CONTROLLED AND ACTIVE DEBRIS REMOVAL FROM LOW EARTH ORBIT

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OUTLINE

What is orbital debris?

From where should it be removed?

What kind of orbital debris should be removed?

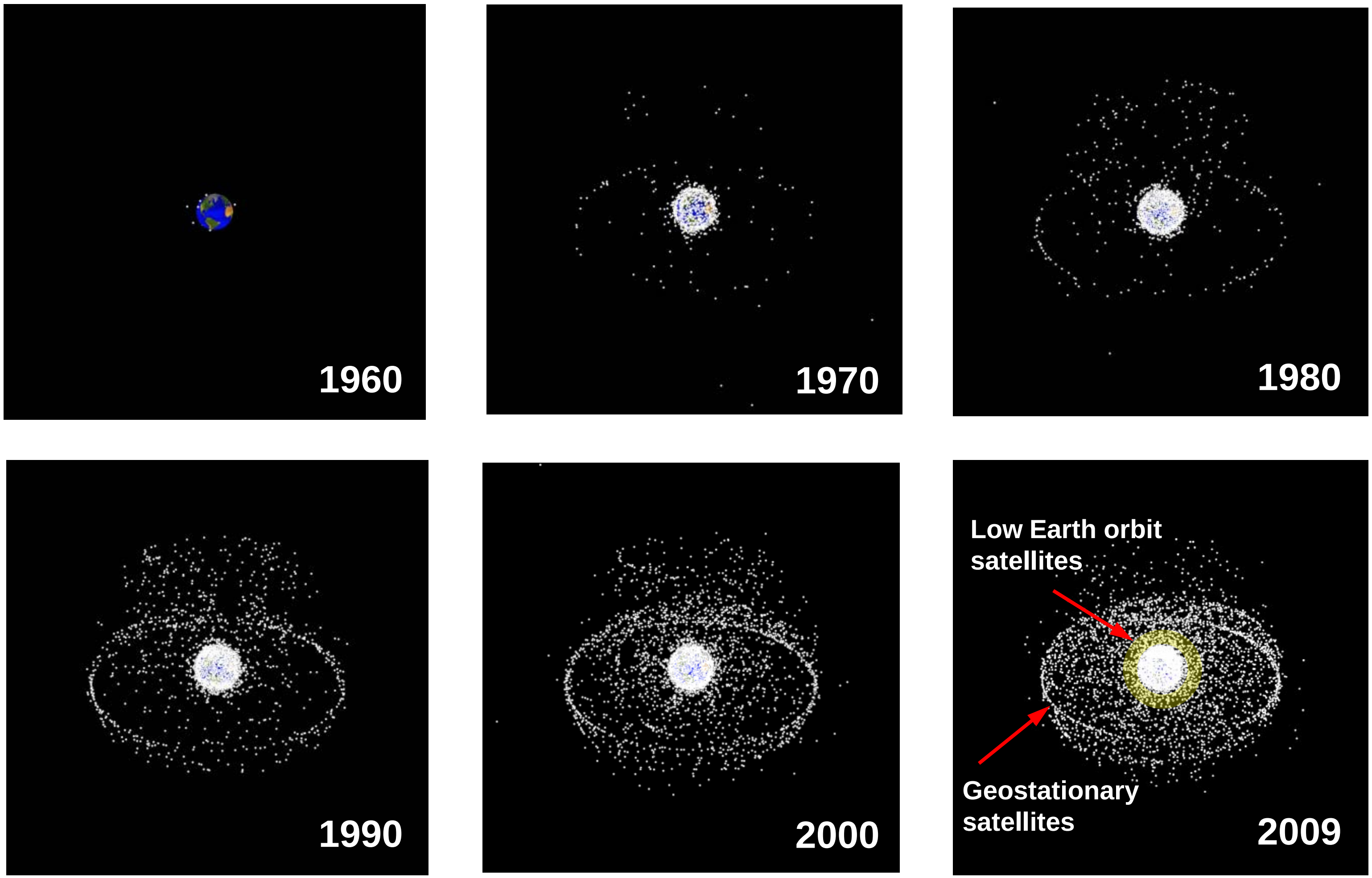
How should it be removed?

Concept of operations for a debris removal mission

Summary

ORBITAL DEBRIS

All of the man-made objects in Earth orbit which no longer serve a useful purpose



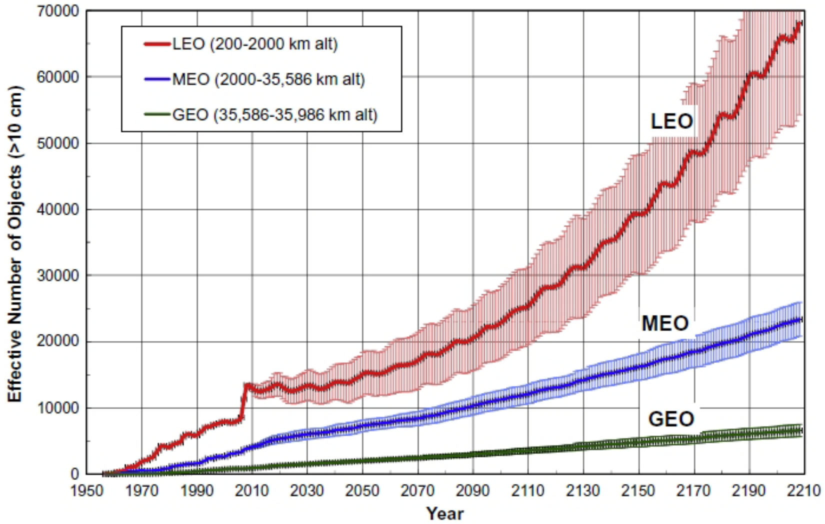
Images courtesy of NASA

95% of the objects tracked in Earth orbit are debris
Since the beginning of the space age 2,000,000kg of debris have been left in orbit

WHAT ORBIT AND WHY?

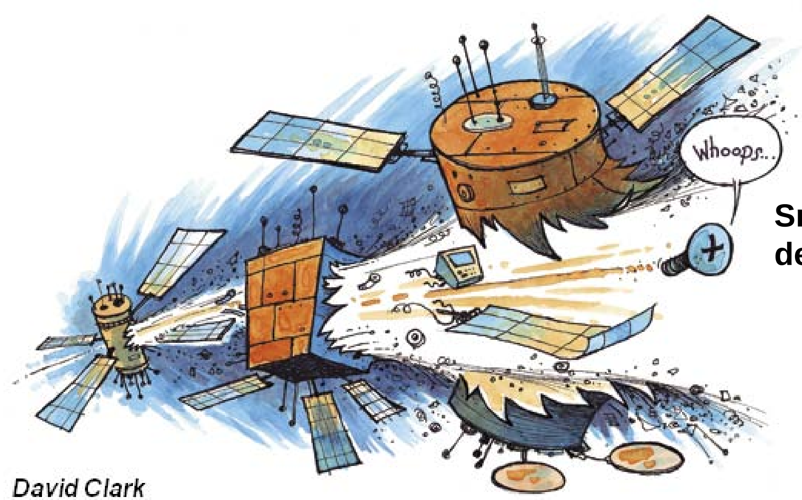
Low Earth orbit (LEO) 200km < altitude < 2000km

LEO is the orbital region with the highest predicted risk of collisions and largest predicted growth



Liou, J.-C. "*An active debris removal parametric study for LEO environment remediation*" J. Adv. Space Res. (2011)

Hundreds of active science and commercial satellites operate in LEO



Small debris

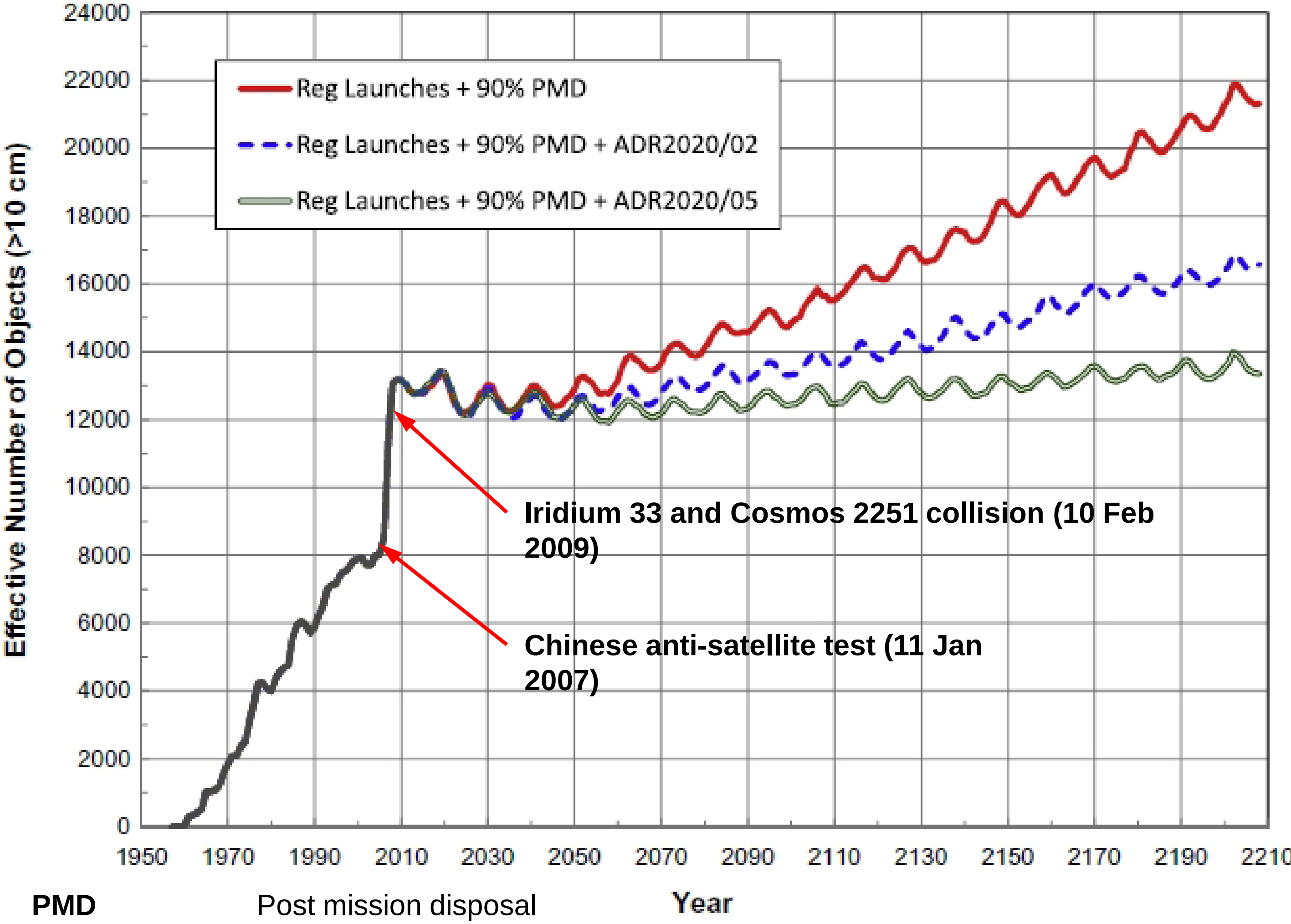
Crewed missions operate in LEO

Debris of all sizes

Screenshot from "Gravity"

ORBITAL DEBRIS IN LOW EARTH ORBIT

Predicted growth of orbital debris in LEO



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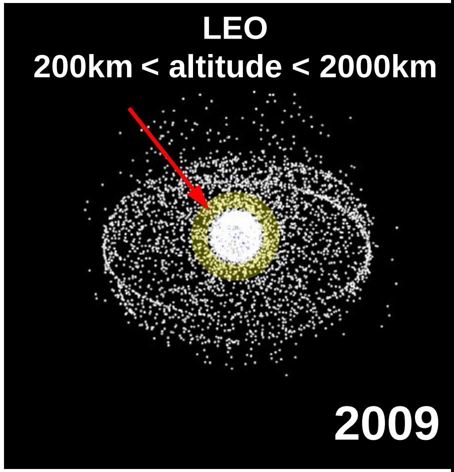


PMD Post mission disposal

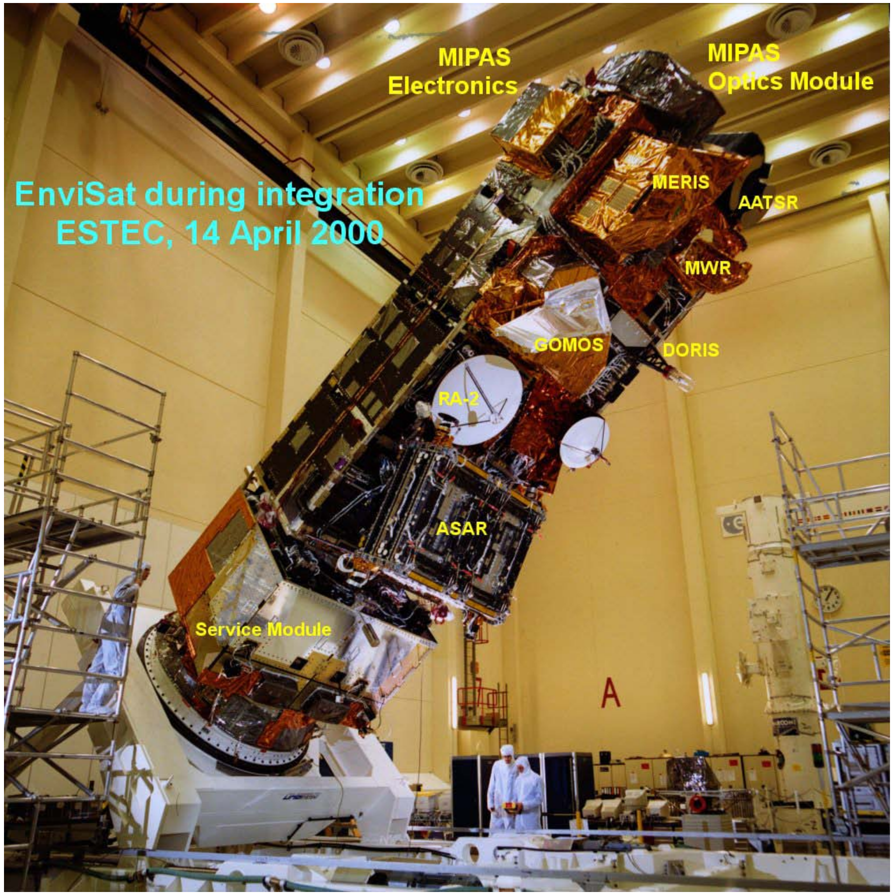
ADR2020/02 Active debris removal starting in 2020 at a rate of ***two*** large objects per year

ADR2020/05 Active debris removal starting in 2020 at a rate of ***five*** large objects per year

WHAT KIND OF LEO DEBRIS?

Large inactive satellites

National security concerns and large flimsy appendages make them difficult targets (for the time being.)



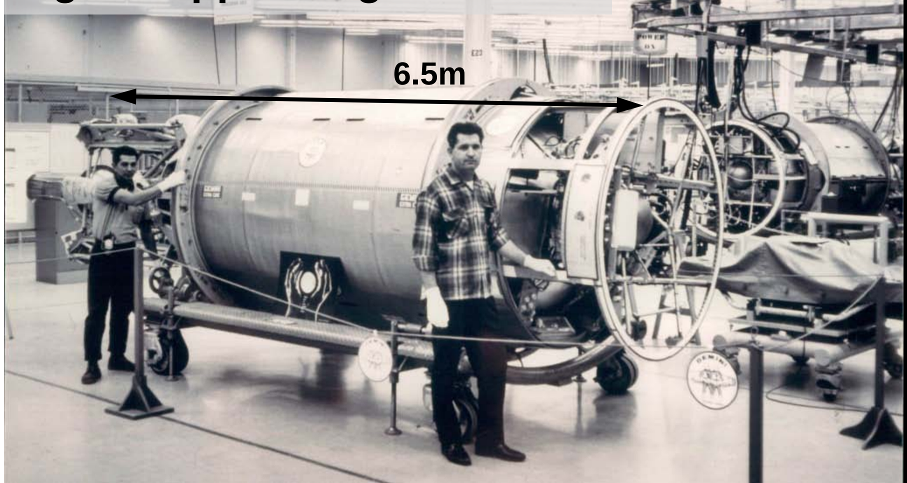
Contact lost: 8 April 2012
Official end: 9 May 2012

Spent upper stages

Robust design that withstood launch loads and lower national security concerns

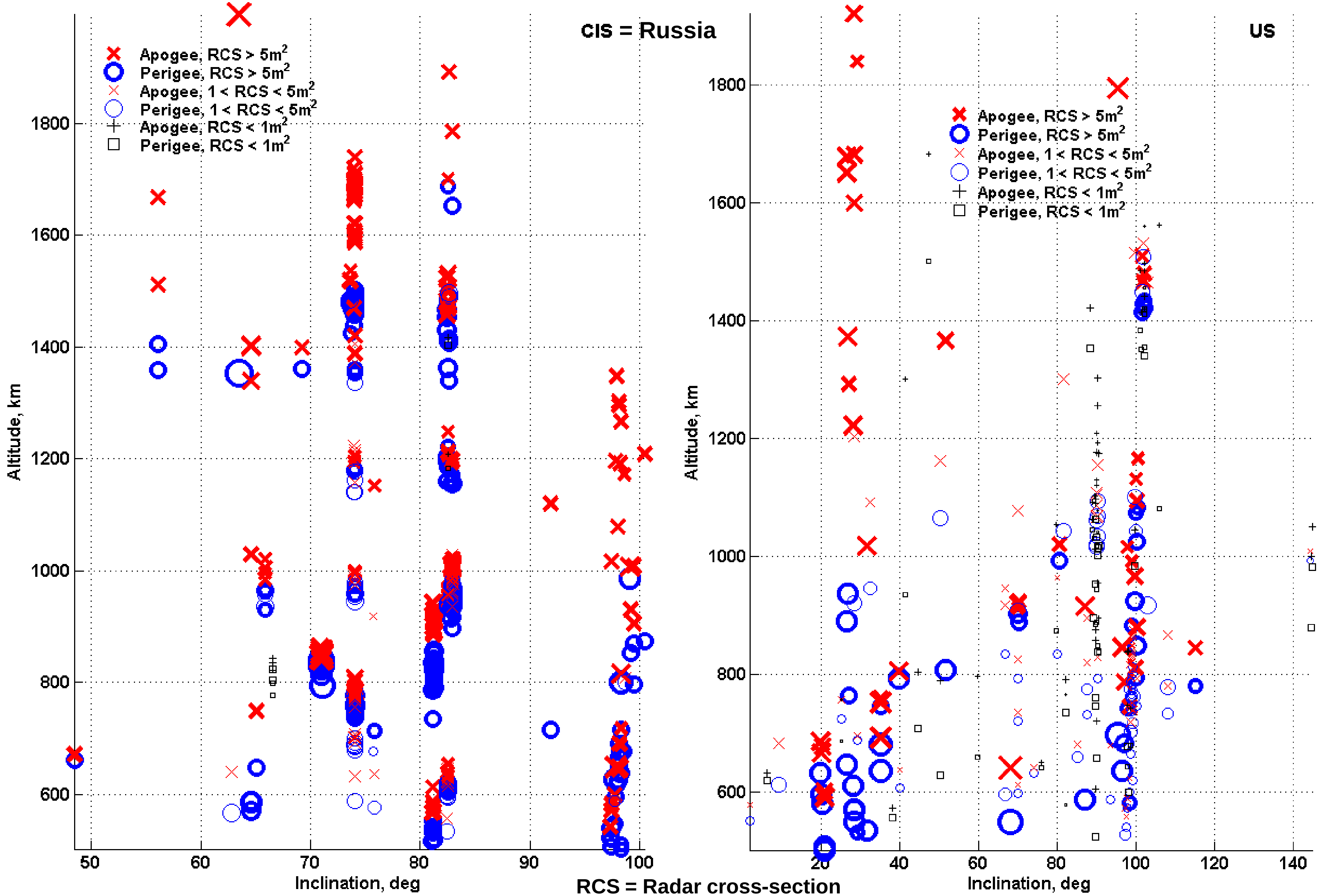
Kosmos 3 / SL8 2nd stage

Agena upper stage



WHERE IN LEO? (1/2)

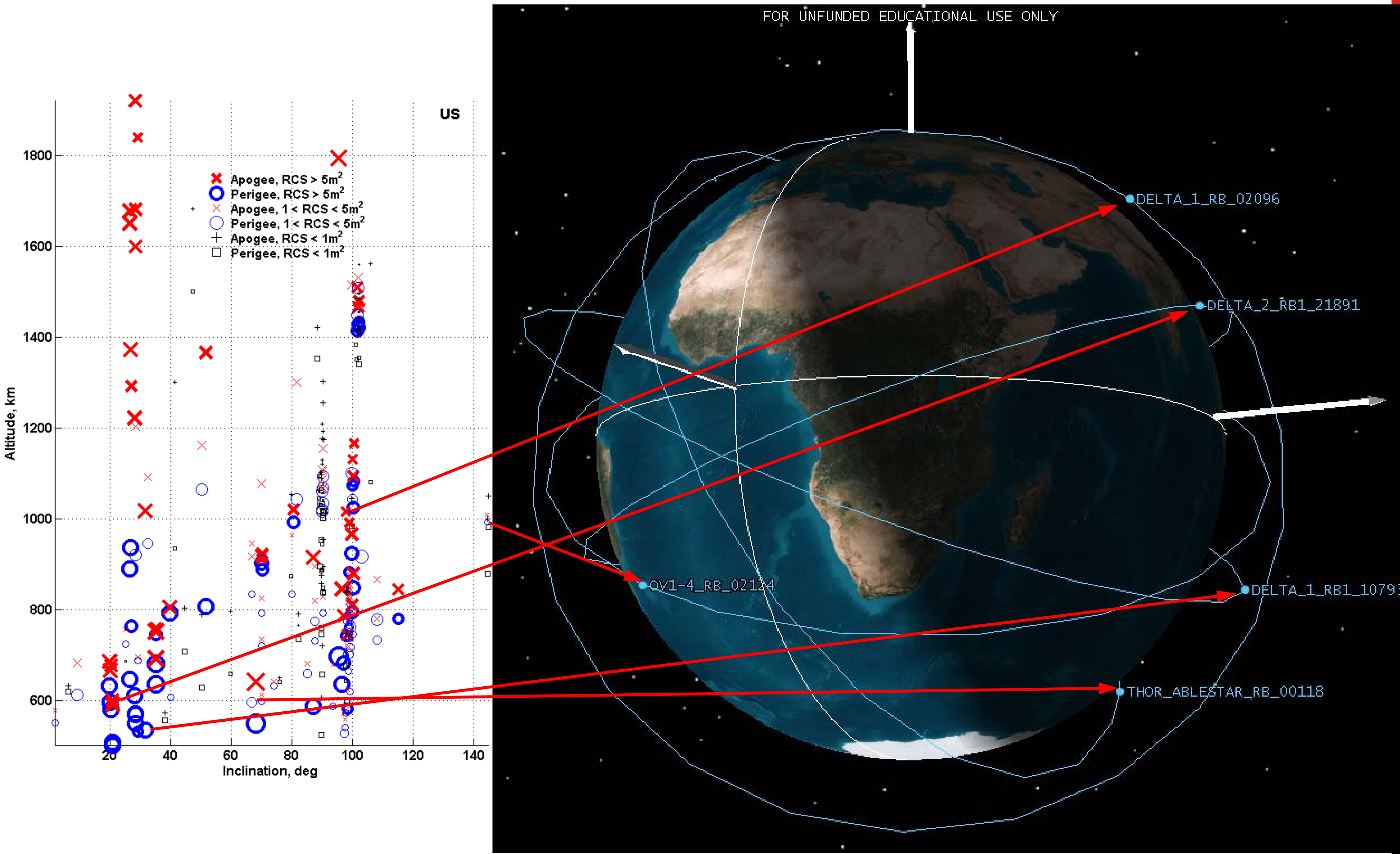
Spent upper stages, aka rocket bodies (R/B), in LEO



RCS = Radar cross-section

WHERE IN LEO? (2/2)

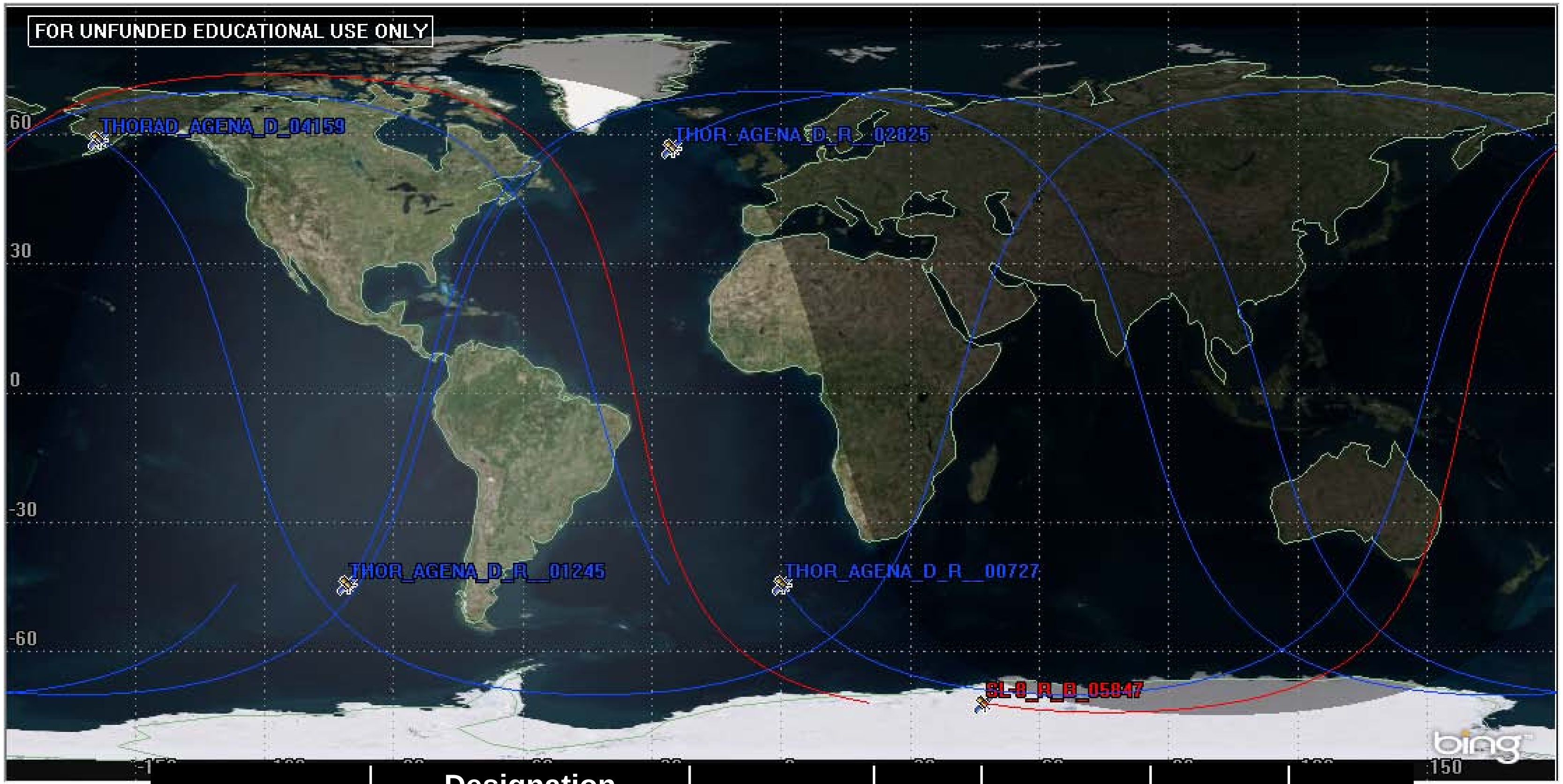
Some US spent upper stage (rocket body) orbits in LEO



RCS = Radar cross-section

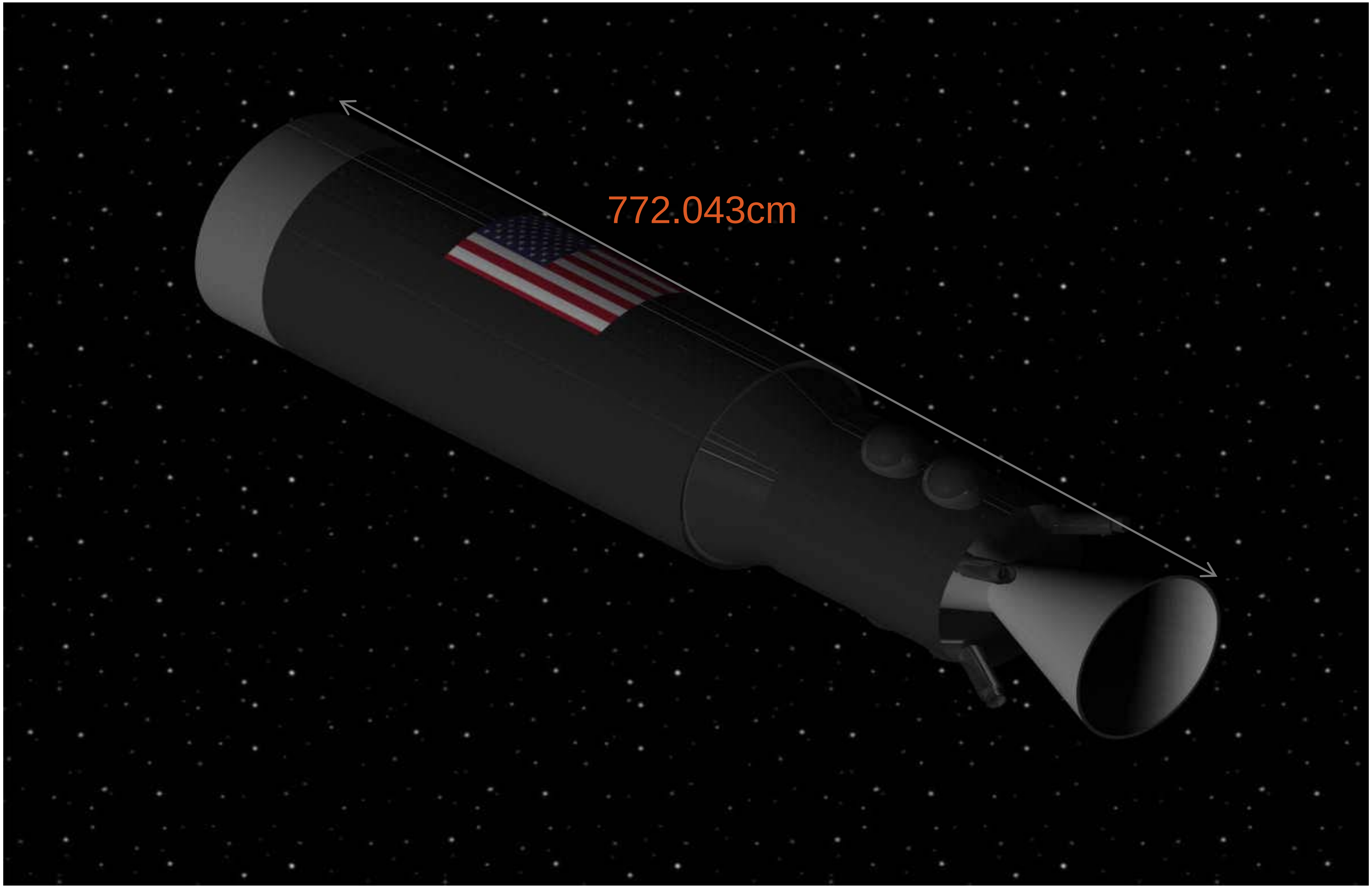
WHAT UPPER STAGE?

Demo Mission To an Agena D upper stage

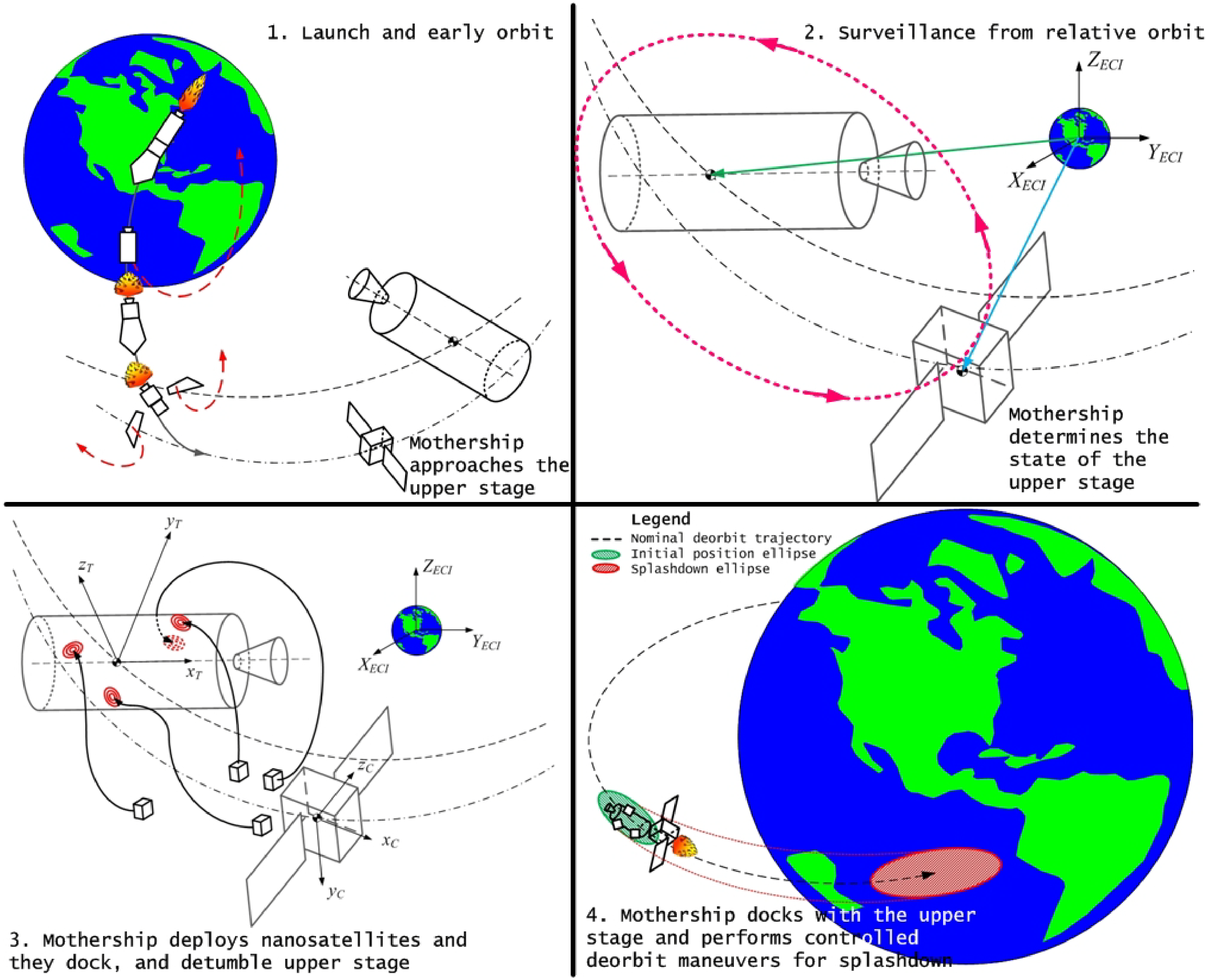


Name	Designation		Launch Date	Incl. (°)	Apogee (km)	Perigee (km)	RCS (m^2)
	International	NORAD					
Thor Agena D R/B	1964-001A	00727	1/11/1964	69.91	1078	906	4.866
	1965-016J	01245	3/9/1965	70.08	912	898	5.212
	1967-053B	02825	5/31/1967	69.97	923	888	6.644
	1969-082AB	04159	9/30/1969	69.96	919	902	7.469
SL-8 R/B	1972-009B	05847	2/25/1972	74.05	989	945	4.837

AGENA UPPER STAGE MODEL



HOW?



1. Launch and early orbit
Mothership approaches the upper stage
2. Surveillance from relative orbit
Z_{ECI}
Y_{ECI}
X_{ECI}
Mothership determines the state of the upper stage
y_T
z_T
x_T
Z_{ECI}
Y_{ECI}
X_{ECI}
z_C
x_C
y_C
3. Mothership deploys nanosatellites and they dock, and detumble upper stage
Legend
Nominal deorbit trajectory
Initial position ellipse
Splashdown ellipse
4. Mothership docks with the upper stage and performs controlled deorbit maneuvers for splashdown

CONCEPT OF OPERATIONS

Active orbital debris removal in seven easy steps

1. **Mother ship carries up to a dozen of nanosats to the proximity of the target**
2. **Mother ship performs surveillance of the target and it determines its rate of tumble and other relevant dynamics**
3. **Mother ship determines the best docking spots for the nanosats and plans their paths**
4. **Nanosats are deployed one by one and they navigate to a soft dock with the target**
5. **Nanosats broadcast data about the spacecraft to the mothership which then refines the dynamic model of the target and performs structural health analysis**
6. **Nanosats detumble the target**
7. **Mother ship docks with the upper stage and performs deorbit burns for controlled reentry**

ADVANTAGE OF THE PROPOSED METHOD

Relies (mostly) on proven technologies and well understood dynamics

- The majority of the development effort is focused on *algorithms for cooperative autonomy*

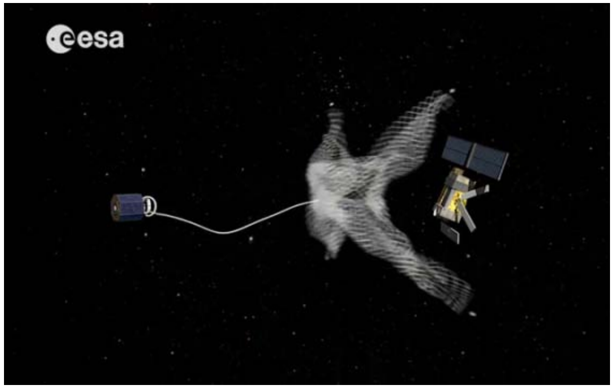
Redundancies

Inexpensive

Other concepts rely on a single debris removal satellite and various capture methods

Robot arm

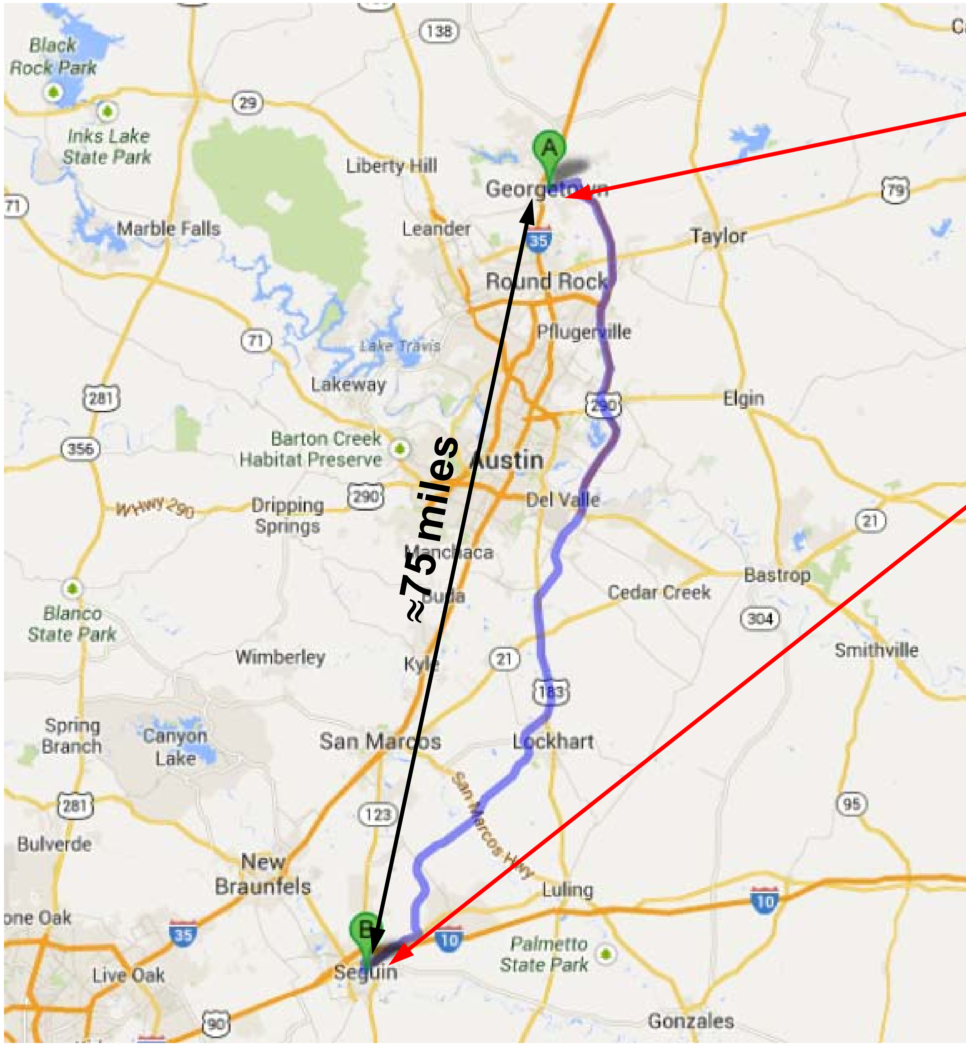
Cast net



Harpoon

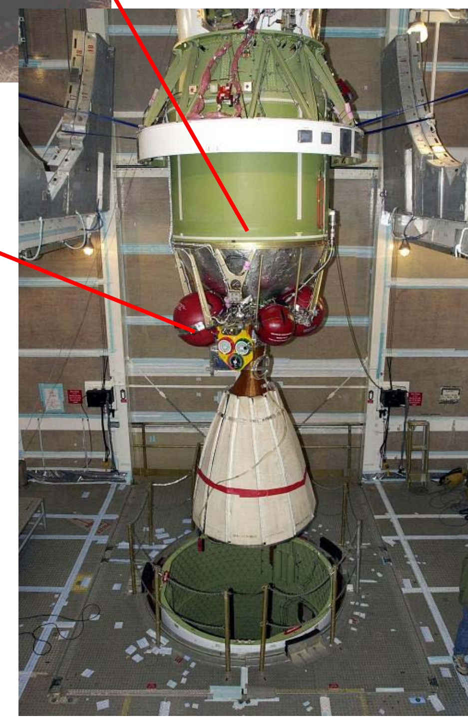
WHY CONTROLLED REENTRY?

Recovered objects from a Delta II upper stage which reentered on 22 Jan 1997



Delta II upper stage propellant tank

Delta II upper stage pressurant tank



Delta II upper stage

NASA-STD8719.14 and DoD Instruction 3100.12 both require that the "*risk from the total debris casualty area for components and structural fragments surviving reentry shall not exceed 1 in 10,000.*"

DEBRIS ASSESSMENT SOFTWARE

64 components present in Agena Upper Stage

Casualty area and kinetic energy obtained using DAS

Only two expected to survive reentry

- Propellant Tank
- Engine

DAS DATA

Component	Casualty Area (m^2)	Kinetic Energy (kJ)
Propellant Tank	10.15	25.9
Engine	5.82	53.7

Debris Casualty Area (m^2)

$$D_A = \sum_{i=1}^{N} \left(0.6 + \sqrt{A_i}\right)^2$$

where:

N = the number of objects

A_i = average cross-sectional area of the i^{th} surviving debris fragment (m^2)

CALCULATING CASUALTY RISK

Total human casualty expectation (E) calculated using the equation:

$$E = D_A * P_D$$

where:

D_A = Debris Area

P_D = Total average population density for the orbit

AVERAGE POPULATION DENSITY

The population density data (shown on Figure E-1) comes from an assessment conducted at Johnson Space Center in 2002 of world-wide population projection databases.

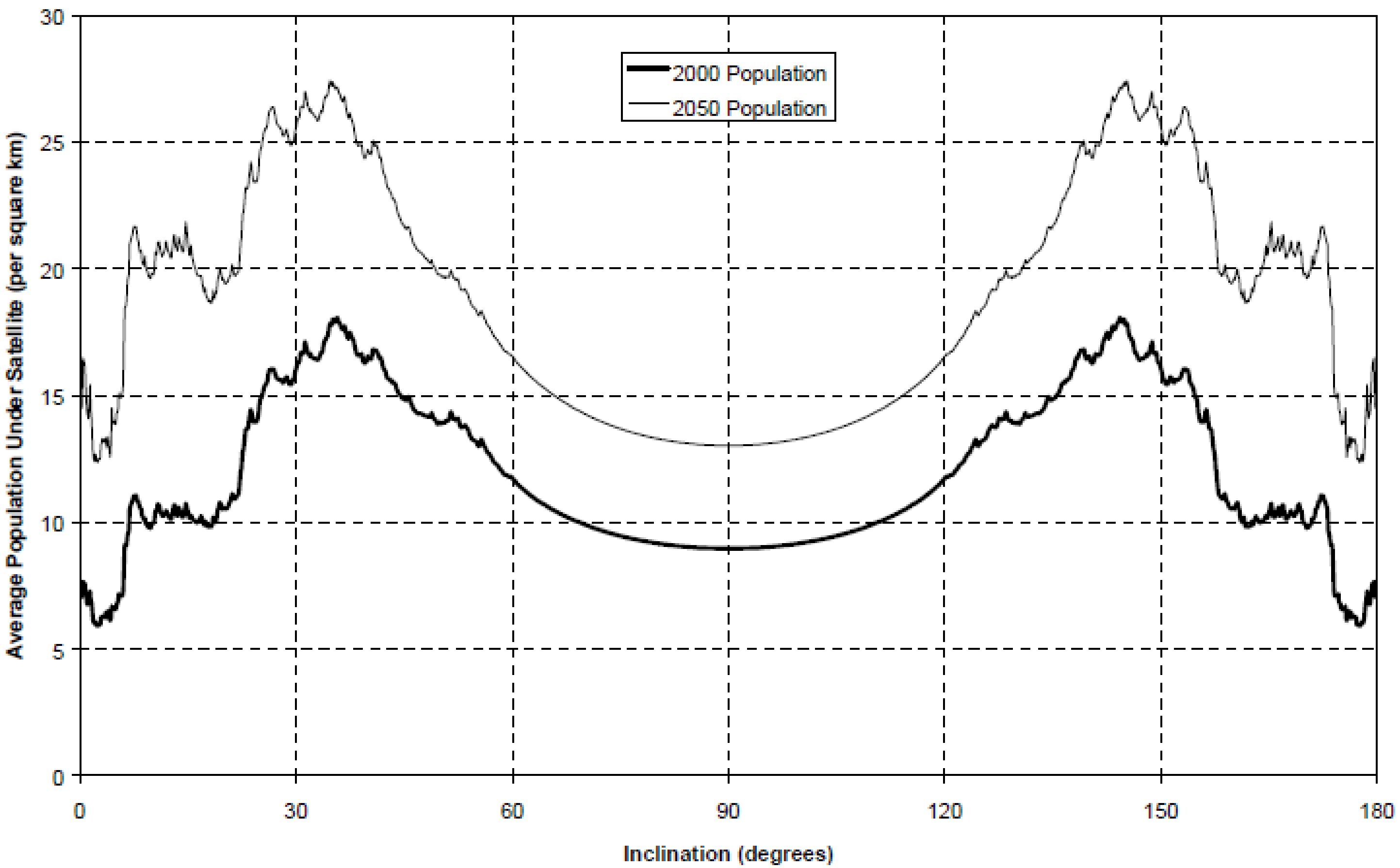


Figure E-1. Average Population Density as a Function of Orbital Inclination

TOTAL CALCULATED RISK

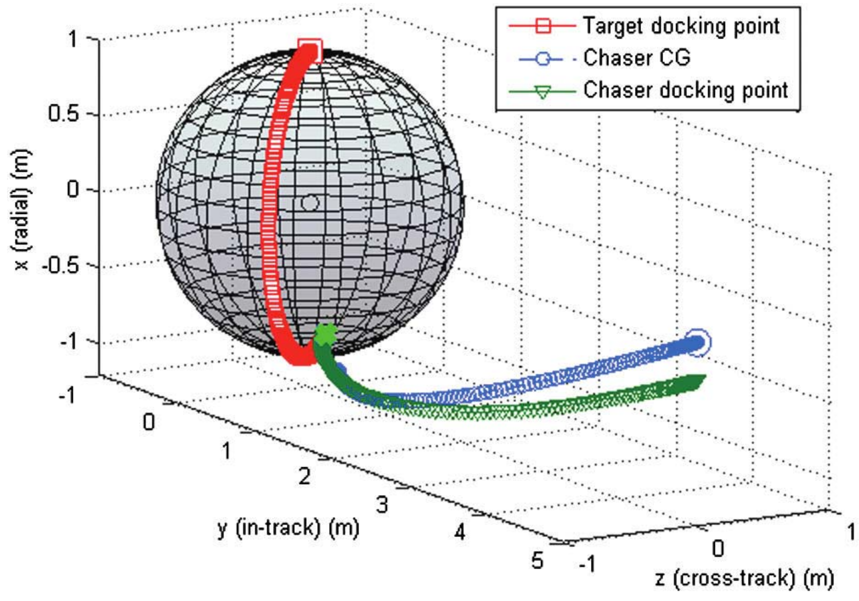
Component	Area (m^2)	Population Density (persons/km^2)	Casualty Risk	Acceptable probability of failure
Propellant Tank	10.15	15	1.52:10,000	65.7 %
Engine	5.82		0.87:10,000	100 %

The propellant tank casualty risk exceeds the acceptable number making it necessary to have a controlled reentry. For a controlled reentry, the product of the probability of failure and the casualty risk cannot exceed 1:10,000.

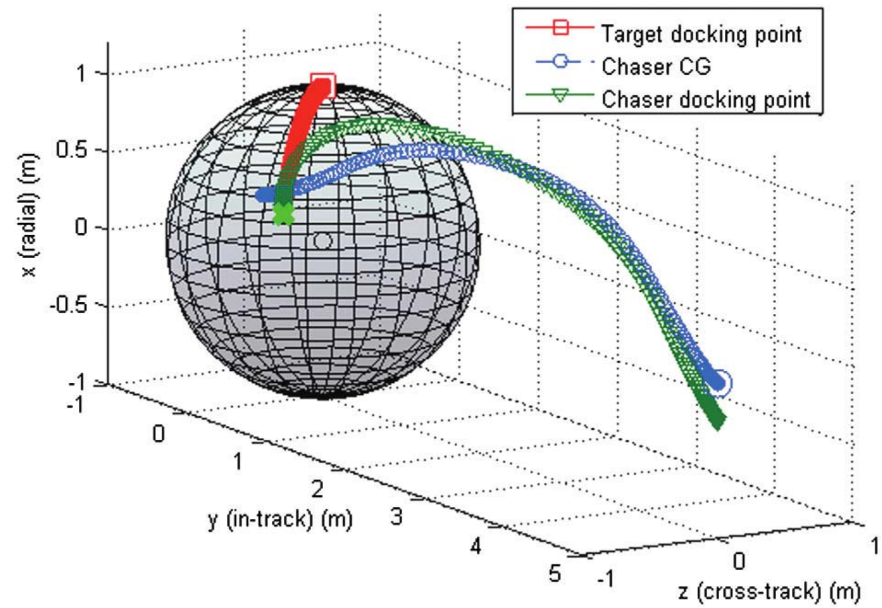
PRELIMINARY FEASIBILITY ANALYSIS

DOCKING MANEUVERS

Maneuvers for docking with a tumbling non-cooperating target



Minimum propellant maneuver



Minimum time maneuver

G. Boyarko, Spacecraft Guidance Strategies for Proximity Maneuvering and Close Approach with A Tumbling Object, Naval Postgraduate School, PhD Dissertation, 2010.

G. Boyarko, O. Yakimenko, M. Romano, Optimal Rendezvous Trajectories of a Controlled Spacecraft and a Tumbling Object, Journal of Guidance, Control, and Dynamics, 34 (2011) 1239-1252.

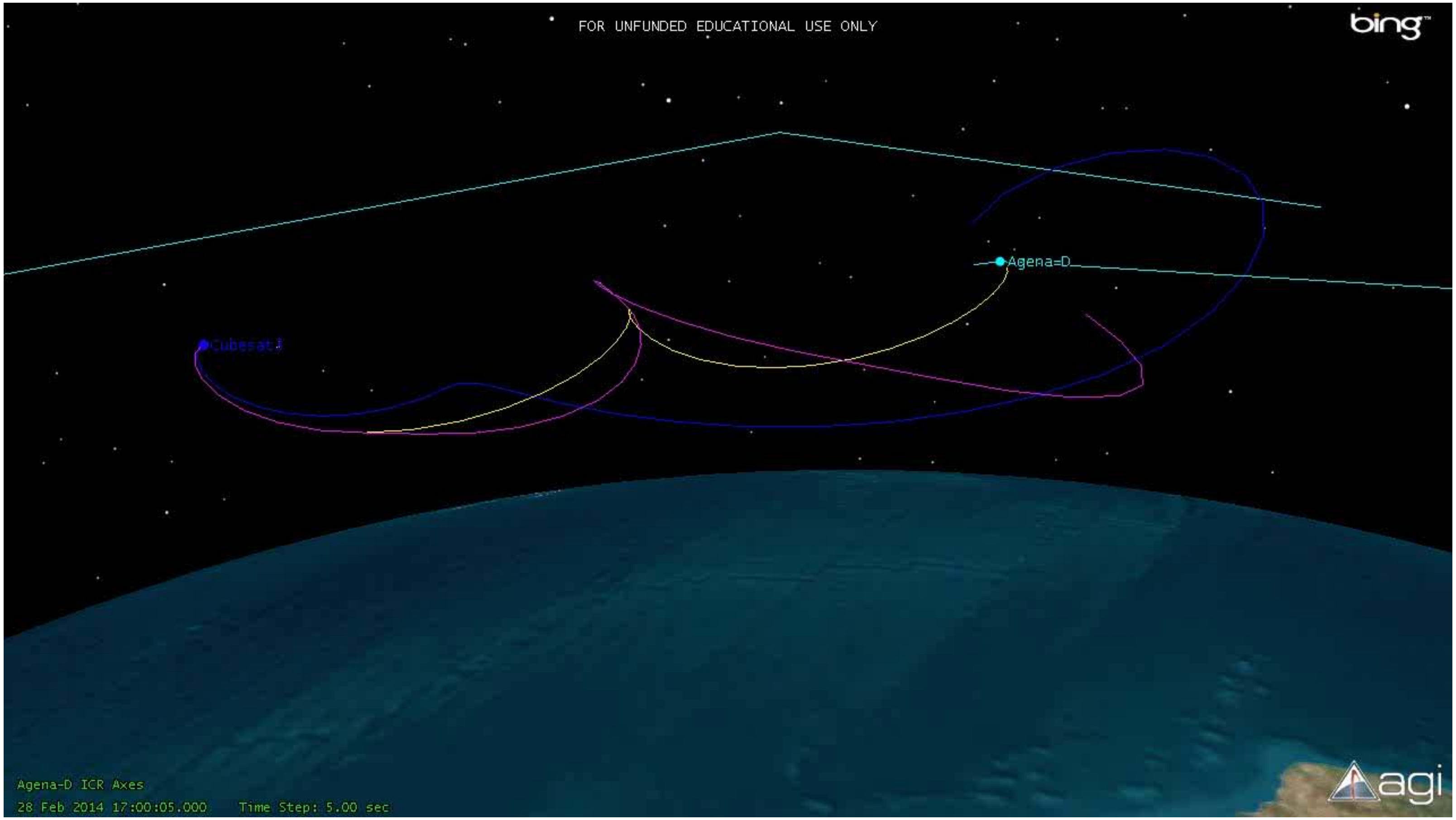
NANOSAT OPTIMAL TRAJECTORY

Minimum propellant maneuver

Cubesat must match final position and velocity of the desired docking point on the rocket body.

Preliminary results show maneuvers taking less than 0.5 m/s deltav to dock per cubesat.

NANOSAT TRAJECTORY VIDEO



PROPOSED DOCKING MECHANISM

The Sticky Boom from Altius Space Machines

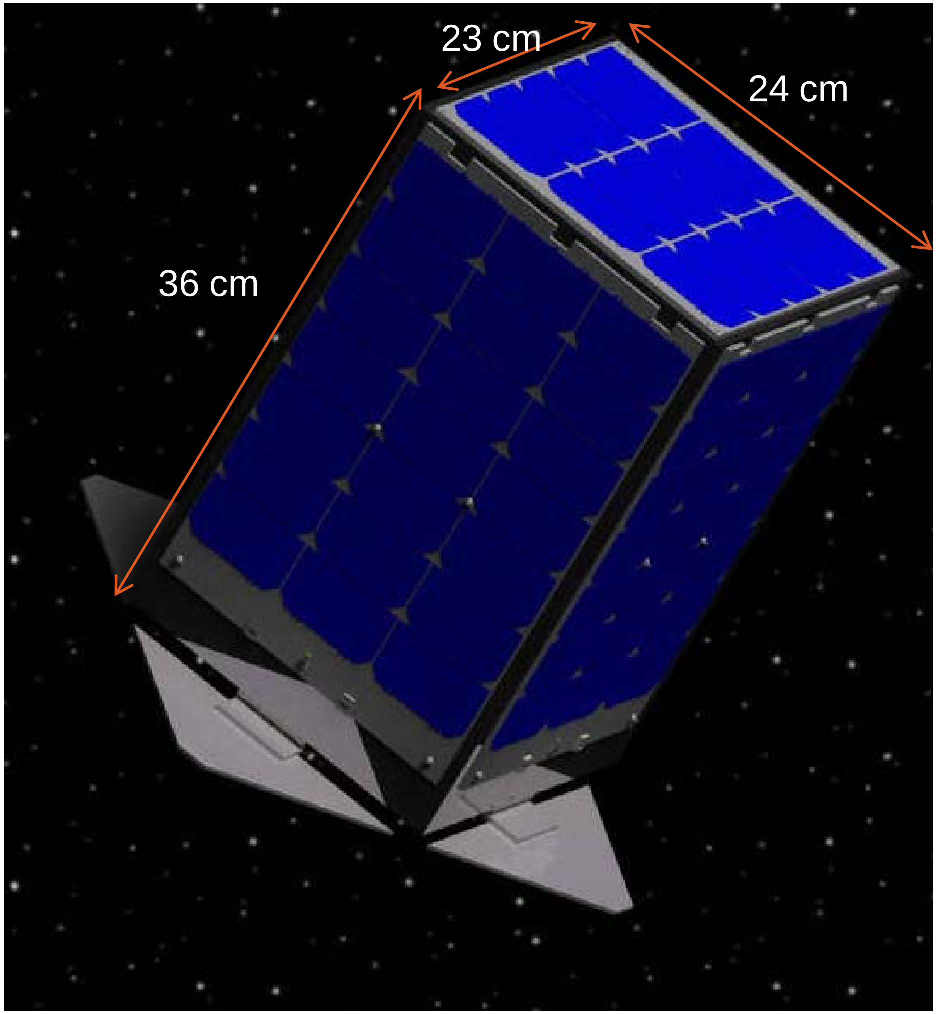
Sticky **mechanism at the end of deployable** ***boom***

WHAT IS ELECTROADHESION?

- Our design uses SRI's patented electro-adhesion technology.
- SRI International's robot demonstrates electro adhesion in the above video.

NANOSAT DESIGN

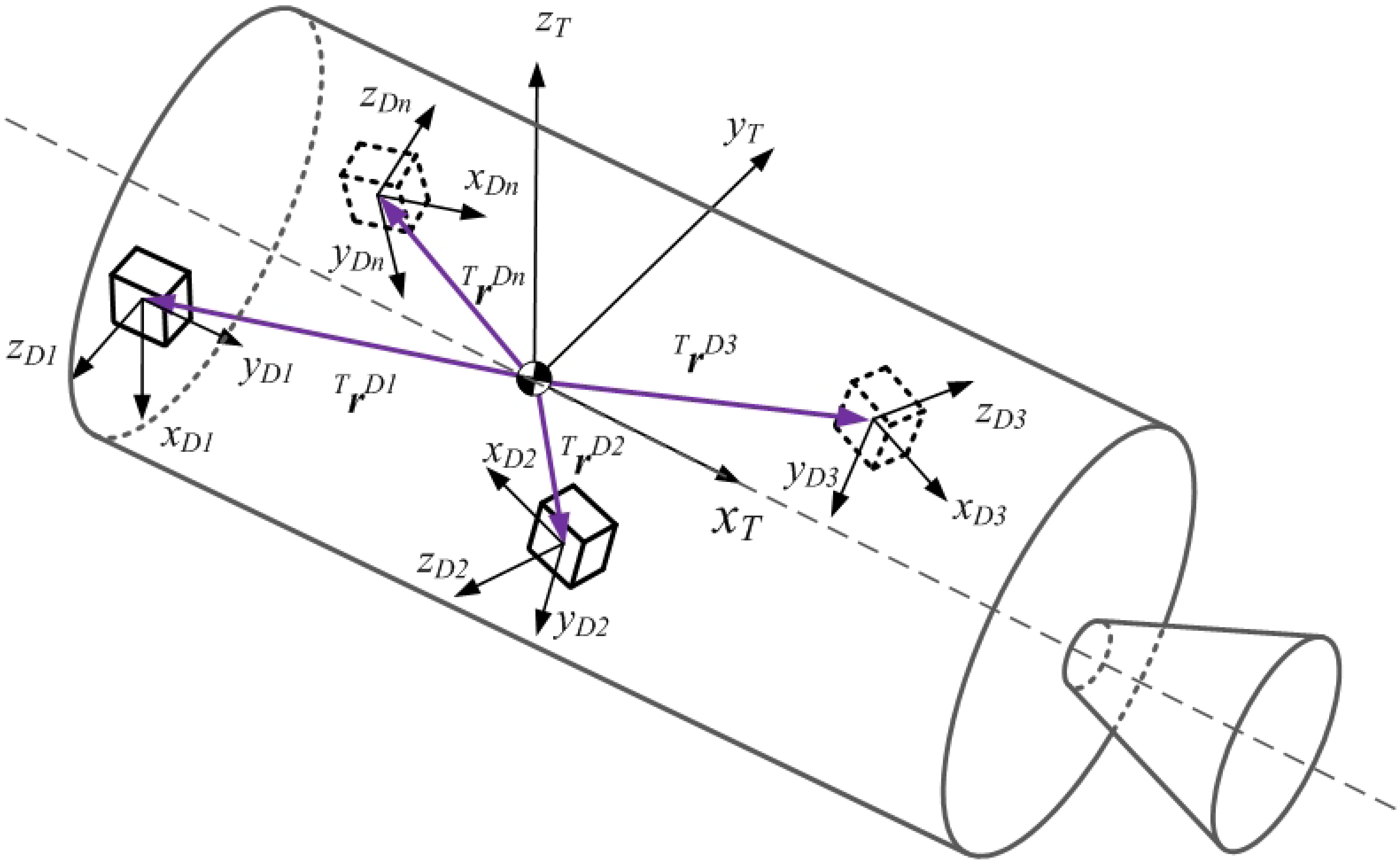
Actual Docking mechanism: Electro adhesive panels mounted on the bottom of the nanosat.



Nanosat with Electroadhesive panels deployed

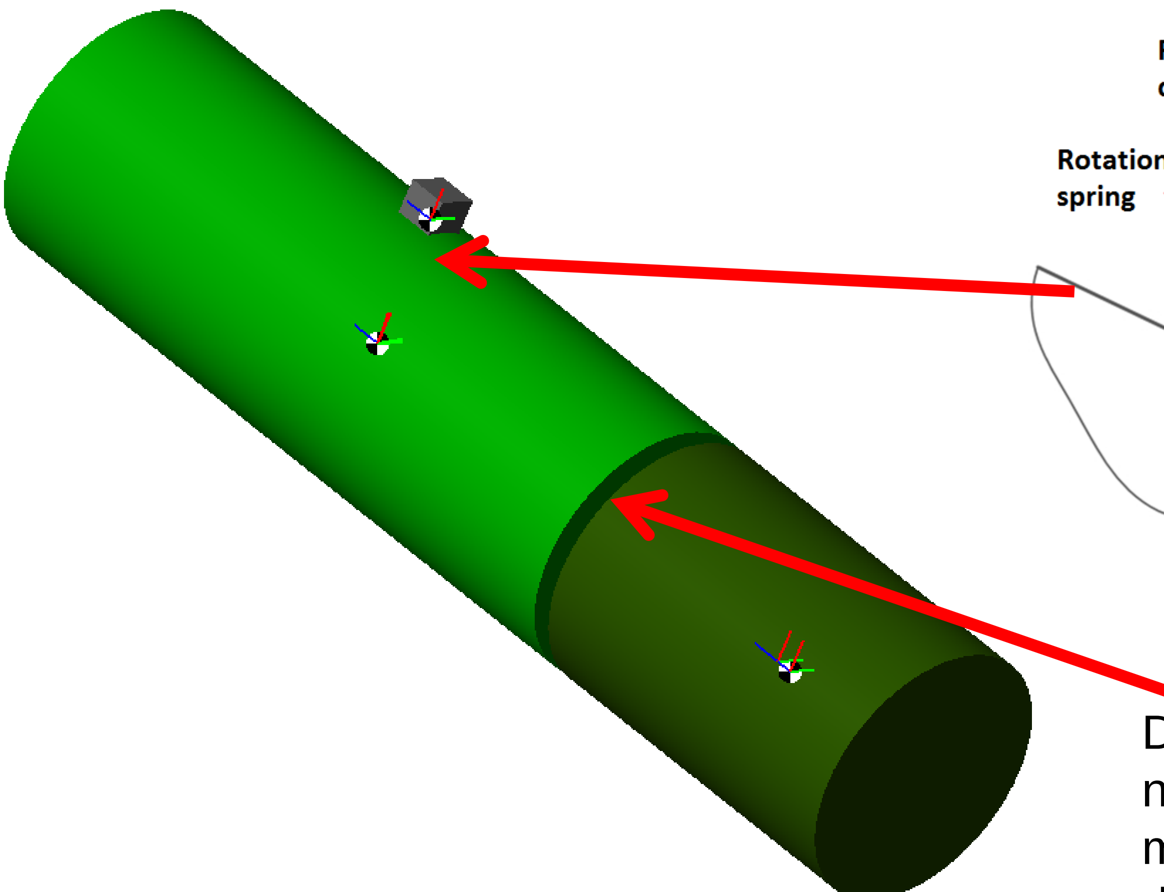
NANOSAT DYNAMIC SYSTEM

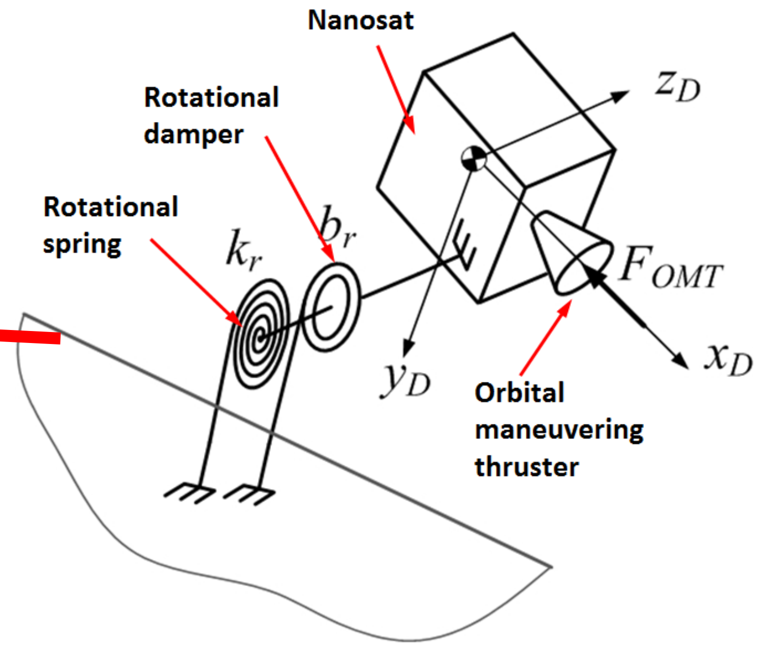
Nanosats docked with the upper stage
Dynamical system treated within the theoretical framework of evolving



M. Balas, S. Frost, and F. Hadaegh, "*Evolving Systems: A Theoretical Foundation*," in *AIAA Guidance, Navigation, and Control Conference and*
S. Frost and M. Balas, "*Evolving Systems: An Outcome of Fondest Hopes and Wildest Dreams,*" in AIAA Guidance, Navigation, and Control Con

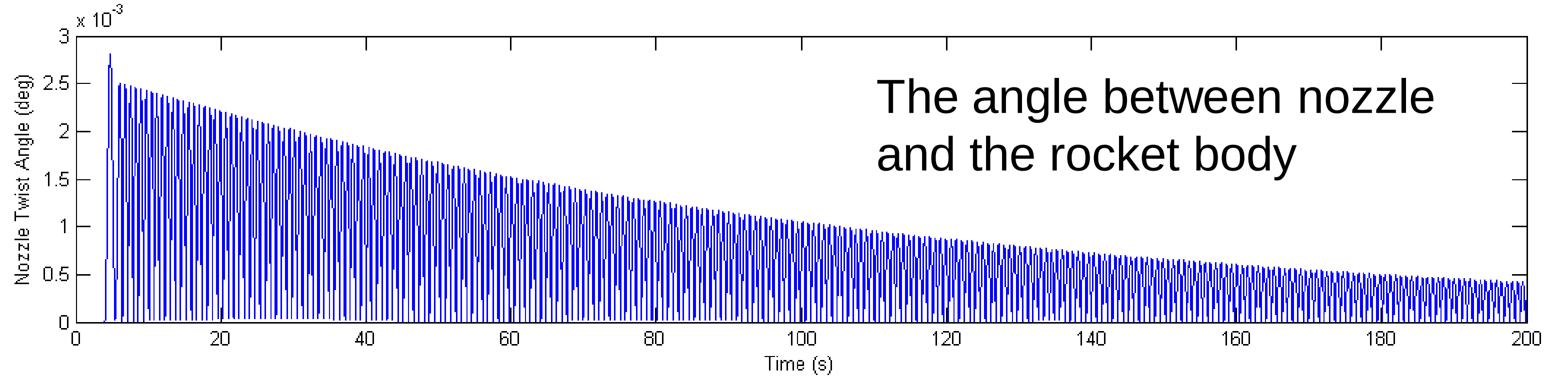
DYNAMICS,MECHANICS, MATLAB®/SIMULINK/SIMMECHANICS

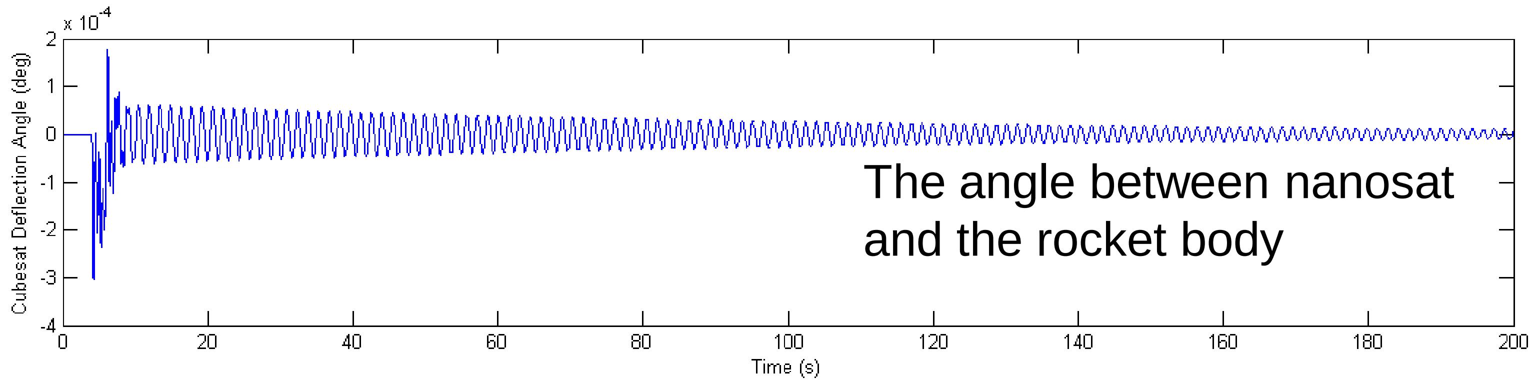


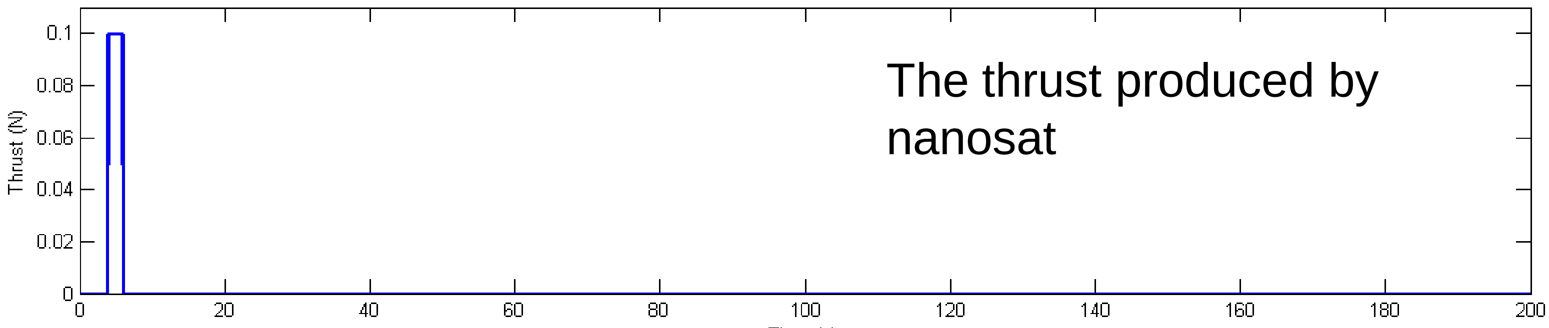


Docking mechanics and nozzle connection are modeled as torsional spring-damper systems

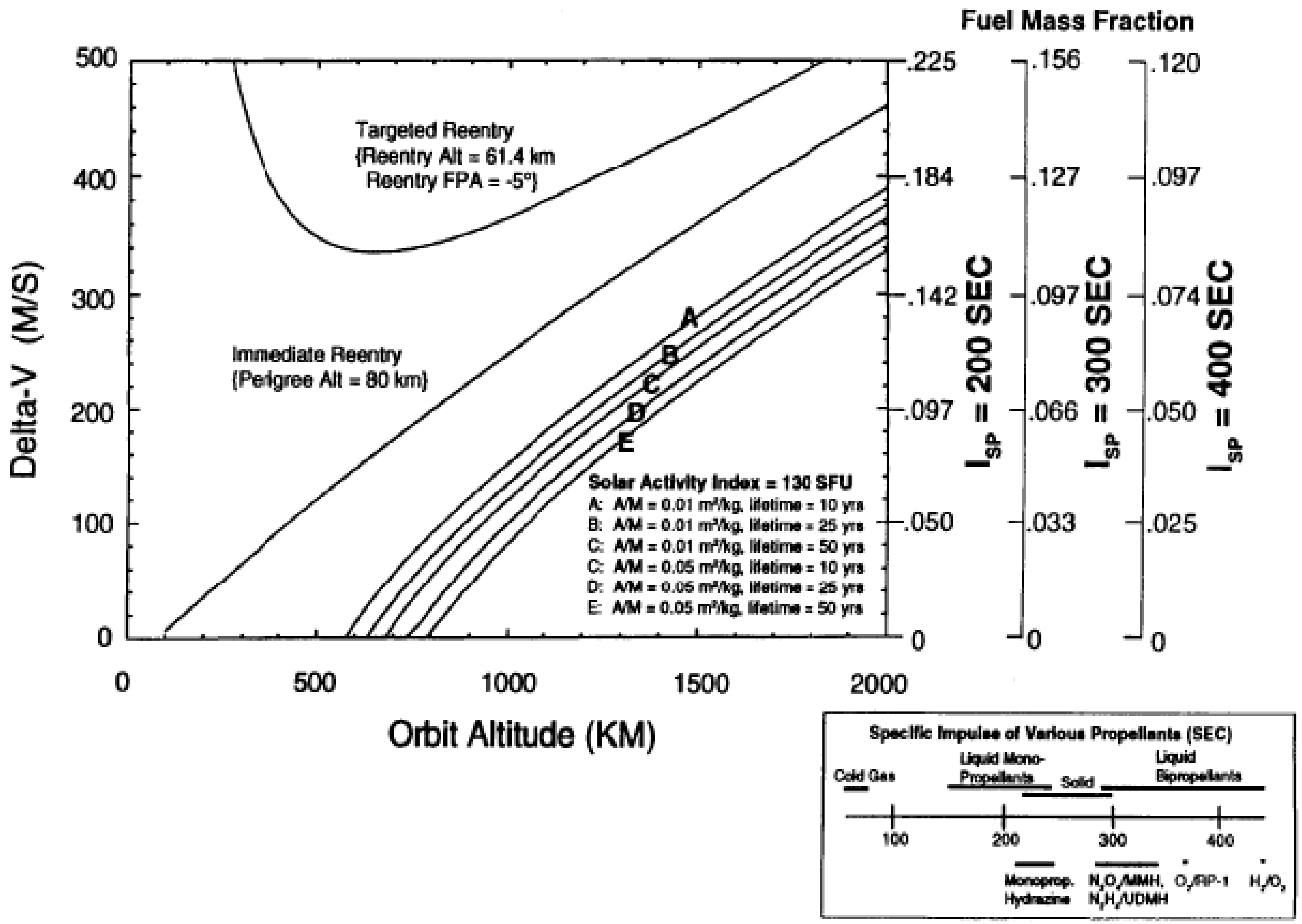
DYNAMICS:
SIMULATION RESULTS



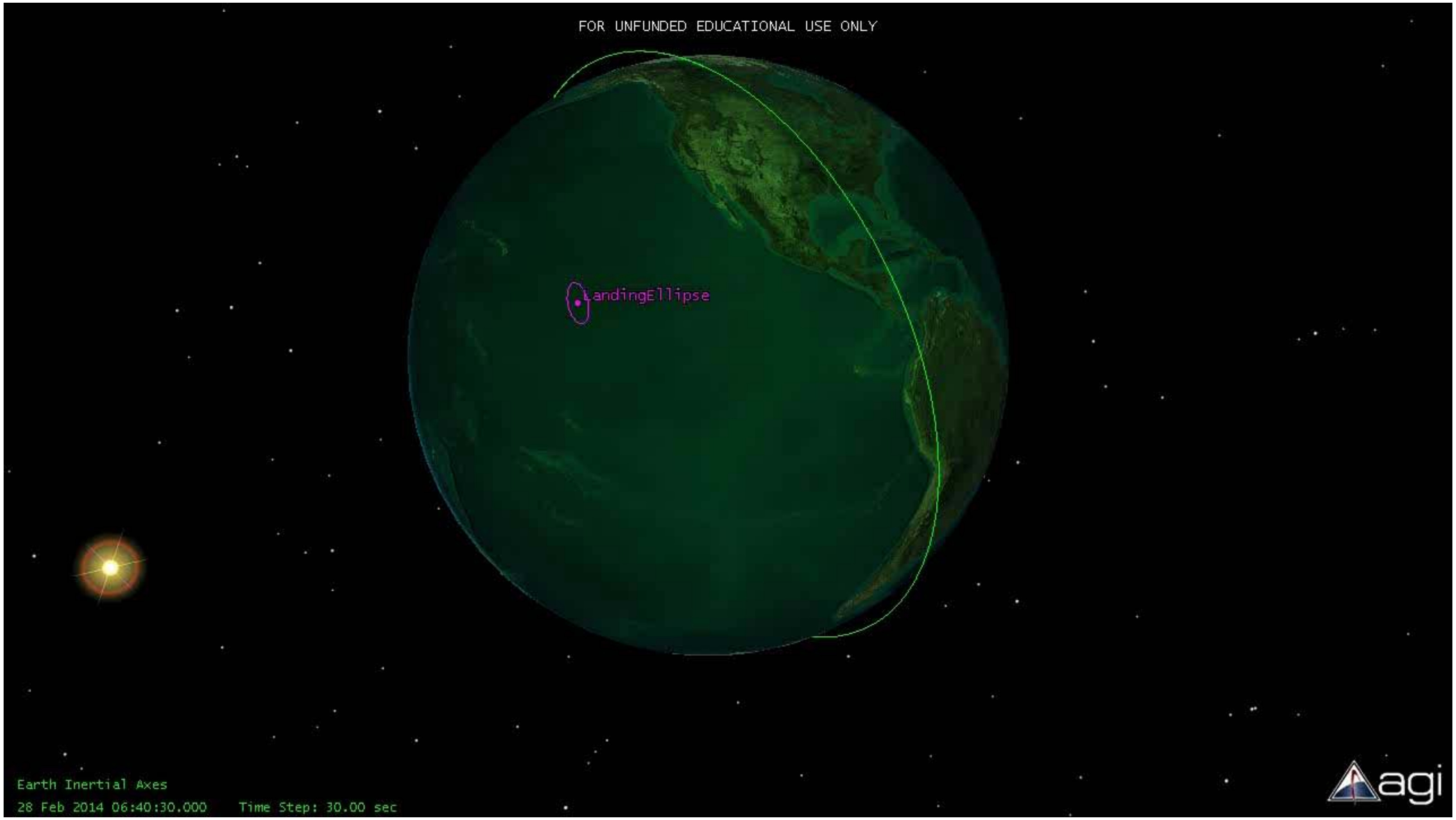




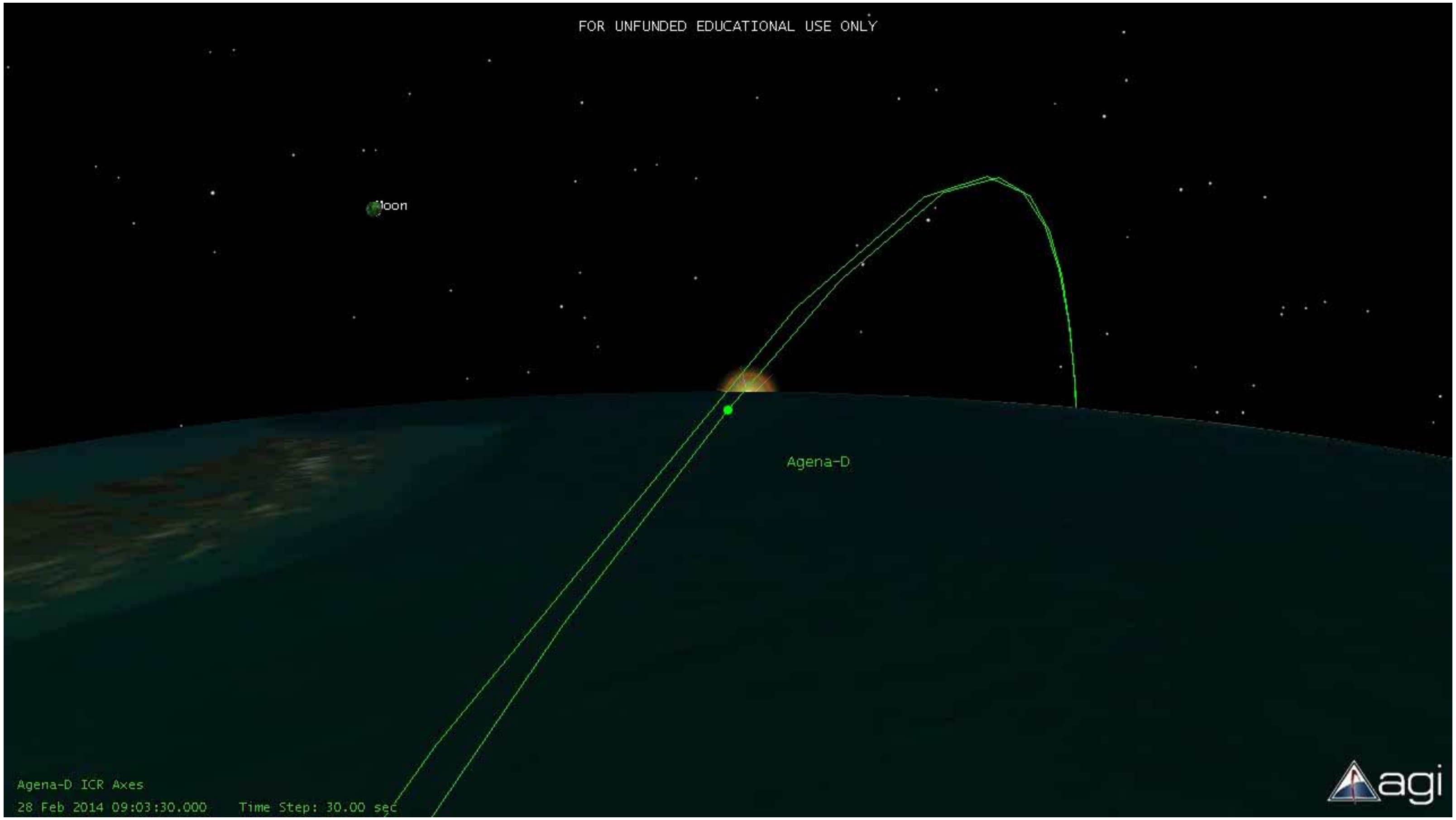
DELTA-V REQUIREMENTS FOR DISPOSAL



DEORBITING VIDEO



DEORBITING VIDEO



SUMMARY (1/2)

The dangers posed by orbital debris is a current problem that will only get worse in the near future

Start with large objects in low Earth orbits and because

- There is potential for exponential growth (Kessler syndrome) in the number of debris due to the collisions of large objects
- LEOs are the most crowded with debris

Start with spent upper stages (aka rocket bodies) because

- They are more robust to the application of reentry loads
- They are less sensitive from the point of view of national security of their owners

SUMMARY (2/2)

Demo mission to an Agena D upper stage (rocket body) because

- The Agena Rocket is owned by the United States
- It has roughly 2/3 the size and 1/2 the mass of a Kosmos3/SL-8 second stage

Concept of operations based on multiple satellites that cooperatively detumble the upper stage and perform deorbit burns

FUTURE GOALS

The first mission is sacrificial because it will be the first test of the proposed concept.

Future missions will be reusable. The nanosats will go back to the mothership and dock with it for refueling.

The mothership is also designed to be refilled with propellant for itself and also be able to take new nanosats in case a few of them are lost or sacrificed.