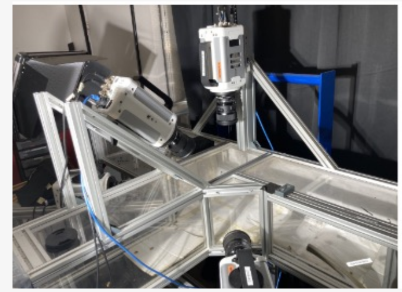
2023
High Speed SRM-Electric
Racing UAS

April 27, 2024

Insect swarming rules for onboard formation

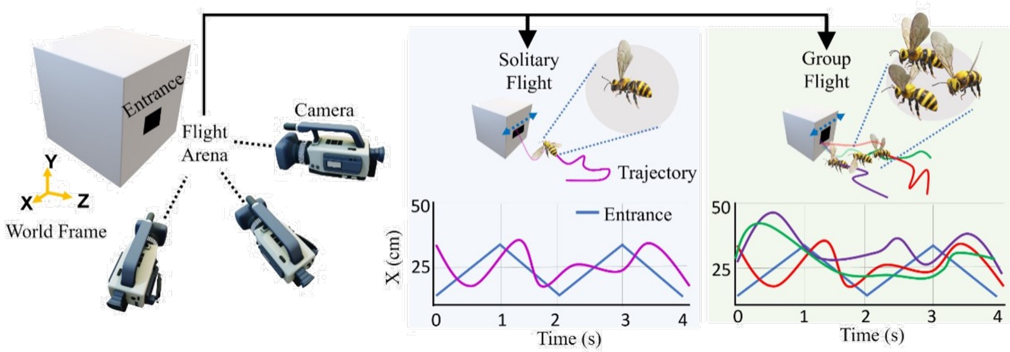
Insects transition from solitary foraging to crowded flight

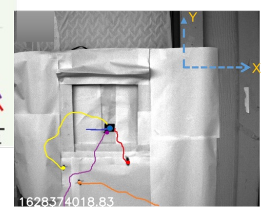


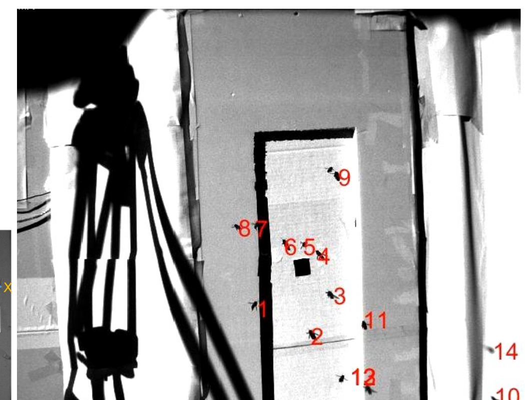


Inside the lab: *first* high speed measurement in crowded group flight (1st measurements, ethanol influence)

Outdoor instrumentation: moving targets and real-time tracking







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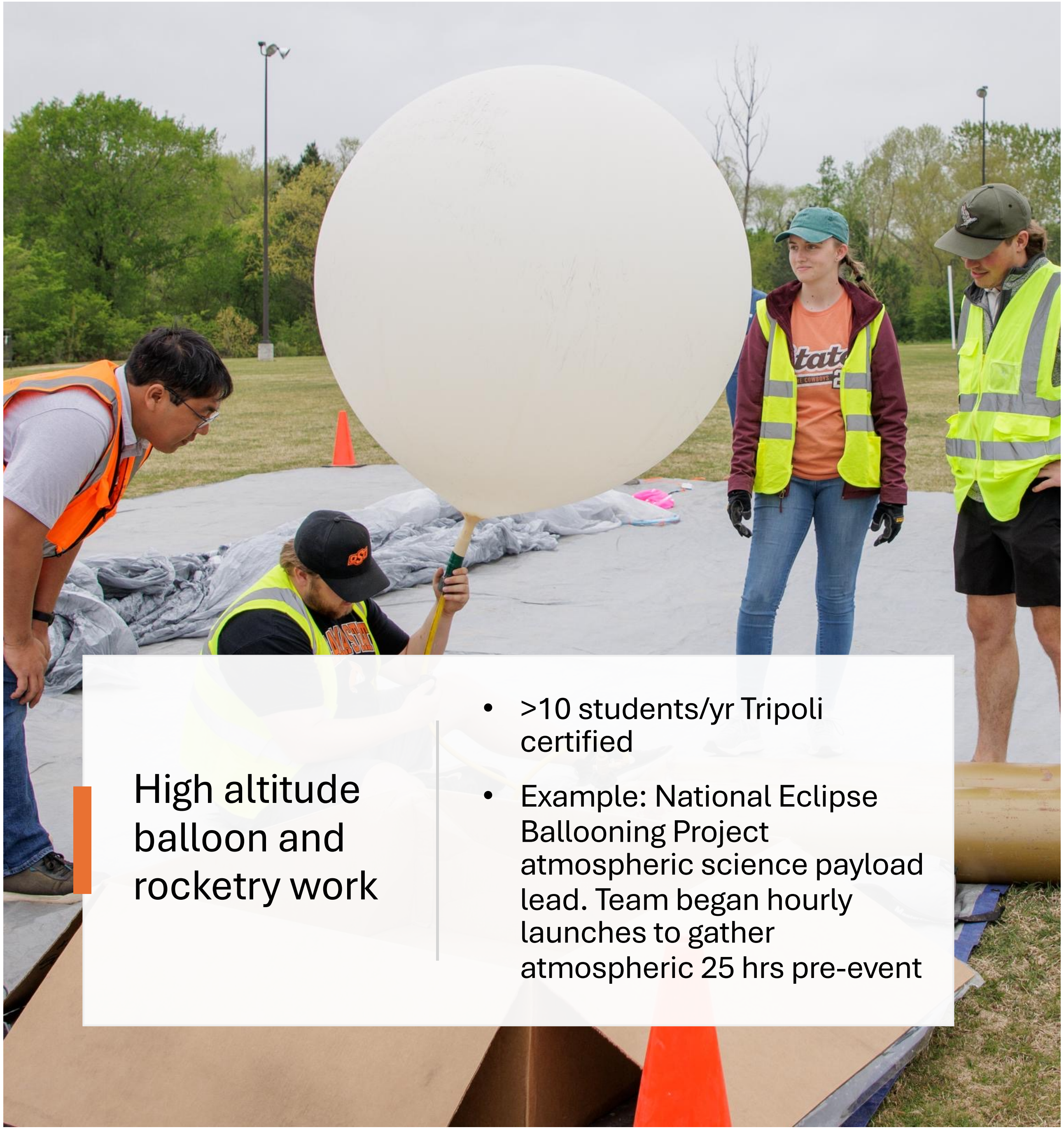
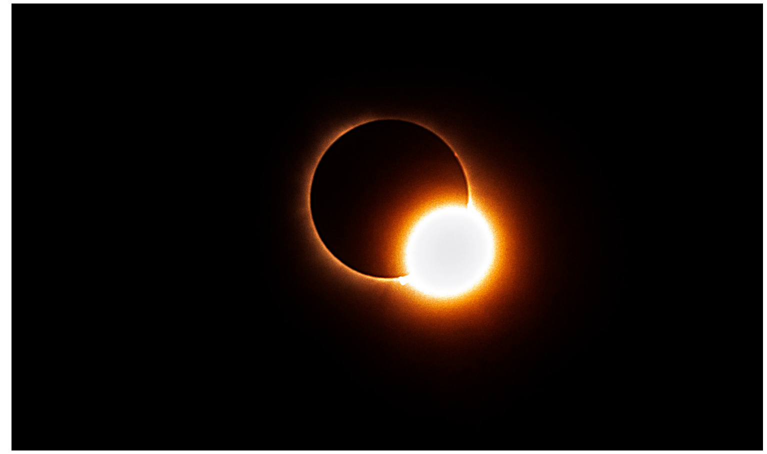
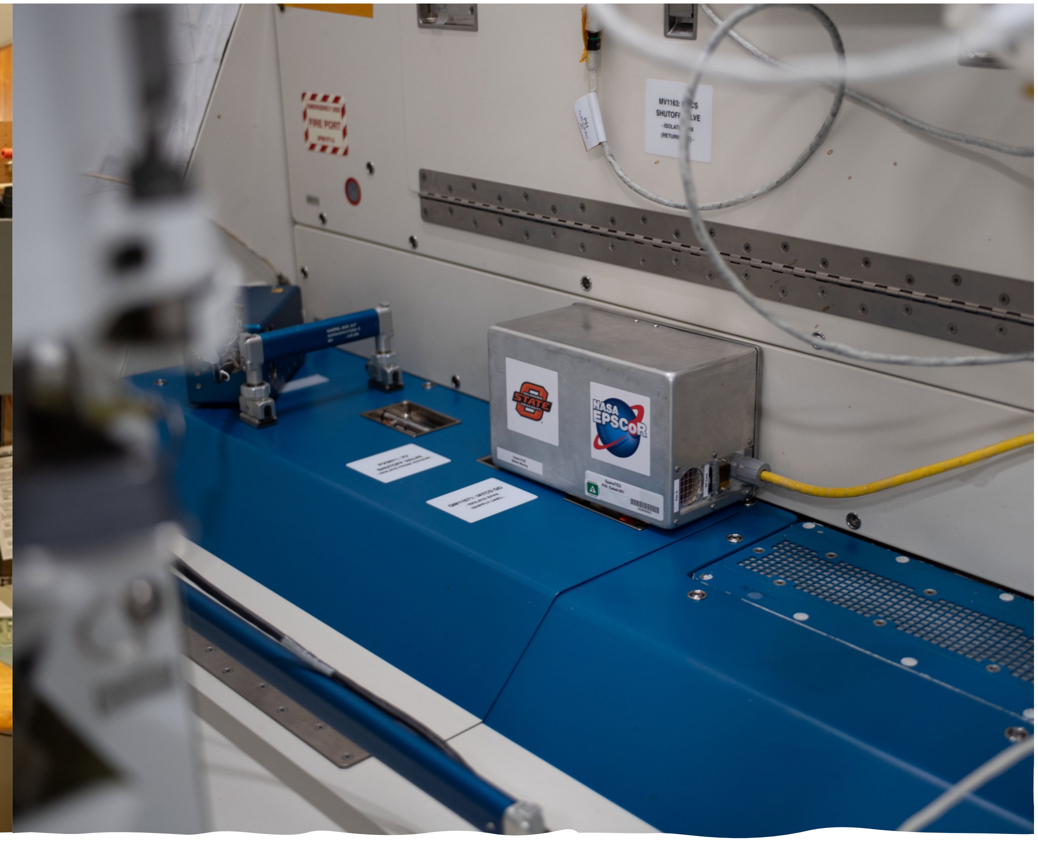


High altitude balloon and rocketry work

- >10 students/yr Tripoli certified
- Example: National Eclipse Ballooning Project atmospheric science payload lead. Team began hourly launches to gather atmospheric 25 hrs pre-event

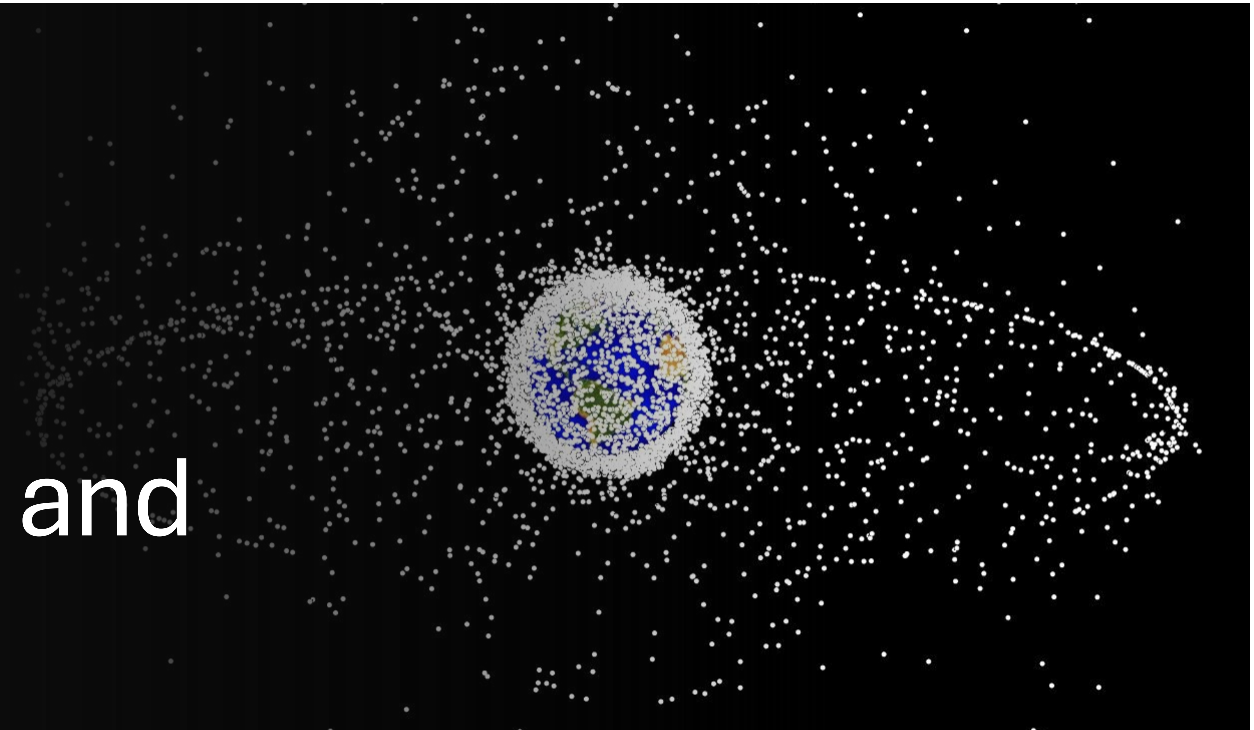




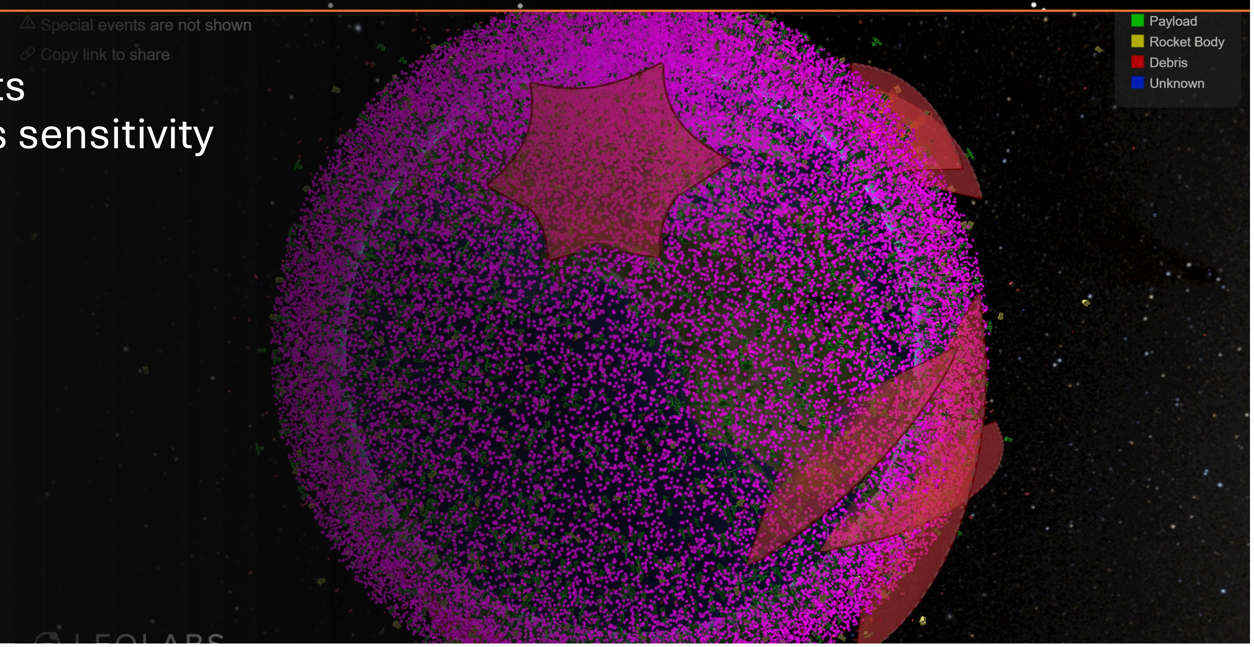
Active tissue equivalent dosimeter

- Onboard ISS now (launched December 2023)
- Previous version launched in 2018 (failed due to impulsive impact). This version is in a less trafficked section

Orbital debris and risk levels



The orbital debris environment, its associated risk levels, and debris sensitivity for future commercial plans



Statistical risk levels and events

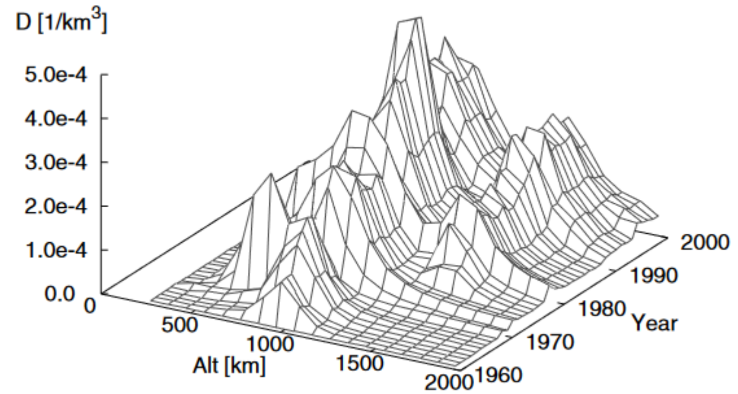
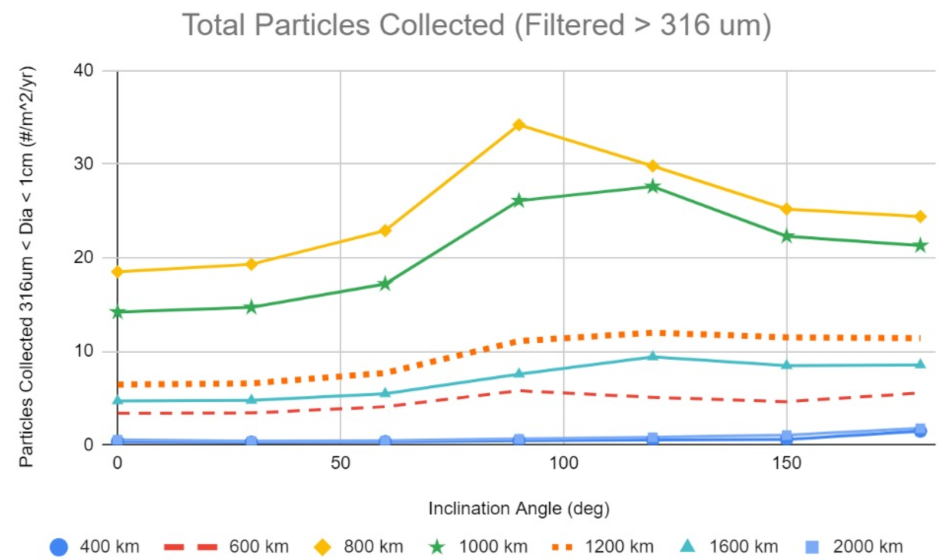


Fig. 3.19. Spatial object density versus altitude and year for objects of $d > 1$ mm according to the MASTER-2001 model.

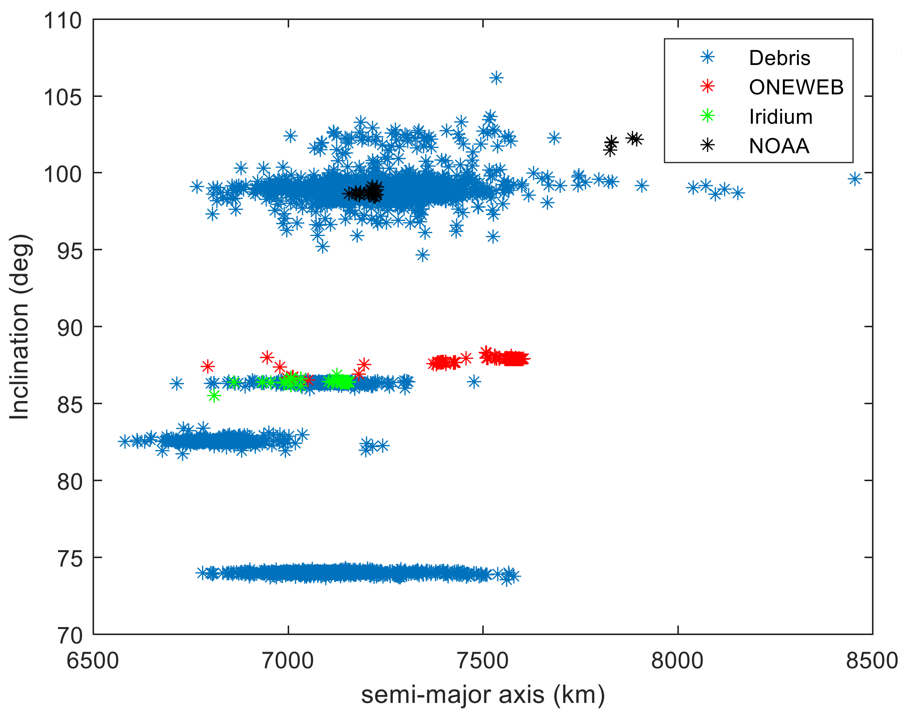


NASA TIMED (625km, i=74.1) and Russian Cosmos 2221 (ex e-SIGINT) Approached within 33ft (10m) on Feb 28, 2024

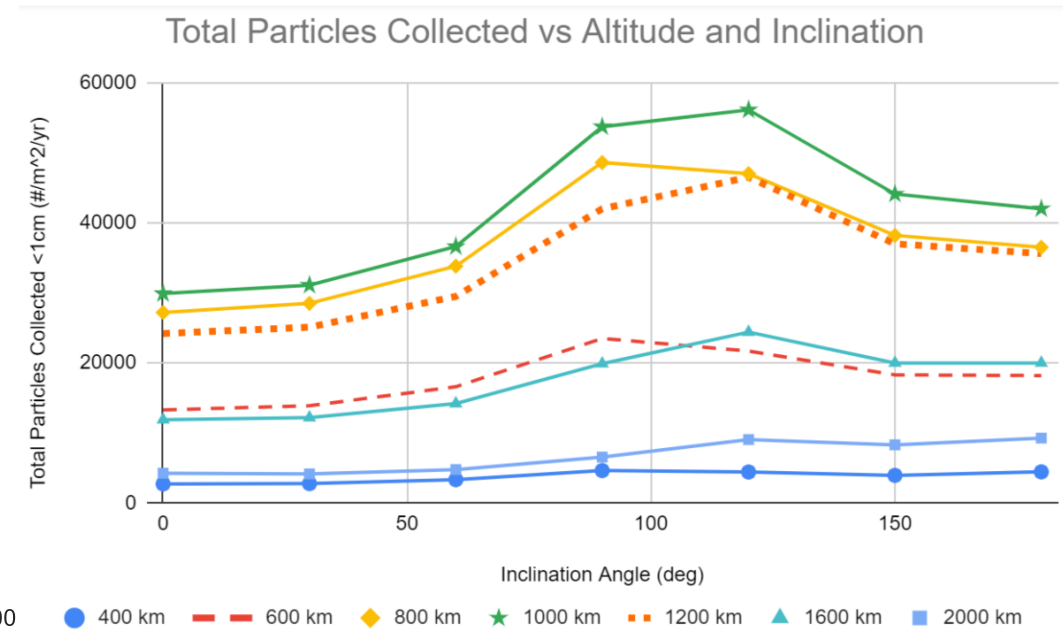
"…very shocking personally, and also for all of us at NASA…really scared us all." NASA Deputy Administrator Pam Melroy

Patrick Williams
(alumnus @ NASA Johnson)

Where is the debris?



Measured debris



Modeled debris

Peak debris density is at

- 90-120° inclination (near-polar orbit)
- 1000km ±200km altitude
- Category 2 (1-10cm particles) present particular risk, due to having low visibility and enough energy to cause substantial spacecraft damage

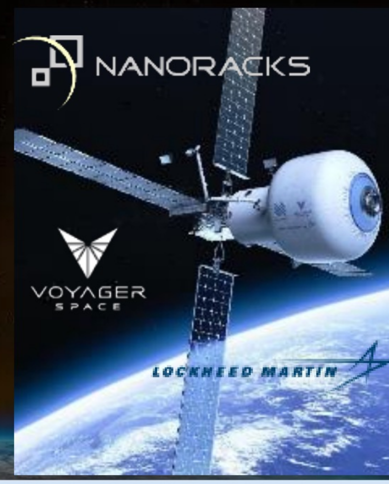
COMMERCIAL LOW-EARTH ORBIT DESTINATIONS

Hab PDR: 2021
Hab CDR: 2022
Transition to Free Flyer: 2028

- Axiom concept initially attaches Commercial Elements to ISS Node 2 Forward Port.
- Launch of first element is planned for 2024.
- Additional modules are added later, including a Power Thermal Module allowing the spacecraft to detach from ISS and operate as a free-flyer.

PDR: 2023 & CDR: 2024
Baseline Configuration: 2027
# of crew initially: 10

- Orbital Reef baseline provides for a permanent presence in space with 90% of ISS's volume, capacity for 10 astronauts, and multiple internal and external payloads.
- Point of departure orbital destination is at a 51.6° inclination and 500+ km altitude to optimize future transfer from ISS and match Earth-observation benefits.



PDR: 2023 & CDR: 2025
IOC: 2027
# of crew at IOC: 4

- Starlab is a large inflatable habitat and a metallic docking node, power and propulsion element, and external robotic arm.
- Four main operational departments: biology lab, plant habitation lab, physical science and materials research lab, and an open workbench.

PDR: 2025
IOC: 2029
# of crew at IOC: 4

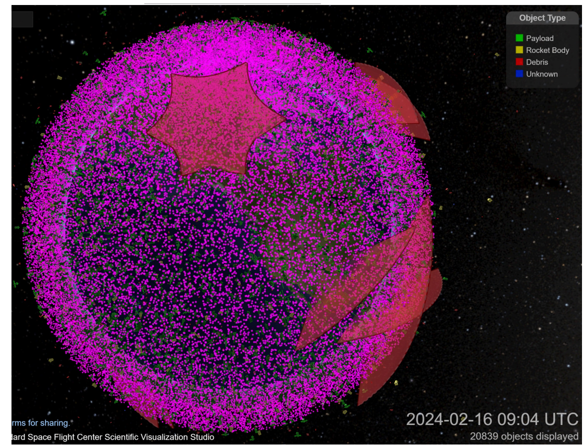
- NG platform provides for a permanent presence of four crew approximately 30 days after launch of Element 1.
- Habitat Modules derived from Habitat and Logistics Outpost (HALO) and Cygnus structures and subsystems and are equipped as permanent crew habitat and cargo modules.

Where is debris most hazardous?

Altitude/Persistence

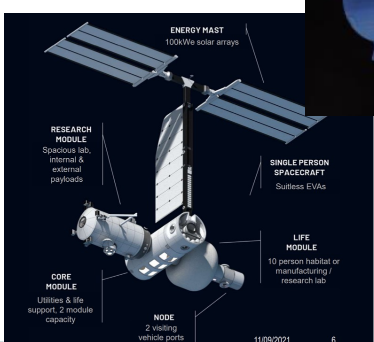
Altitude	Deorbit time
200km	1 day
300km	1 month
400km	1 year
500km	10 years
700km	100 years
900km	1000 years

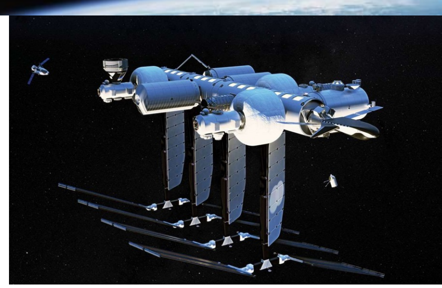
Inclination angle



Visibility

GBR >10cm





Risk to human spaceflight

- **ISS ZARYA**: h=370-460km, e=0.00067, 15.721 rev/day, i=51.6 deg
- **AXIOM** segment/station: ~ISS-like orbit, circa 2026
- **Orbital Reef** (Sierra/BlueOrigin): h=~500km, i=51.6deg (ISS salvage tug), SDR 2022, operation 2027
- **Starlab** (Nanoracks/Voyager/LM): similar to ISS, Circa 2028
- **HAVEN** (vast): h=500km, i=51.6deg, Circa 2025

Space at 500km will be less hospitable: both more impacts from small untrackable debris and more collision avoidance maneuvers

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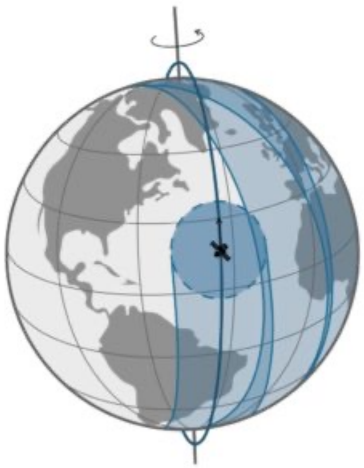
Satellites in polar orbit debris field



Polar orbits: image earth 2x/day

Altitude	Inclination	Name	Quantity	Notes
550km	53.2deg	Starlink	5289	
653km	98°	LANDSAT NEXT	3	120° spacing
705km	98.2°	LANDSAT 8,9	2	8 total in orbit
709km	98.21°	TERRA		
780km	86deg	Iridium	66	11 satellites in 6 planes with 30° spacing (long)
830km	98.79°	NOAA-20		
804km	98°	WSF-MW		
830-870km	98.79,98.70°	NOAA POES	5	
832km	98.7°	SPOT	7	
833km	98.74°	SUOMI NPP		
917km	99°	LANDSAT 1		
1200km	42,55,87.9deg	OneWeb	1200-6372	

	NOAA-12	NOAA-14	NOAA-15	NOAA-16
Launch date	14 May 1991	30 Dec 1994	13 May 1998	21 Sep 2000
Date operations began	17 Sep 1991	10 Apr 1995	15 Dec 1998	20 Mar 2001
Orbit inclination	98.5	99.1	98.6	98.8
Mean altitude (km)	808	847	810	851
Equator crossing time (A: Northbound, B: Southbound)	16:49A, 04:49D	17:52A, 05:52D	19:08A, 07:08D	13:54A, 01:54D
Period (min.)	101.2	101.9	101.2	102.1

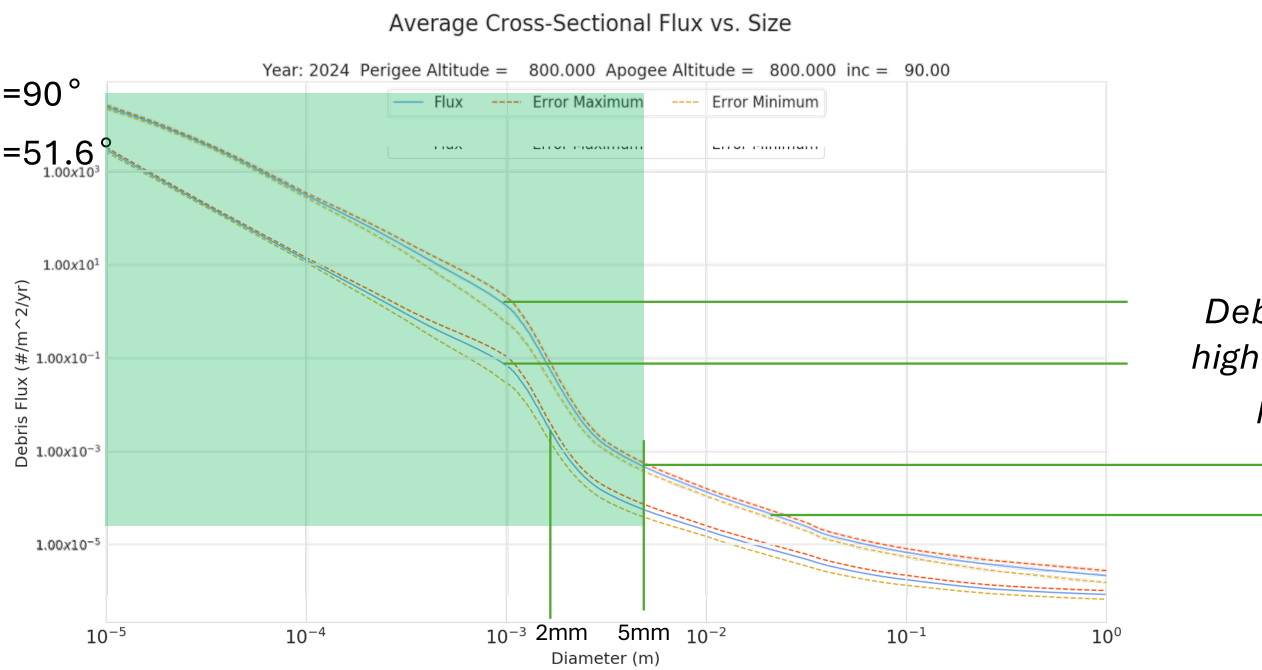
Most of these are imaging satellites in sun-synchronous orbits in 600-800km synchronized to a down or dusk region for visibility. The most desirable region is 700-800km. IE, this is valuable orbital space

Ref: "Implications of Ultra-Low-Cost Access to Space

Debris comparison across candidate orbits

800km, i=90°

500km, i=51.6°



Debris flux is 10x higher in the larger polar orbit

There is 1/10th the debris at 2cm as there is at 5mm

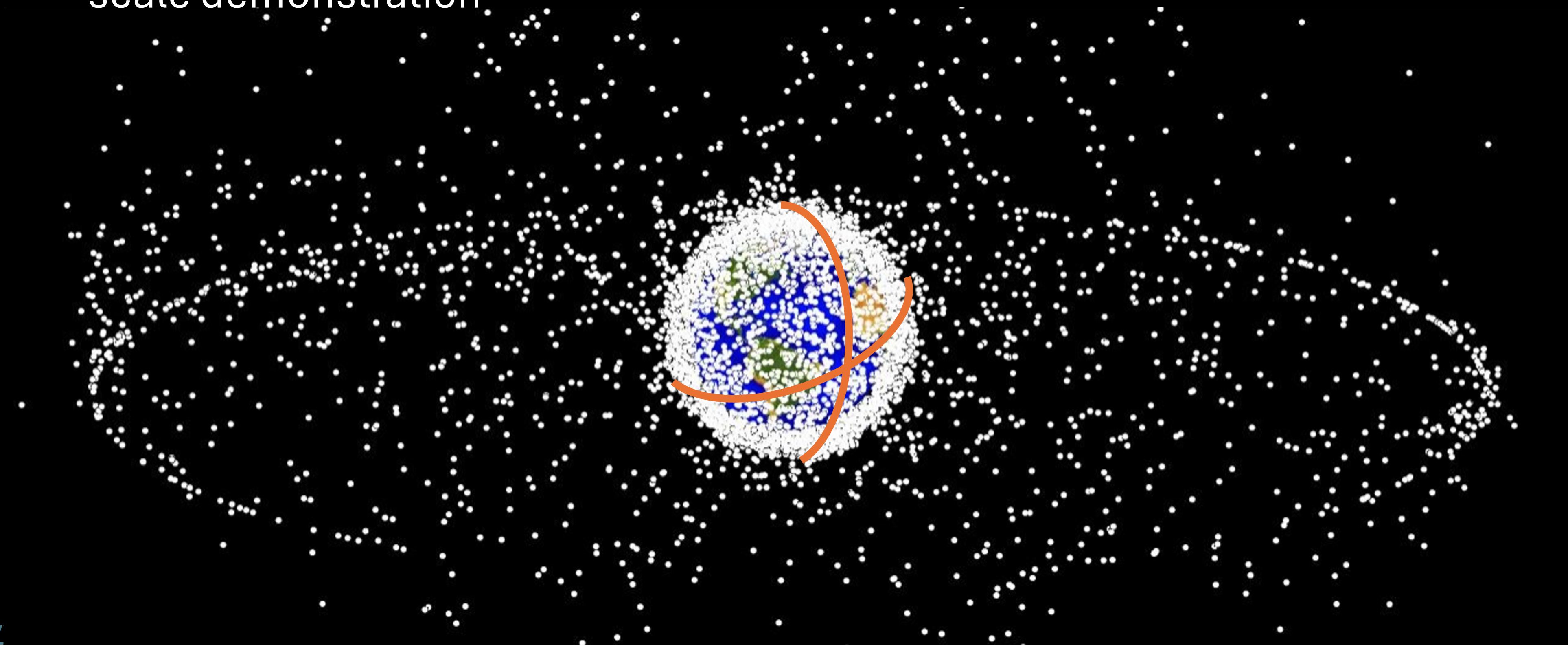
Inflection point centered at 2mm

Candidate 5mm

Debris in 500km orbit persists about 10 years while debris in the 800km orbit persists ~800 years

Mission:

- Smallsat: Field an orbital debris deployable collector at 800km & 500km orbits capable of collecting cm-scale debris at 7-10km/s
  - Fixed inclination per mission (fuel)
- Cubesat: Reduce measurement uncertainty via quantification and sub-scale demonstration



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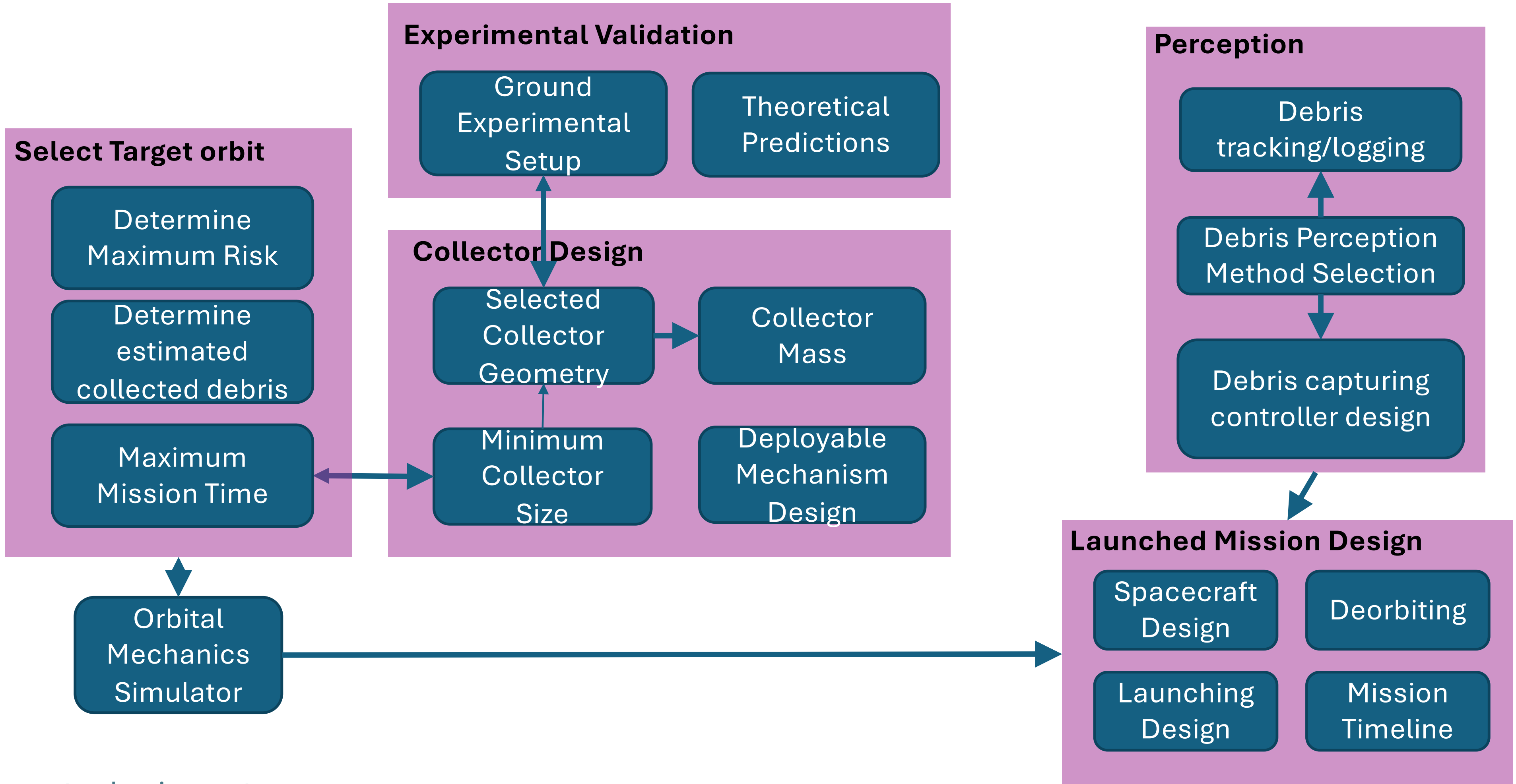
Overall Workflow



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In orbit perception & control

(a) Optical perception, (b) deltaV from debris, and (c) debris-relative control

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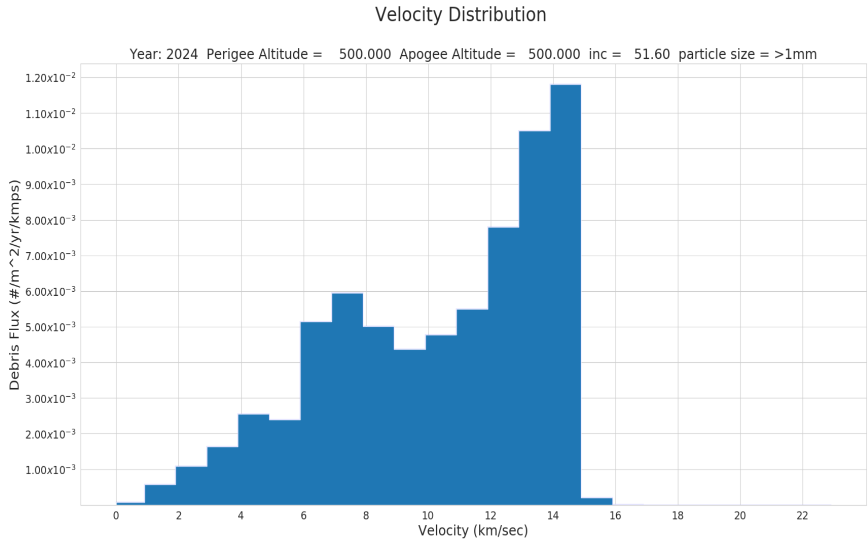
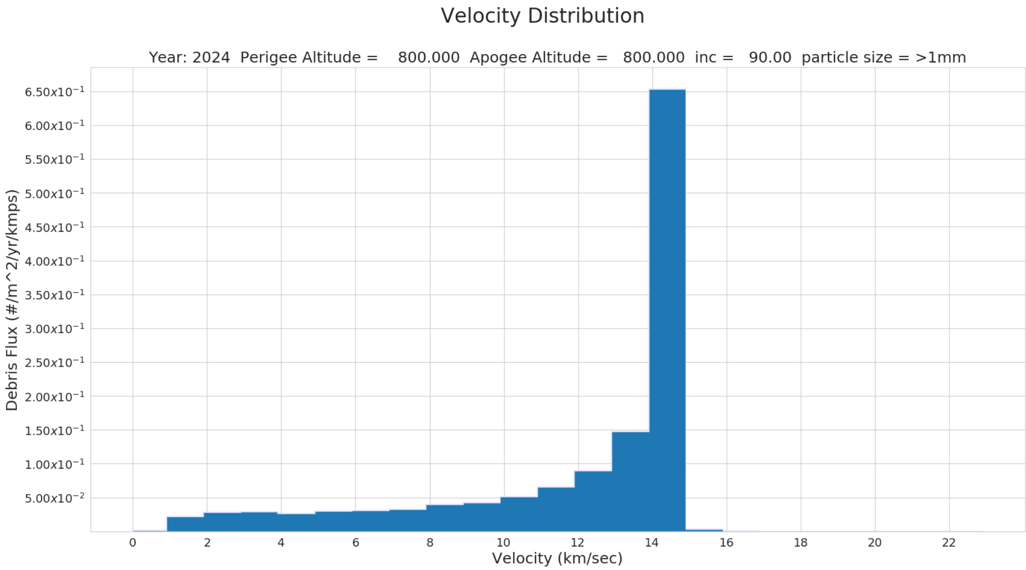
Momentum transfer: collisions

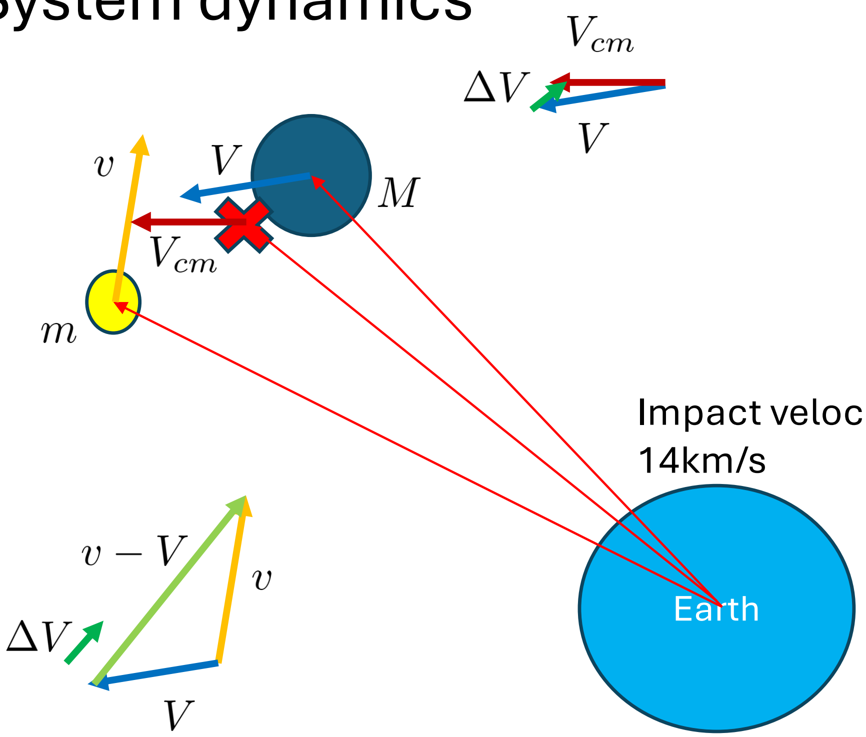
- Head-on type collision at 14-15 km/s providing max delta-v is the most probable case
- 800km polar orbit: 9.1 collisions/m^2/yr
- 500km 51.6deg orbit: 0.16 collisions/m^2/yr





Collision-induced trajectory change

System dynamics



CG dynamics of two-particle system is unaffected by the collision

Measurable. Agreement with detailed numerical dynamics

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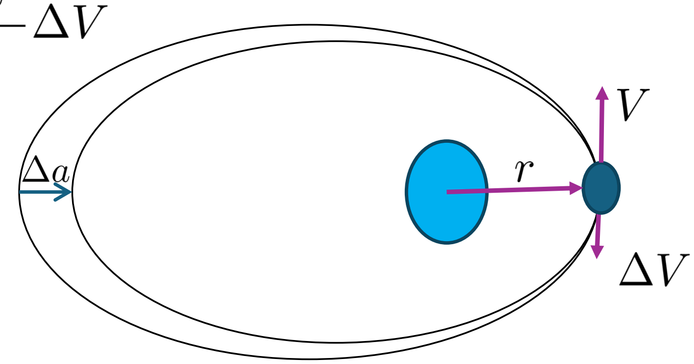
- From vis-viva equation for tangential delta-v

$$\frac{V^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2a}$$

$$\implies da = \frac{2Va^2}{\mu} dV$$

$$\implies \Delta a \approx \frac{2Va^2}{\mu} \Delta V$$

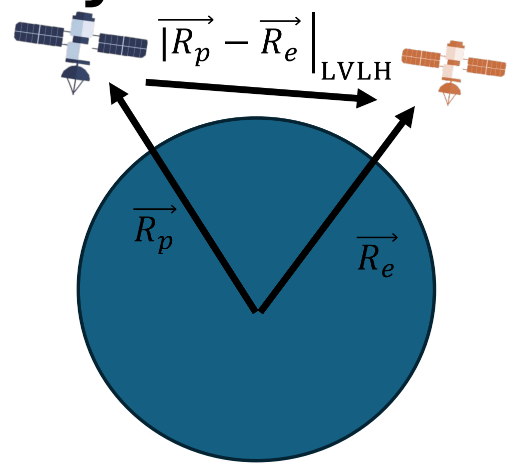
Assume: Head-on collision at perigee



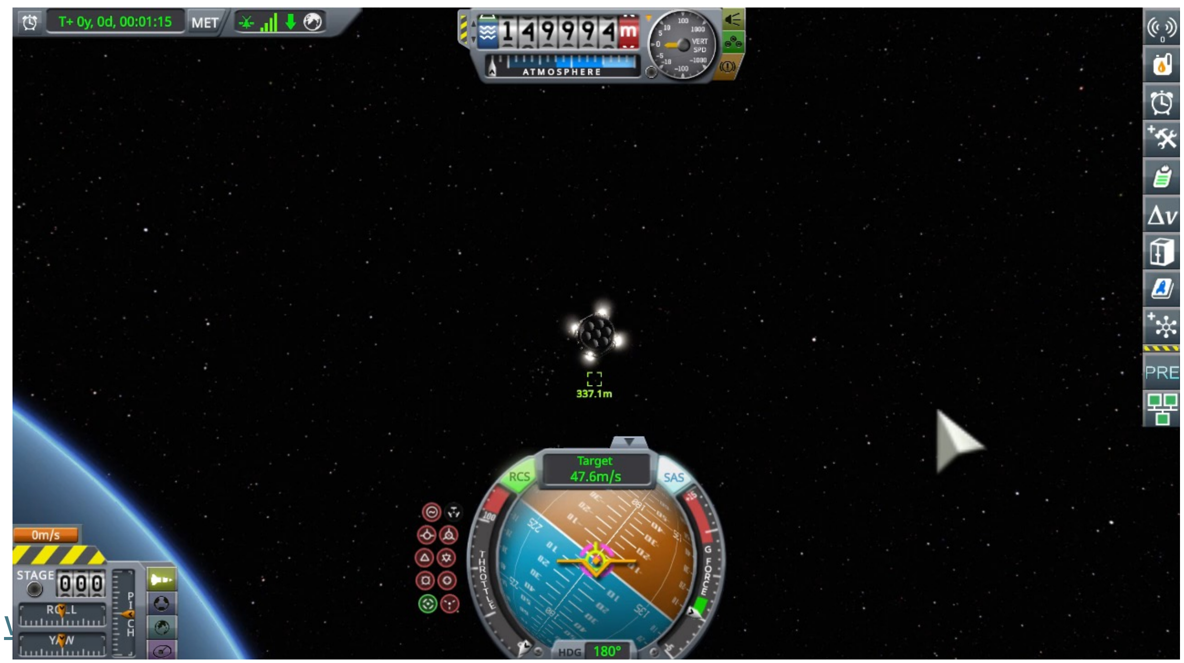
m/(m+M)	h ($r-R_e$) (km)	ΔV (m/s)	Δa (m)
1e-5 (Full Scale)	800 km	0.1445	280.2112
1e-3 (Cubesat)	800 km	14.45	28021
1e-5	500 km	0.1461	260.1404
1e-3	500 km	14.61	26014

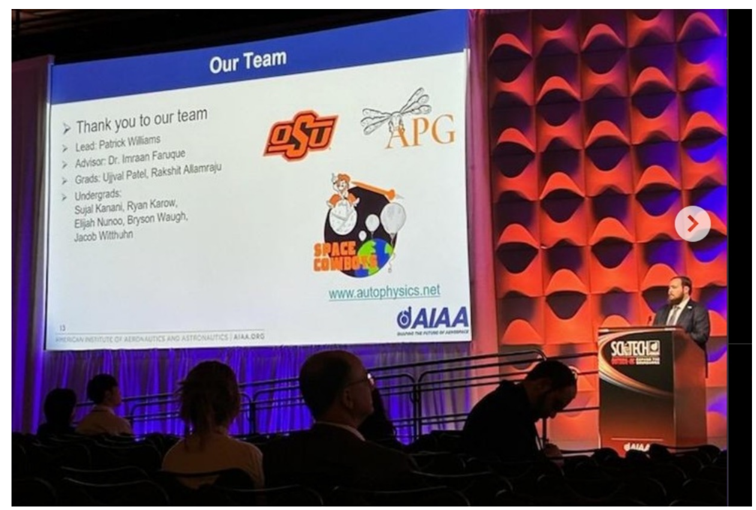
Rendezvous Controllers in SpaceGym

- AIAA KSP Differential Games Challenge
  - Localized space environment built in Kerbal Space Program,
  - Six scenarios (pursuit-evasion, lady bandit guard, sun blocking…)
- Python User interface, connected to C++ Server, to JavaScript Interface (KSP) developed by MIT LL
- Approach PID control and double deep Q neural network control approaches



- Placed 3rd of 25 teams
- PID control worked as well as RL in most scenarios





Collector Design

Hypersonic impactors based on adaptations to MMOD protection systems

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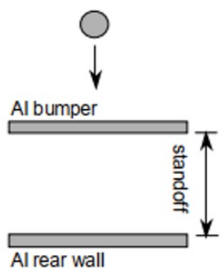
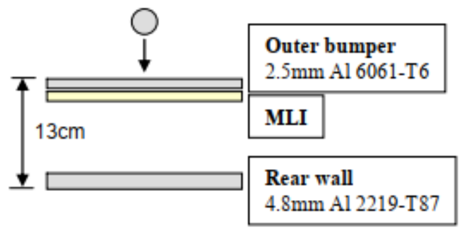
Configuration designs based on handbook methods

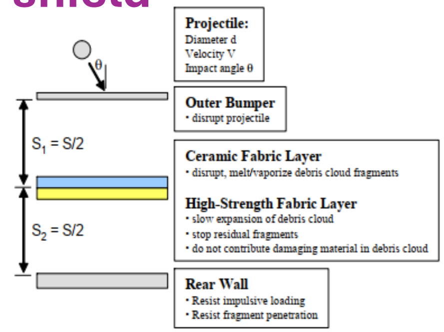
Whipple shield



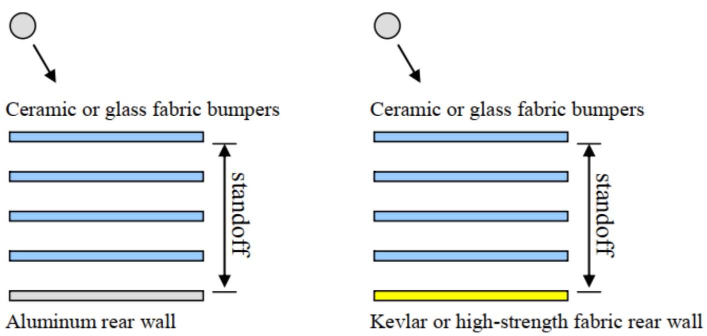
Whipple shield with thermal blanket



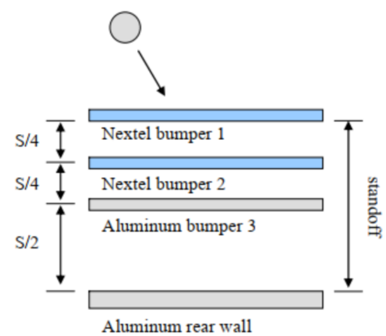
Stuffed Whipple shield



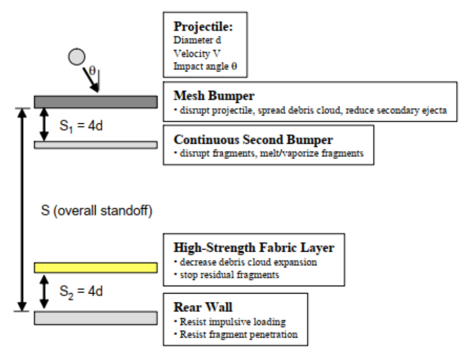
Multi shock layer/hybrid



Hybrid multi shock



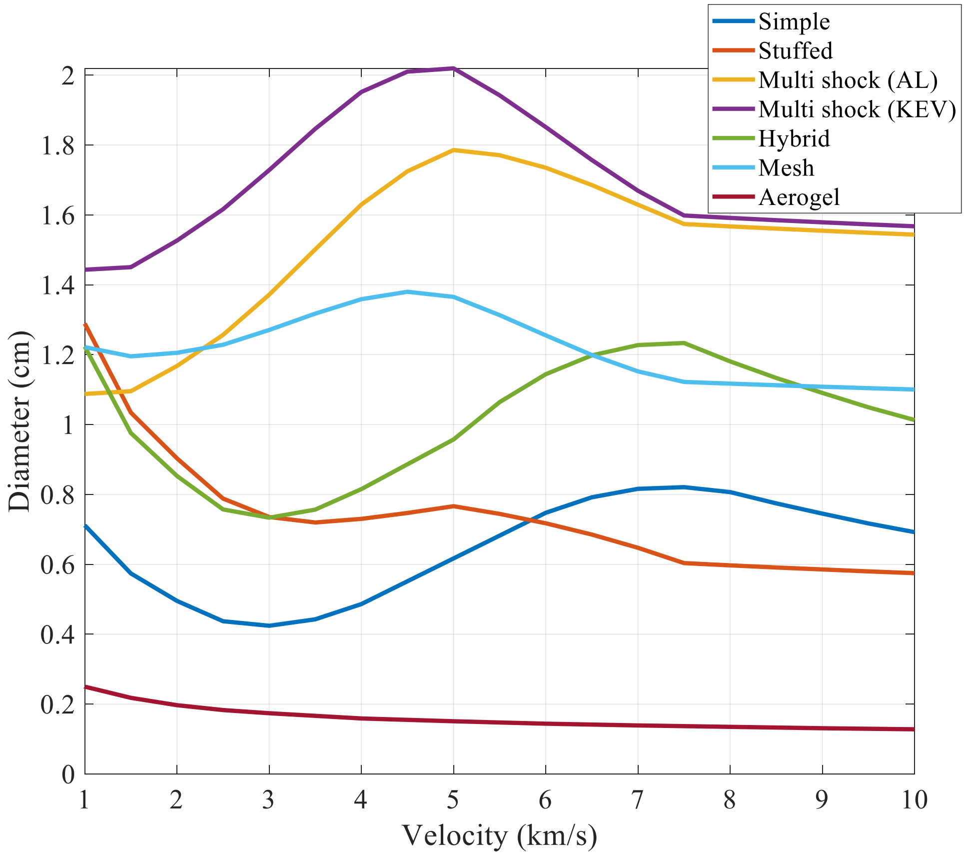
Mesh double bumper



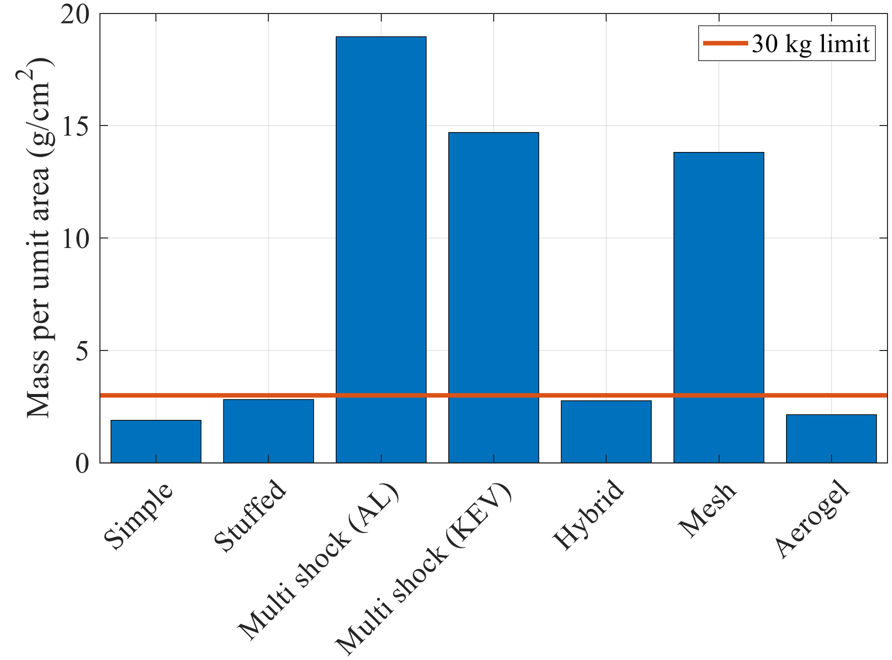
[1] Handbook for Designing MMOD Protection, NASA Johnson space center, https://ntrs.nasa.gov/api/citations/20090010053/downloads/20090010053.pdf

Existing design methods are focused on binary (pass/fail) performance

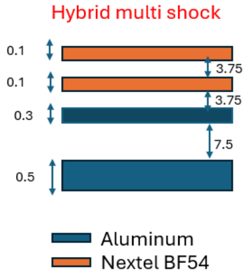
Overall configuration comparison

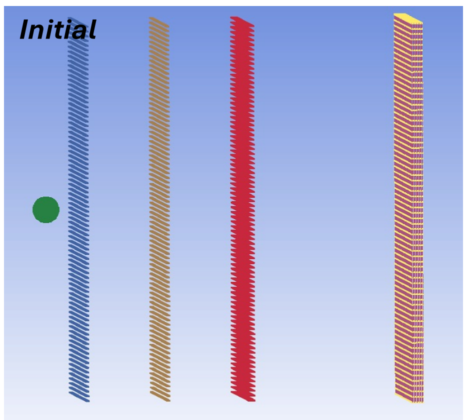


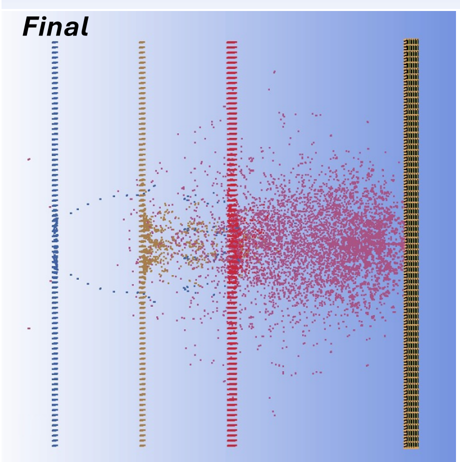
Aerogel: 30 cm, 3 layers (each 10 cm)
Density: 14,50,150 kg/m^3



Numerical hypersonic studies







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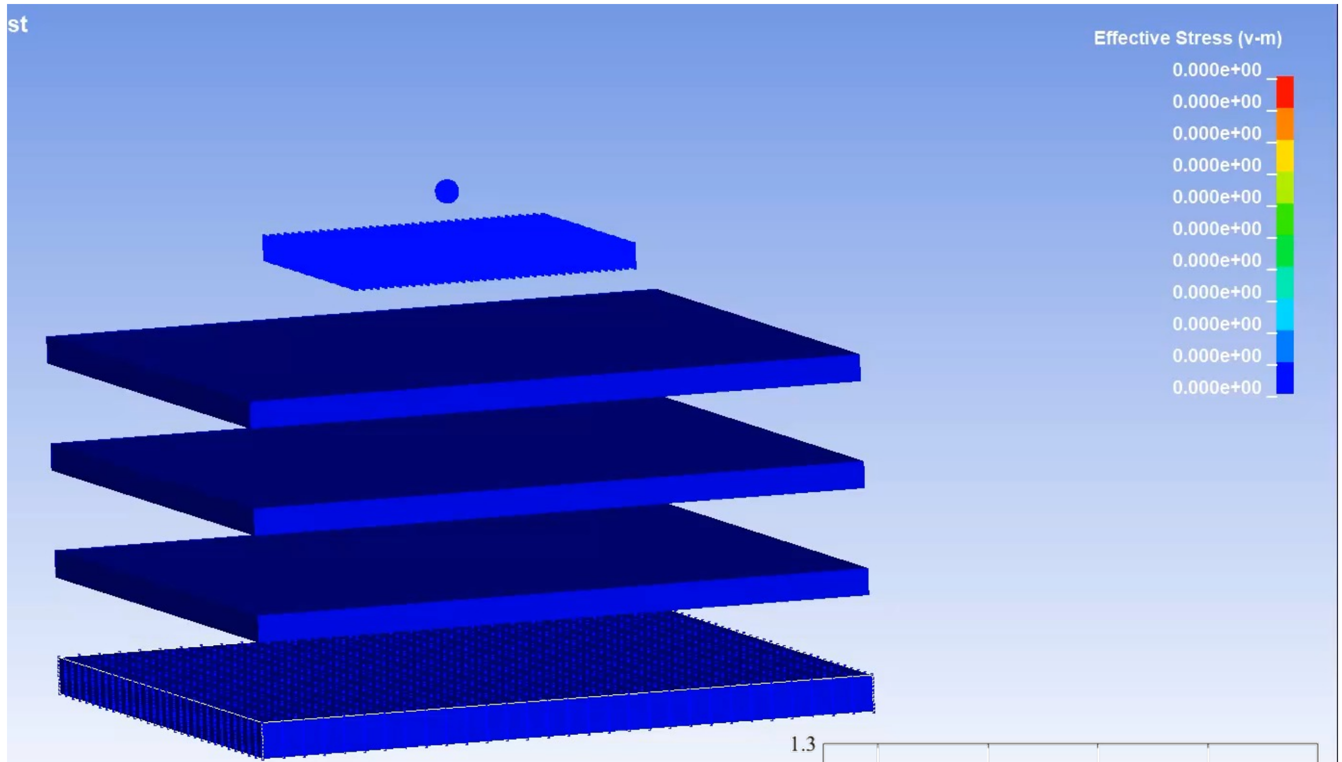
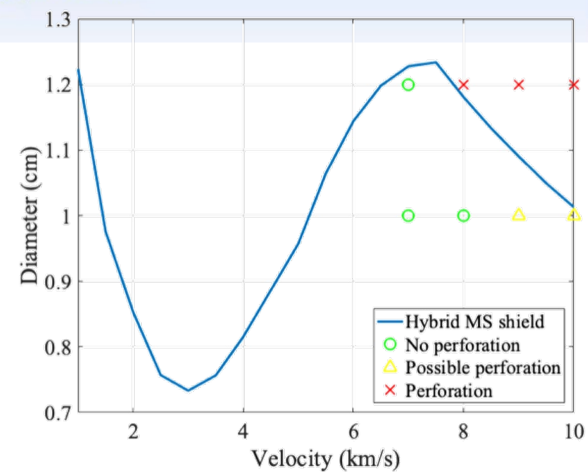
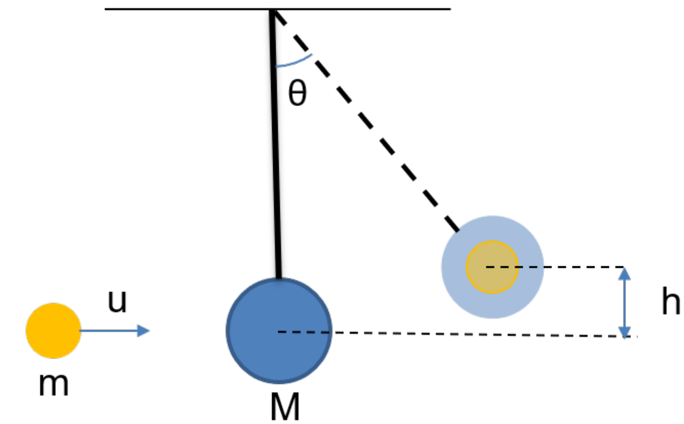


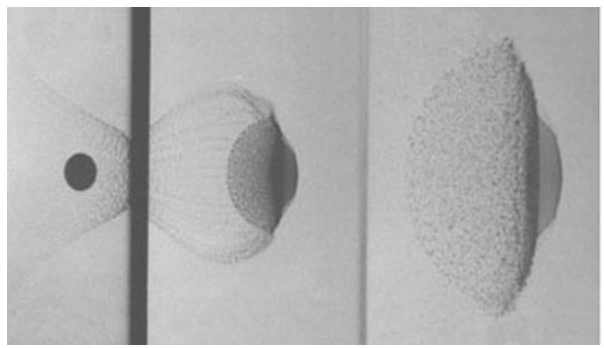
- Projectile: Al2017-T4 (1 or 1.2 cm diameter)
- Front two plates: Nextel BF54 (0.1 mm each)
- Rear two plates: Al6061-T6 (0.3 and 0.5 mm)
- HVI velocity: 7,8,9 or 10 km/s

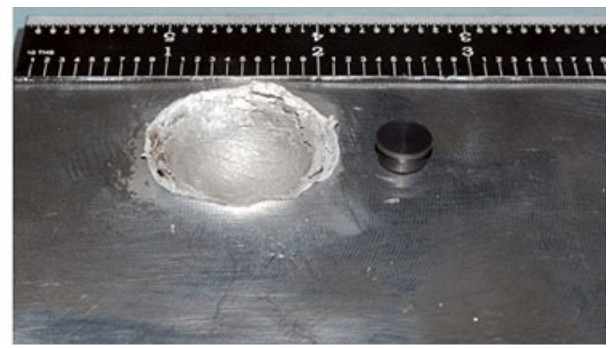


Ground experiment validation



Hypervelocity impact testing center & experimental scaling





1cm aluminum spheres using two-stage, light-gas gun.

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Demonstration flight test

Cubesat demonstration mission for (a) in-orbit perception and (b) in orbit impactor for cm-scale debris

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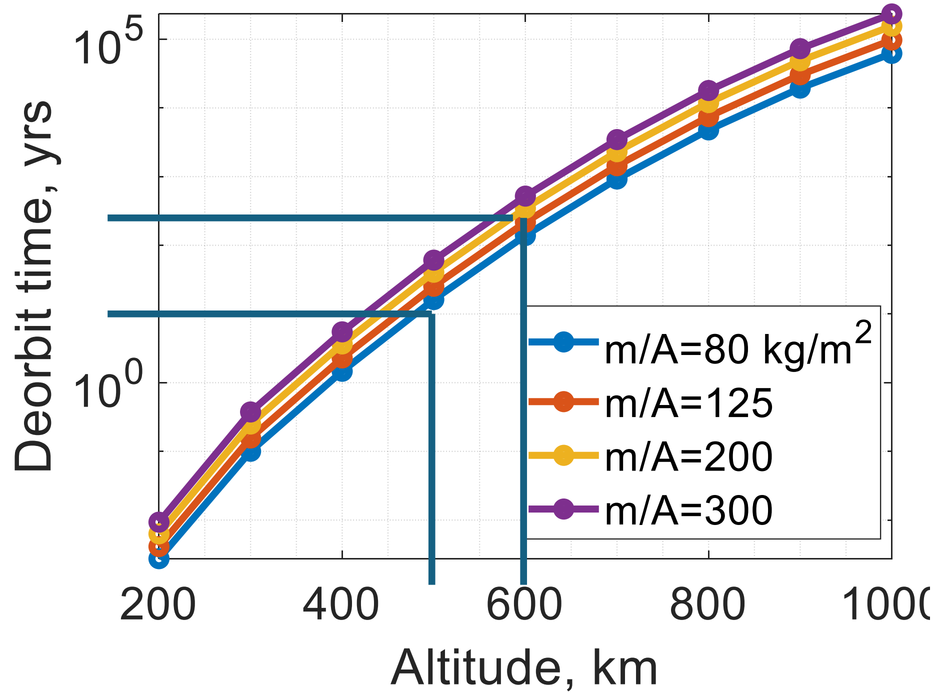
Cubesat in-orbit persistence & DAS

Form Factor	Max Mass (kg)	A/m [m²/kg]
1 U	2.0	7.50E-3
1.5 U	3.0	6.67E-3
2 U	4.0	8.33E-3
3 U	6.0	8.75E-3
6 U	12.0	4.58E-3
12 U	24.0	3.33E-3

CubeSats are not typically compliant with 25 yr lifetime limit when deployed above 600 km



500km provides a 10yr de-orbit time for typical cubesat area loadings

Regulatory requirements

- “The integrated probability of debris-generating explosions for all credible failure modes … is less than 0.001 during deployment and mission operations” (ODMSP Obj. 2-1)
- “functional requirements for collision avoidance when deploying above ~550km” Ostrom/Opelia 2021
- Cubesat practices growing to consider orbital debris assessment DAS, the official tool for NASA compliance Eg https://software.nasa.gov/software/MSC-26690-1
- Components <15g are ignored in DAS compliance

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Cubesat mission requirements

	Minimum	Maximum	Ideal	Goal
Endurance	2 years	5 years	5 years	**5 years**
Max Size	3U	6U	3U	**3U**
Mass	X	4 kg	3 kg	**<3.5 kg**
Optical Range	30 km	X	50 km	**40 km**
Radar Range	1 km	X	200 km	**2 km**
Avg Power Consumption	X	18 W	9 W	**<12 W**
Number of debris collisions	10	1000	100	**70**

Power, mass, budgets

Component	Mass (kg)
IM200 – Optical Imager	0.118
AAC PHOTON-SIDE (3U)	0.135
BA01S Battery Array	0.115
MT01 Compact Magnetorquer	0.036
MM200	
ZAPHOD CubeSat 3U Structure	0.394
KRYTEN-M3 PLUS	0.062
NanoCom AX100U	0.025
SkyPlate	0.487
Camera Guard	0.390
Back Plate	0.216
Total	**1.98**

Component	Name	Sun Visible (W)	No Sun (W)
Camera / Optical Sensor	IM200 – Optical Imager	-1	-0
Solar Panels	AAC PHOTON-SIDE (3U)	+9	+0
Magnetorquers + Magnetometer	(3) MT01 Compact Magnetorquers MM200	-0.64	-0.64
Computer + Antenna	KRYTEN-M3 PLUS Pulsar-SANT	-2.7	-2.7
Total	**X**	**+4.66**	**-3.34**

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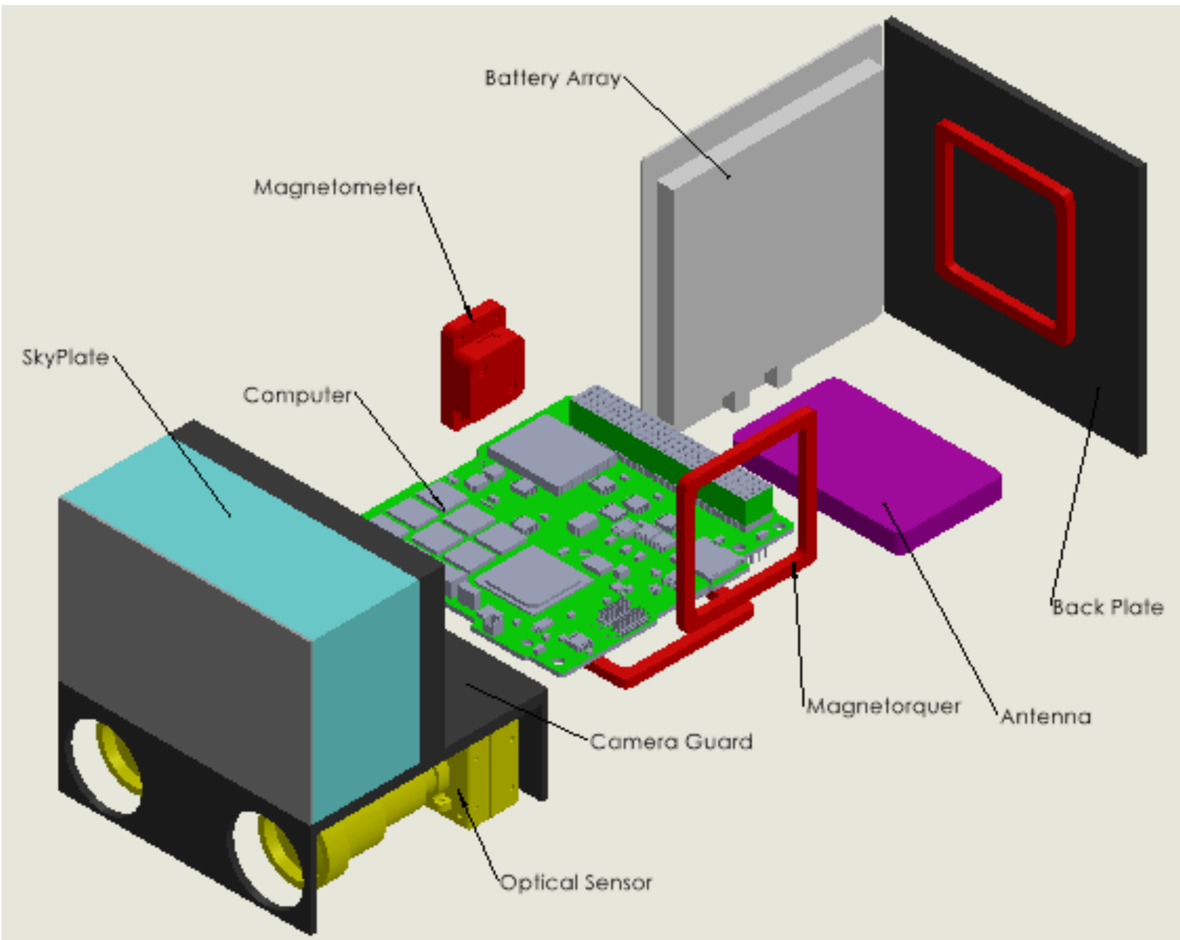
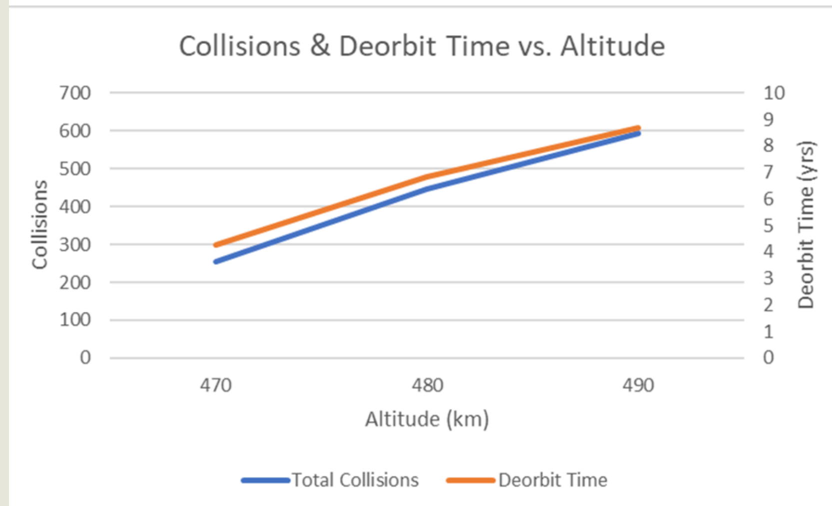
Layout, performance





59 collisions/yr at 480km

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Summary & thank you

- Active debris removal satellite based on hypersonic impact collector
  - In-orbit perception (optical, momentum) and intercept maneuvering
  - Collector design and validation—beyond binary MMOD
- Cubesat:
  - Validation mission to measure and provide impacts
  - 3U, expected collision count

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Students & staff

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