

# Reinforcement Learning Based ADP:

Computational reductions, faster learning, and more complex problems

– An Application



# Space is Becoming Congested

## LEO & MEO Broadband Constellations

At least 15 companies have declared their intent to develop broadband satellite constellations in low Earth orbit (LEO) or medium Earth orbit (MEO), according to Northern Sky Research. Most of these companies intend to have their first-generation systems deployed within five years. O3b, which is nearing completion of a 20-satellite constellation begun in 2013, will add seven mPower second-generation broadband satellites starting in 2021.

### PROGRESS KEY

- Constellation builder selected
- Launcher(s) identified
- Prototype satellite(s) launched
- Operational satellite(s) in orbit

Source: Northern Sky Research

**SPACE**NEWS

**Laser Light**  
# Satellites: 12  
Altitude (km): 10,000

**LeoSat**  
# Satellites: 108  
Altitude (km): 1,432

**Samsung**  
# Satellites: 4,600  
Altitude (km): 1,500-2,000

**Lucky Star**  
# Satellites: 156  
Altitude (km): 1,000

**Hongyan**  
# Satellites: 300  
Altitude (km): 1,100

**SpaceX Starlink**  
# Satellites: 4,425  
Altitude (km): 1,100-1,325

**Yaliny**  
# Satellites: 135  
Altitude (km): 600

**OneWeb**  
# Satellites: 900  
Altitude (km): 1,200

**Viasat**  
# Satellites: 24  
Altitude (km): 8,200

**Telesat LEO**  
# Satellites: 117  
Altitude (km): 1,000

**Xinwei**  
# Satellites: 52  
Altitude (km): N/A

**Astrome Technologies**  
# Satellites: 600  
Altitude (km): 1,400

**Boeing V-band**  
# Satellites: 2,956  
Altitude (km): 1,050-1,080

**Comsat**  
# Satellites: 800  
Altitude (km): 600

GLOBAL COVERAGE  
It to everyone, here on Earth

LOW EARTH CONSTITUTION  
High-speed internet equivalent to fiber-optic networks

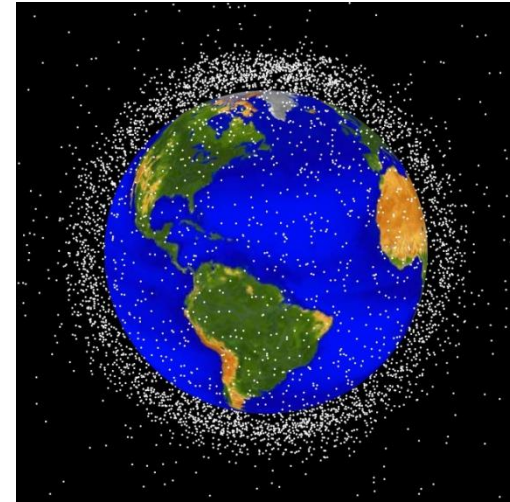
[constellations/](#)





- 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 ( $\geq 10$  cm)  $\sim 23$ K
  - Marble size ( $\geq 1$  cm)  $\sim 500$ K
  - Dot size small ( $\geq 1$  mm)  $\sim 100$ M

} Small (mm-to-cm) sized debris  
dominate mission ending threat
- Population growth projected
  - Mega constellations  $\Rightarrow$  significant SSA/space traffic management challenge
    - OneWeb: > 600 satellites (w/ Airbus)
    - SpaceX Starlink: > 4,000 satellites
    - Samsung: > 4,000 satellites
    - Others
  - *Kessler Syndrome*  $\Rightarrow$  additional debris created from collisions with debris

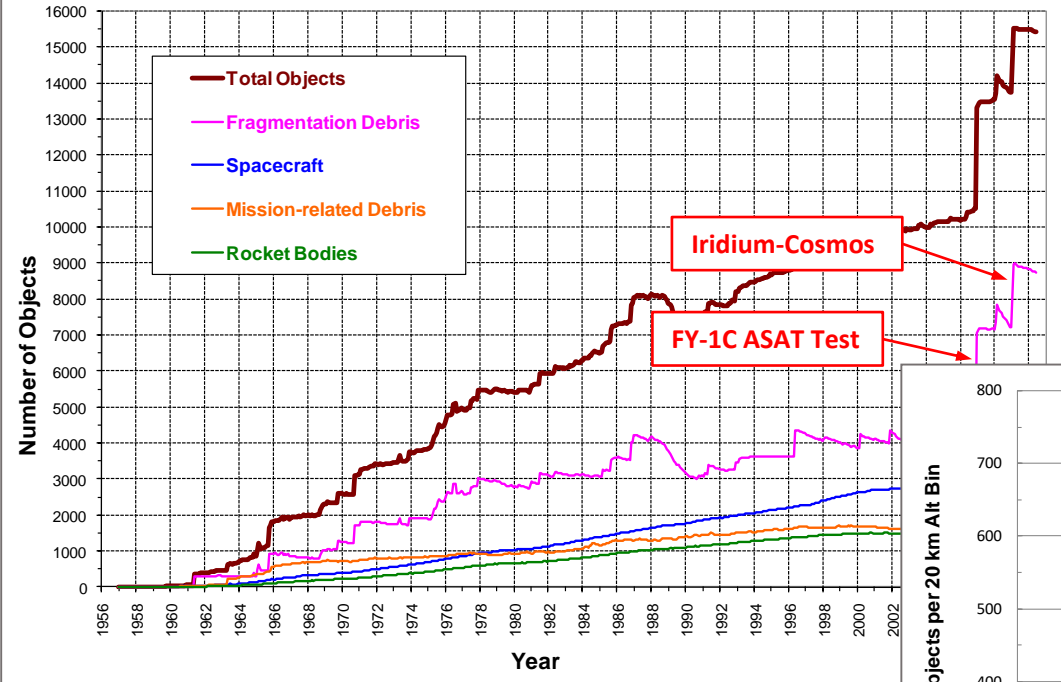


Reference: <http://orbitaldebris.jsc.nasa.gov>

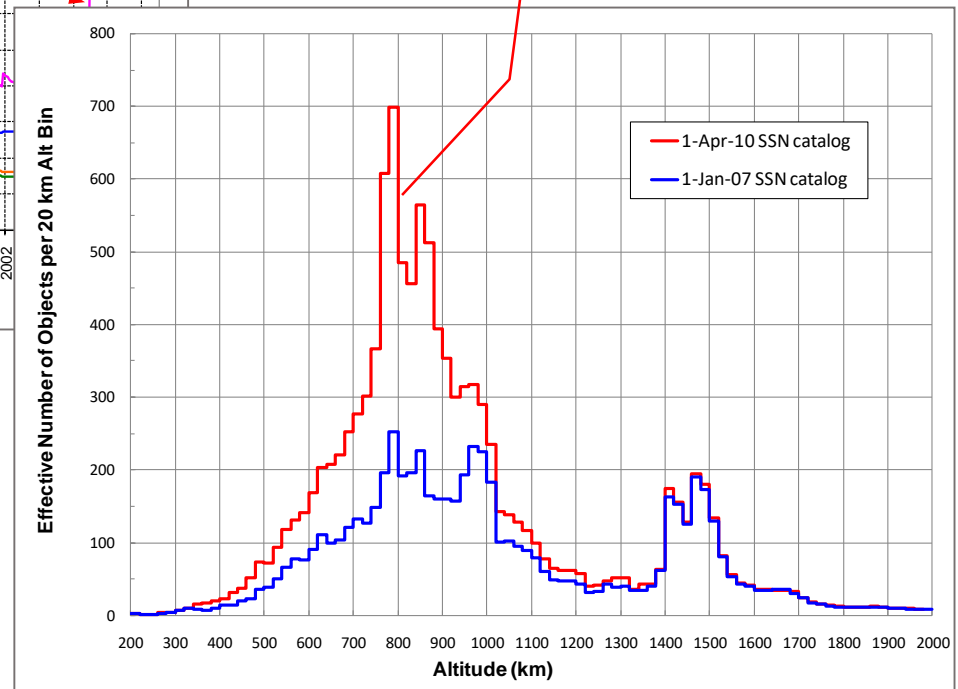
# The Debris Problem



Monthly Number of Objects in Earth Orbit by Object Type (US Satellite Catalog)



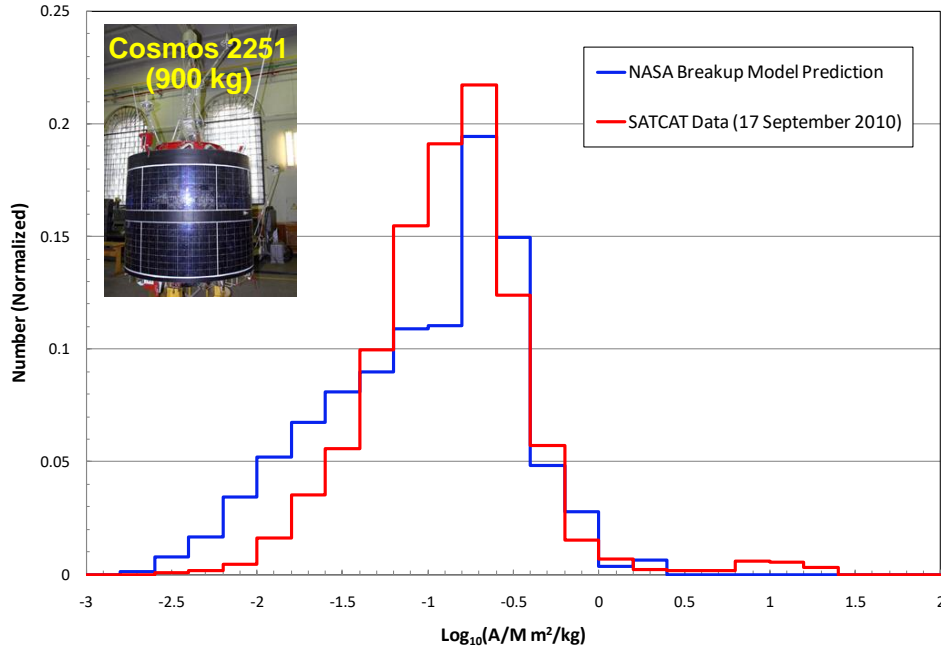
Chinese ASAT resulted in ~120% increase in the region below 1000 km



# The Debris Problem



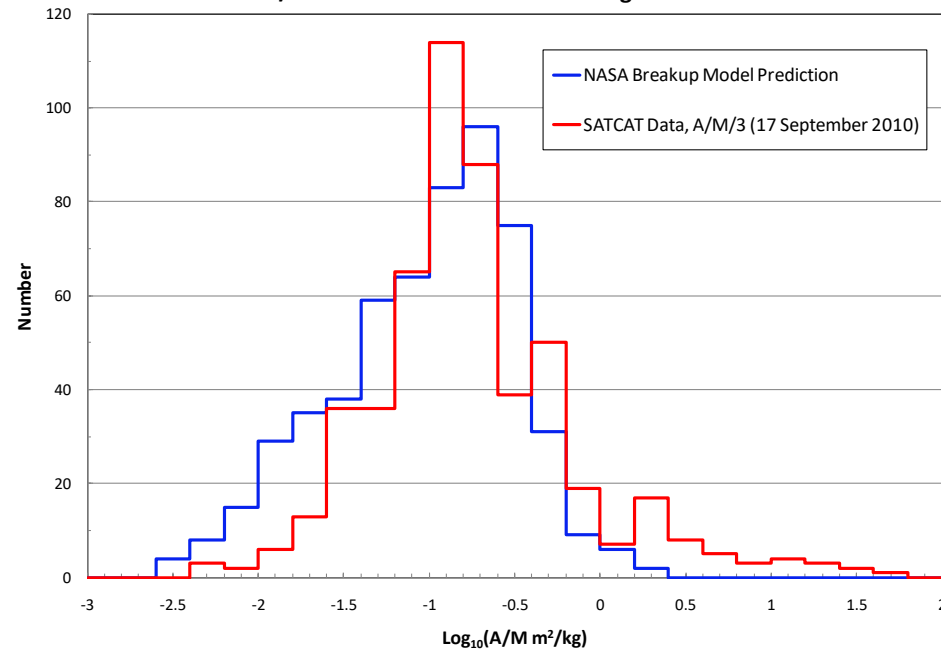
### A/M Distribution of Cosmos 2251 Fragments



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

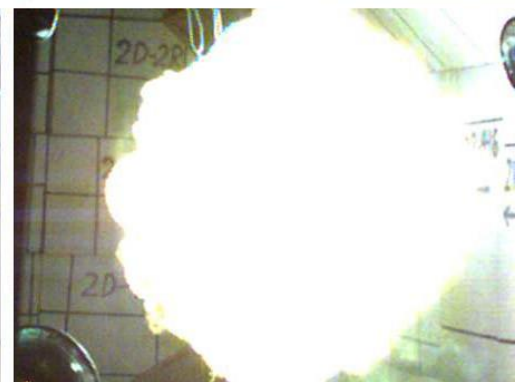
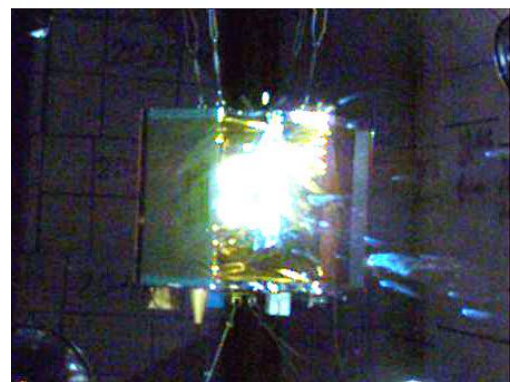
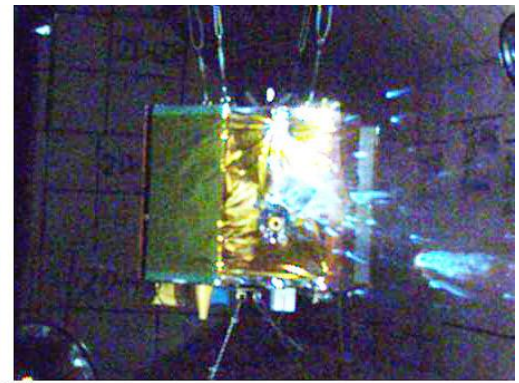
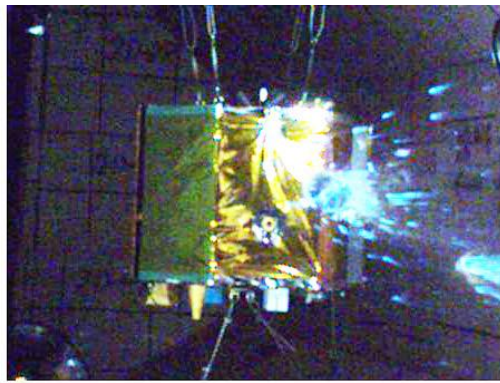
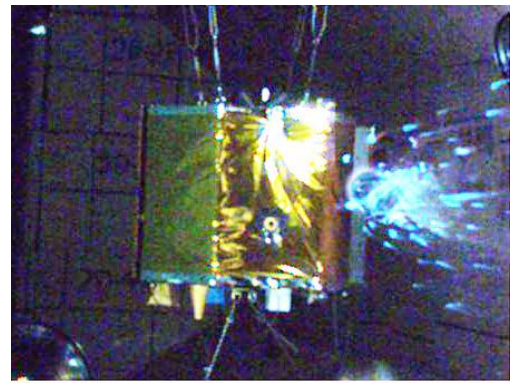
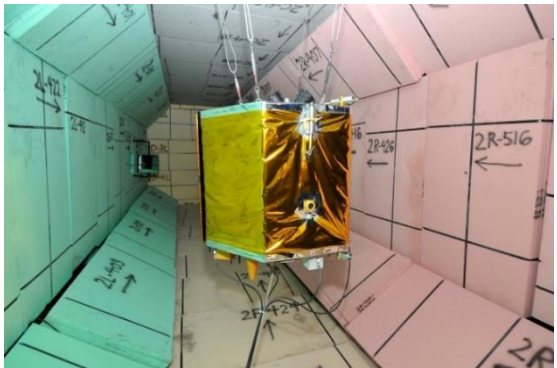
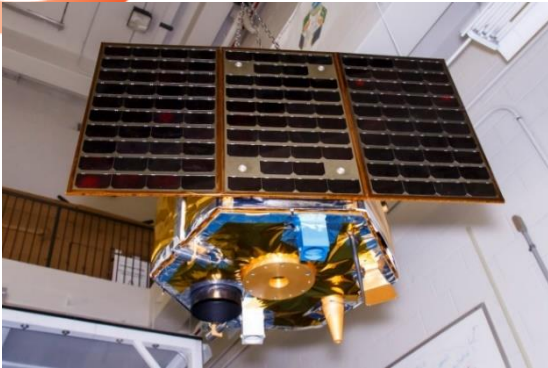
- Observed A/M distribution of Iridium 33 fragments is higher than prediction; **~3 times higher**
- Possible source of difference: lightweight materials (e.g., MLI, CFRP) used in the newer vehicle

### A/M Distribution of Iridium 33 Fragments



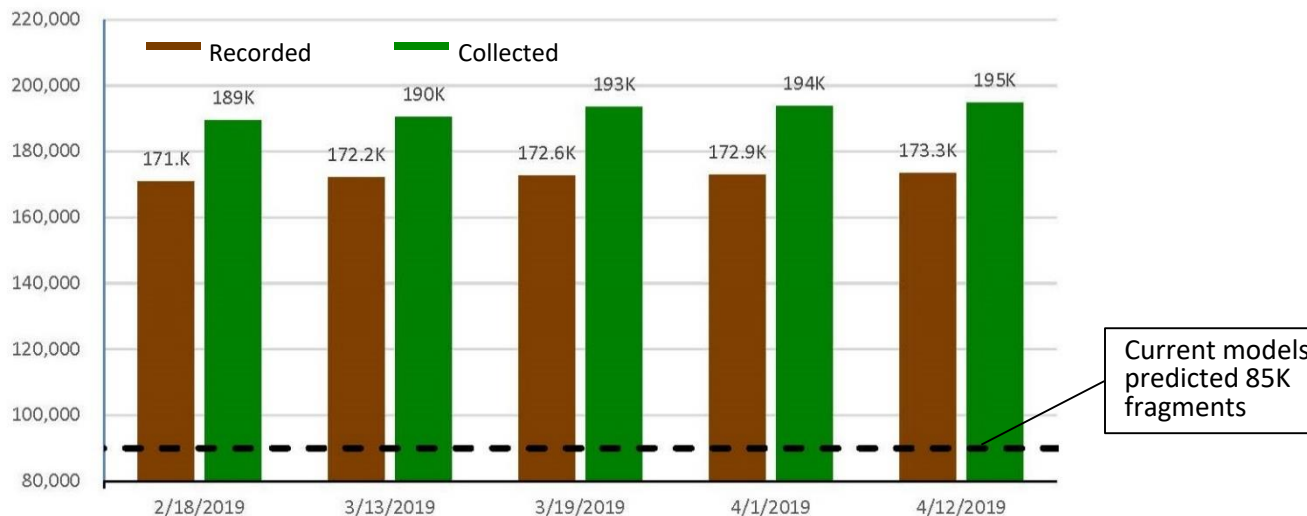


# DebrisSat Laboratory HVI Test





- 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

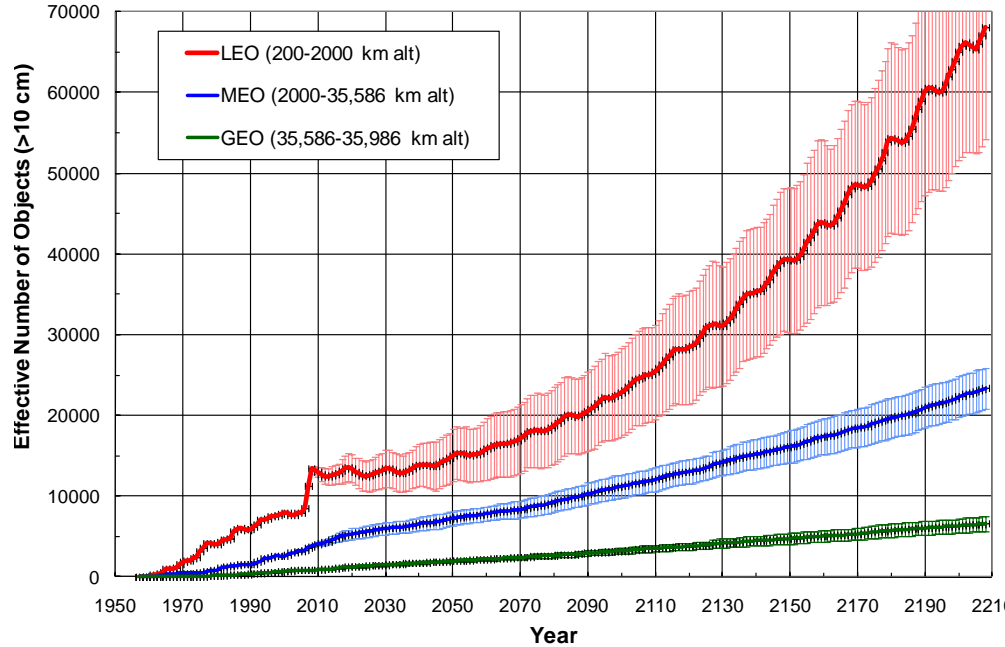


- Task: Utilize center's modelling tools to develop models to better characterize the debris environment and facilitate future space traffic management / SSA capabilities in congested and/or contested environments (e.g., COLA maneuvers)

# The Debris Problem



**Non-Mitigation Projection (averages and 1-σ from 100 MC runs)**

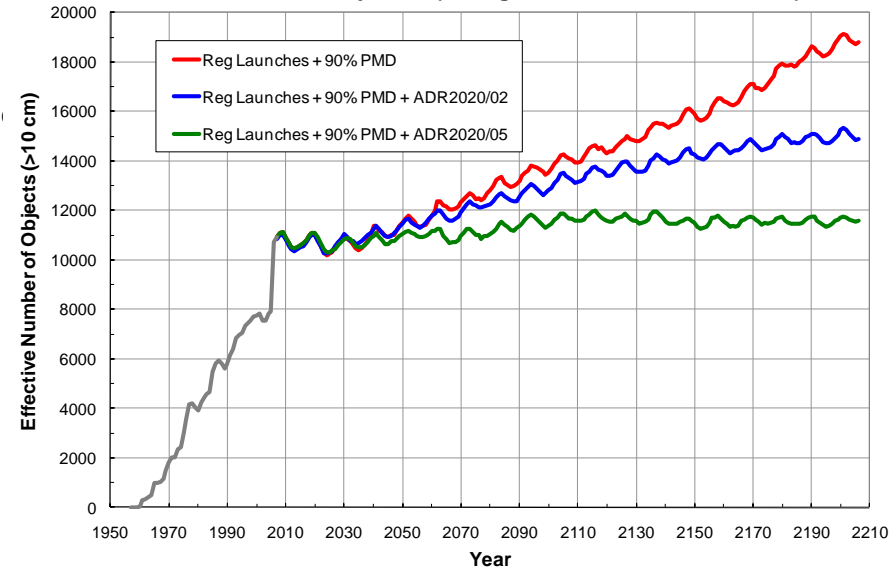


- PMD scenario predicts the LEO populations would increase by ~75% in 200 years
- LEO environment can be stabilized with PMD and a removal rate of ~5 objects/year

**Average collisions in the next 200 years (non-mitigation scenario)**

	Cat.	Non-cat.	Total
LEO	<b>83</b>	95	178
MEO	<b>0.5</b>	1.5	2
GEO	<b>1.5</b>	1.5	3

**LEO Environment Projection (averages of 100 LEGEND MC runs)**







## 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

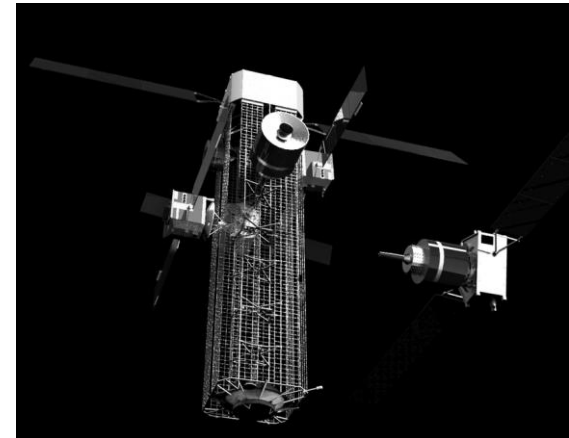
## Necropolis Concept (European)

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

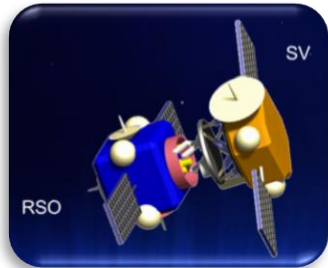
## Others:spacecraft

- 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](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

### Noncontact

#### Cooperative

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

#### Non-cooperative

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

- 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

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

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

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

- 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

$$J_1(\underline{u}_{1n}, \underline{u}_{2n}) \leq J_1(\underline{u}_1, \underline{u}_{2n})$$

$$J_2(\underline{u}_{1n}, \underline{u}_{2n}) \leq J_2(\underline{u}_{1n}, \underline{u}_2)$$

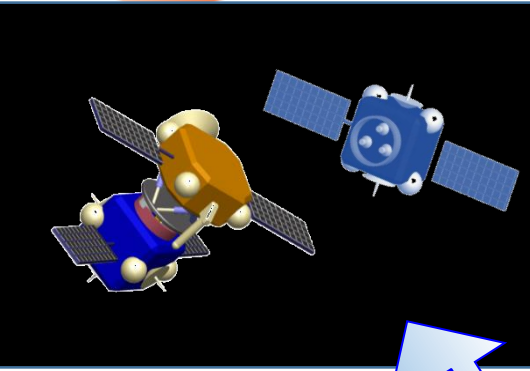
Multiple and/or no solution  
(e.g., Prisoner's Dilemma)

- Stackelberg: non-zero sum, leader-follower

$$J_1(\underline{u}_{1s}, \underline{u}_{2s}) \leq J_1(\underline{u}_1, \underline{u}_{2s})$$

$$J_2(\underline{u}_{1s}, \underline{u}_{2s}) \leq J_2(\underline{u}_1, \underline{u}_2)$$

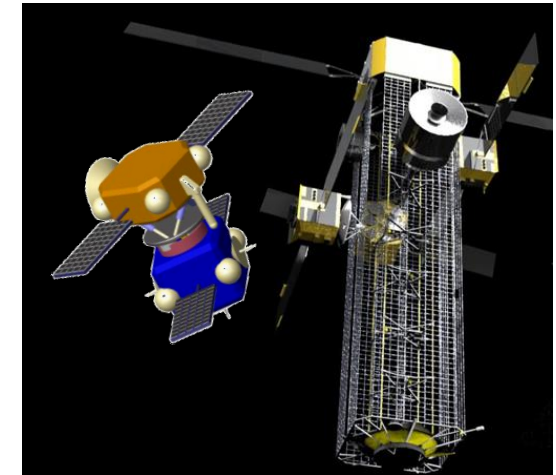
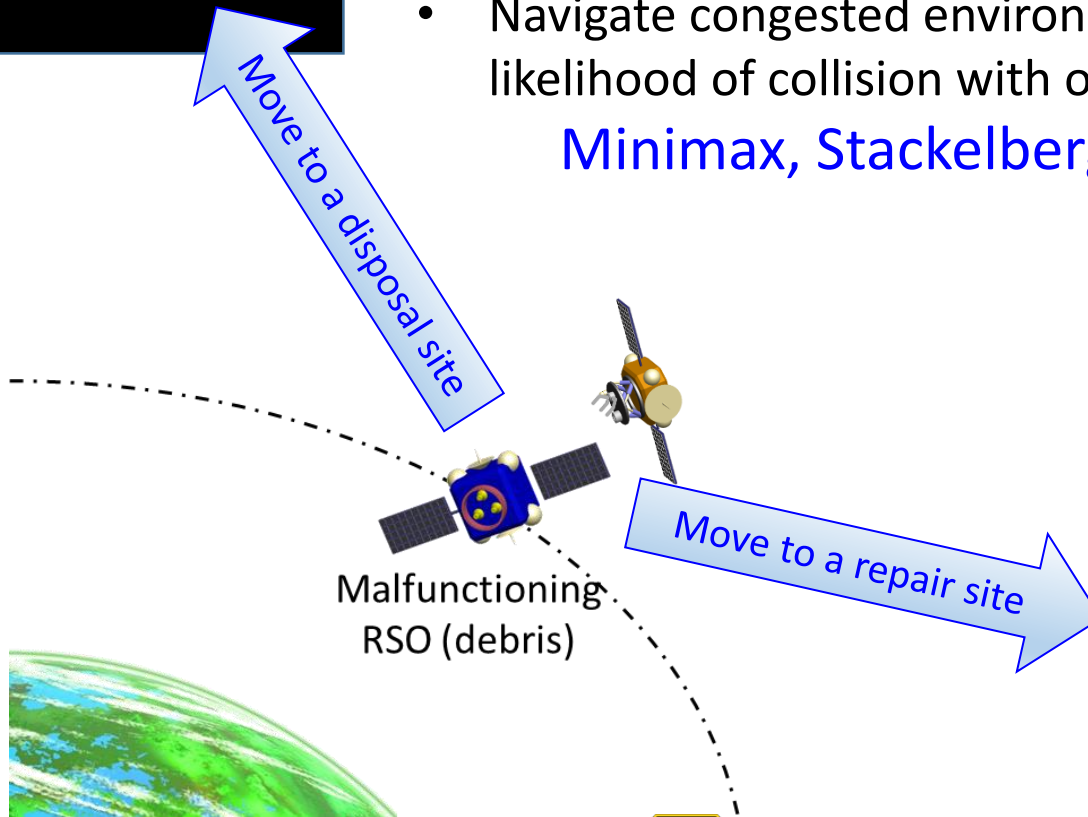
$$J_2(\underline{u}_{1s}, \underline{u}_{2s}) \leq J_2(\underline{u}_{1n}, \underline{u}_{2n})$$



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**





- 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/>