Reinforcement Learning Based ADP:

Computational reductions, faster learning, and more complex problems

– An Application

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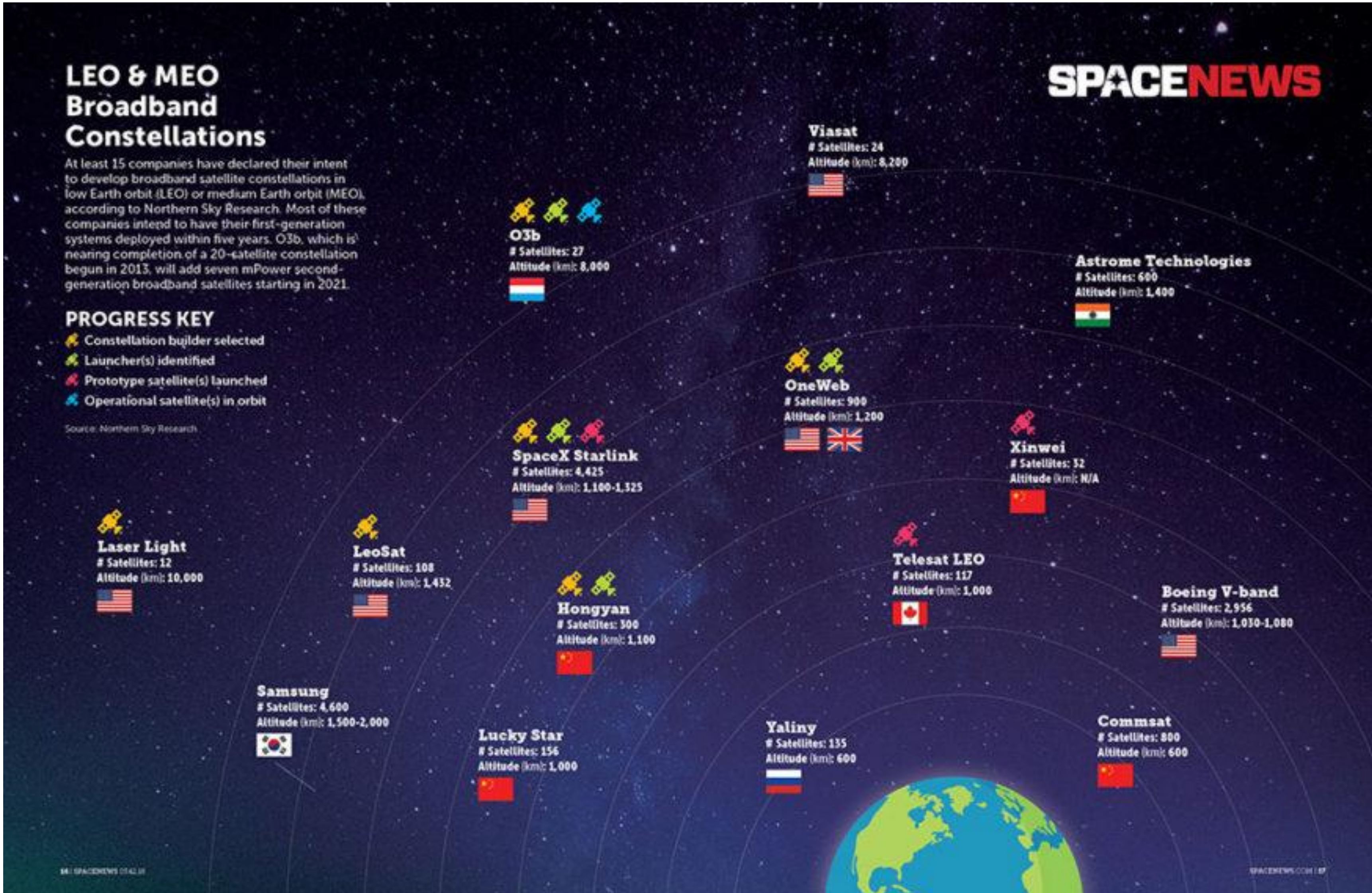
Space is Becoming Congested



onstellations/

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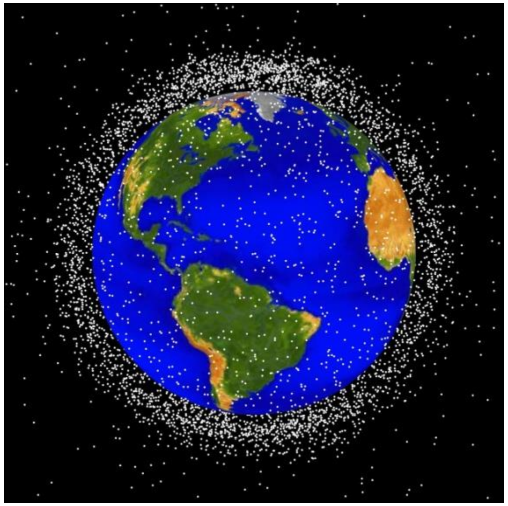
Challenges

- Threats
  - Cyber
  - Physical (i.e., debris)
- Sources of space debris
  - Abandoned upper stages and satellites
  - Collisions, ASAT demos, fragmentation
- Space debris population
  - Baseball size & larger (≥ 10 cm) ~23K
  - Marble size (≥ 1 cm) ~500K
  - Dot size mall (≥ 1 mm) ~100M

} Small (mm-to-cm) sized debris dominate mission ending threat

- Population growth projected
  - Mega constellations ⇒ significant SSA/space traffic management challenge
    - OneWeb: > 600 satellites (w/ Airbus)
    - SpaceX Starlink: > 4,000 satellites
    - Samsung: > 4,000 satellites
    - Others
  - *Kessler Syndrome* ⇒ additional debris created from collisions with debris



Reference: http://orbitaldebris.jsc.nasa.gov

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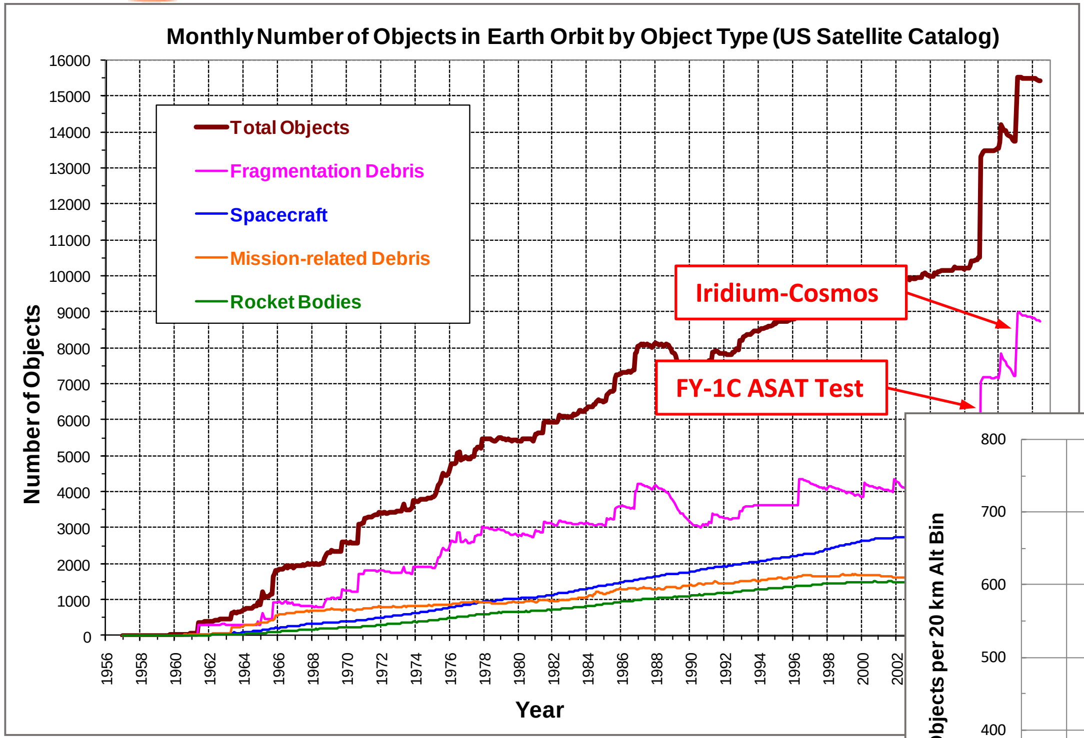
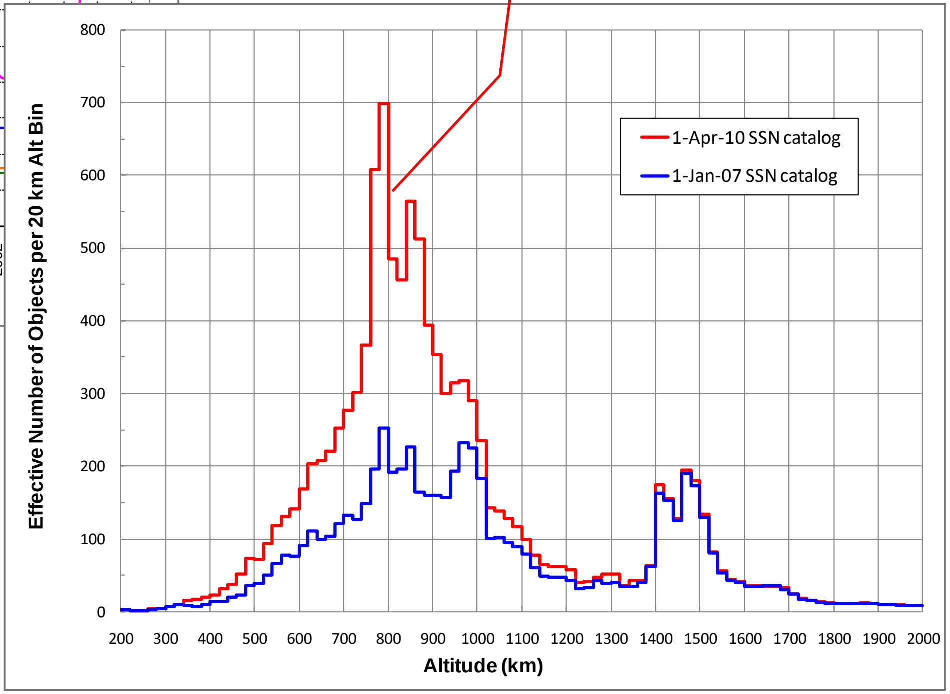
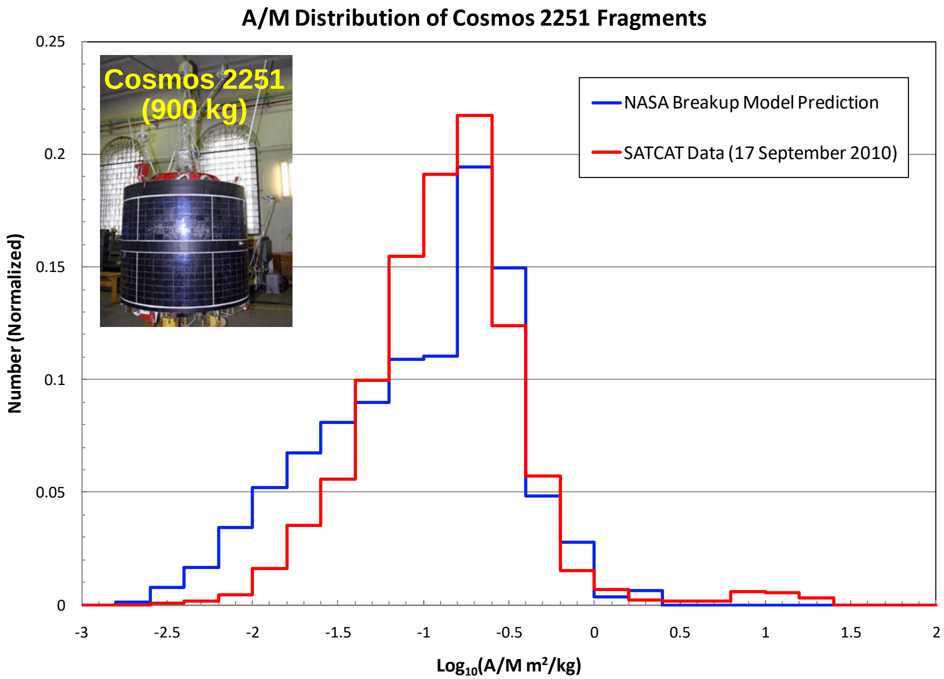
The Debris Problem



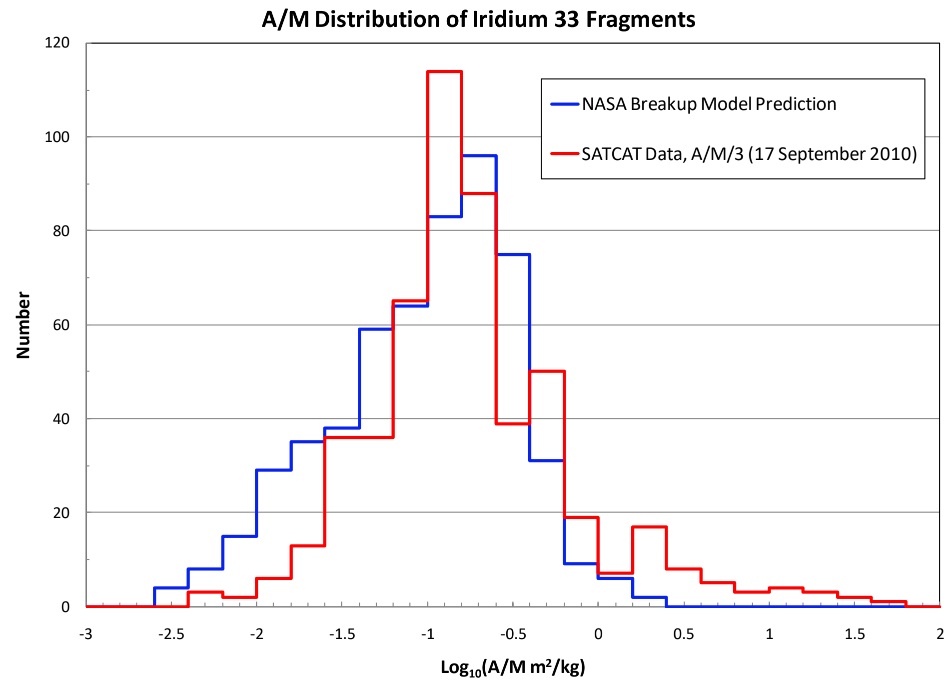
Chinese ASAT resulted in ~120% increase in the region below 1000 km



The Debris Problem



- Observed and predicted A/M distribution of Cosmos 2251 fragments matches well



- Observed A/M distribution of Iridium 33 fragments is higher than prediction; ~3 times higher
- Possible source of difference: lightweight materials (e.g., MLI, CFRP) used in the newer vehicle

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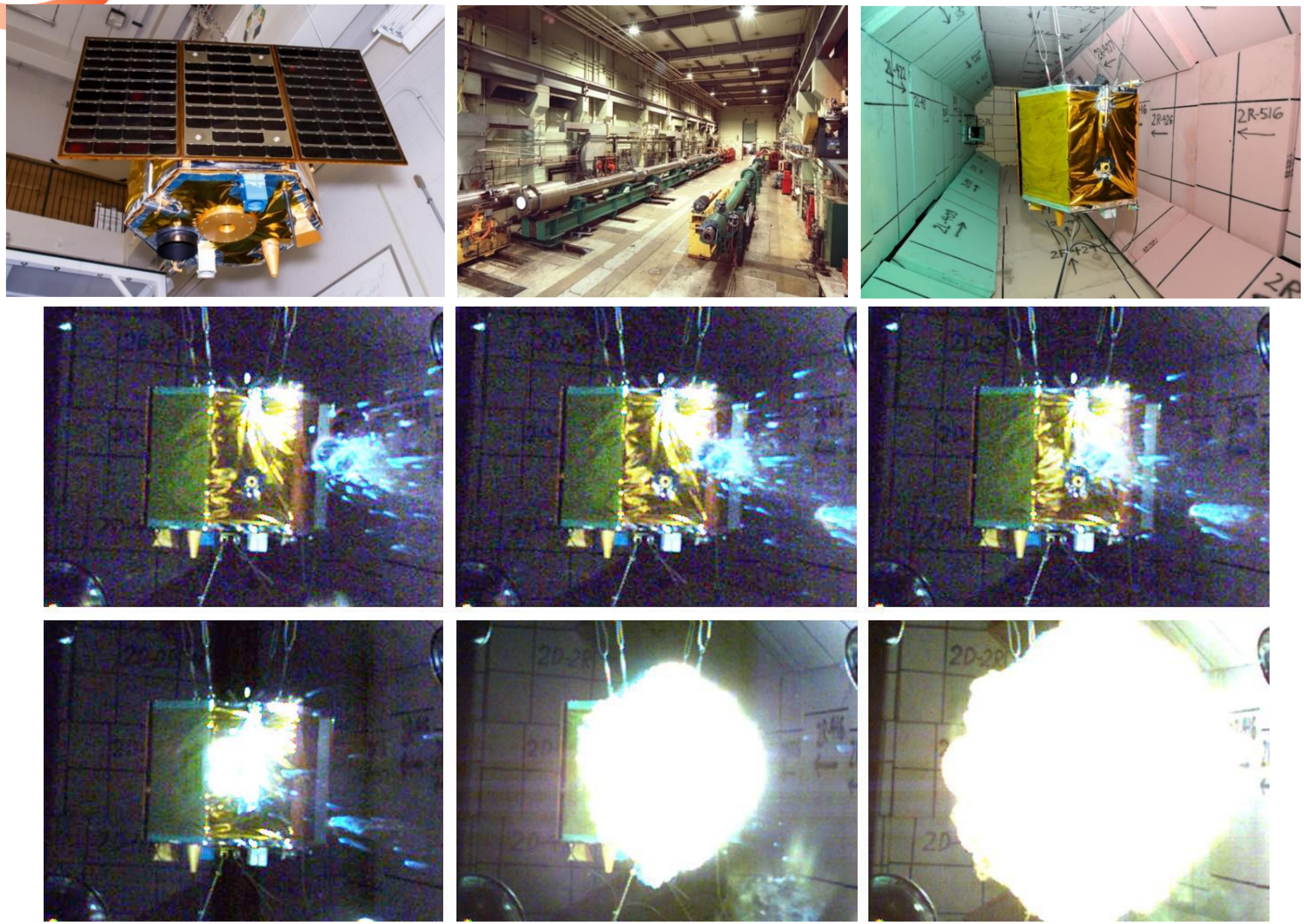
DebriSat Laboratory HVI Test



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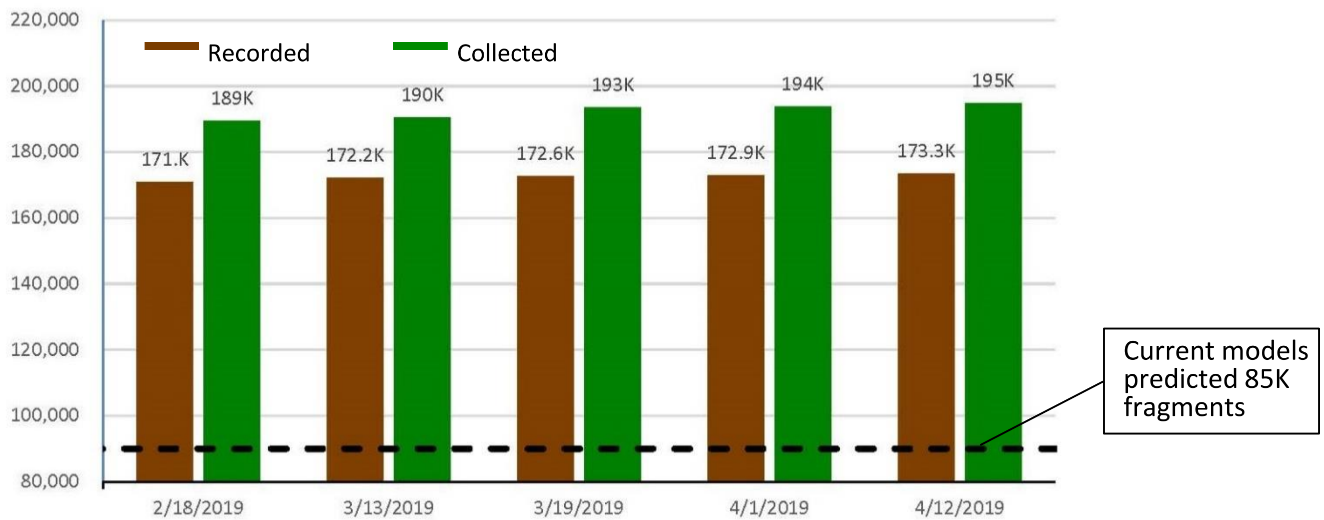
Results

- Preliminary outcomes of the HVI test
  - Developed a unique database with ~200K fragments (> 250K projected – x3?)
  - Imaging systems developed to characterize fragments
  - Models developed to compute fragments' (i) characteristic length (ii) average cross-sectional area, (iii) volume



➢ Task: Utilize center's modelling tools to develop models to better characterize the debris environment and facilitate future space traffic management / SSA capabilities in congested and/or contested environments (e.g., COLA maneuvers)

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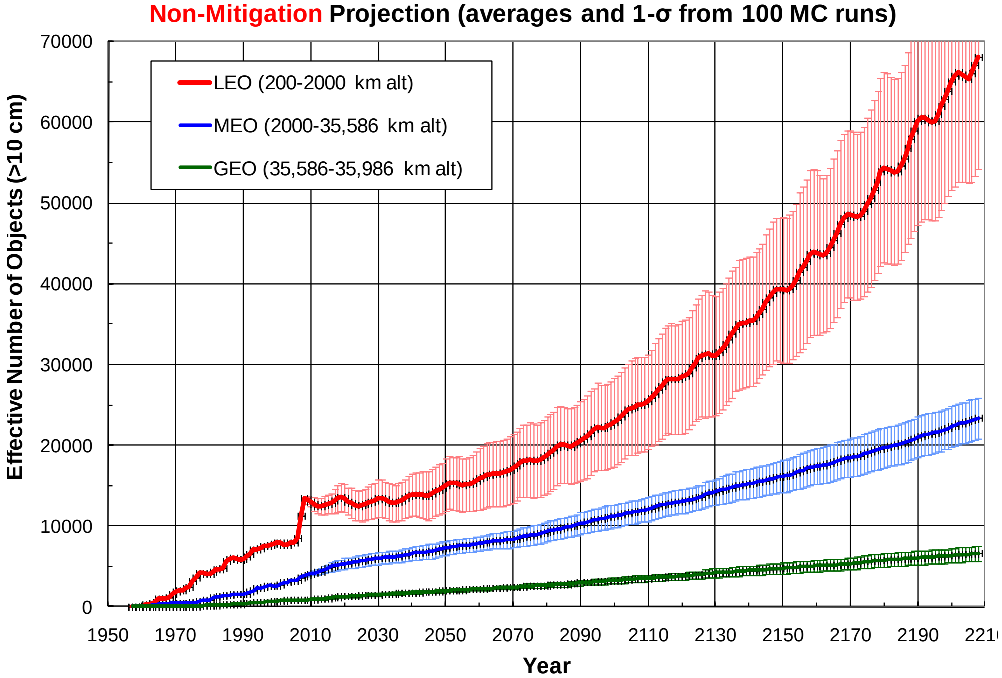
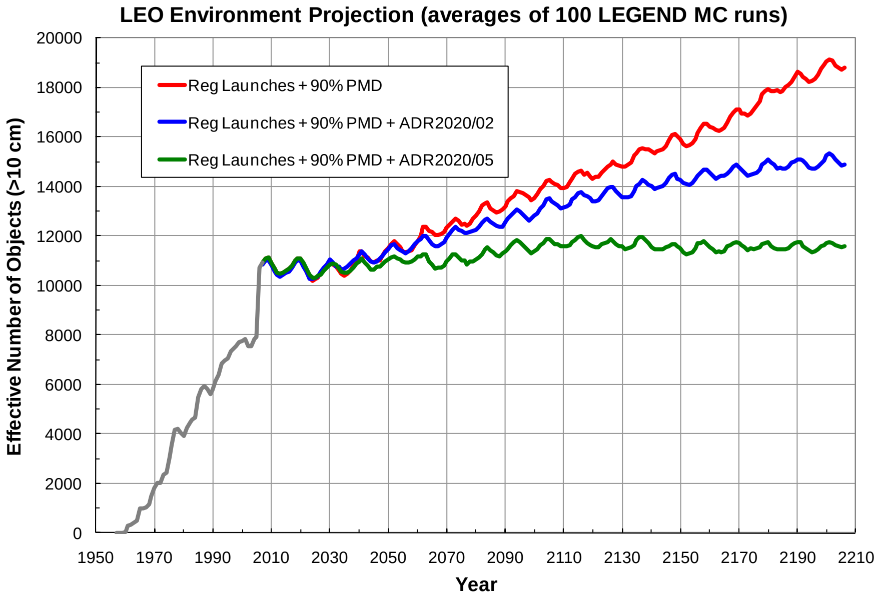
The Debris Problem



Average collisions in the next 200 years (non-mitigation scenario)			
	Cat.	Non-cat.	Total
LEO	**83**	95	178
MEO	**0.5**	1.5	2
GEO	**1.5**	1.5	3

- PMD scenario predicts the LEO populations would increase by ~75% in 200 years
- LEO environment can be stabilized with PMD and a removal rate of ~5 objects/year



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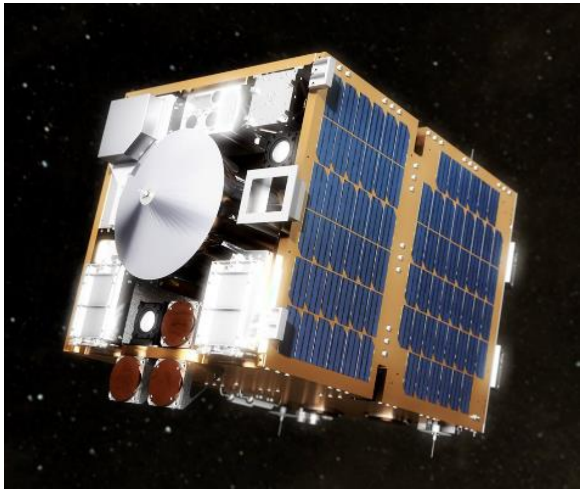
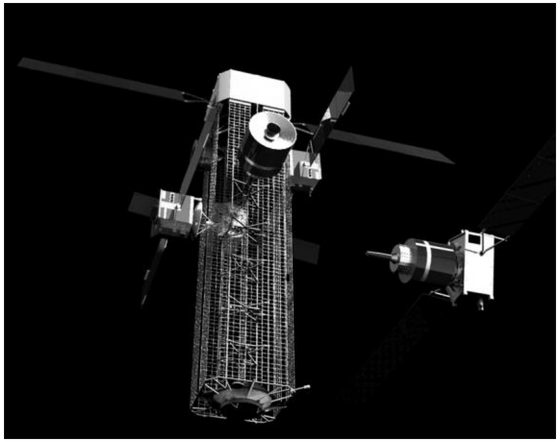
ADR Approaches



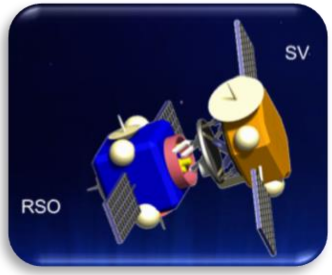
RemoveDEBRIS Mission
- On-orbit demo by Surrey Space Centre for active debris removal (ADR)
- Successfully demonstrated (i) on-orbit debris identification via vision-based navigation (ii) “debris” capture via tethered net and harpoon, and (iii) deorbiting via drag sail



Necropolis Concept (European)
- A two spacecraft system
- A “Hunter” that hunts, collects, and transports spent GEO spacecraft and a “Terminus” for final storage

Others:spacecraft
- GLiDeR – electrostatic tug (Hanspeter Schaub)
- Tether-Nets for ADR (Botta, Sharf, Misra)
- ESA’s Clean Space Initiative (E.DeOrbit mission)
  http://www.esa.int/Our_Activities/Space_Safety/Clean_Space/ESA_s_e.Deorbit_debris_removal_mission_reborn_as_servicing_vehicle

ADR Approaches



Active Debris Removal (ADR)

Contact

Cooperative

- Orbital Express (DARPA)
- SUMO/FREND (DARPA ARD)
- RemoveDEBRIS

Non-cooperative

- Risky (nets, harpoons)
- Needs investigation
  - Game-based (minimax, Stackelberg, Nash)

Noncontact

- GLiDeR (and others)
- Necropolis Hunter
- Herding approaches
  - Game-based (minimax, Stackelberg, Nash)

Task: Design strategies to address interactions (contact/noncontact) with non-cooperative RSOs

Two-Person Differential Games

Two-person differential game

$$J_1 = \phi_1\left(\underline{x}_0, \underline{x}_f, t_0, t_f\right) + \int_{t_0}^{t_f} L_1\left(\underline{x}, \underline{u}_1, \underline{u}_2, t\right) dt$$

$$J_2 = \phi_2\left(\underline{x}_0, \underline{x}_f, t_0, t_f\right) + \int_{t_0}^{t_f} L_2\left(\underline{x}, \underline{u}_1, \underline{u}_2, t\right) dt$$

$$\dot{\underline{x}} = \underline{f}\left(\underline{x}, \underline{u}_1, \underline{u}_2, t\right), \quad \underline{x}\left(t_0\right) = \underline{x}_0$$

- Minimax: zero sum, cooperative

$$J_1 = -J_2 = J \;\Rightarrow\; \underline{u}_1 = \arg\min_{\underline{u}_1} \max_{\underline{u}_2} J$$

- Nash: non-zero sum, non-cooperative game

$$J_1\left(\underline{u}_{1n}, \underline{u}_{2n}\right) \le J_1\left(\underline{u}_1, \underline{u}_{2n}\right)$$
$$J_2\left(\underline{u}_{1n}, \underline{u}_{2n}\right) \le J_2\left(\underline{u}_{1n}, \underline{u}_2\right)$$

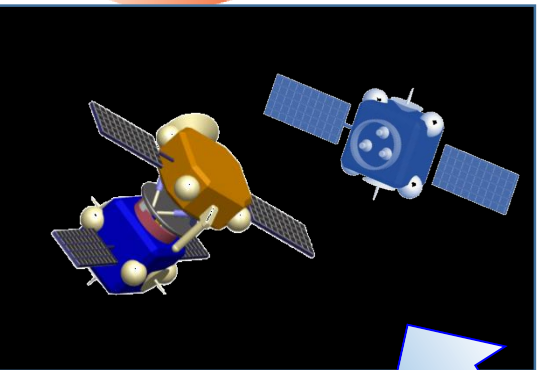
Multiple and/or no solution
(e.g., Prisoner's Dilemma)

- Stackelberg: non-zero sum, leader-follower

$$J_1\left(\underline{u}_{1s}, \underline{u}_{2s}\right) \le J_1\left(\underline{u}_1, \underline{u}_{2s}\right)$$
$$J_2\left(\underline{u}_{1s}, \underline{u}_{2s}\right) \le J_2\left(\underline{u}_1, \underline{u}_2\right)$$

$$J_2\left(\underline{u}_{1s}, \underline{u}_{2s}\right) \le J_2\left(\underline{u}_{1n}, \underline{u}_{2n}\right)$$

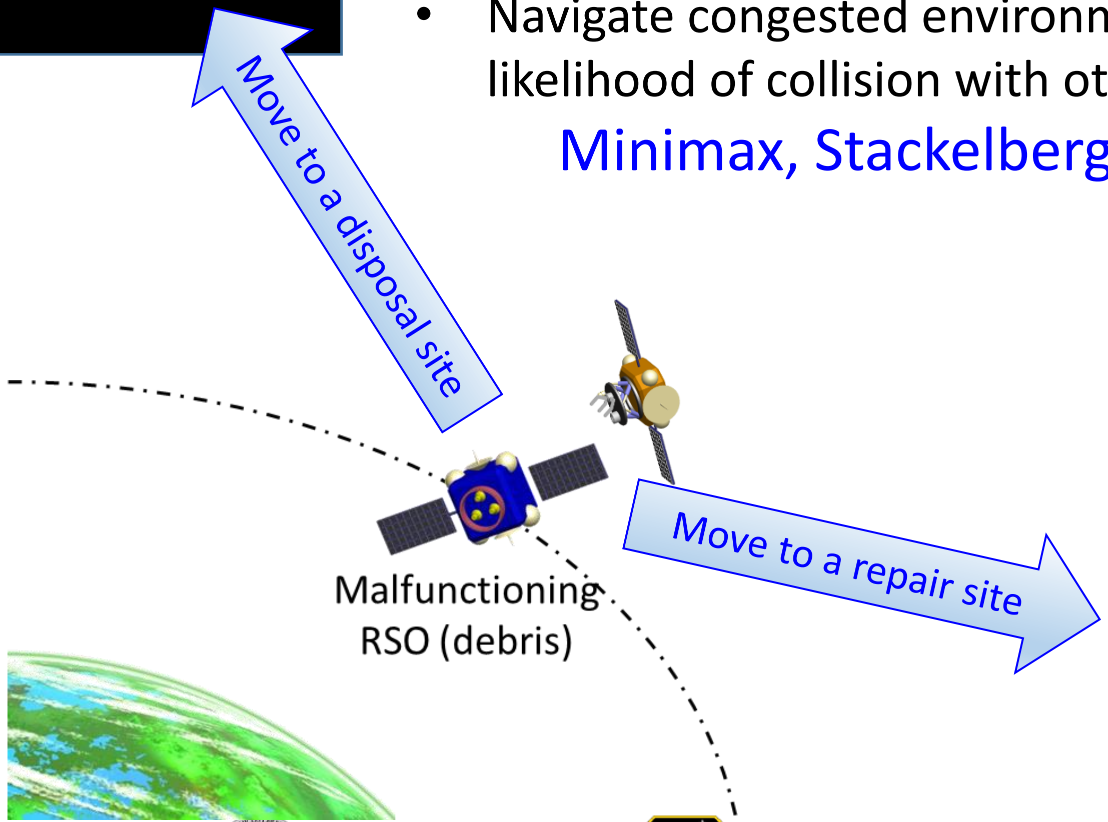
Summary

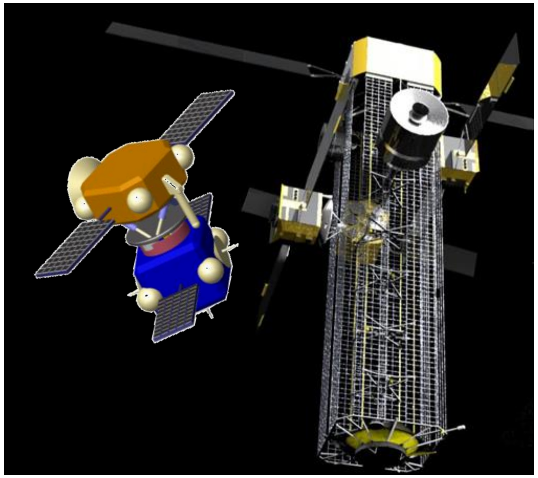


Debris abatement includes removal for disposal (or repair) – need to:

- Minimize interactions between vehicles (space tug and disabled RSO)
- Navigate congested environment while minimizing likelihood of collision with other RSO (herding)

Minimax, Stackelberg, Nash strategies





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Conclusion

- The National Space Traffic Management Policy (SPD-3), includes the following:
  - Space Situational Awareness (SSA) shall mean the knowledge and characterization of space objects and their operational environment to support safe, stable, and sustainable space activities.
  - Space Traffic Management (STM) shall mean the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment.
  - Orbital debris (OD), or space debris, shall mean any human-made space object orbiting Earth that no longer serves any useful purpose.
  - Advance SSA and STM Science and Technology. The United States should continue to engage in and enable S&T research and development to support the practical applications of SSA and STM. These activities include improving fundamental **knowledge of the space environment**, such as the characterization of small debris, advancing the S&T of critical SSA inputs such as observational data, algorithms, and **models necessary to improve SSA capabilities**, and developing new hardware and software to support data processing and observations.

https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/