Space Debris and De-Orbiting

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MEW

Aerospace

Definition of: Space Debris

All man made objects, including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional

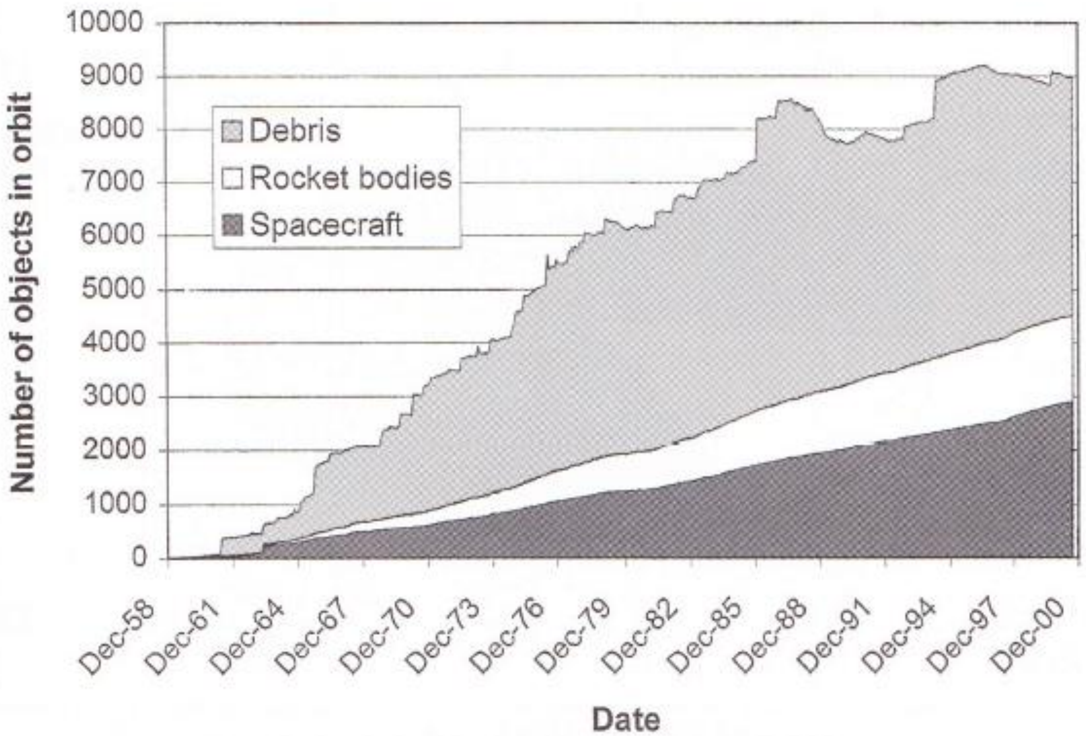
Heiner Klinkrad, Nicholas L. Johnson: Space Debris Environment Remediation, IAA Report 2013

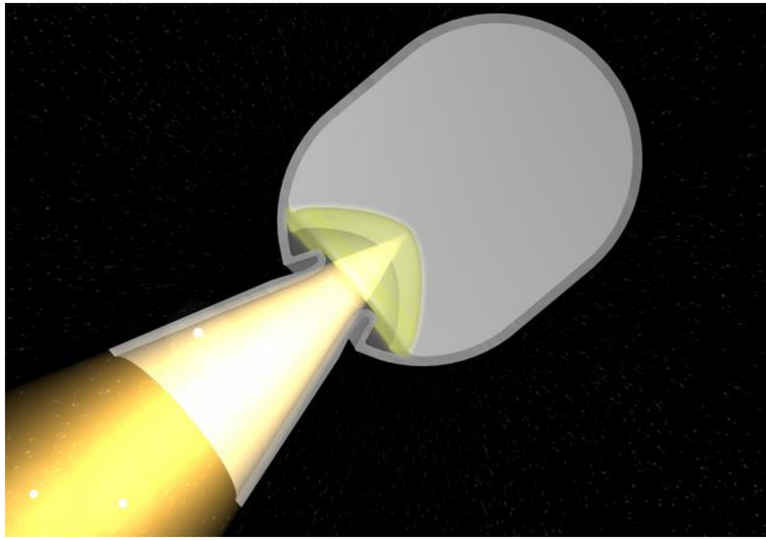
Space Debris

- Spent Satellites
- Launcher Upper Stages
- Launch & Mission Related Objects (LMRO)

- NaK Droplets
- Paint Flakes
- Ejecta
- Solid Rocket Motor (SRM) firings & fragments
- SRM Dust

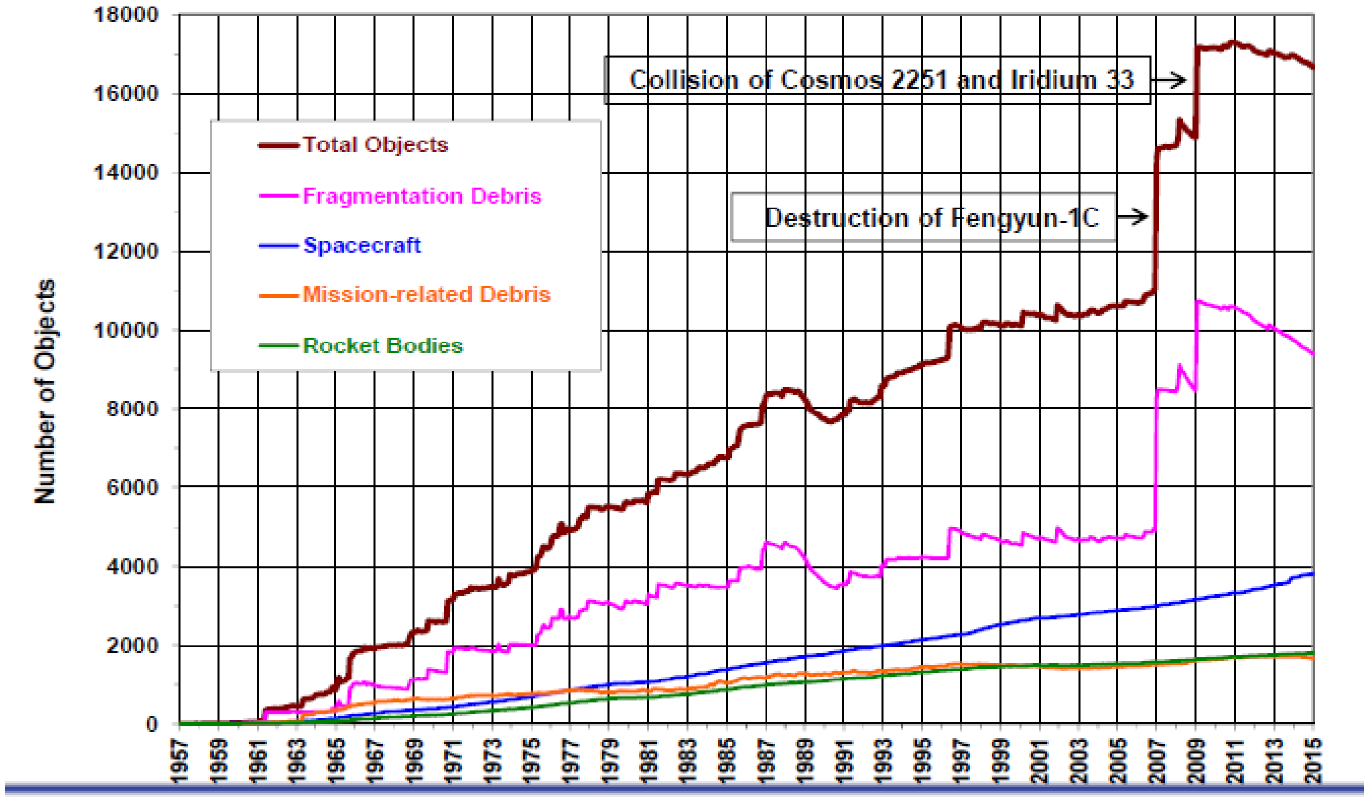
- Meteoroid



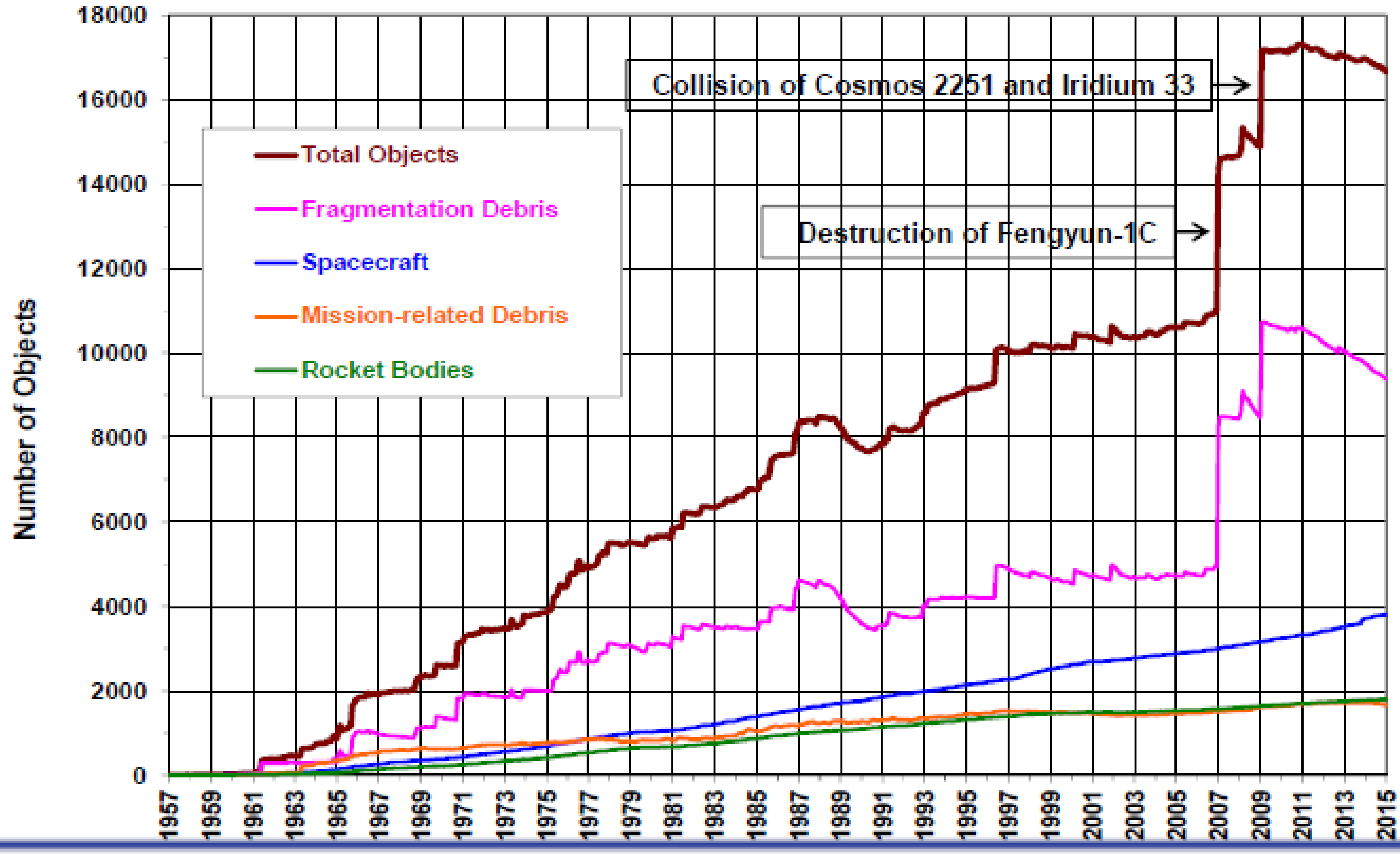


Catalogued On-Orbit Objects

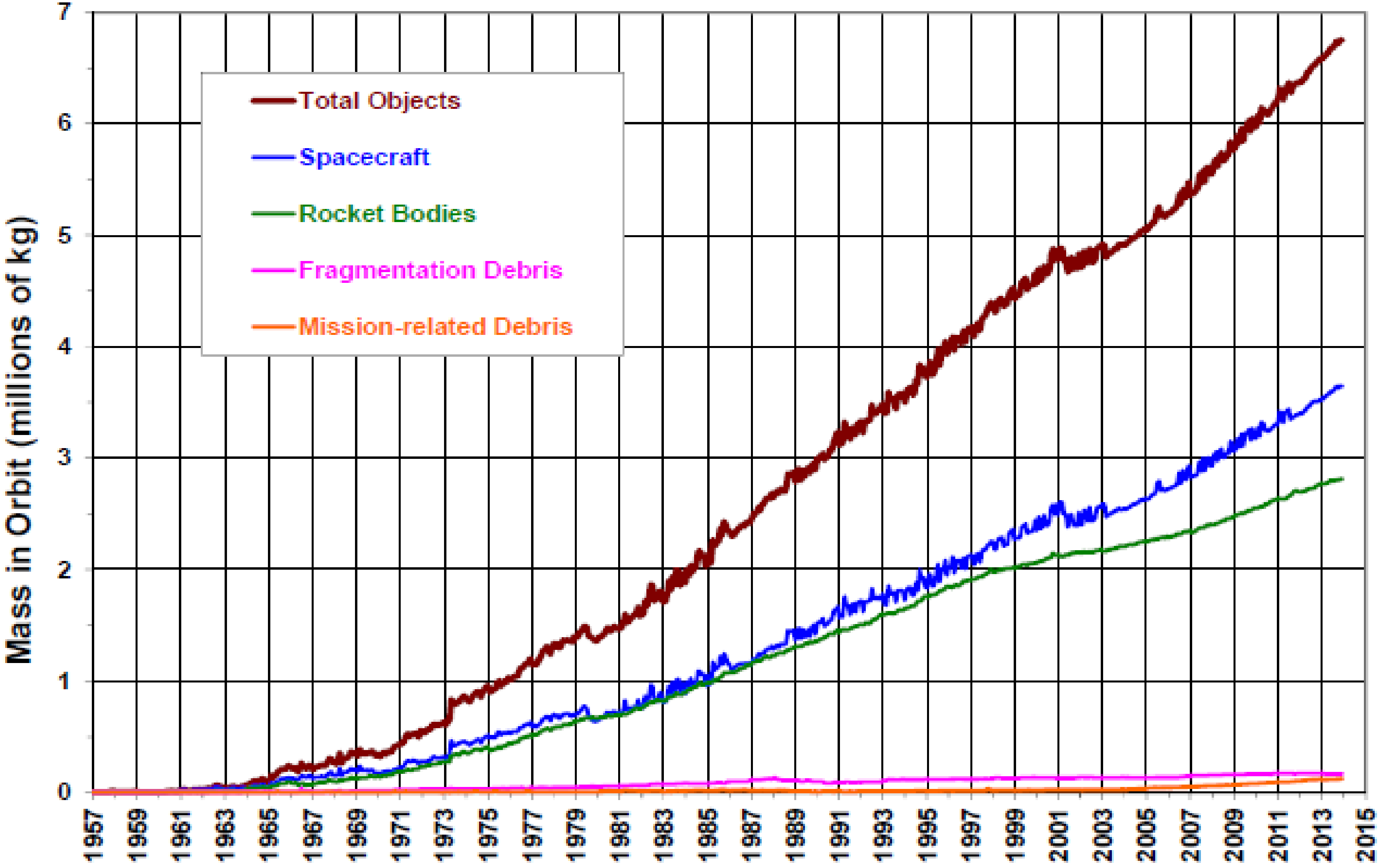
- Up to 2014 we saw 4,950 launches and more than 250 on-orbit satellite fragmentations making 17,000 entries in the US SSN catalogue
- 6,700 metric tons in orbit
- 2,700 metric tons in LEO
- 10 to 20 ton on sub-catalogue size
- 6 % are operational spacecrafts
- 37 % are non-functional but intact
- 57 % fragments from explosions and collisions
- 76 % are in LEO
- 17 % are in MEO
- 7 % are in (near) GEO



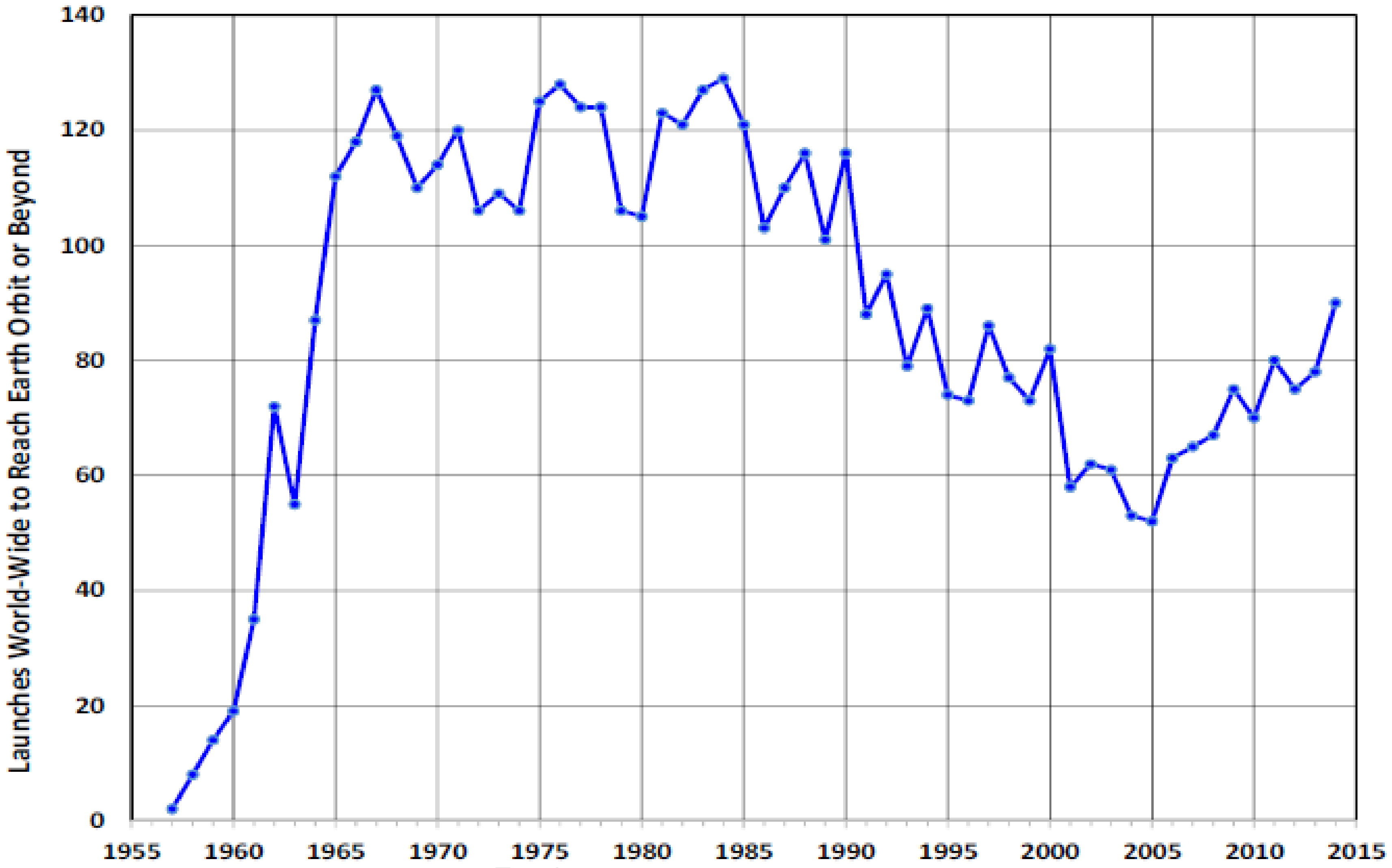
Catalogued On-Orbit Objects



Catalogued On-Orbit Objects



Launch Activities



Kinetic Energy of a Satellite

- The kinetic energy is $T = \frac{m}{2} v^2$

- The mass of a box of dimension D is $m = \varrho D^3$

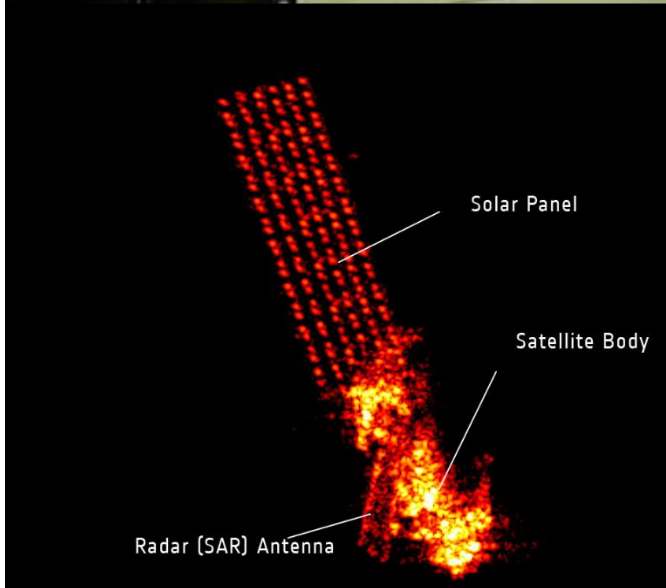
- The velocity of a potentially colliding satellite is 7 km/s

- For example D = 10 cm, m = 1 kg (a **CubeSat**) has a kinetic energy
  T = **24.5 MJ**, which is equivalent to **6 Kg TNT**

- 1 ton TNT contains $4.184 * 10^9$ J of energy

Threads in LEO: Envisat

- Launched 1 March 2002
- Last Contact 8 April 2012
- Kinetic Energy
  - 8211 kg – 319 kg fuel
  - 773 km Perigee, 774 km Apogee
  - Kinetic Energy 193 GJ equivalent to 46 ton TNT

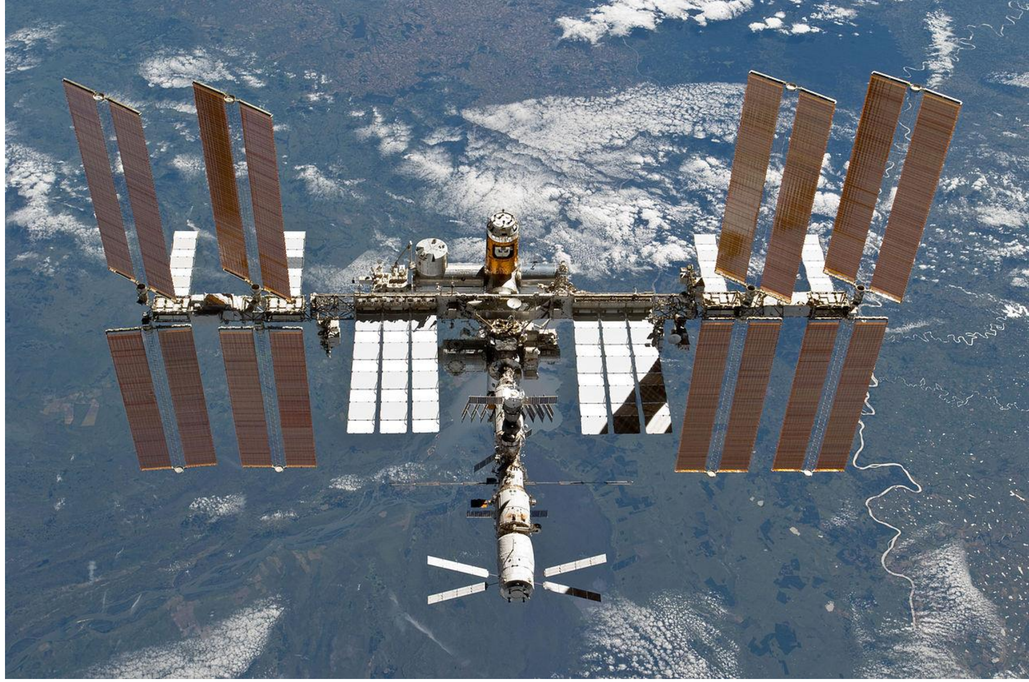


Threads in LEO: Hubble

- Launched 24 April 1990
- Still Controlled
- Kinetic Energy
  - 11,110 kg
  - 559 km Orbit Height
  - Velocity 7500 km/s
  - Kinetic Energy 312 GJ equivalent to 75 ton TNT

S82E5937 1997:02:19 07:06:57

International Space Station



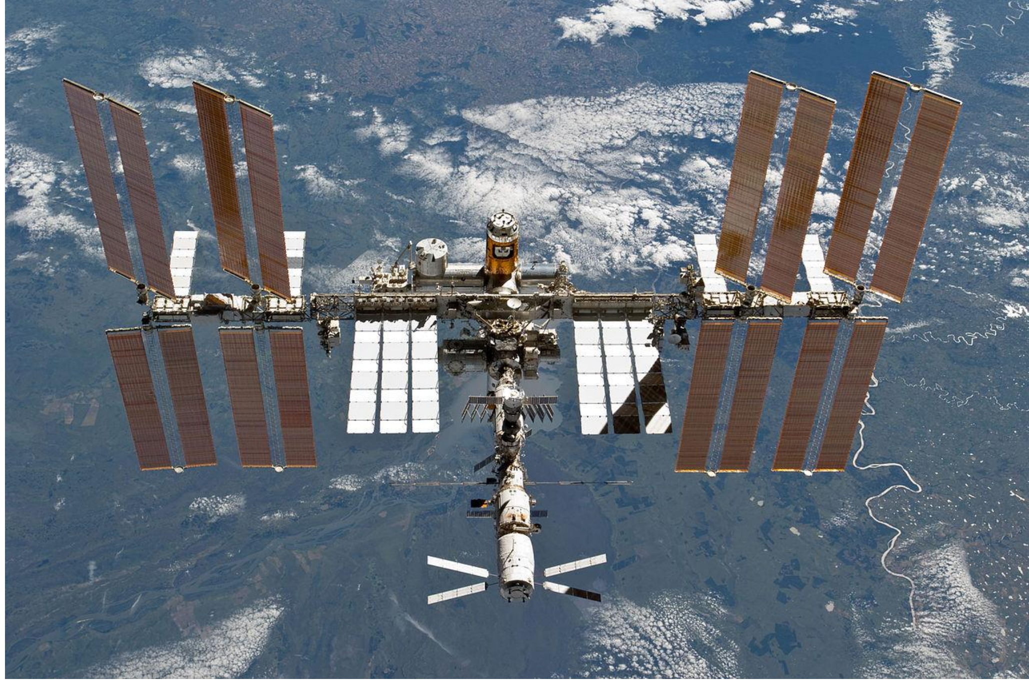
- Mass 455 t
- Velocity 7.7778 km/s
- Orbital Height 400 km

- Kinetic Energy $T = 13.7624$ TJ
- Potential Energy $V = 1.7854$ TJ

- Total Energy $E = T + V = 15.5478$ TJ

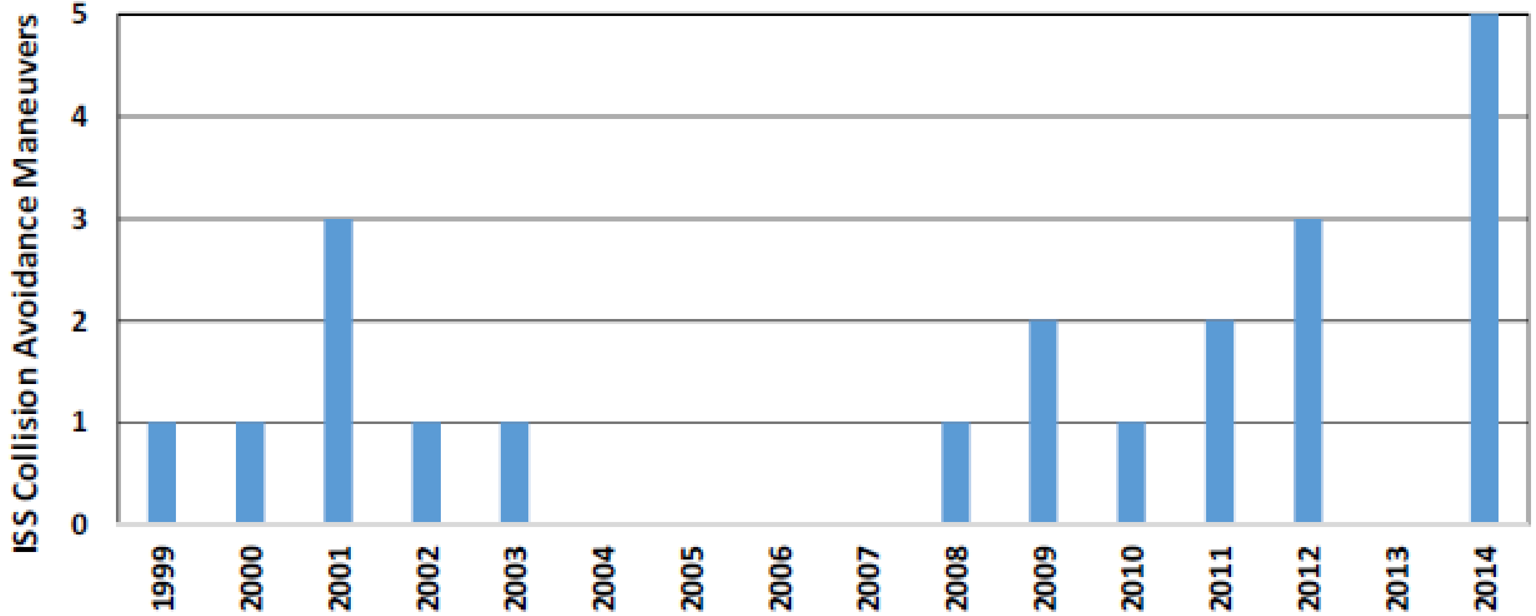
equivalent to 3.7 Mton of TNT

International Space Station



- Since 1999 ISS has performed 19 Debris Collision Avodance Manoeuver

- In 2014 alone 5



Satellite Reentries in 2014

- More than 600 satellites, launch vehicle upper stages and other debris were recorded by U.S. Space Surveillance Network in 2014
  - Satellites 86
  - Upper Stages 49
  - Debris 467

- High Reentry Rate due to Solar Maximum in 2014

- Total mass was more than 100 tons

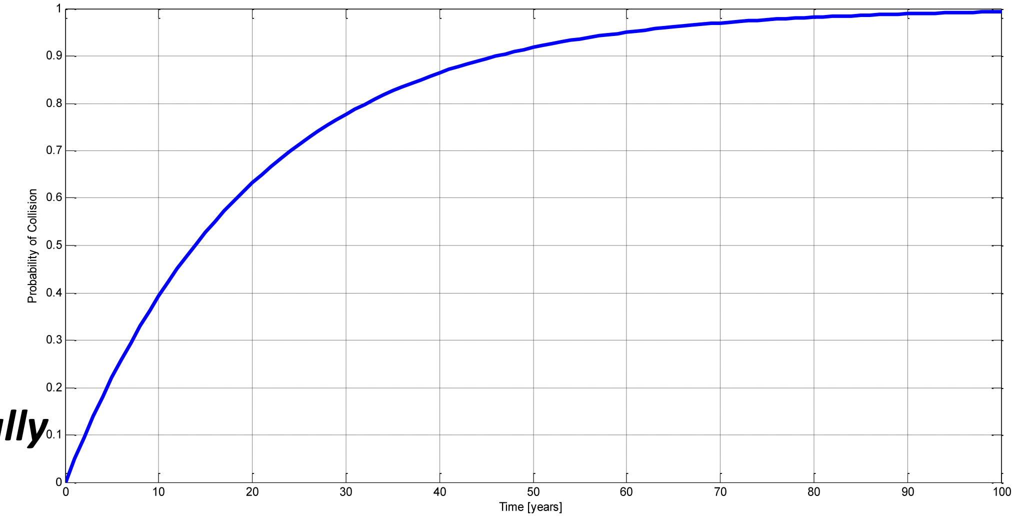
A "Gedanken Model“

Two satellites in the same or different orbit may collide with a propbability P > 0

The probability of Collision increases proportional with the number of satellites N

$$\frac{dP}{dt} = kP(N)N$$

Integration provides $P = 1 - e^{kNT}$



The Probabilty of Collision between Satellites increases Exponentially

"Kessler Syndrom“

Warning: Numbers are arbitary

Landmark Paper on Space Debris

VOL. 83, NO. A6 JOURNAL OF GEOPHYSICAL RESEARCH JUNE 1, 1978

Collision Frequency of Artificial Satellites: The Creation of a Debris Belt

DONALD J. KESSLER AND BURTON G. COUR-PALAIS

NASA Johnson Space Center, Houston, Texas 77058

As the number of artificial satellites in earth orbit increases, the probability of collisions between satellites also increases. Satellite collisions would produce orbiting fragments, each of which would increase the probability of further collisions, leading to the growth of a belt of debris around the earth. This process parallels certain theories concerning the growth of the asteroid belt. The debris flux in such an earth-orbiting belt could exceed the natural meteoroid flux, affecting future spacecraft designs. A mathematical model was used to predict the rate at which such a belt might form. Under certain conditions the belt could begin to form within this century and could be a significant problem during the next century. The possibility that numerous unobserved fragments already exist from spacecraft explosions would decrease this time interval. However, early implementation of specialized launch constraints and operational procedures could significantly delay the formation of the belt.

Don Kessler's Prediction

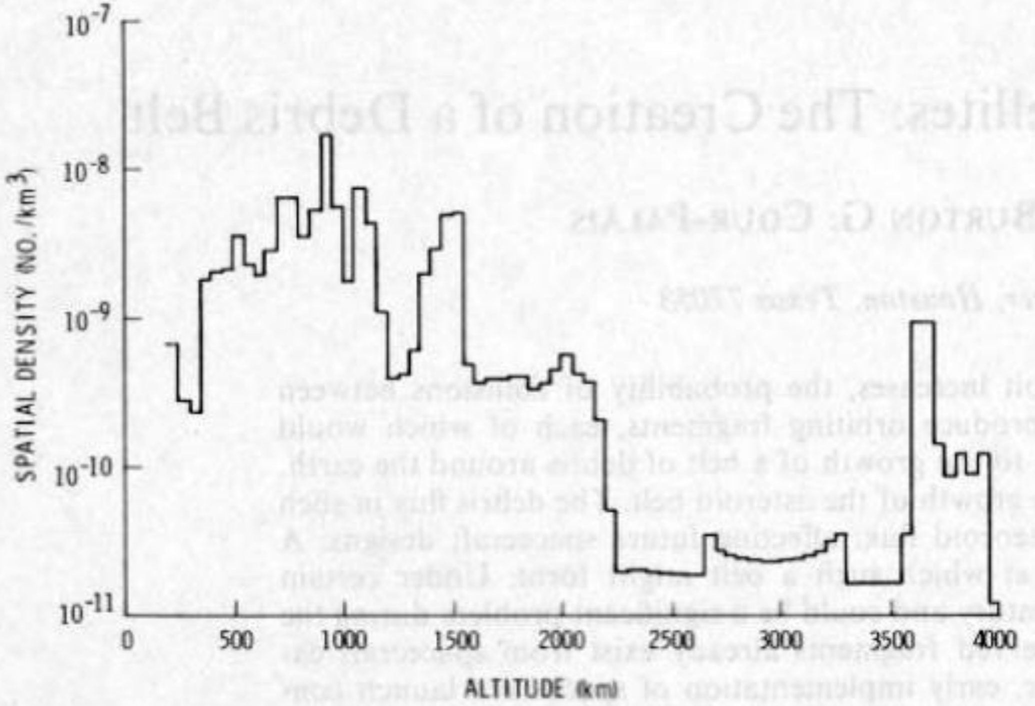


Fig. 1. Current distribution of satellites in earth orbit as observed by radar. A total of 3866 satellites are in the April 1976 catalog and are represented here.

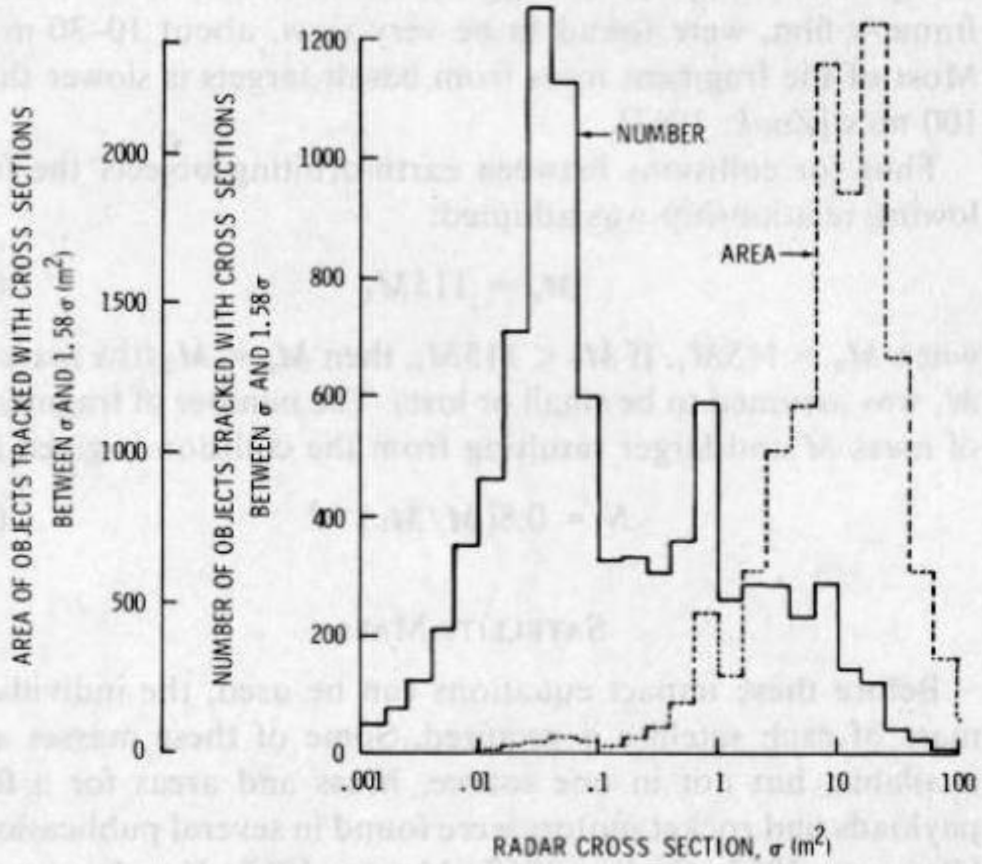


Fig. 3. Size distribution of earth-orbiting satellites observed by radar. The largest number of satellites have a radar cross section of about 0.04 m², while the largest area contribution is around a radar cross section of 10 m².

Don Kessler‘s Prediction

Impact Rate on a Spacecraft

$$\frac{dI}{dt} = S\bar{V}_s A_c$$

S … spatial density of spacecrafts in orbit

V_s … average velocity

A_c … cross section area of spacecraft

Collision Rate between all Spacecrafts

$$\frac{dC}{dt} = \frac{1}{2}\int S^2 \bar{V}_s \bar{A}_{cc} dU$$

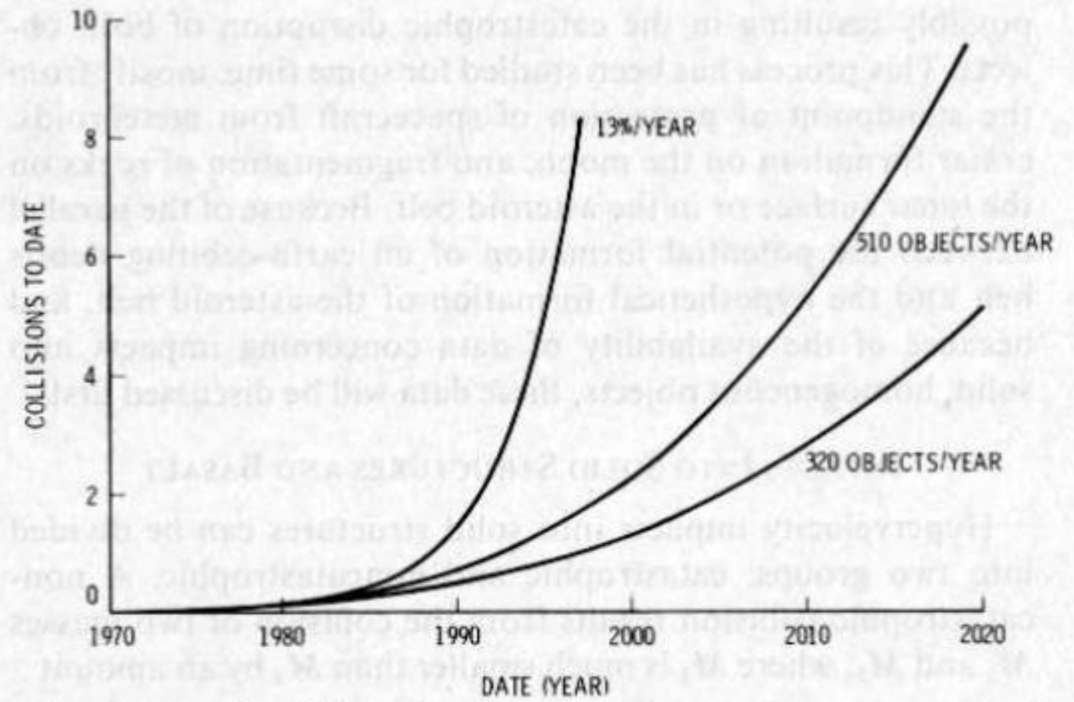
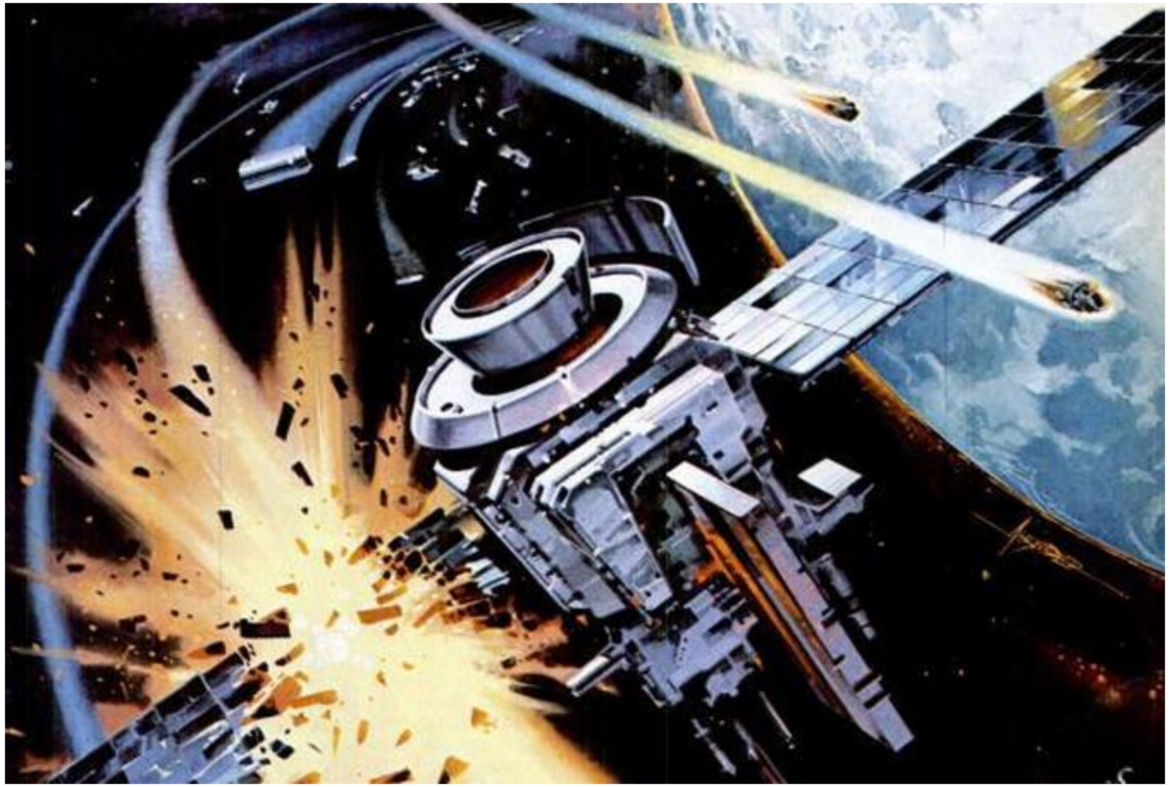
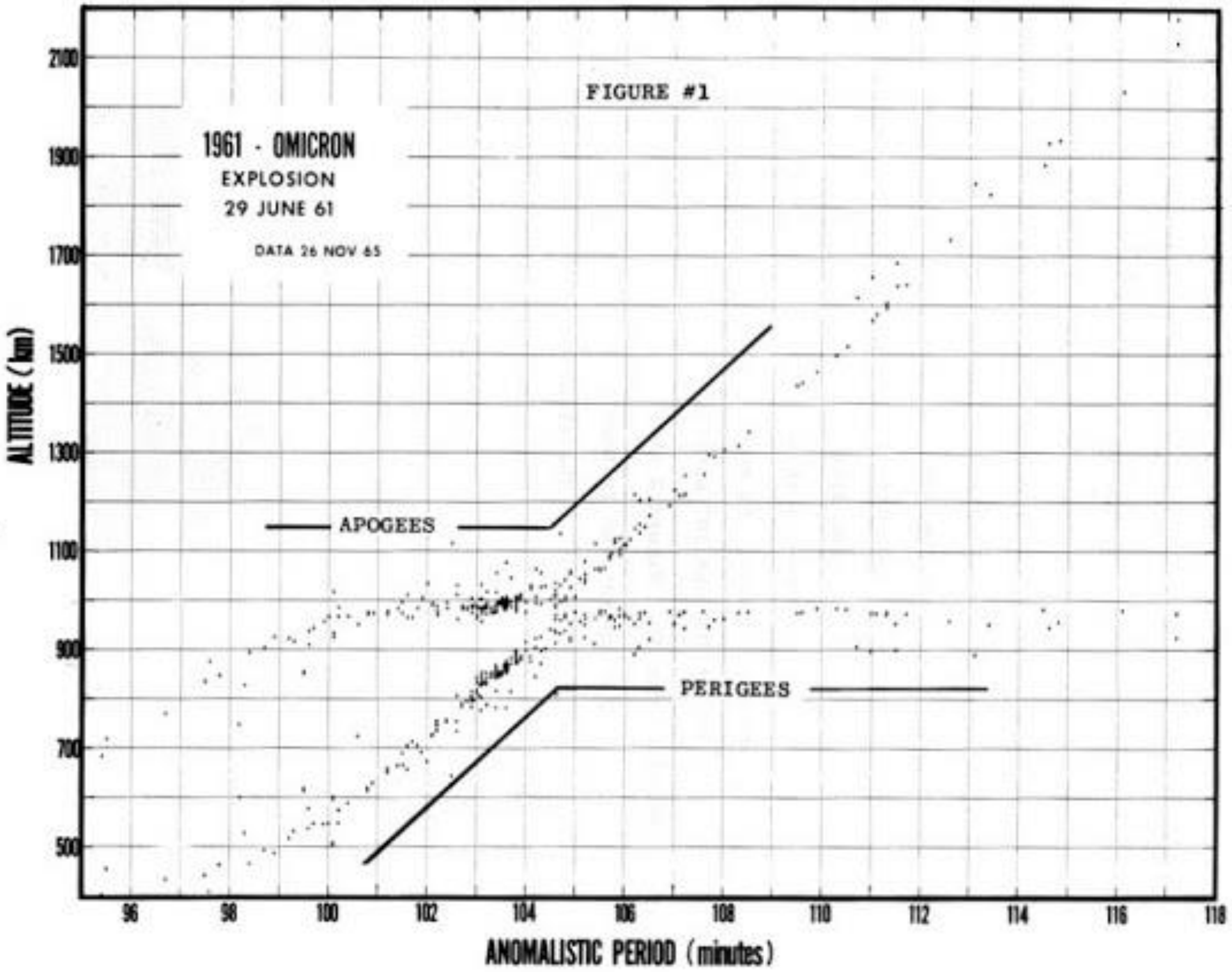


Fig. 4. Total collisions by the given date under various growth assumptions. The first collision is expected between 1989 and 1997.

Effect of an Explosion in Orbit

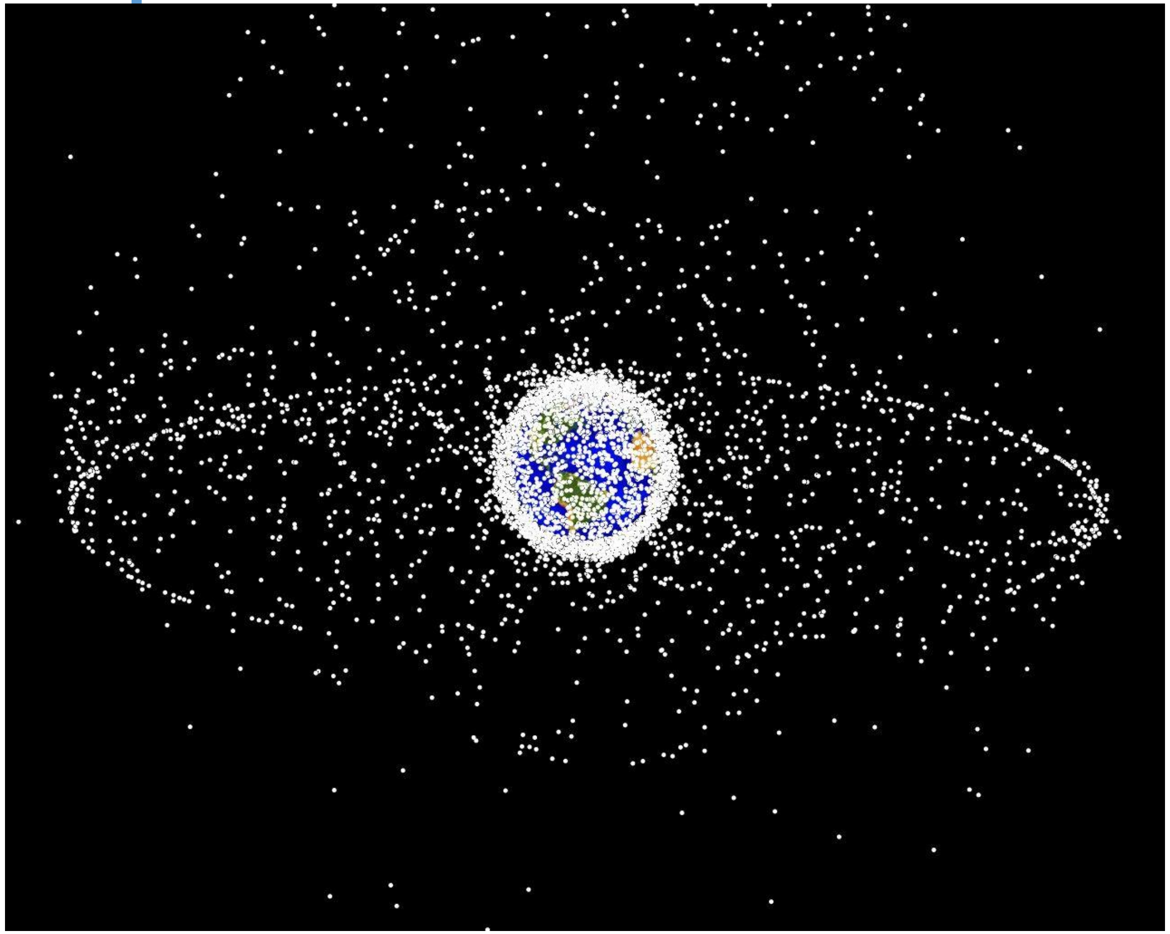


Popular Science, July 1982

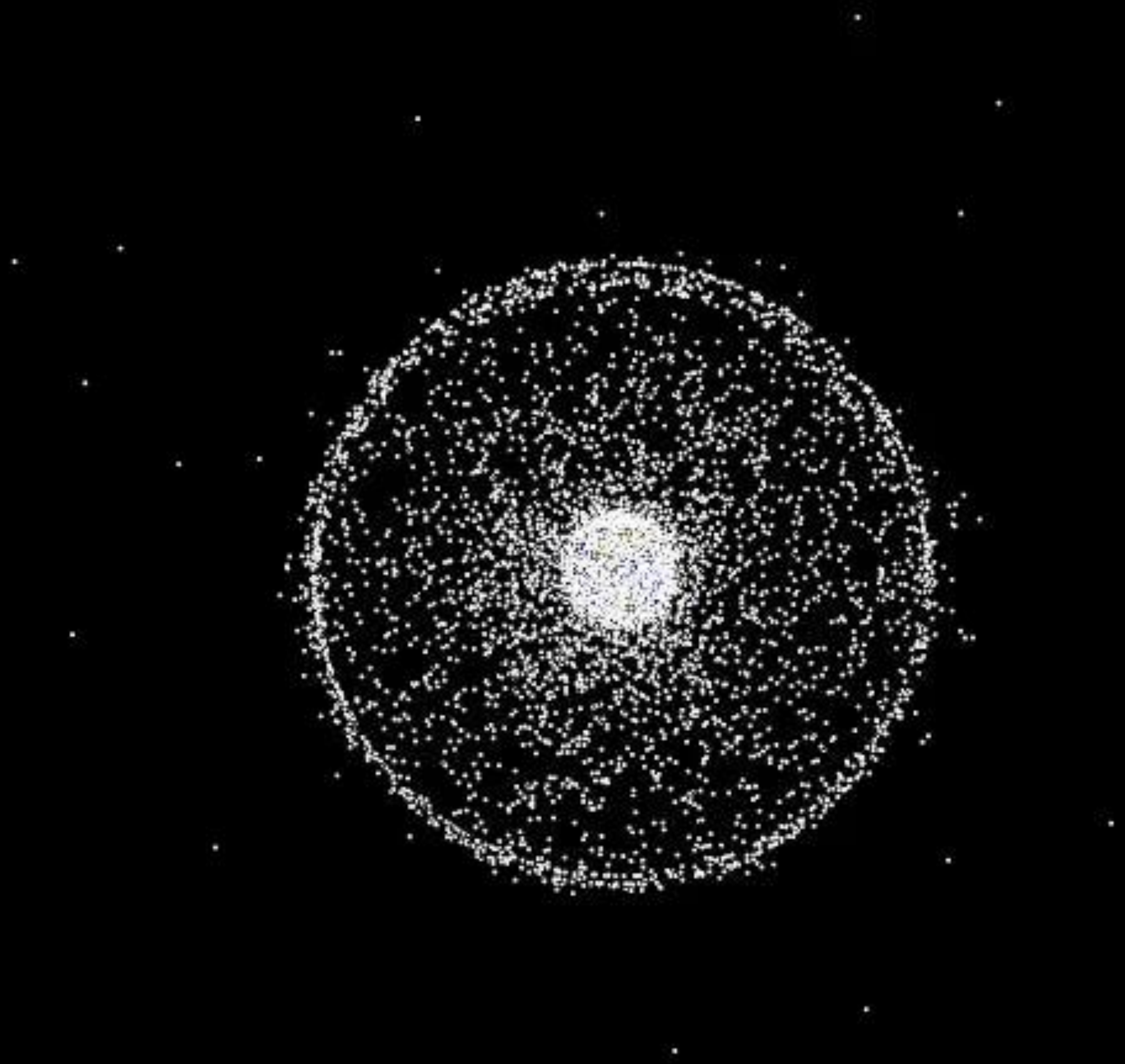


Gabbard (NORAD) Plot 1971

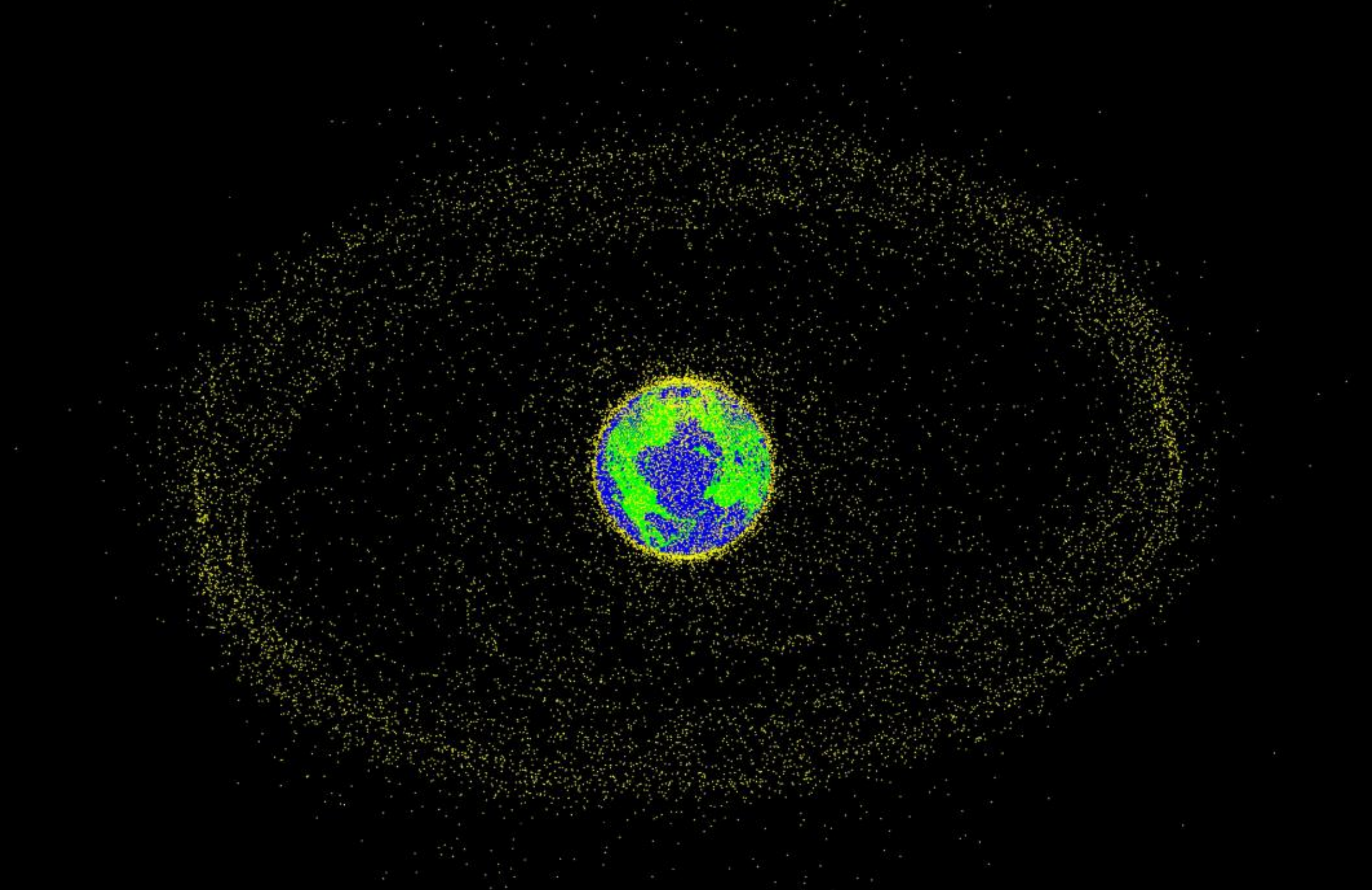
Objects in Space



- > 16.000 Objects in the radar catalog (> 5 cm)
- Of these, only 960 active satellites

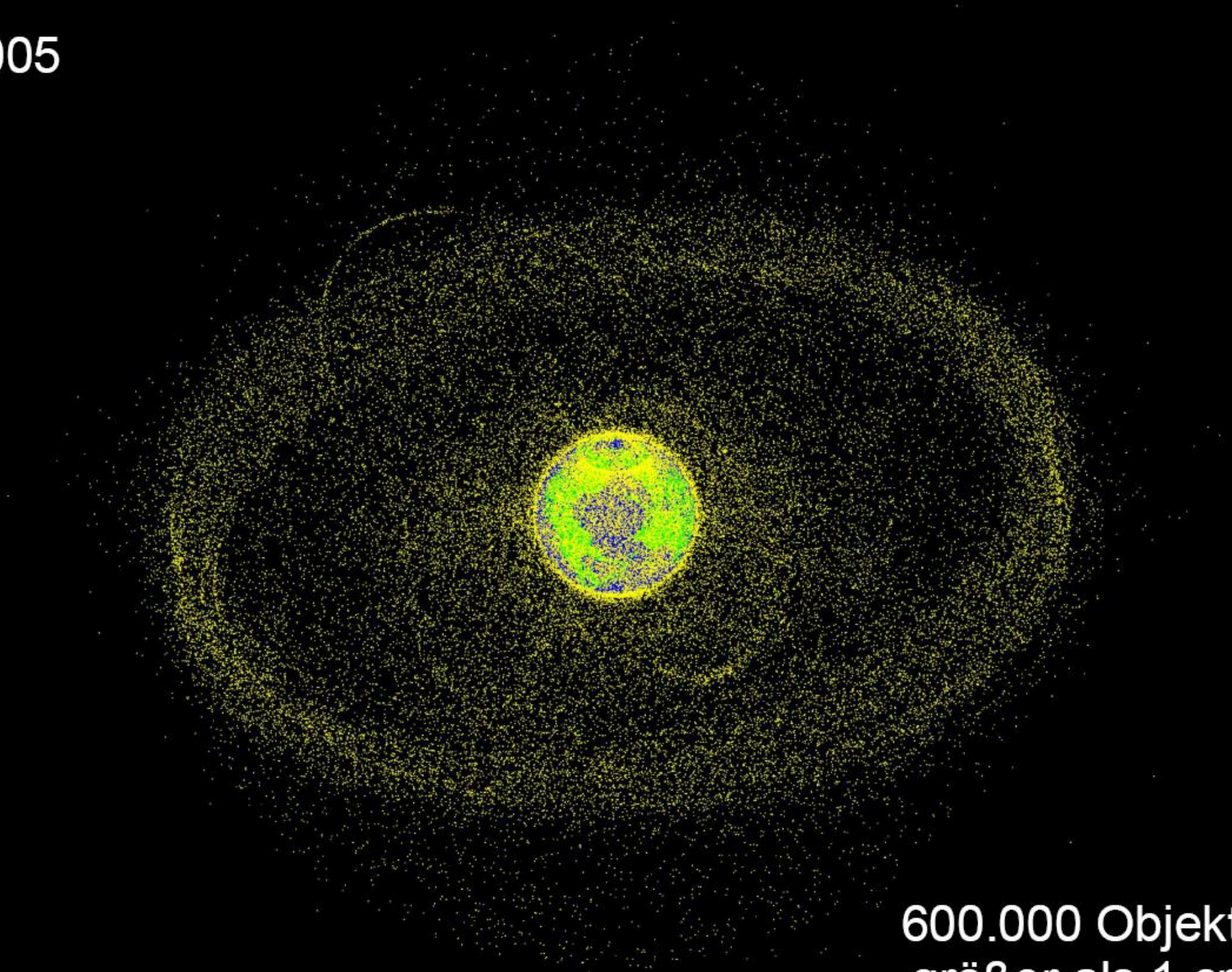


2005

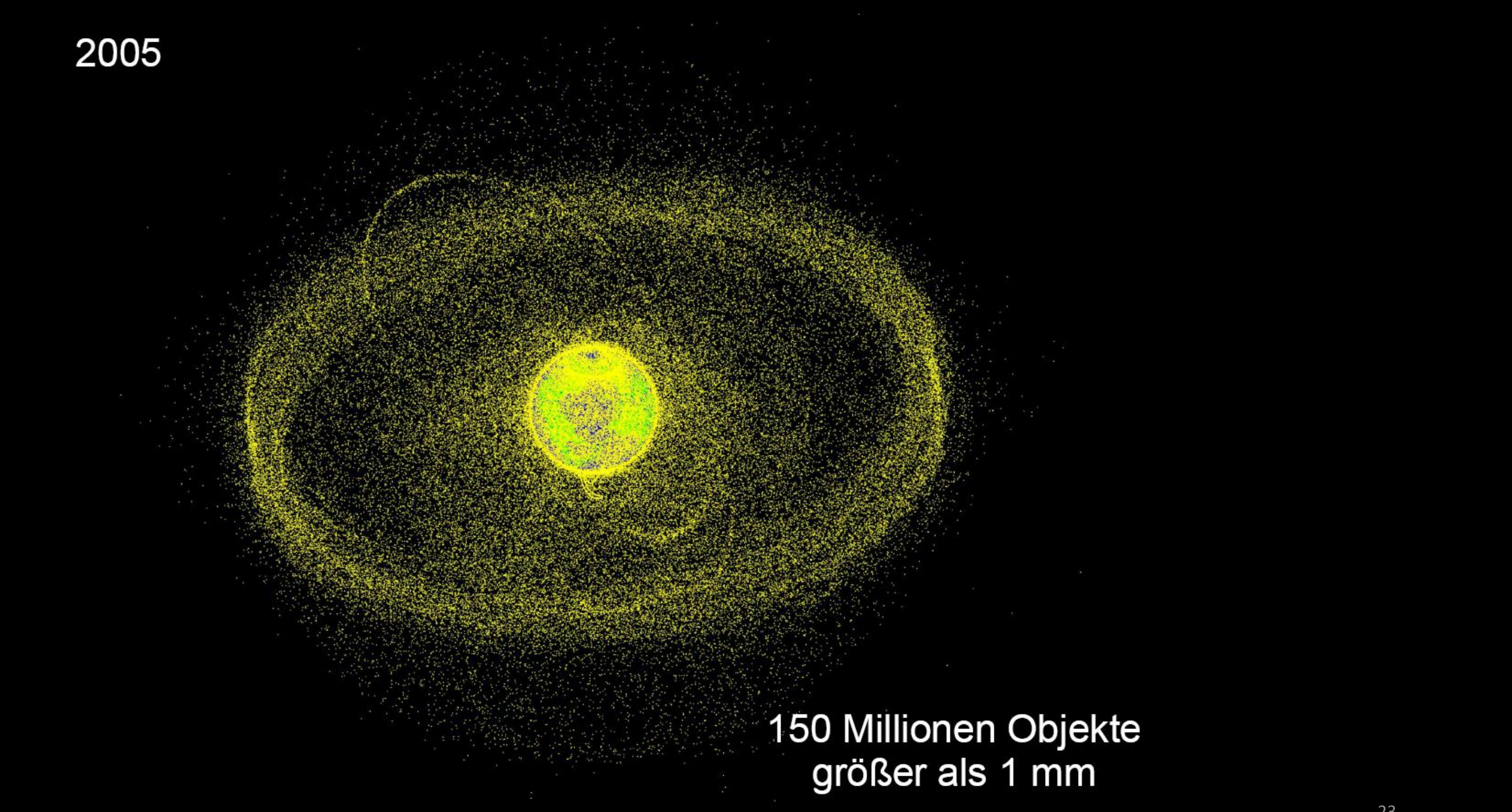


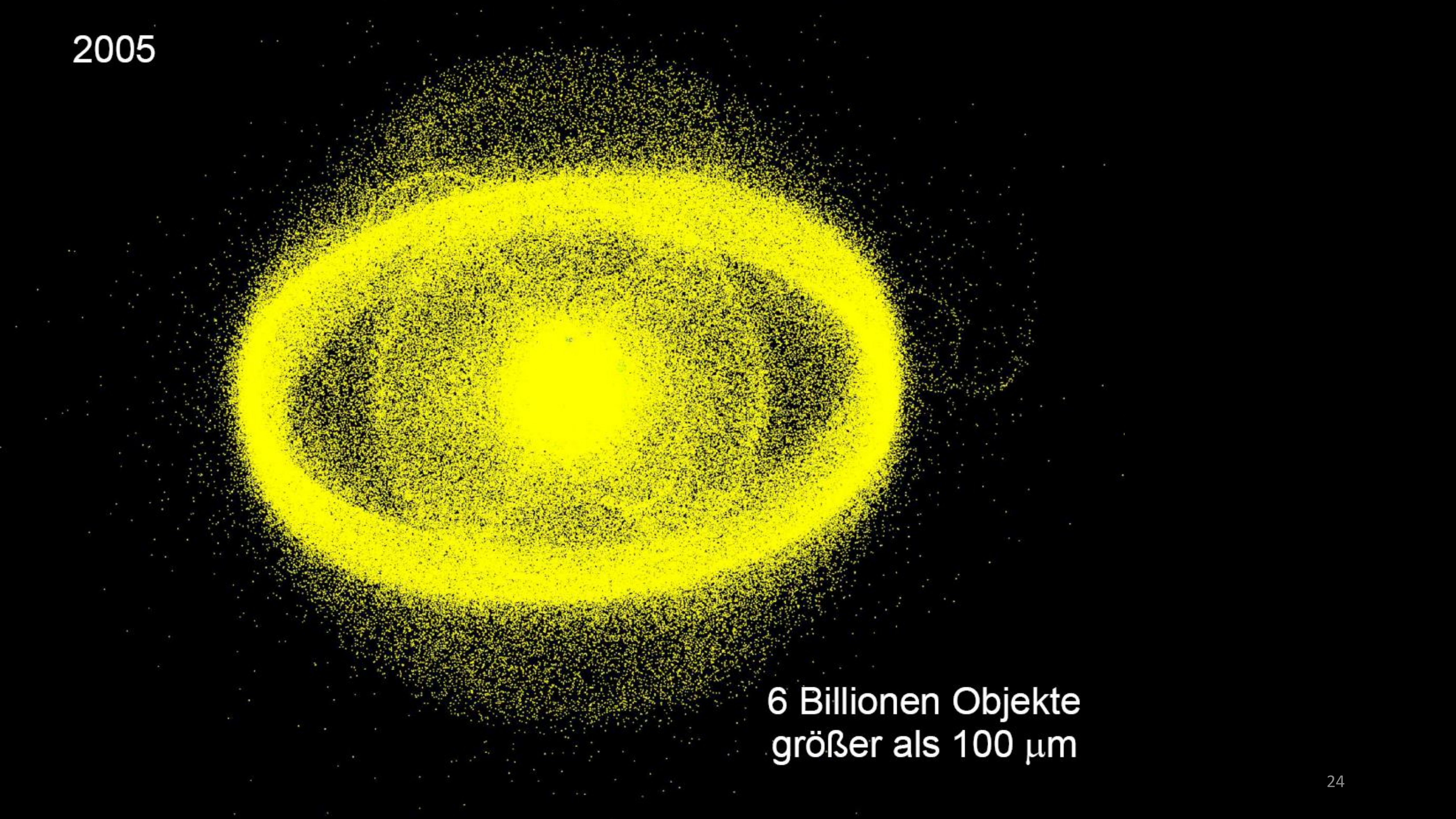
44.000 Objekte
größer als 5 cm

2005



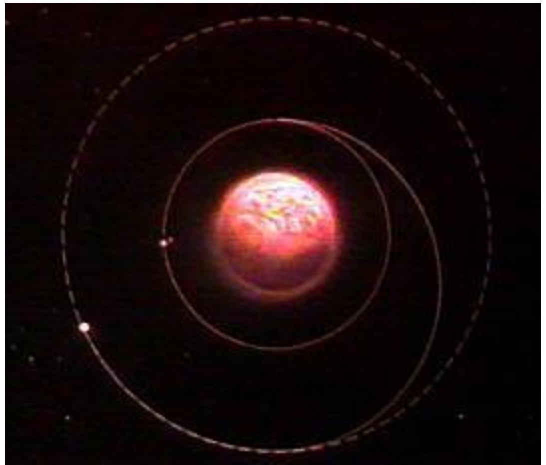
600.000 Objekte
größer als 1 cm


2005
150 Millionen Objekte
größer als 1 mm


2005
6 Billionen Objekte
größer als 100 µm

RORSAT

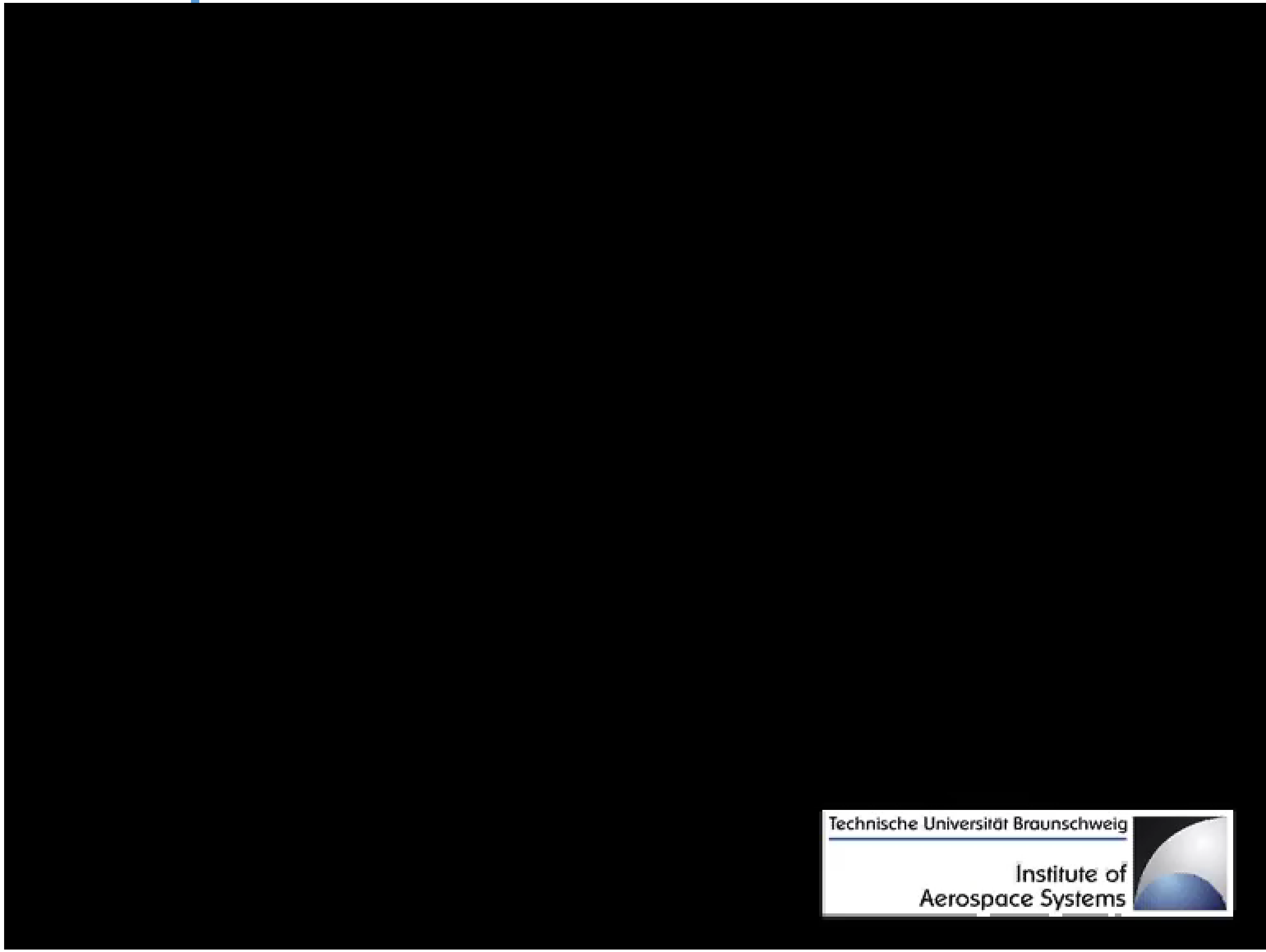
- **Upravlyaemy Sputnik Aktivnyj**
- (*Управляемый Спутник Активный*)
- **US-A, Radar Ocean Reconnaissance Satellite**, **RORSAT**,
- Launched between 1967 and 1988
- 4,300 kg mass
- Active Radar Satellite to monitor US vessels
- Powered by Nuclear Reactors
- Fission of 2.6 kg U 235 (5% of critical mass) produce a constant power of 28 KW (2 KW of Electricity) for 250 years
- 33 Nuclear Reactors launched
- At EOL disposal to higher "Nuclear Safe“ Storage-Orbit
- Argon 39 has a half life of 270 years



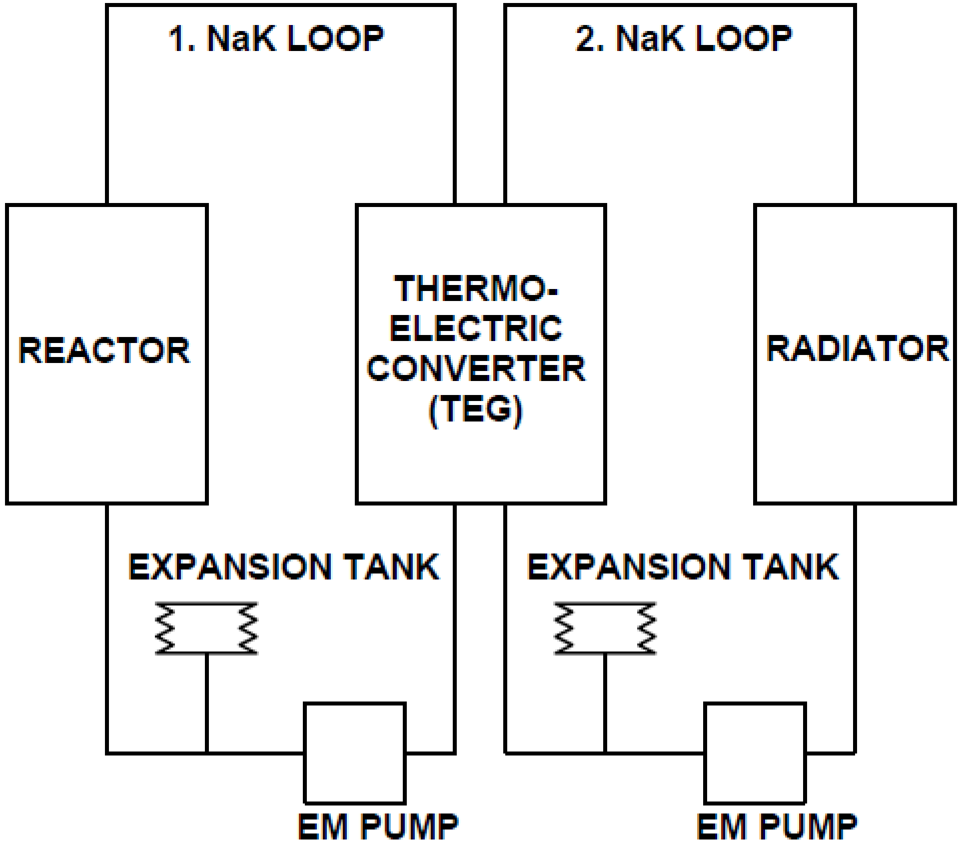
Sodium-Potassium Droplets

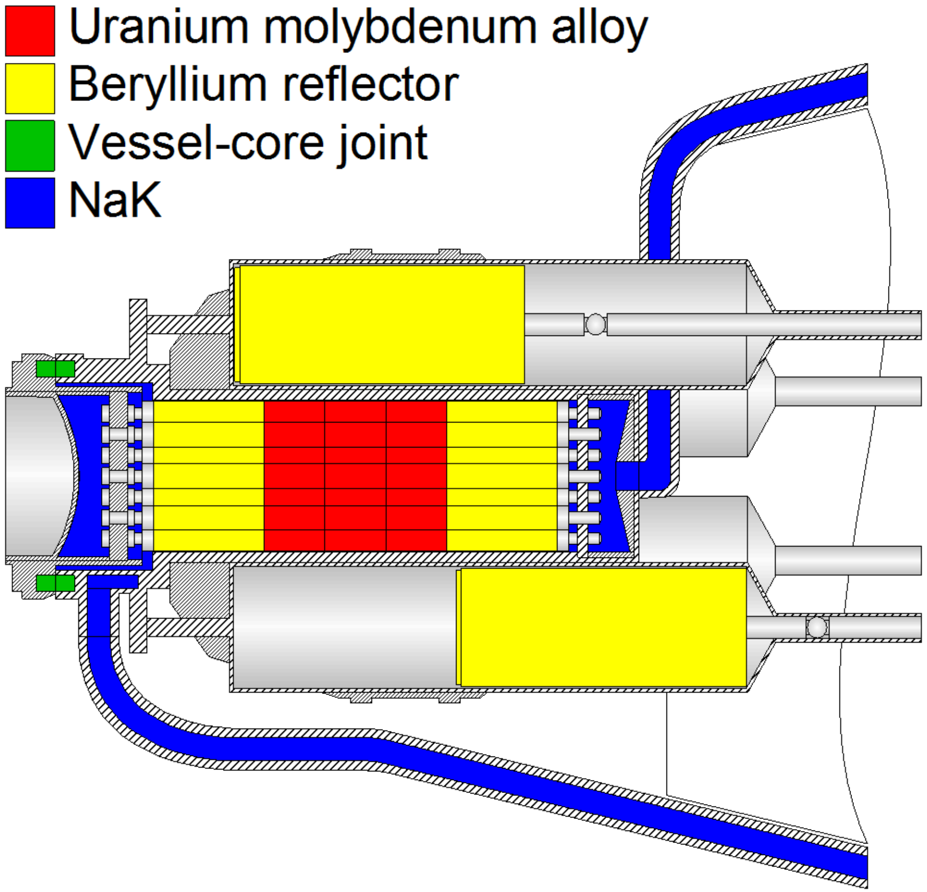
NaK Coolant Release

- Core ejection: Opening of the primary coolant loop of the Buk reactor (RORSAT)
- 8 kg of eutectic sodium-potassium alloy (NaK-78)
- 128 kg NaK released during 16 events
- Currently 45,300 droplets with a total mass of 97 kg in orbit
- Droplet diameters: 5 mm to 5.67 cm

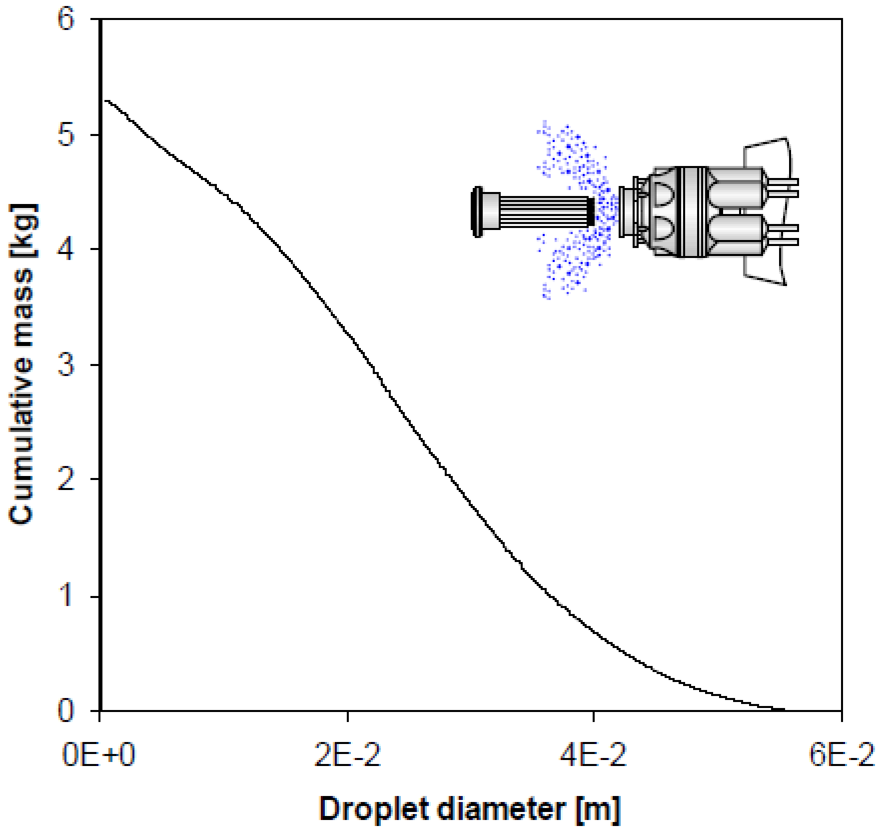


Two Loop Space Reactor

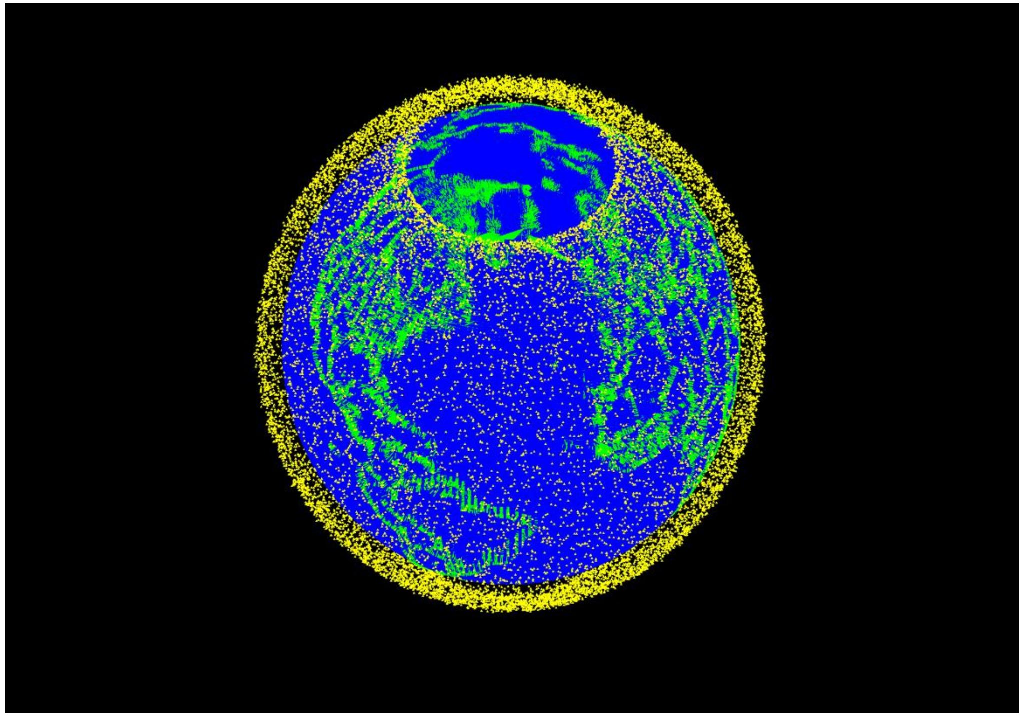




MASTER Modelling Results

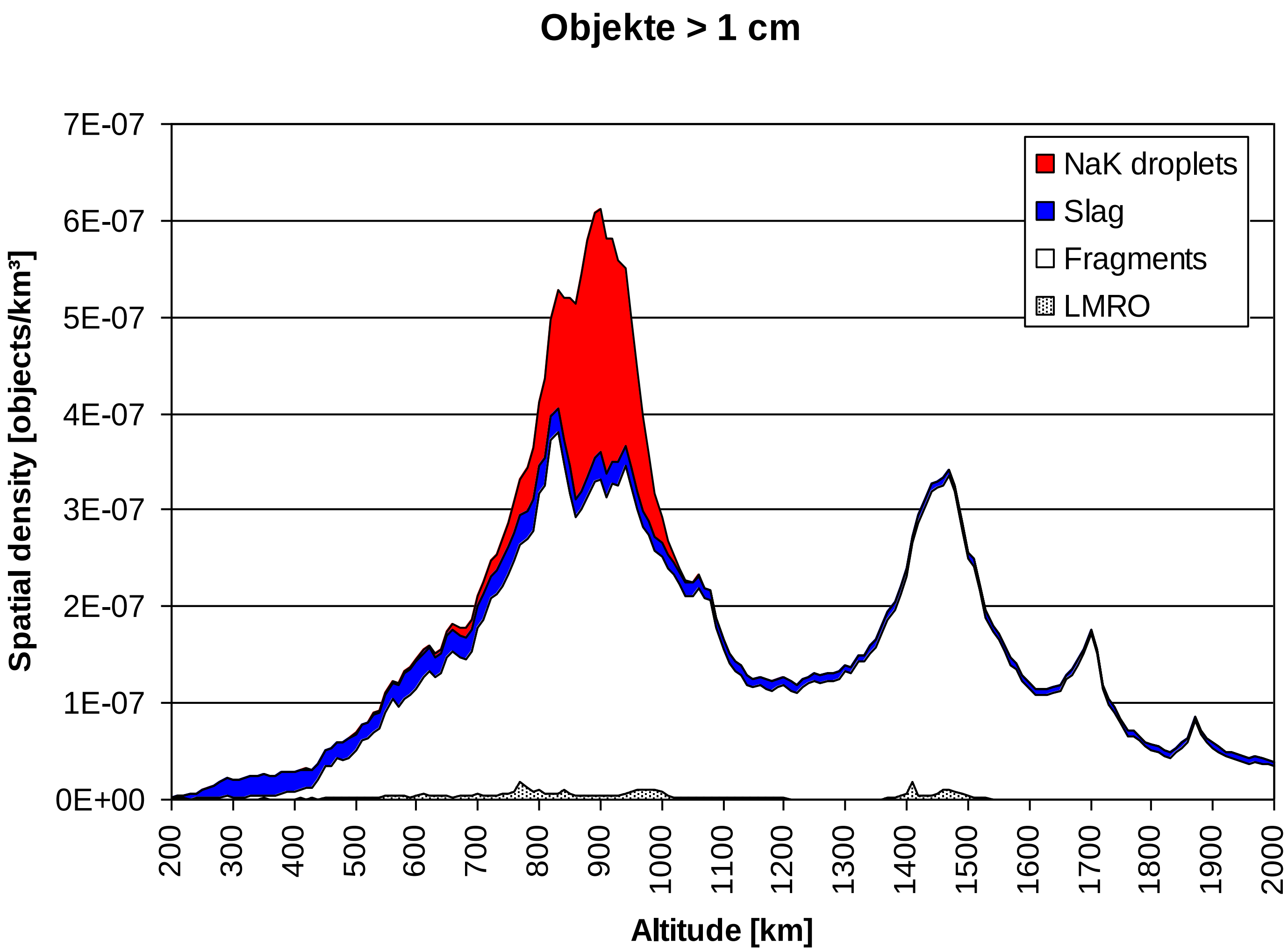


Mass distribution of the NaK droplet size distribution model for one single event.

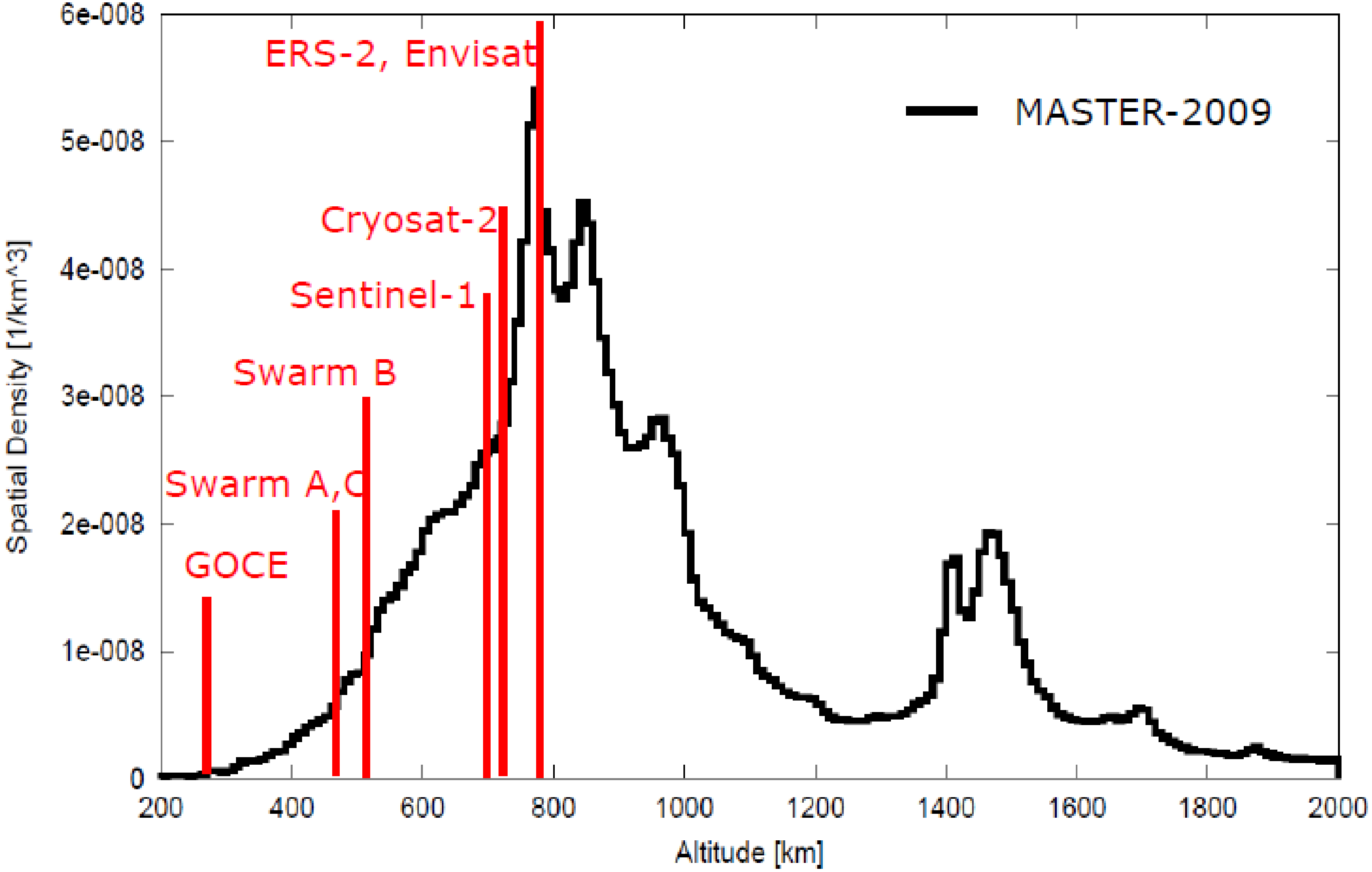


Simulated distribution of NaK droplets around the Earth (May 1, 2009). Each dot resembles 10 droplets.

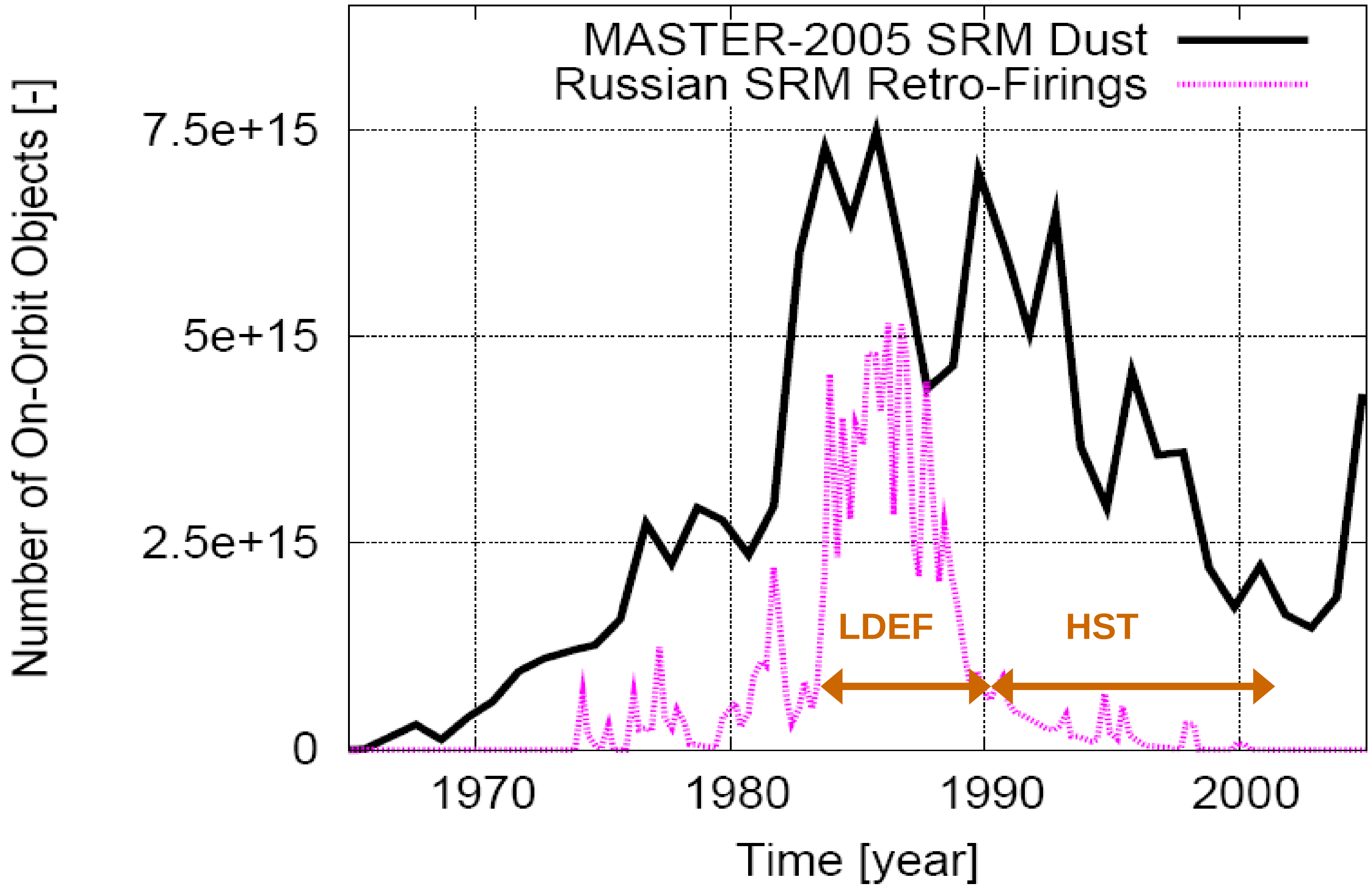
Spatial Density (2005)



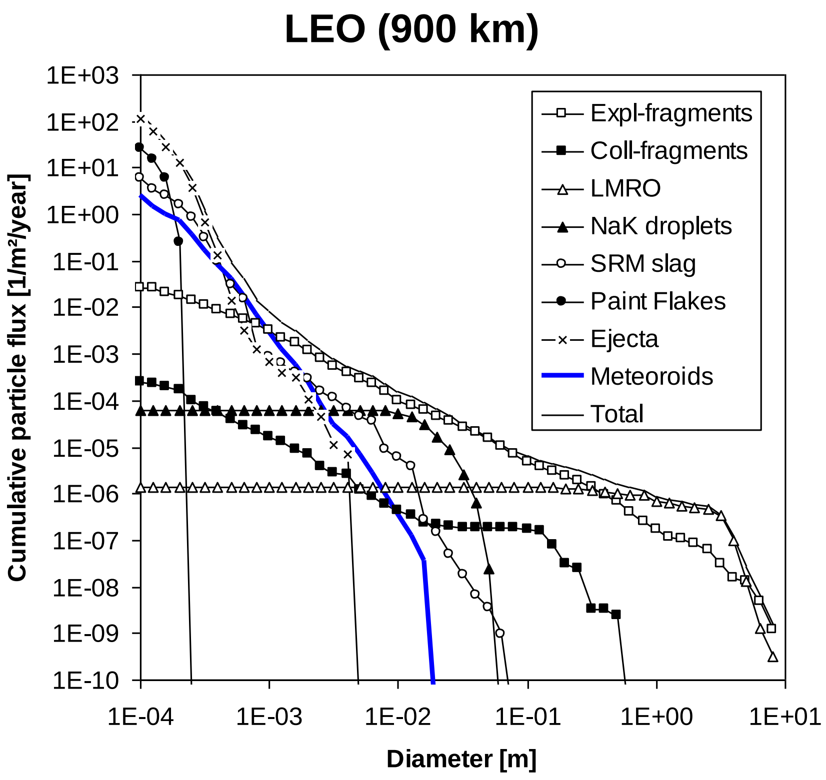
Spatial Density (2009)

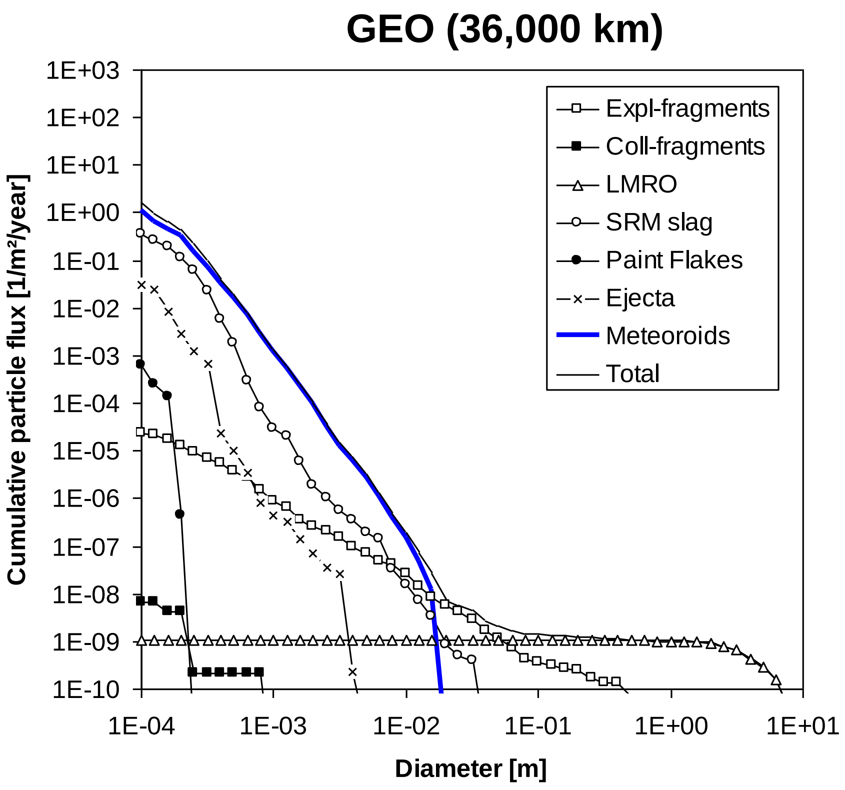


Solid Rocket Motor Dust Particles



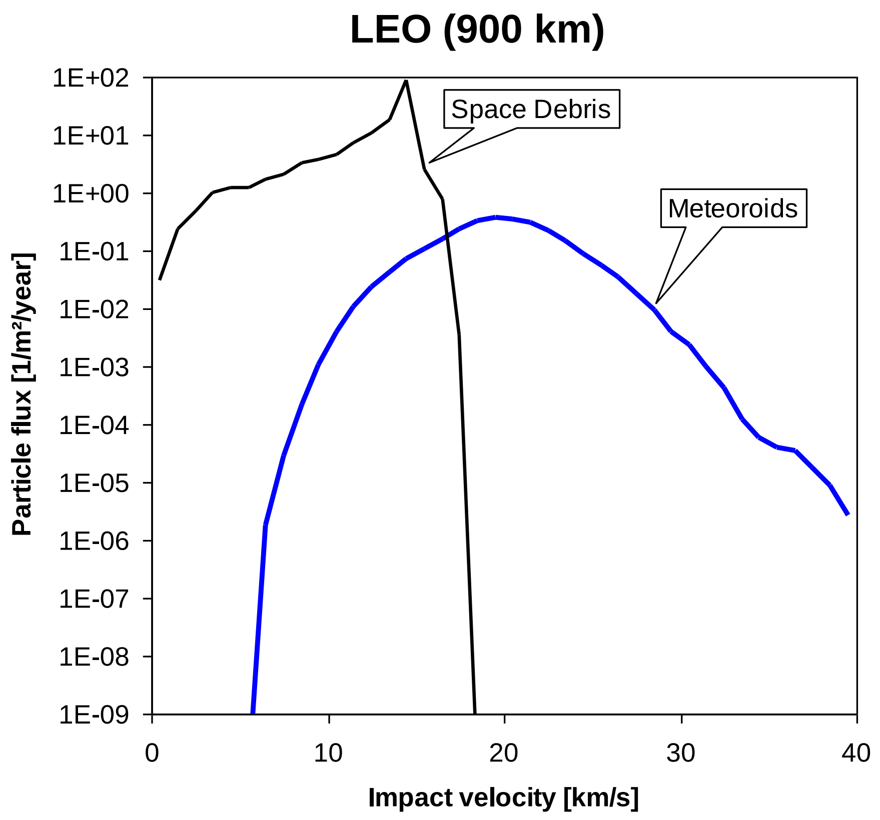
Particle Flux on Satellites

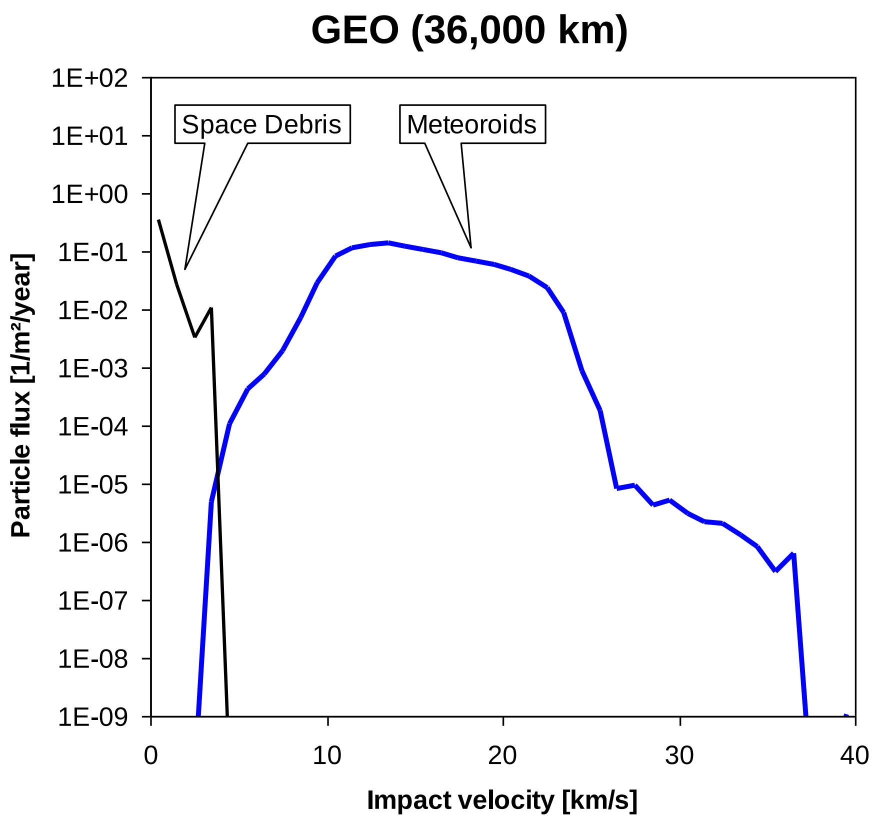




Cumulative flux of impacting particles greater than 100 microns versus diameter on the front surface of an earth-oriented satellite according to MASTER-2005 (1 May 2005).

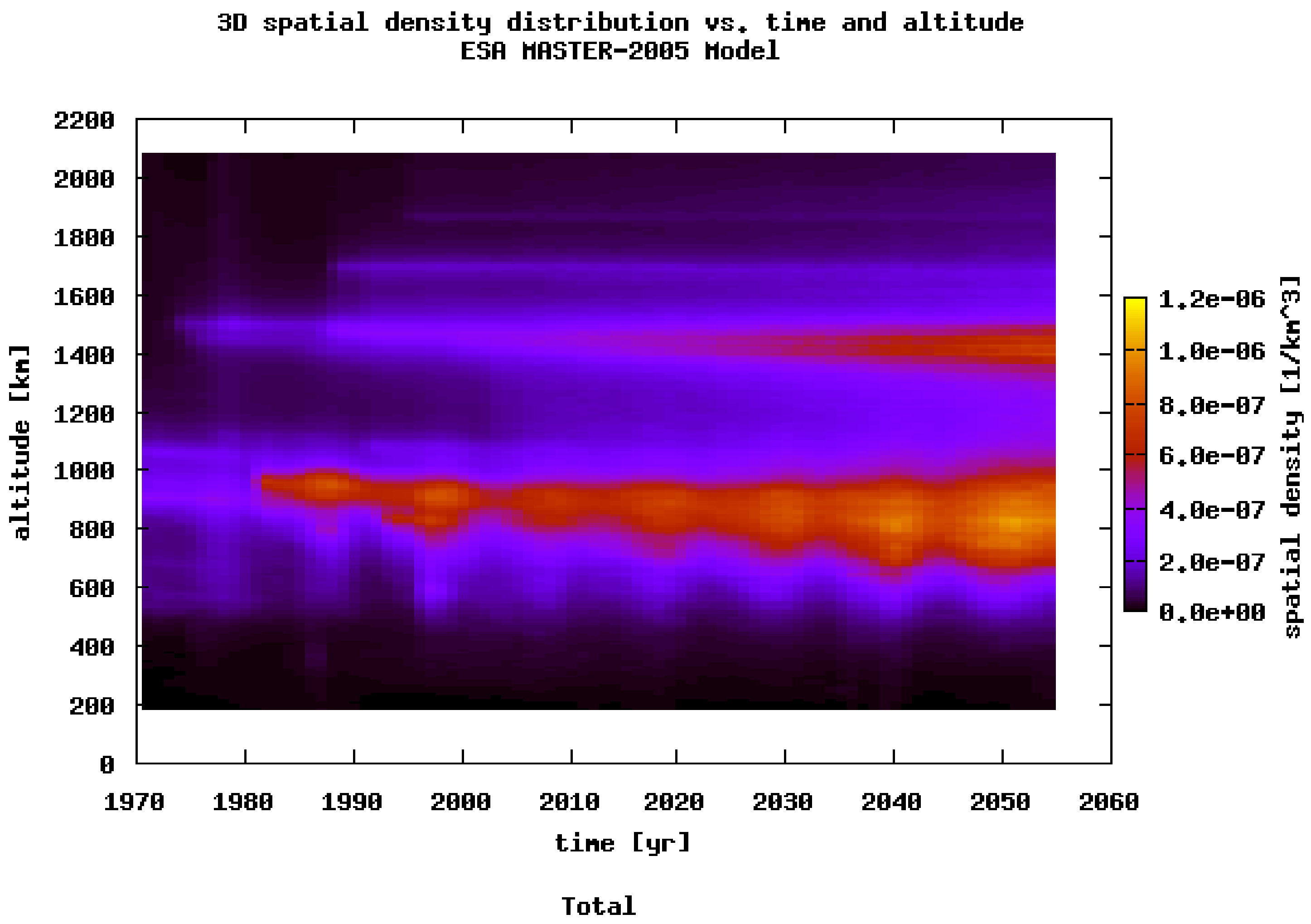
Impact Velocity of Particles





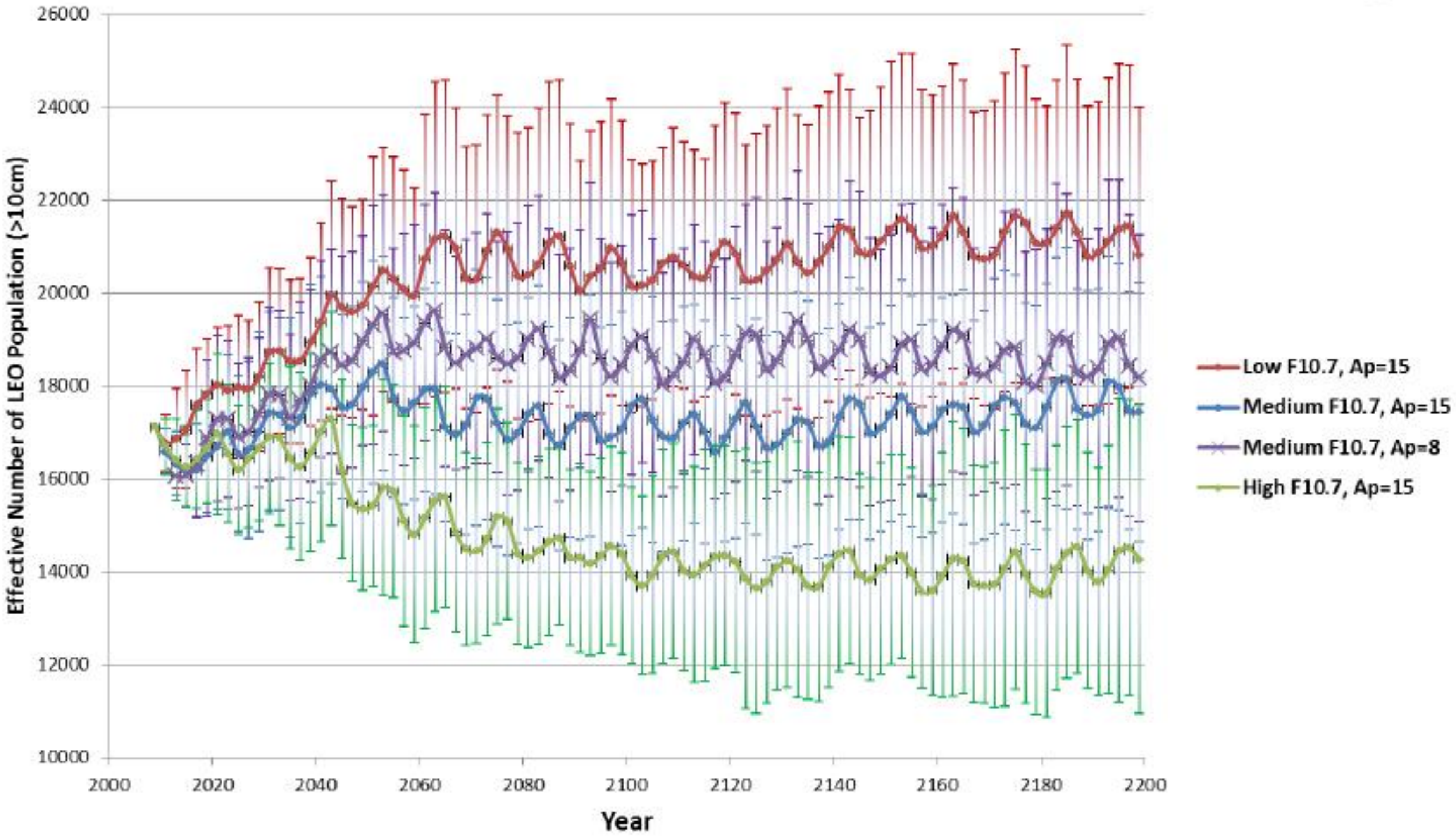
Flux of impacting particles greater than 100 microns versus impact velocity on the front surface of an earth-oriented satellite according to MASTER-2005 (1 May 2005).

Instability of the LEO Population

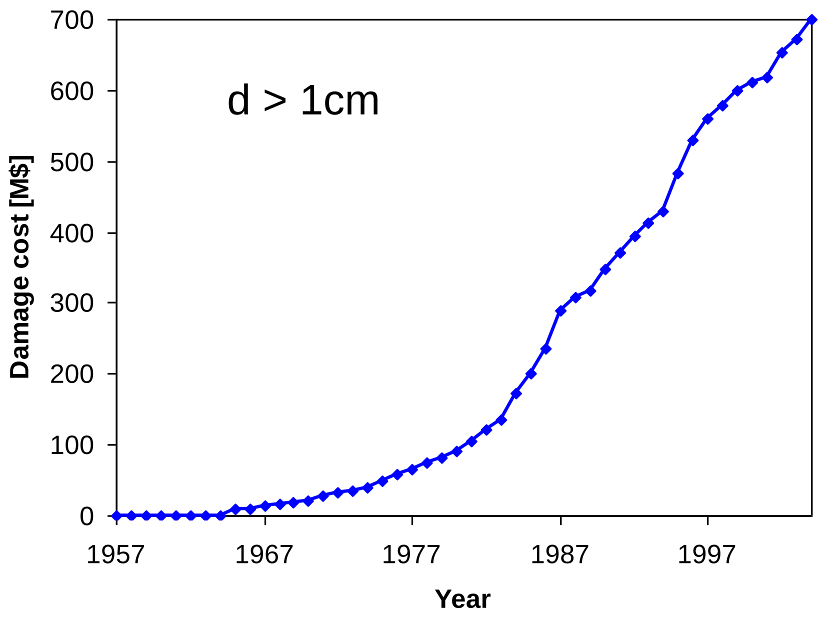


Increasing threat for the orbits used by Earth Observation Satellites

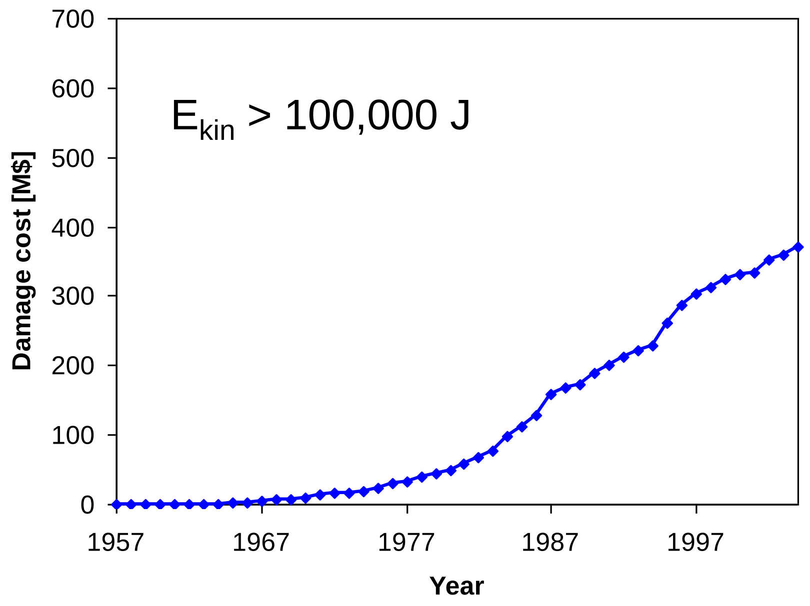
Increase of the LEO Population for various Solar Activities



Cumulative Damage Cost



Damage Cost up to 2004:
- Damages altogether: 700 M$
- Equivalent of about five lost satellites



Damage Cost up to 2004:
- Damages altogether: 370 M$
- Equivalent of about three lost satellites

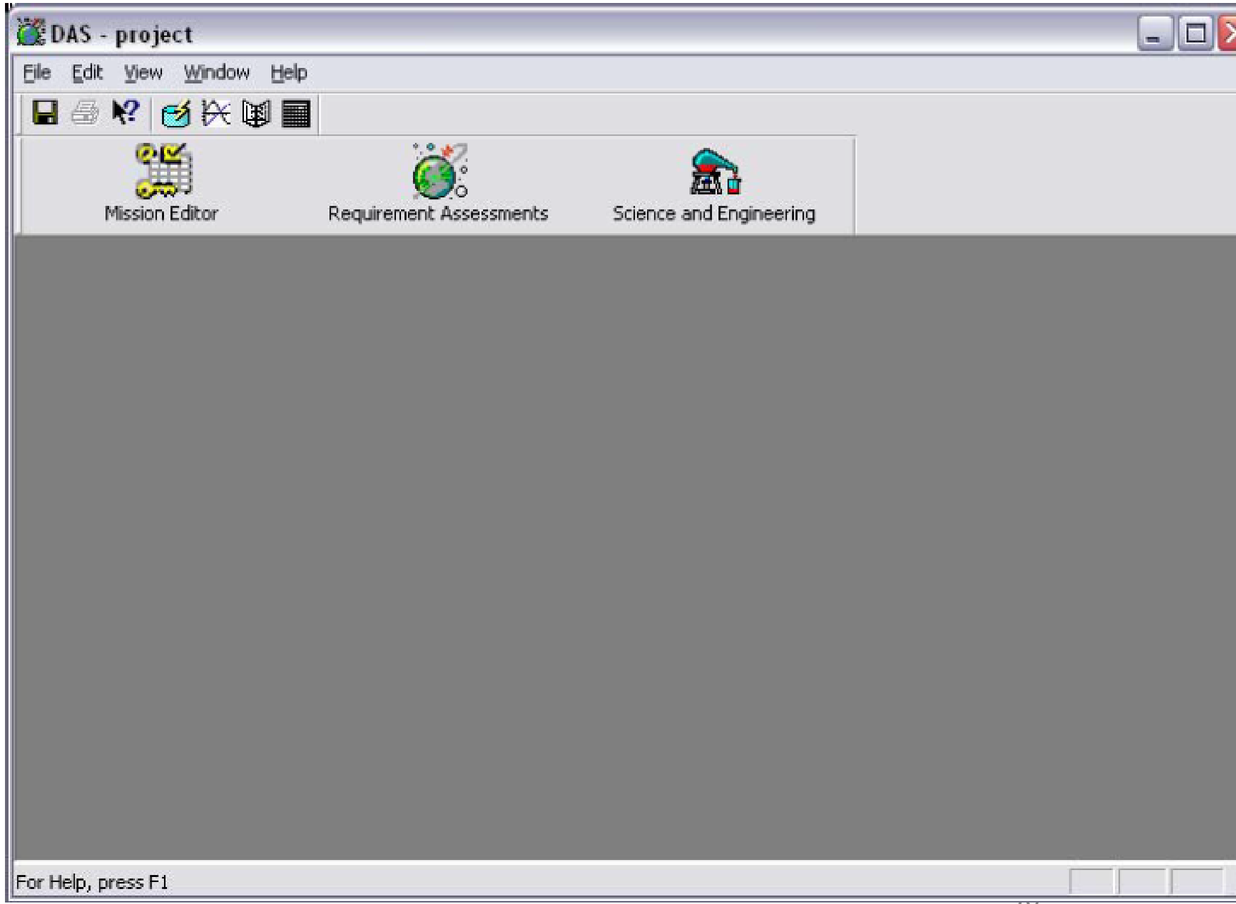
Debris Related Software

- ESA MASTER 2005
  - Meteoroid and Space Debris Terrestrial Environment Reference 2005

- NASA DAS
  - Debris Assessment Software
  - Performing Orbital Debris Assessment (ODA) to according to NASA Technical Standard 8719.14 *Process for limiting orbit debris*

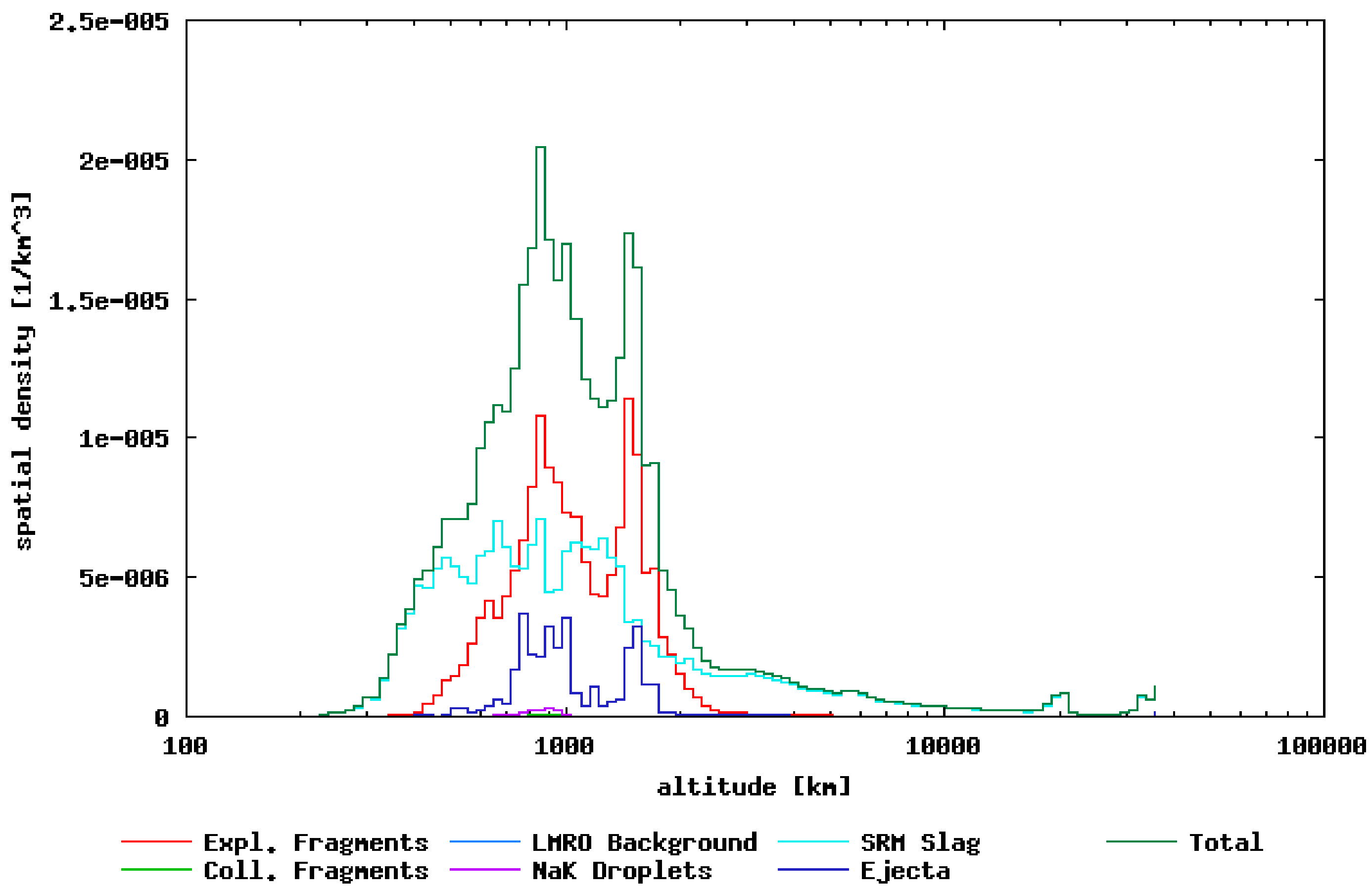
MASTER 2005 DAS

Initial Screen



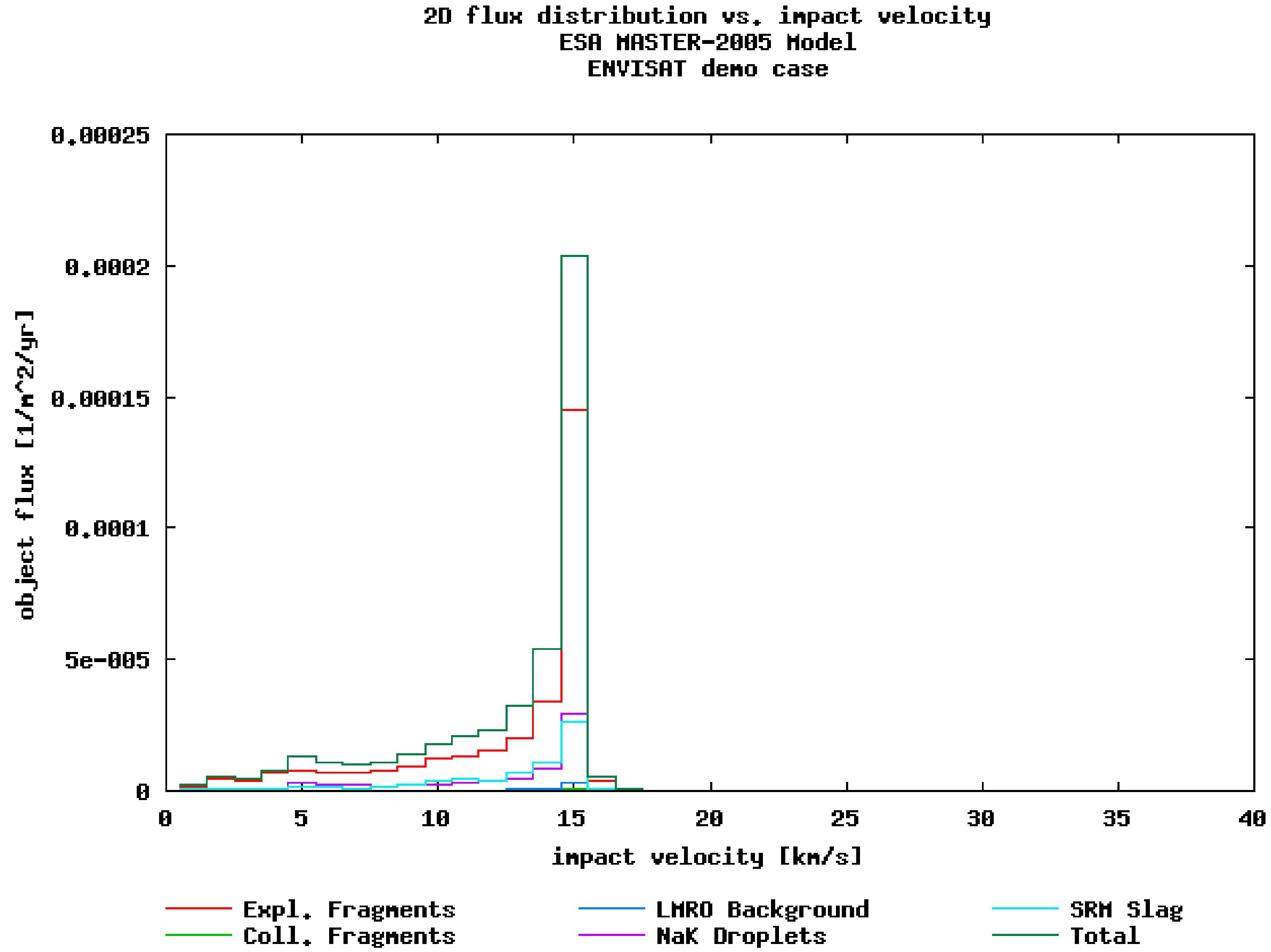
MASTER 2005 Result

2D spatial density distribution vs. altitude
ESA MASTER-2005 Model
Spatial density demo case

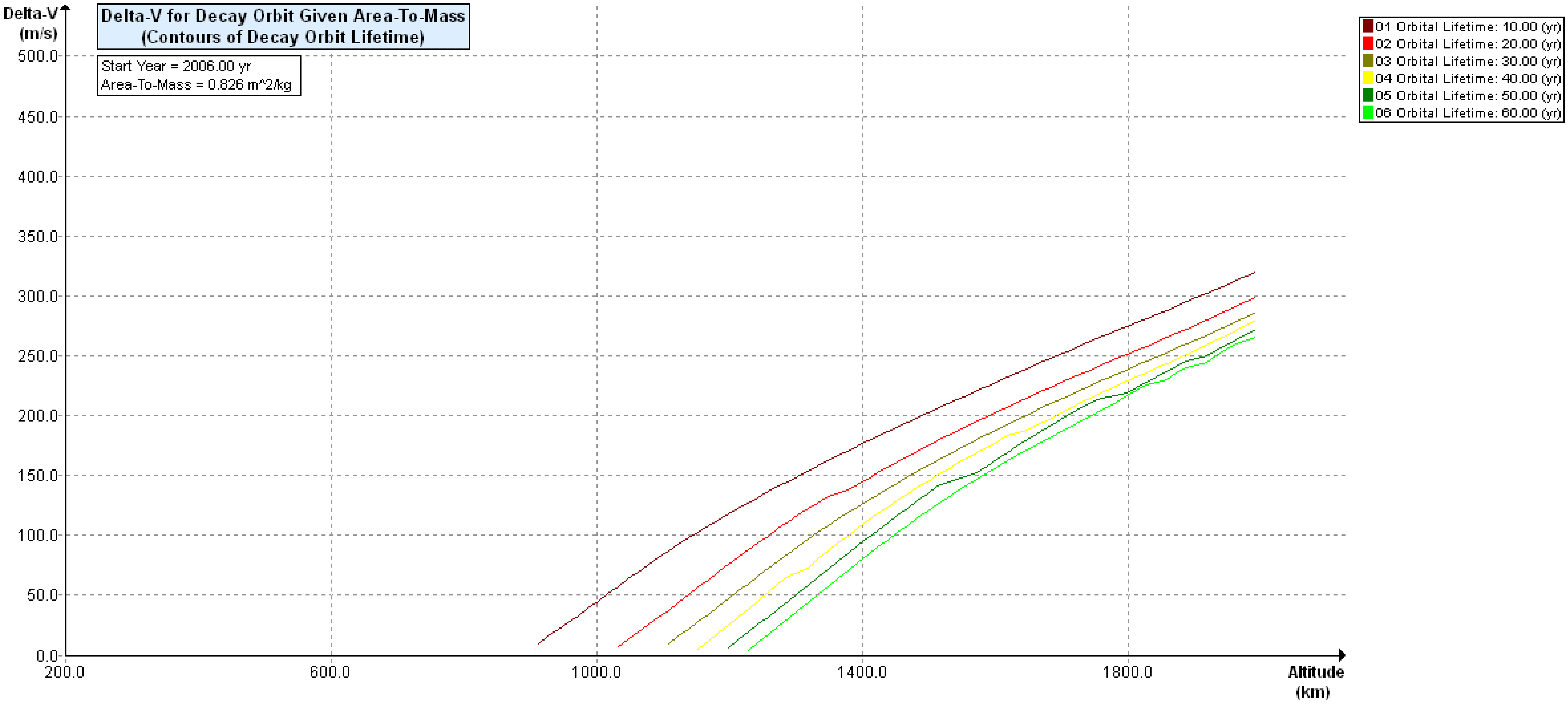


3D spatial density distribution vs. altitude and declination
ESA MASTER-2005 Model
Spatial density demo case

MASTER 2005 Result

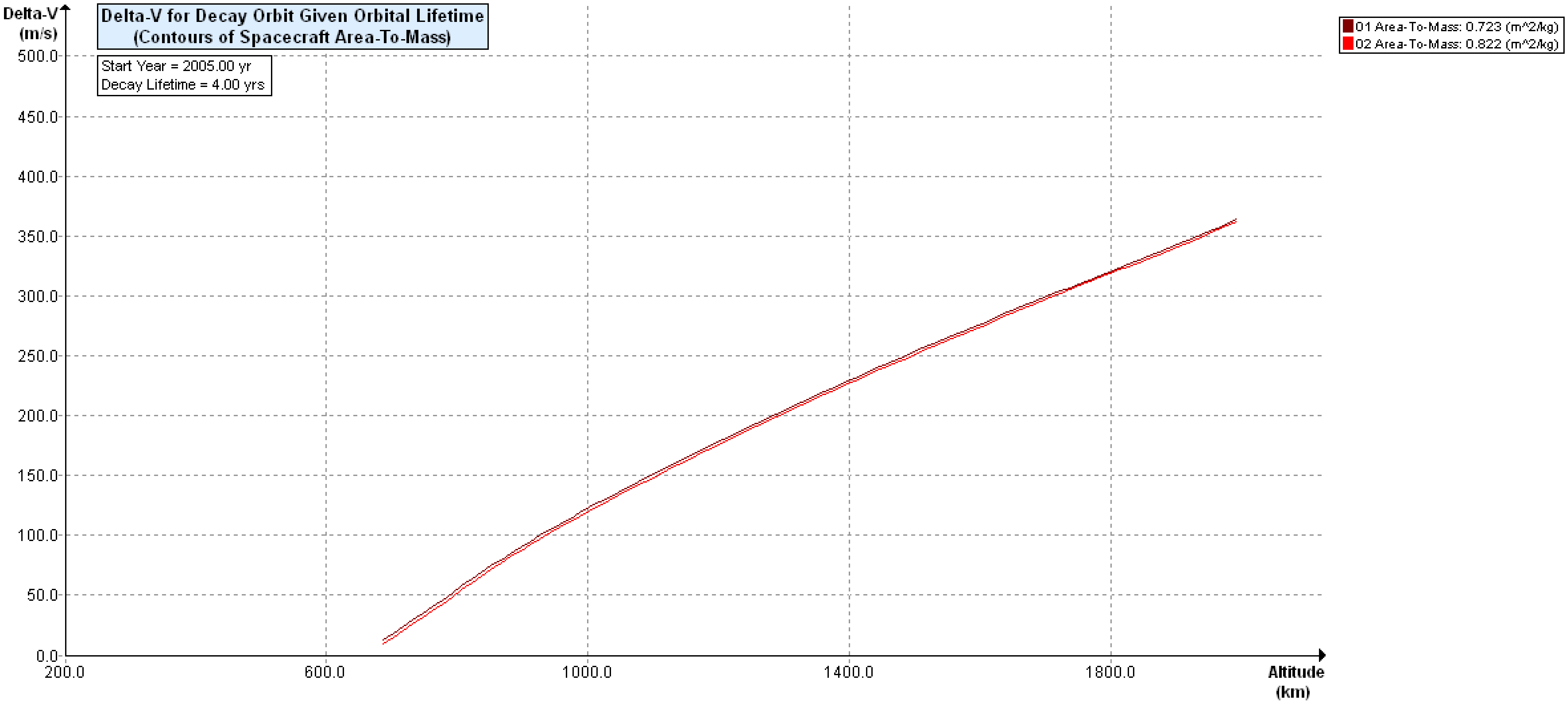


DAS Result



Delta-V for Decay Orbit Given Area-To-Mass
(Contours of Decay Orbit Lifetime)
Start Year = 2006.00 yr
Area-To-Mass = 0.826 m^2/kg
Delta-V
(m/s)
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
200.0
600.0
1000.0
1400.0
1800.0
Altitude
(km)
01 Orbital Lifetime: 10.00 (yr)
02 Orbital Lifetime: 20.00 (yr)
03 Orbital Lifetime: 30.00 (yr)
04 Orbital Lifetime: 40.00 (yr)
05 Orbital Lifetime: 50.00 (yr)
06 Orbital Lifetime: 60.00 (yr)

DAS Result

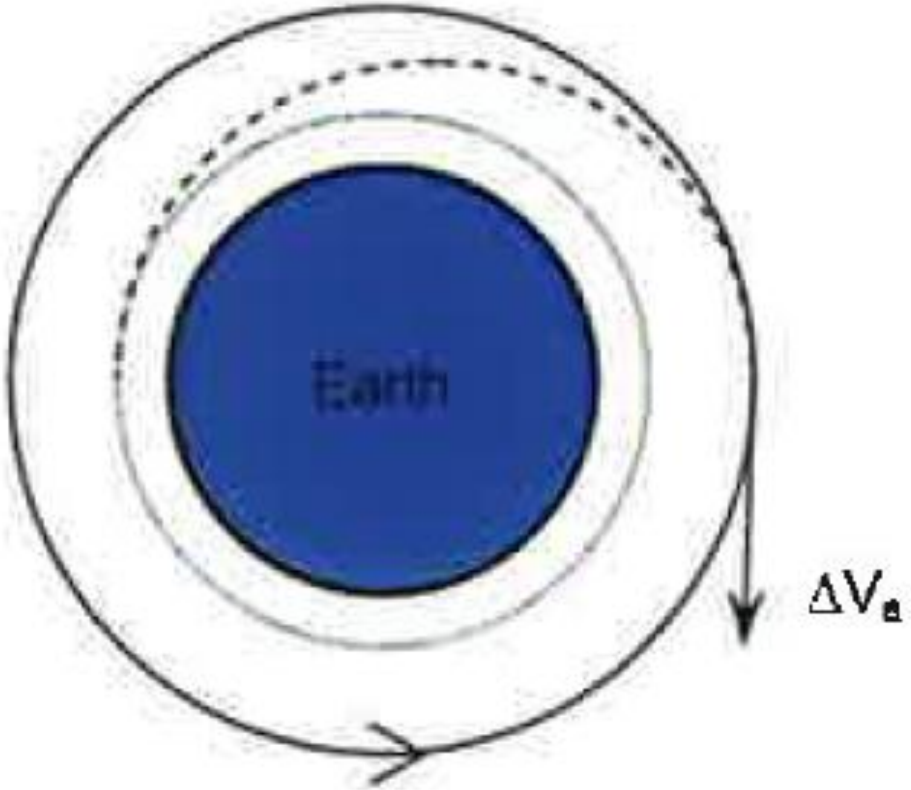

Delta-V for Decay Orbit Given Orbital Lifetime
(Contours of Spacecraft Area-To-Mass)
Start Year = 2005.00 yr
Decay Lifetime = 4.00 yrs
Delta-V (m/s)
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
200.0
600.0
1000.0
1400.0
1800.0
Altitude (km)
01 Area-To-Mass: 0.723 (m^2/kg)
02 Area-To-Mass: 0.822 (m^2/kg)

Don Kessler‘s Statement

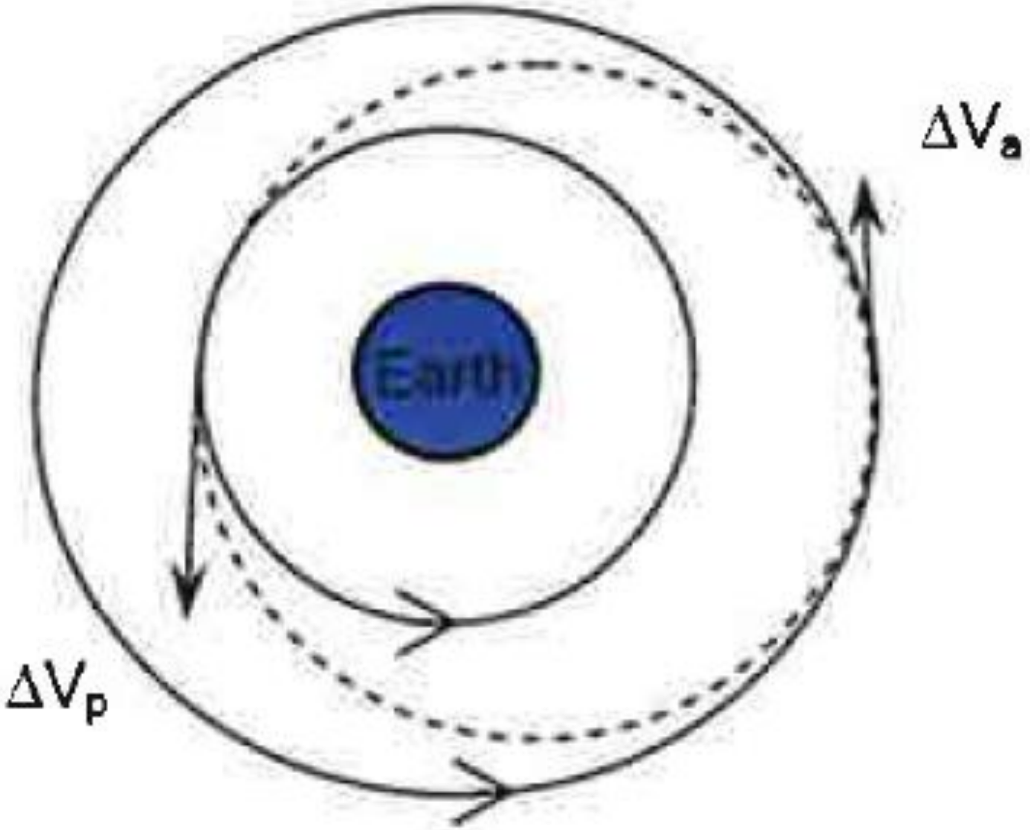
The control of future debris requires, at a minimum, that we not leave future payloads and rocket bodies in orbit after their useful life and might require that we plan launches to return some objects already in orbit.

Debris Reduction

De-orbit procedure



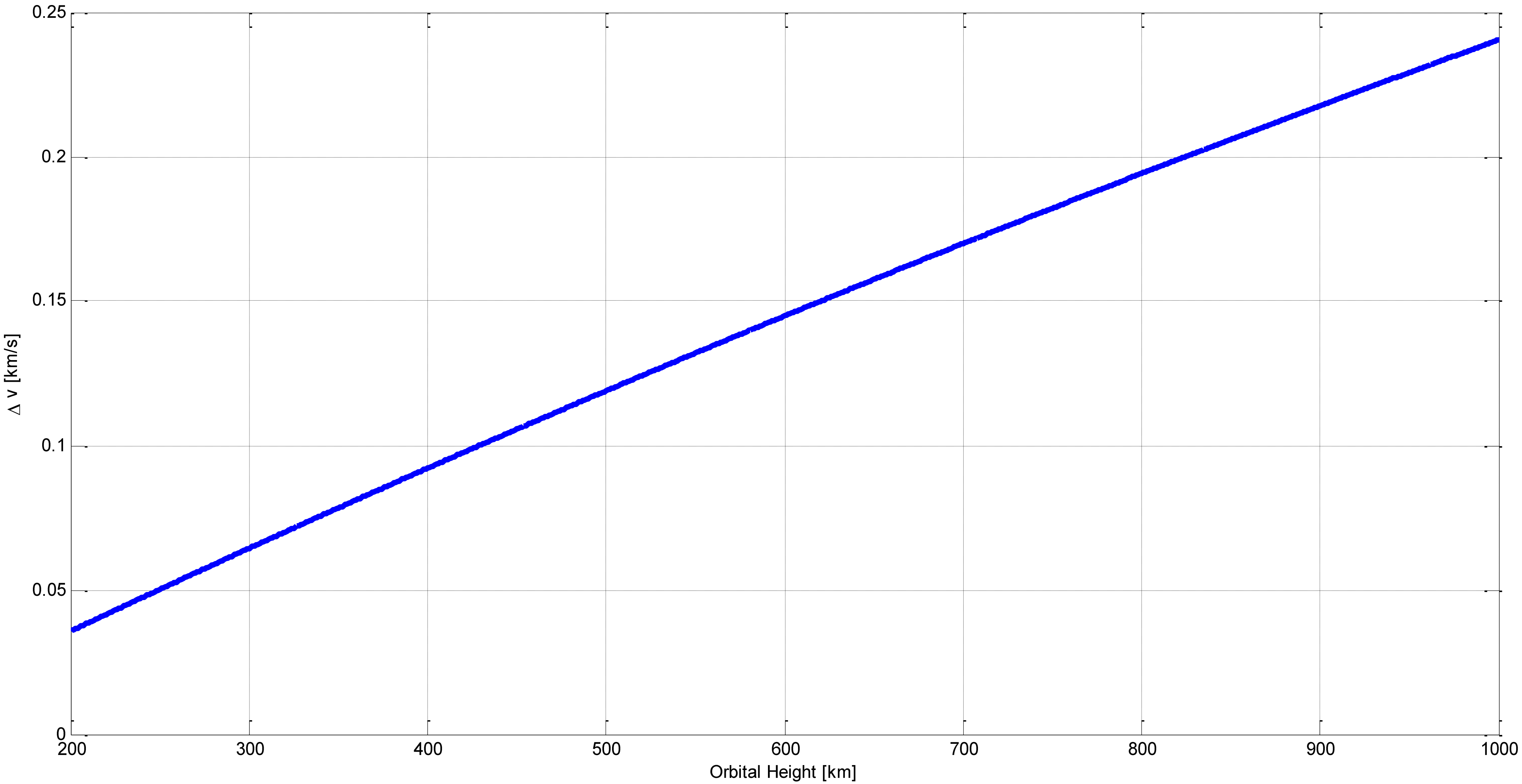
Re-orbit procedure



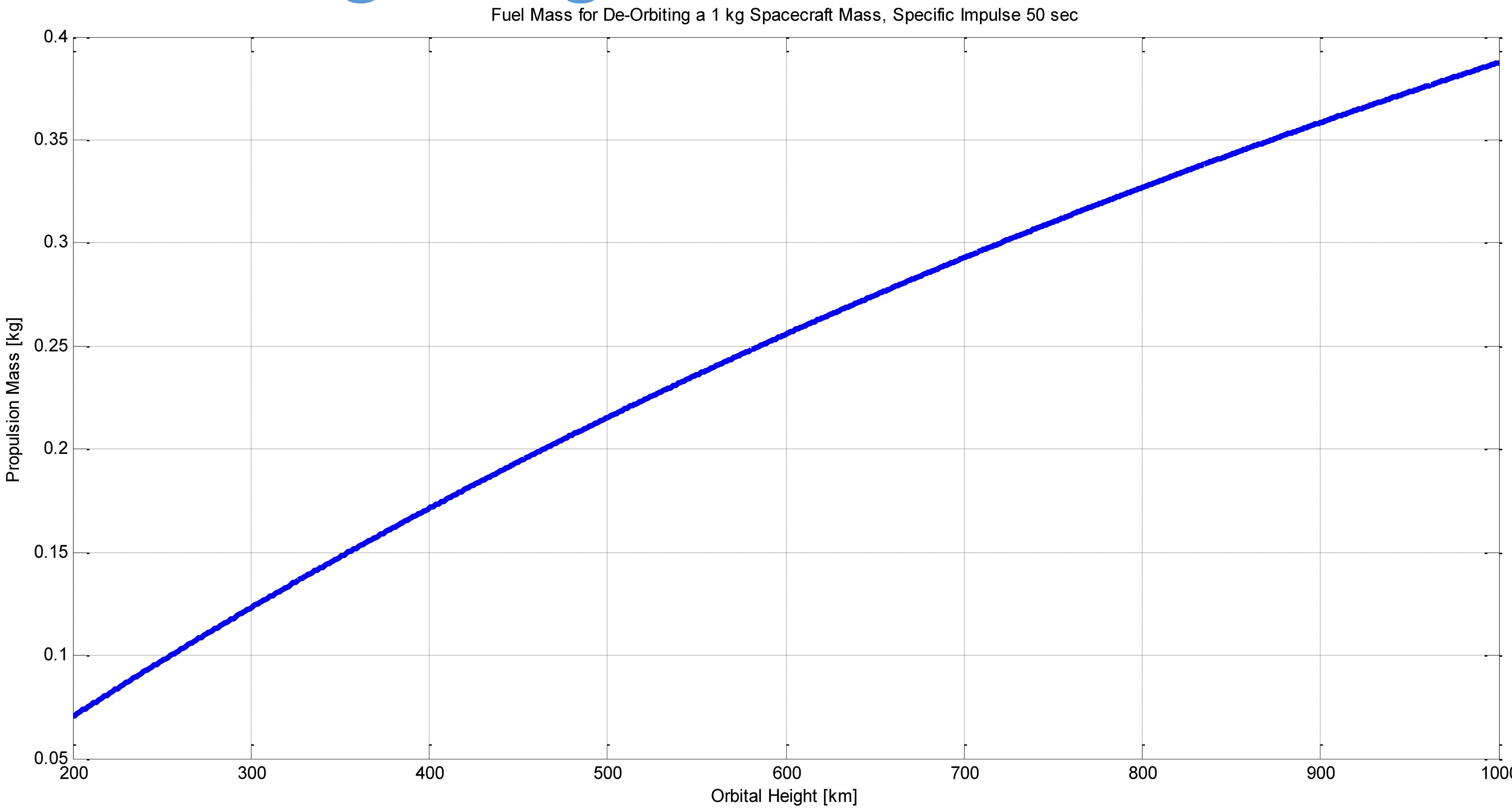
Debris Mitigation Methods

- De-Orbiting using Propulsion
- Atmospheric Re-Entry
- Active Removal by On-Orbit-Servicing Vehicles
- Solar Sails
- Tether

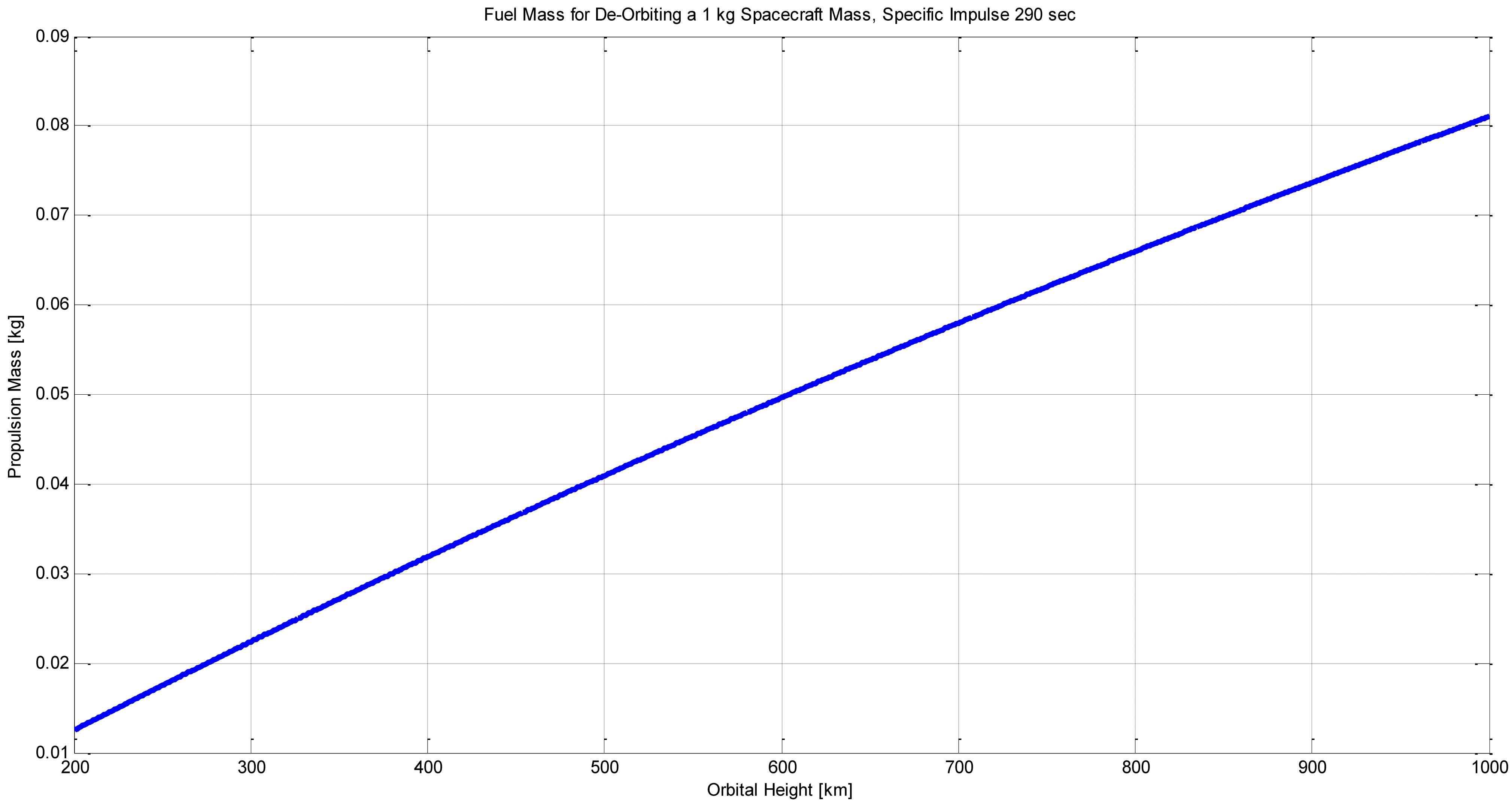
Velocity Increment Required to De-Orbit to 80 km Altitude



Cold Gas Propellant Mass required for De-Orbiting a 1 kg Cubesat



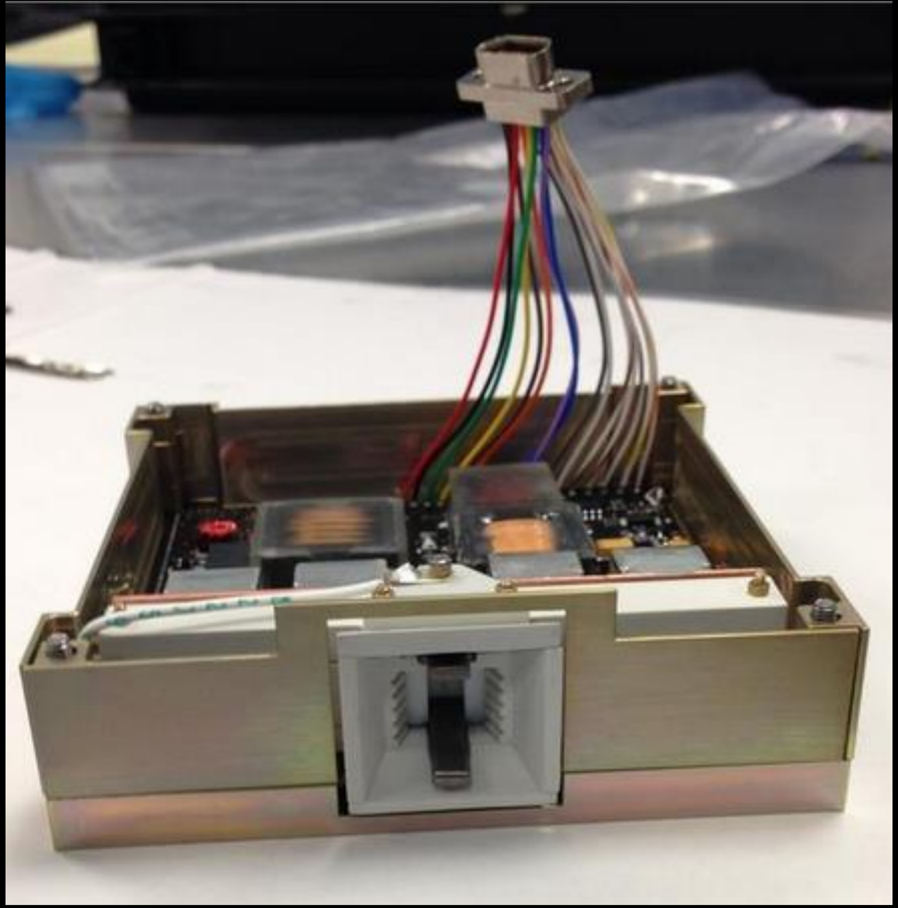
Solid Propellant (& Hydrazine) Mass required for De-Orbiting a 1 kg Cubesat



CubeSat Pulse Plasma Thruster

Part number: CS-MARS-PPT-01

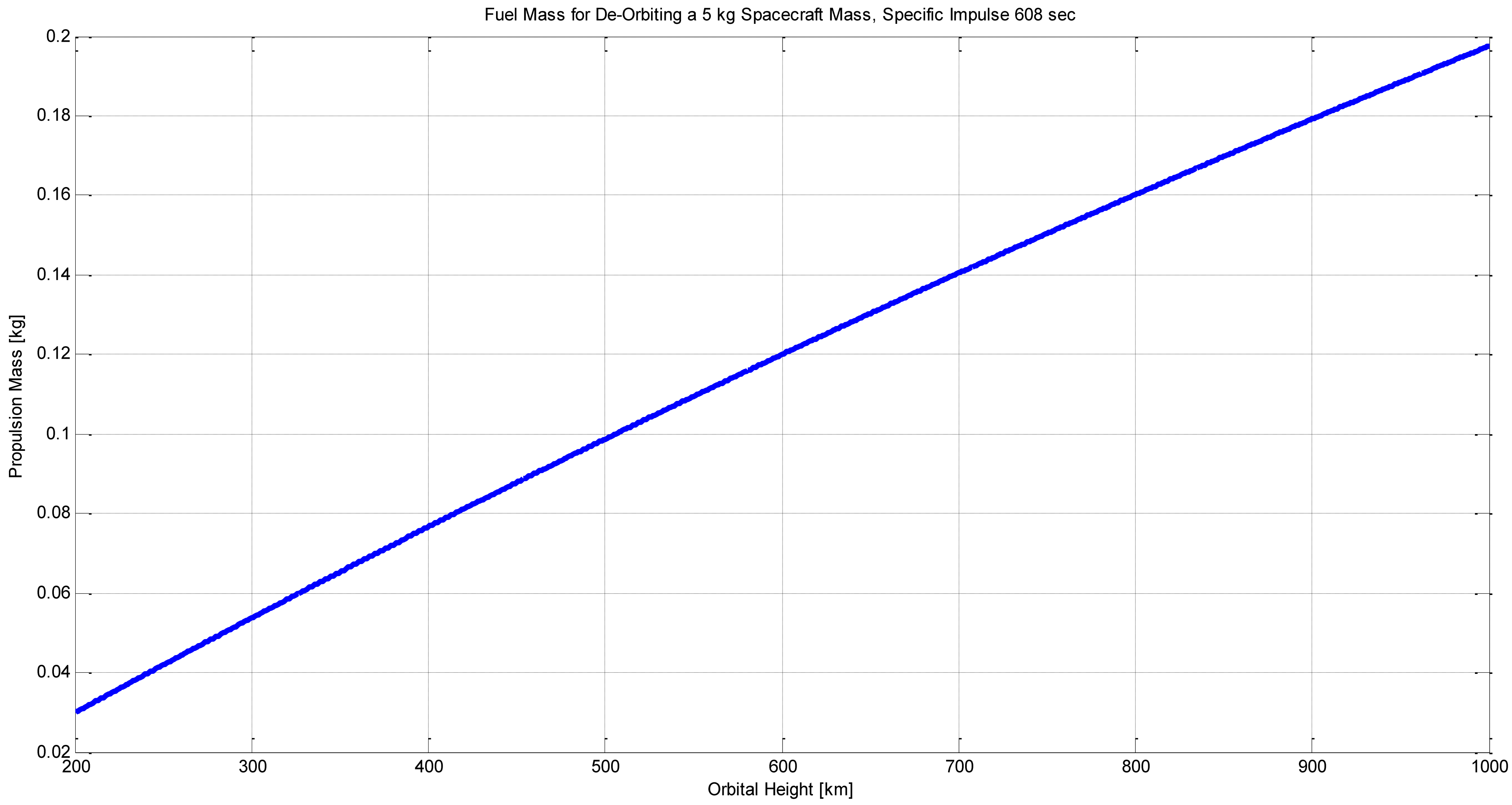
Cost: $18,850.00



MAIN FEATURES

- Joint Product from Clyde Space and Mars Space
- Typical shot energy 2J , total impulse ~42Ns
- Unit mass <280g, including 7g of propellant
- Copper Tungsten electrode for durability
- Life tested to 1.5M shots
- Power Draw of 2.7W
- Specific impulse measured at 608s
- Digital firing interface compatible with Cubesat I2C bus
- Integrated PIC16 microcontroller to synchronise charge / discharge circuits
- Side fed configuration, to maximise discharge length within 90x90x27mm envelope
- Sine sweep vibration tested to match FE model: 1st mode 185Hz
- Extensive testing at Southampton University and Institute for Space Systems, Stuttgart
- Datasheet: CubeSat PPT Datasheet

Plasma Propulsion Propellant Mass required for De-Orbiting a 5 kg Cubesat

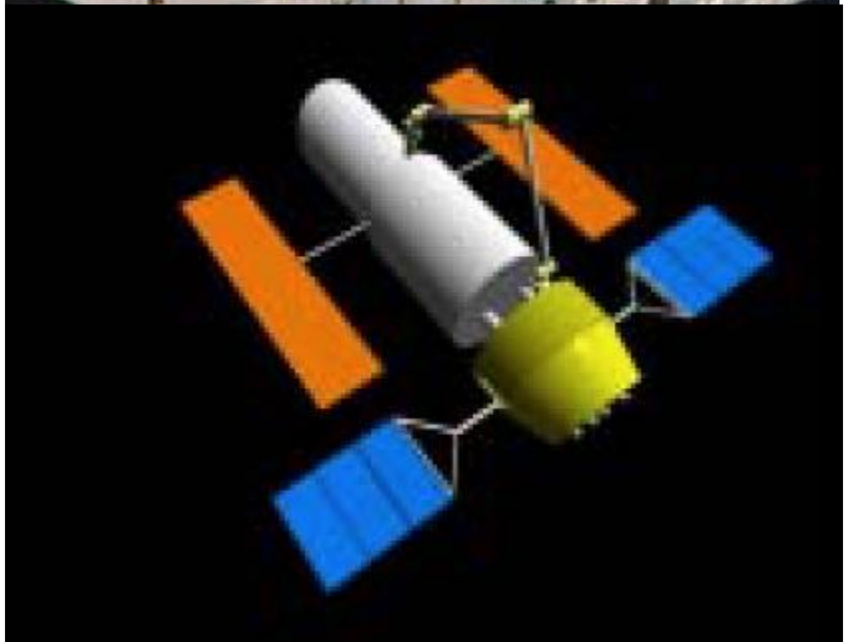


Propulsion for De-Orbiting Summary

- Cold Gas
    - Isp = 50 s
    - Requires 25 % of S/C Mass as Fuel
    - Thruster Unit Mass 300 g
- Hydrazine Propellant
    - Isp = 290 s
    - Requires 8 % of S/C Mass as Fuel
    - Thruster Mass 460 g, Thruster Unit 1.3 kg
- Solid Propellant
    - Isp = 290 s
    - Requires 8 % of S/C Mass as Fuel
- Plasma Propulsion
    - Isp = 608 s
    - Requires 3 % of S/C Mass as Fuel
    - Unit Mass 280 g

HUBBLE Retrieval

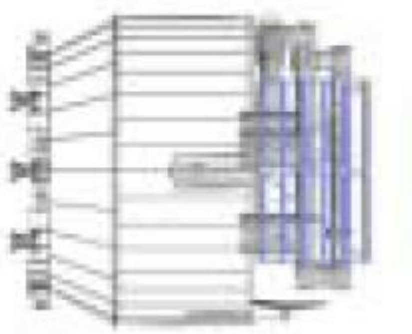
- Estimated cost is \$1.8 B - \$2.5 B
- Hubble servicing missions cost \$1 B - \$2B
- Shuttle is no longer available
- No Hubble servicing mission is possible
- Hubble De-Orbiting mission is to be performed by NASA



Possible HUBBLE De-Orbiting Vehicle based on JAXA HTV

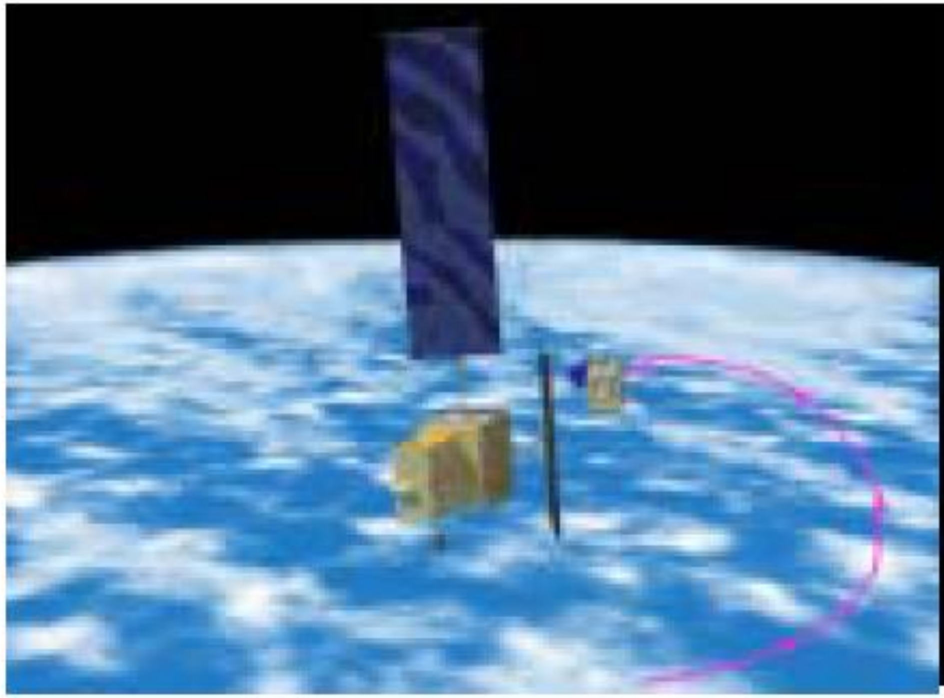
- HTV Propulsion & avionics module 3.1 ton
- robot, docking mech. 1.7 ton
- Fuel 2.4 ton

(Total) 7.1 ton

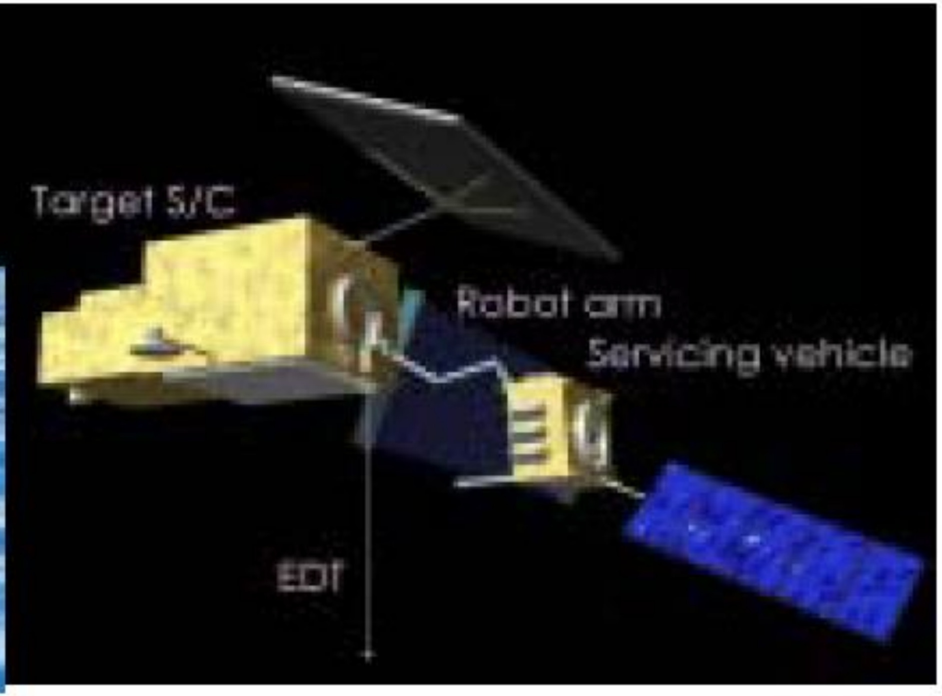


Robotic Debris Removal

- Robotic debris removal system carries several to ten small electro dynamic tethers (EDT).
- The vehicle attaches each one to each target.

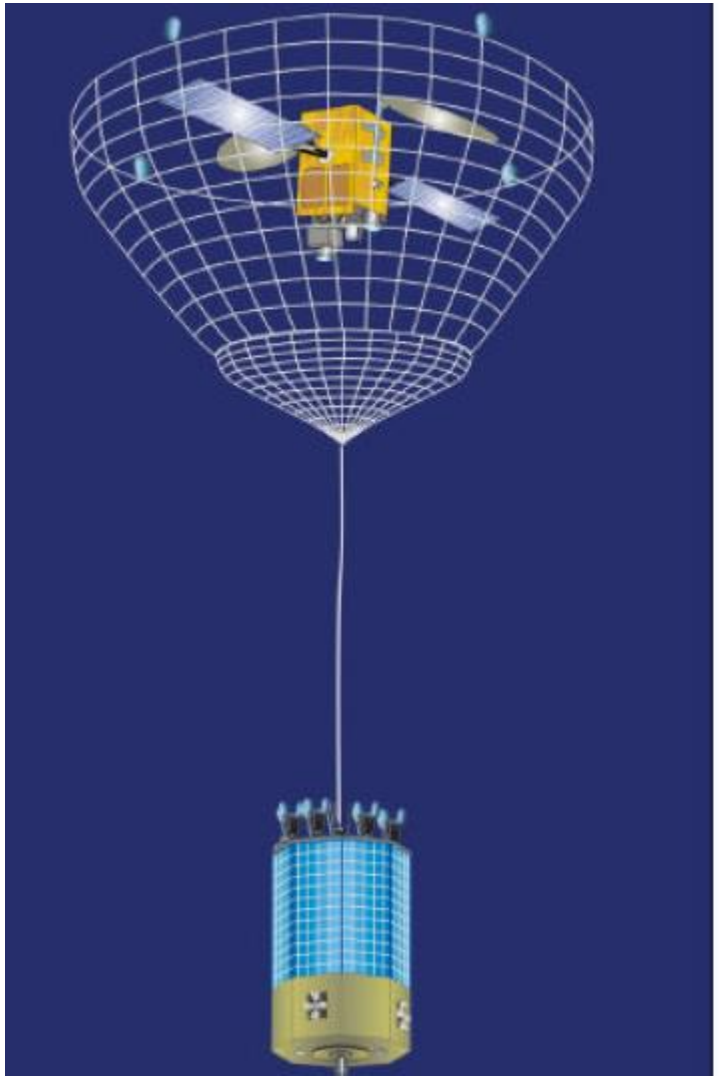


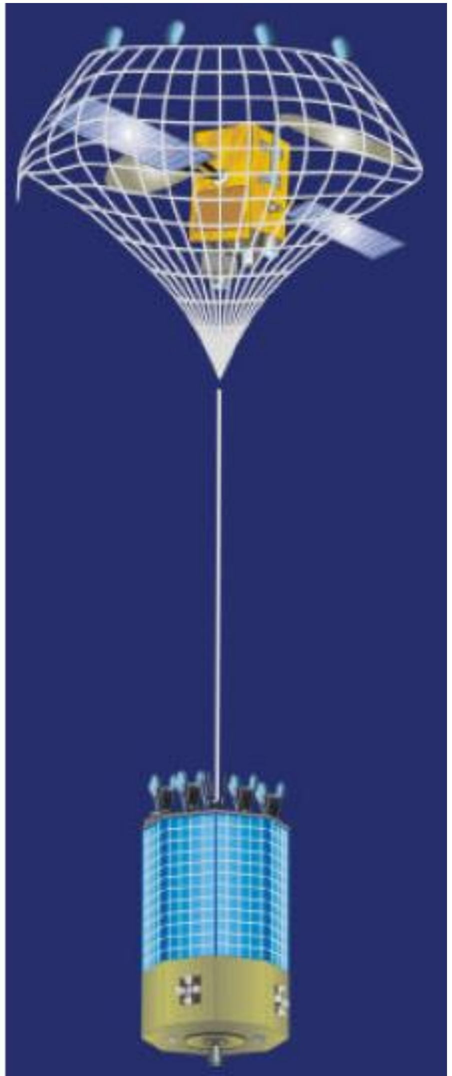
Motion measurement and flying around



Deployment of electro dynamic tether

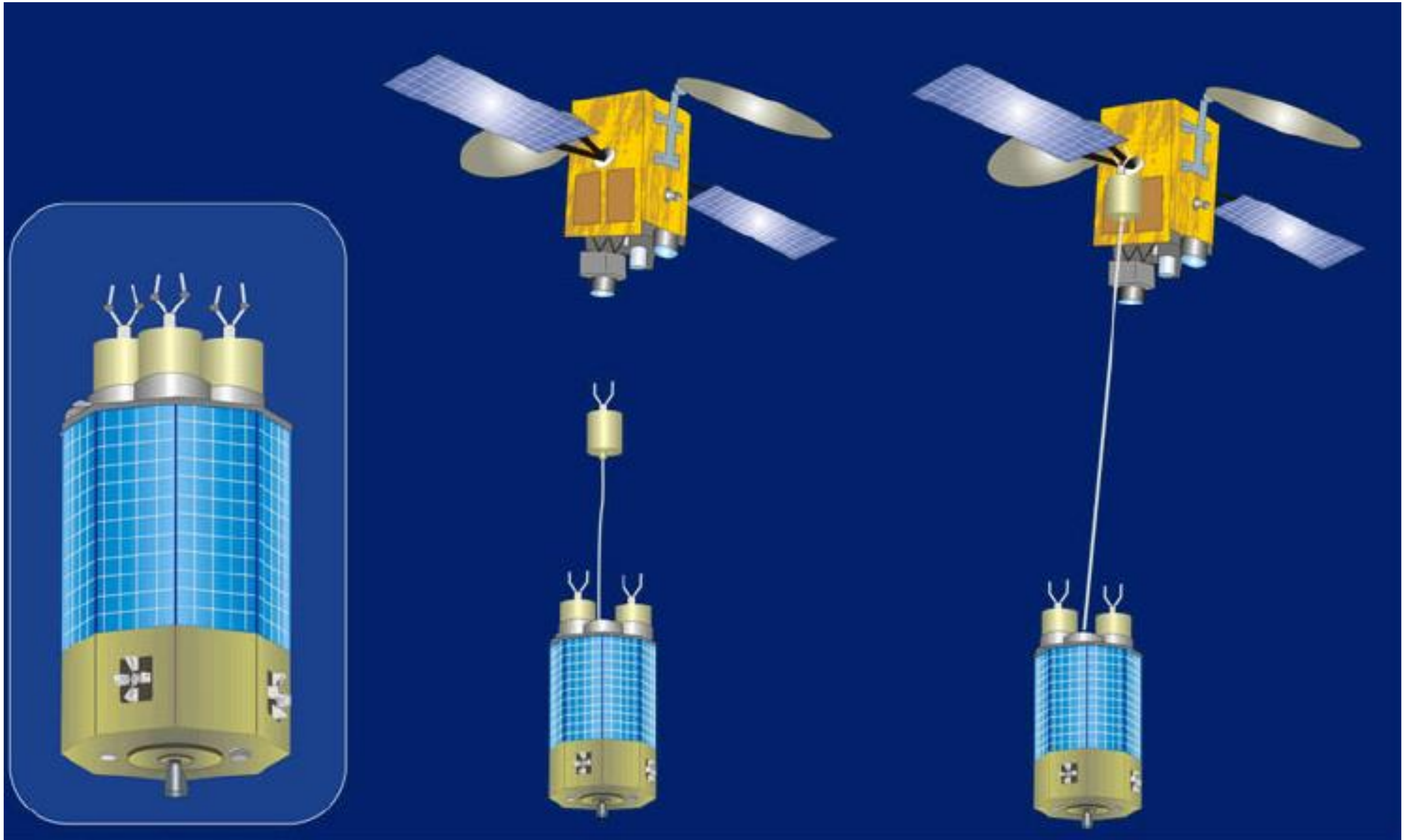
ROGER: RObotic GEostaionary Orbit Restorer



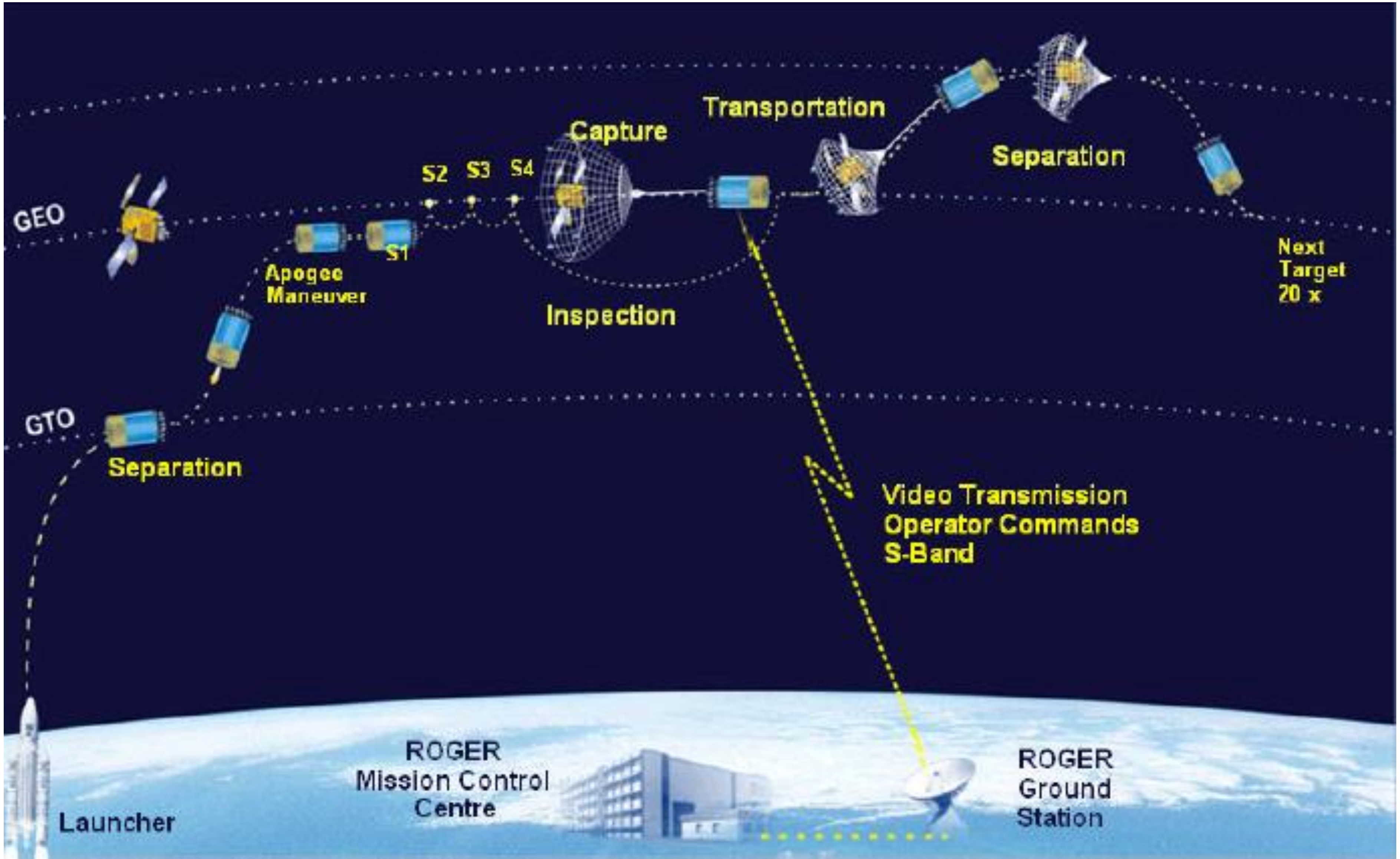


ESA Study 2003 by Airbus

ROGER Tether Mechanism



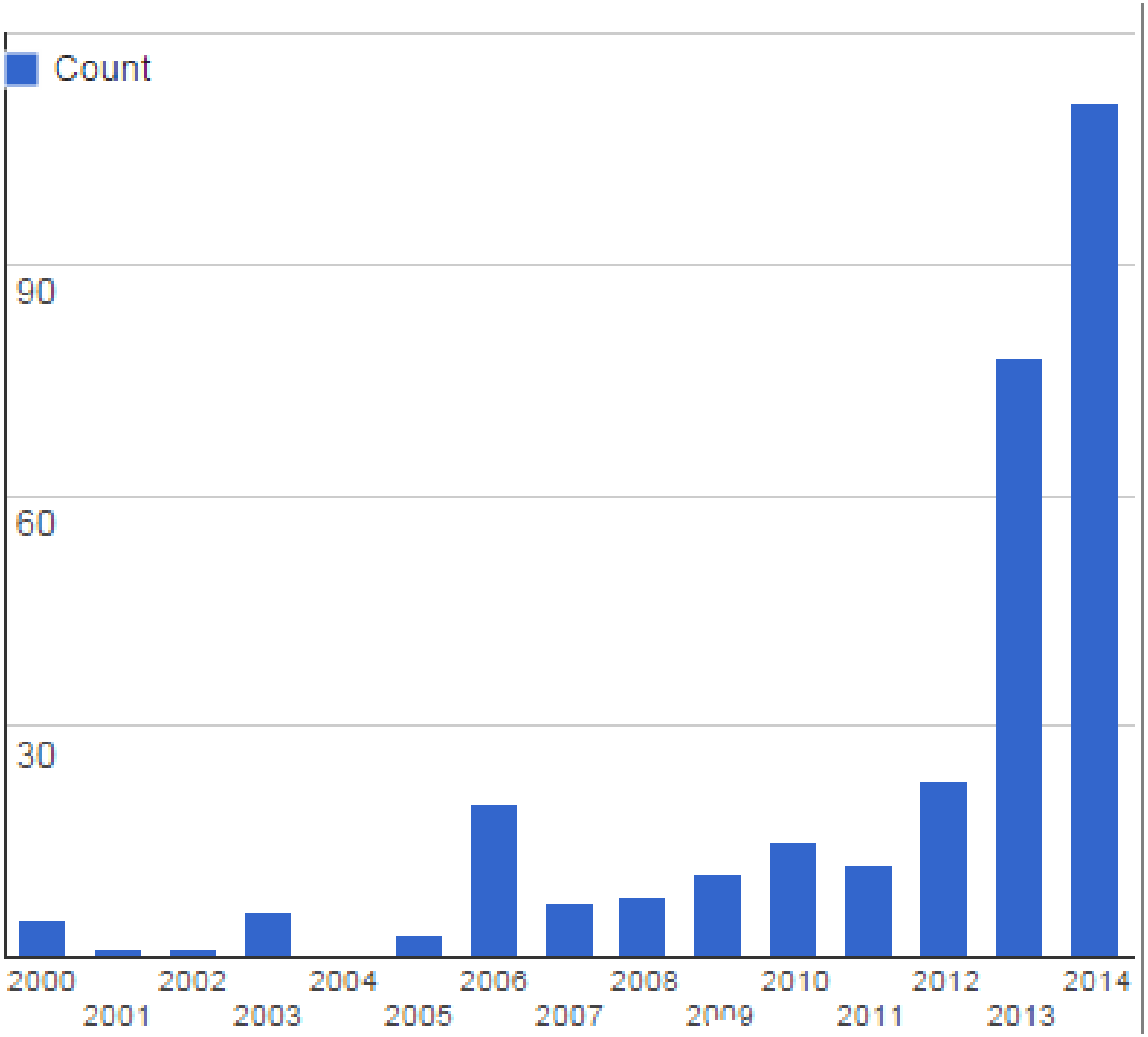
ROGER Concept of Operations



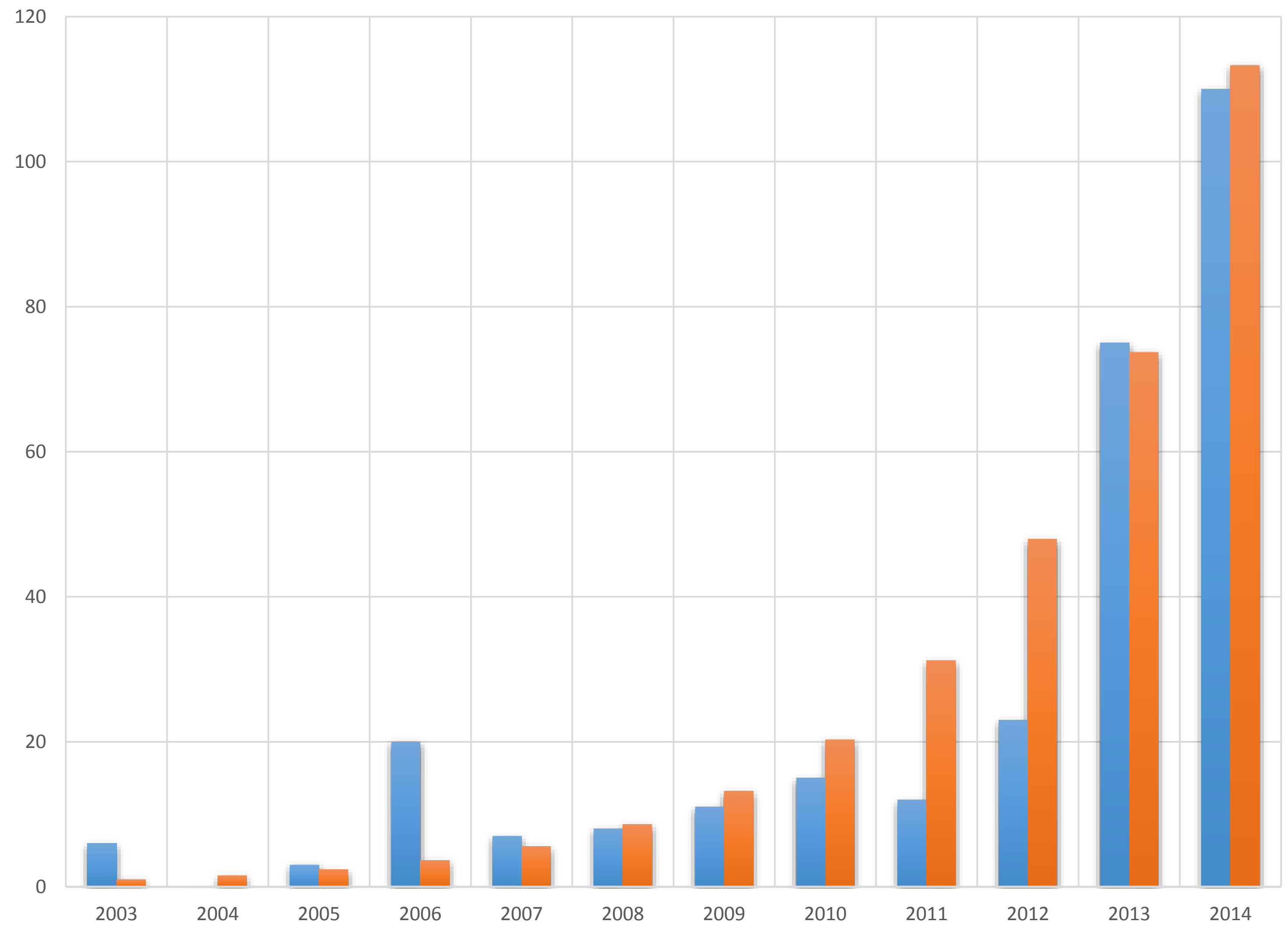
ROGER Business Model

	ROGER 1		Follow-on ROGER
	M€		**M€**
Agency Costs	186,9		7,6
Industry Costs	27,6		158,7
Industry Refinancing	9,3		53,7
Insurance	11,7		13,6
Total Program Costs	**235,6**		**233,5**
Revenue	329,2		381,6
Earnings	93,5		148,1
Tax Amount	14,0		22,2
Total Profit (after tax)	79,5		125,8
Annual Profit Rate (off tax)	6,0%		9,0%

Number of CubeSats launched between 2000 and 2014



Number of CubeSats launched between 2000 and 2014



Blau … launched
Red … Exponential Growth

Removal Methods of Satellites from Orbit

- Re-entry into Atmosphere
  - Requires large ballistic co-efficient B

$$B = C_D \frac{A}{m}$$

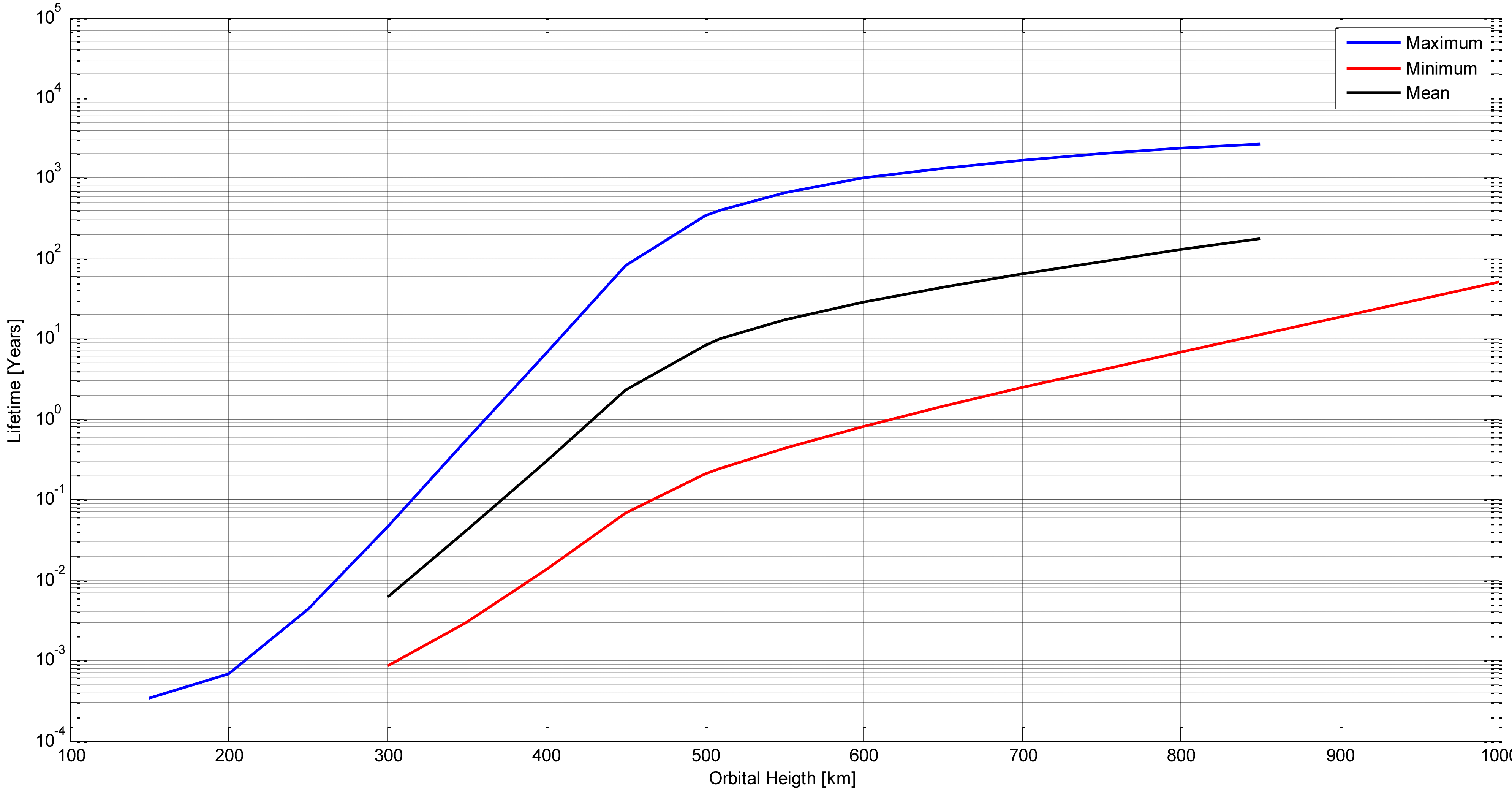
- Solar Sail
  - Requires a solar sail to generate a force to decay

$$p_{rad} = \frac{I}{c}$$

- Electromagnetic Tether
  - Requires a tether to produce a force to decay

$$F = IBA$$

Lifetime vs Orbital Height Ballistic Coefficient $m/(C_d * A) = 166.67\ kg/m^2$

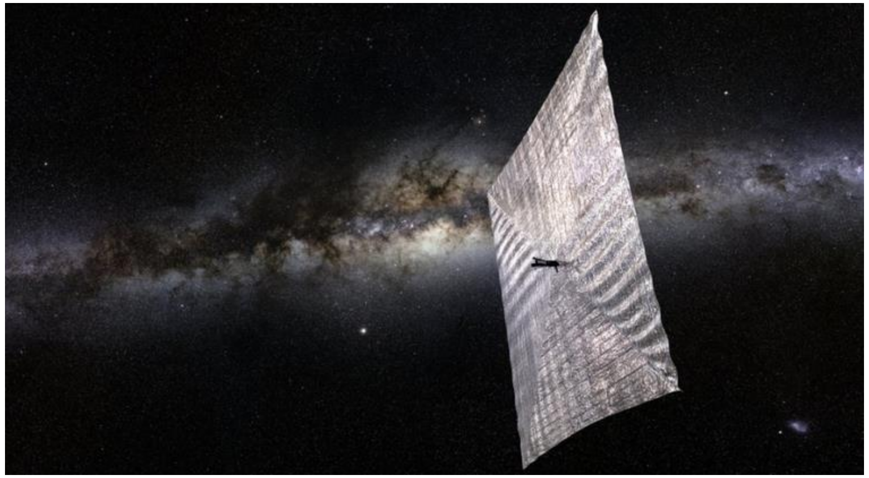


Solar Sail

- Radiation pressure $$p_{rad} = \frac{I}{c} = \frac{E}{c}$$

- The solar constant 1370 W/m^2 produces p_{rad} = 4.5 $\mu N/m^2$

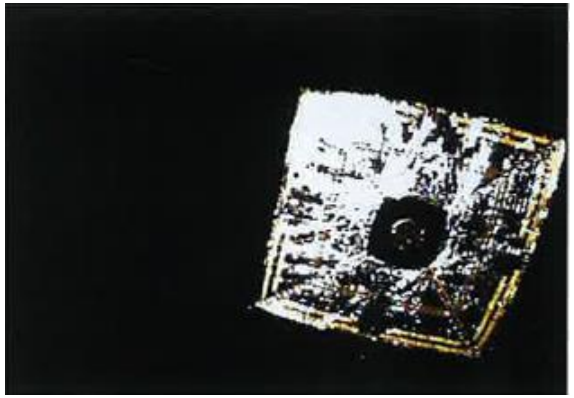
- By orientating the solar sail properly the force will result in a decay of the orbit



Solar Sail Missions

- Solar sail deployement by ISAS 9 August 2004 in 122 km height

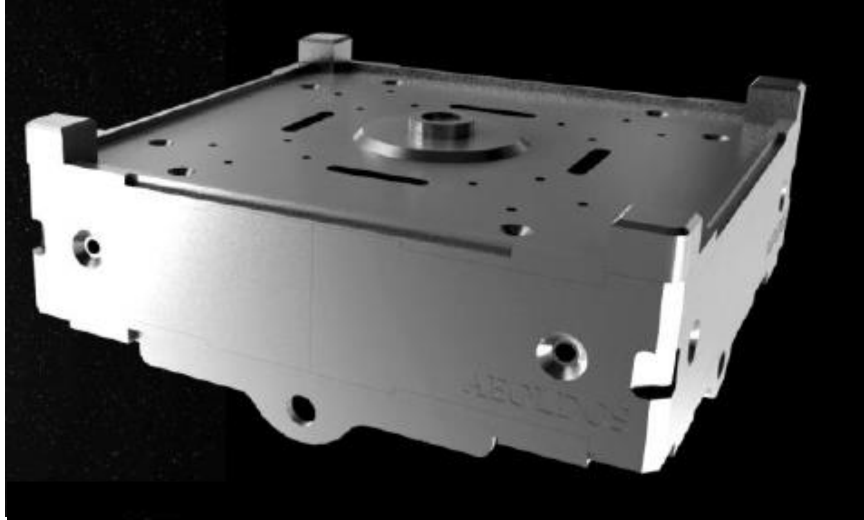
- ICAROS (JAXA 2010) 20 m sail

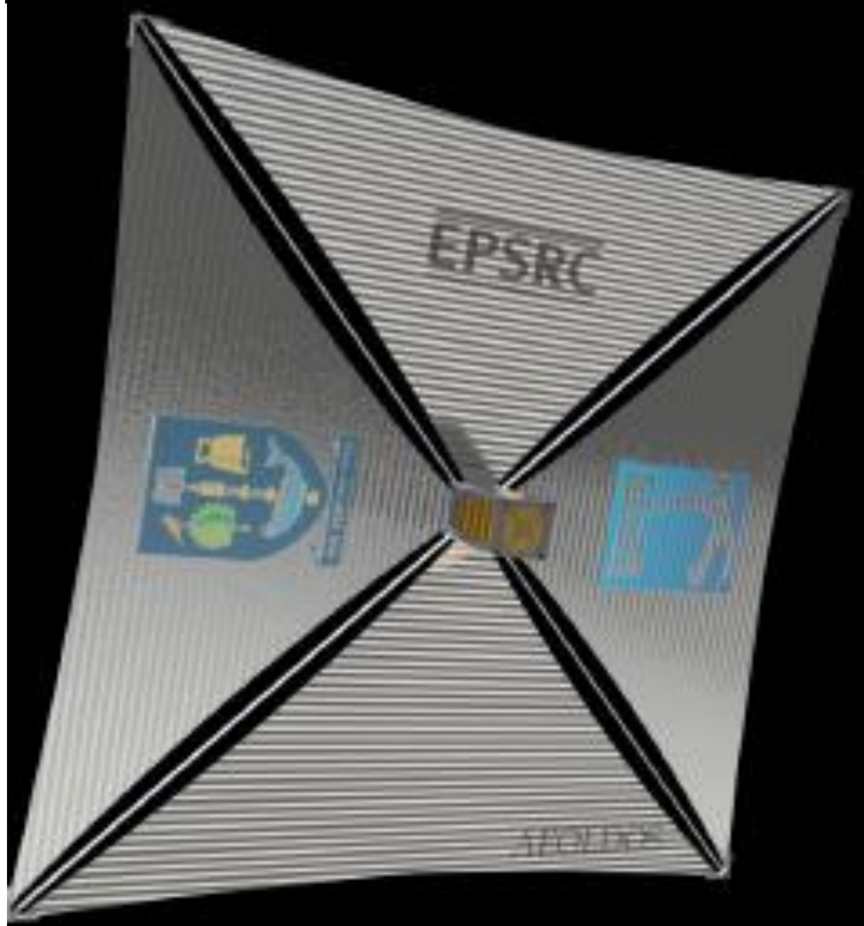


- November 2010 NASA Nanosail D2 10 m^2 sail

Solar Sail Kit

- AEOLDUS of Clyde Space
- 0.4 U kit
- Deployed 1.5 m^2
- $ 15,000



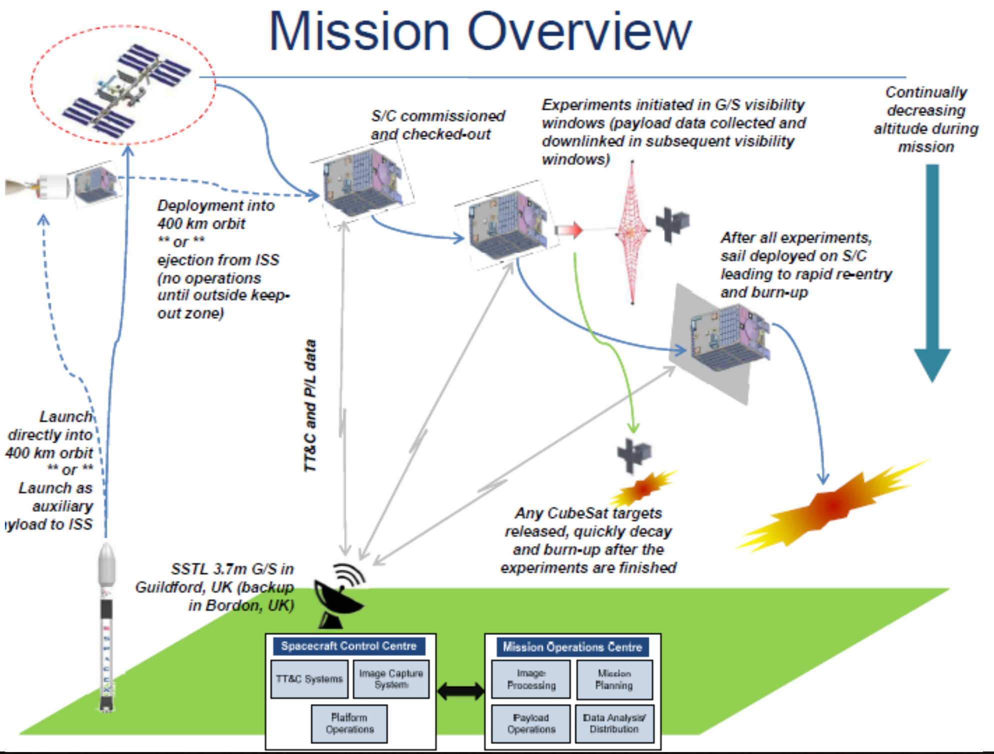


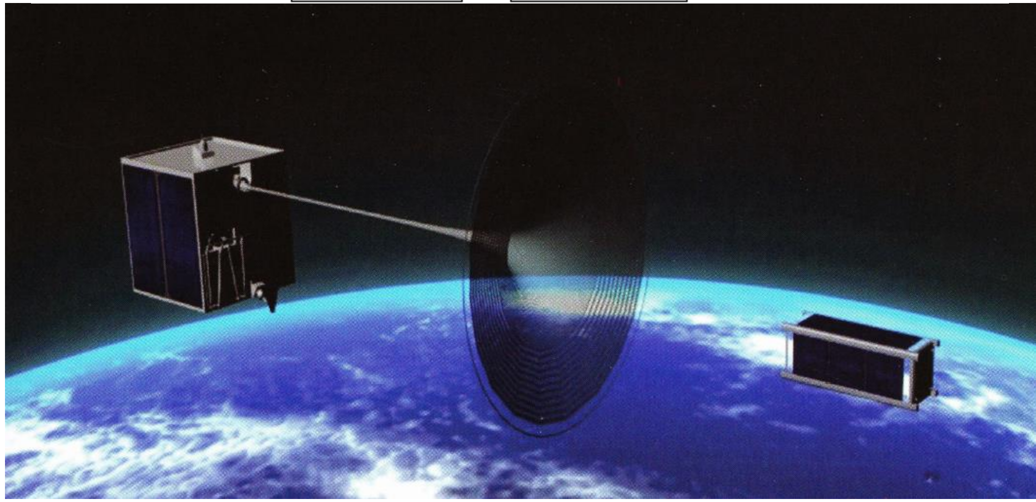
Tether

- Tether of length l in the Earth magnetic field B moving with a velocity v ≈ 7 km/s produce a voltage $U = Blv$
- Earth magnetic field strength B = 30…60 µT
- If the tether has an electrical resistance R a current of $I = \frac{U}{R}$ will flow through the tether
- This produces a force $F = IBA = \frac{U}{R} BAl = \frac{B^2 lAv}{R}$
- This force acts against the satellite movement

RemoveDEBRIS

- EU FP7 Activity
- Project Partners
    - University of Surrey (UK)
    - SSTL (UK)
    - Airbus (D, F, UK)
    - ISIS (NL)
    - CSEM (CH)
    - INRIA
    - Stellenbosch University (South Africa)
- Objective
    - Active Debris Removal by launching a 'RemoveSat‘ in 2016 which will eject three smaller Cubesats
    - 1st Cubesat deploys an inflatable structure, RemoveSat will capture this sat with a net
    - 2nd Cubesat captured by a harpoon fired from removeSat
    - 3rd Cubesta will be used to mature LIDAR-assisted vision-based navigation technology
- Cost
    - Total Cost € 11.730.796
    - EU Contribution € 6.999.867





Debris Mitigation

- The general trend of the historical evolution of the space debris environment has been an ever increasing number of space debris objects.

- The (exponential) growing launch of CubeSats is another factor not yet considered in debris growth.

- The most important mitigation measure is the de-orbiting of spend satellites and upper stages on LEO, to prevent an instable population.
  - Reduction of the orbital lifetime to 25 years.
  - Passive removal by drag augmentation (inflatable structures increasing the ballistic coefficient or solar sails).
  - Active removal by (electric) propulsion.
  - Active removal of larger objects, by robotic systems.

- The suppression of the release of small particles is a stringent mitigation measure.

CubeSats are Critical Objects

- Critical object sizes: Objects (fragments or intact objects) of sizes that can lead to a catastrophic break-up for a collision with a typical intact object at typical LEO collision velocities leading to a specific kinetic energy exceeding 40 KJ per kg of the target object.

- A 1U-1 kg Cubesat has a specific kinetic energy of 24.5 MJ/kg.

- Since CubeSats are mostly launched piggy-back with other LEO satellites (mainly EO-LEO spacecrafts) they are in similar orbits and pose or are targets for an increasing thread for collision.

Legal Aspects

- Outer Space Treaty (OST) of 1967
  - The community recognizes the freedom of all States to explore and use outer space. Excercising this freedom is bound to the obligation for doing so for the benefit and in the interest of all countries.

- Space debris, as safety and environmental hazard as well as thread to security, falls into the domain of International Space Law

- There is no legally binding statement regarding debris removal.

- Liability for Damage incurred by Space Debris
  - Emerging international environmental law principle " polluter pays“ is a work around solution.

Risk Metric

Metric # 1:

[Catastrophic Collision Rate] = [10 cm collision flux] * [mean target cross-section]

Metric # 2:

[Short-Term Risk due to a Catastrophic Collision] = [10 cm collision flux] * [mean target cross-section] * [target mass]

Metric # 1:

[Long-Term Risk due to a Catastrophic Collision] = [10 cm collision flux] * [mean target cross-section] * [target mass] * [target orbit lifetime]

Effect of CubeSat Launches

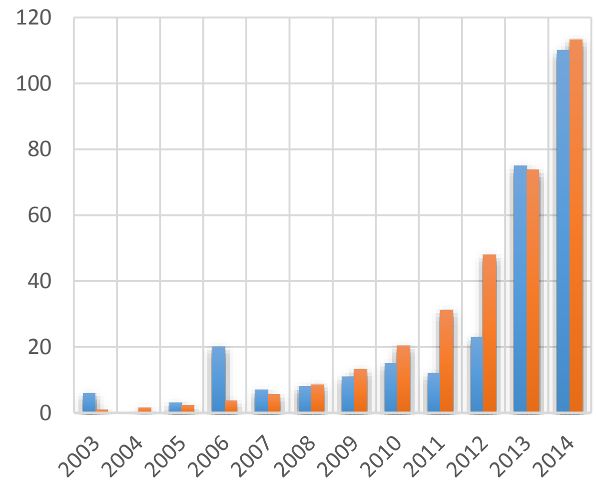
The Risk-Metric's 1 – 3 all contain 10 cm collision flux.

We have seen up to now a-kind of exponential growth of CubeSat launches.

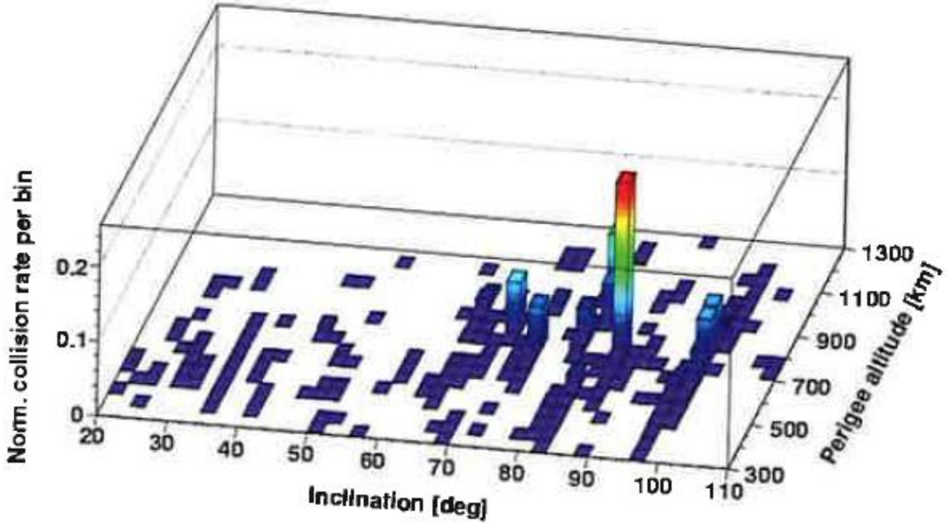
CubeSat's are 10 cm * 10 cm * 10 cm and multiples thereof.

Growing launch rate of CubeSat's add (exponentially) the 10 cm Collision Flux.

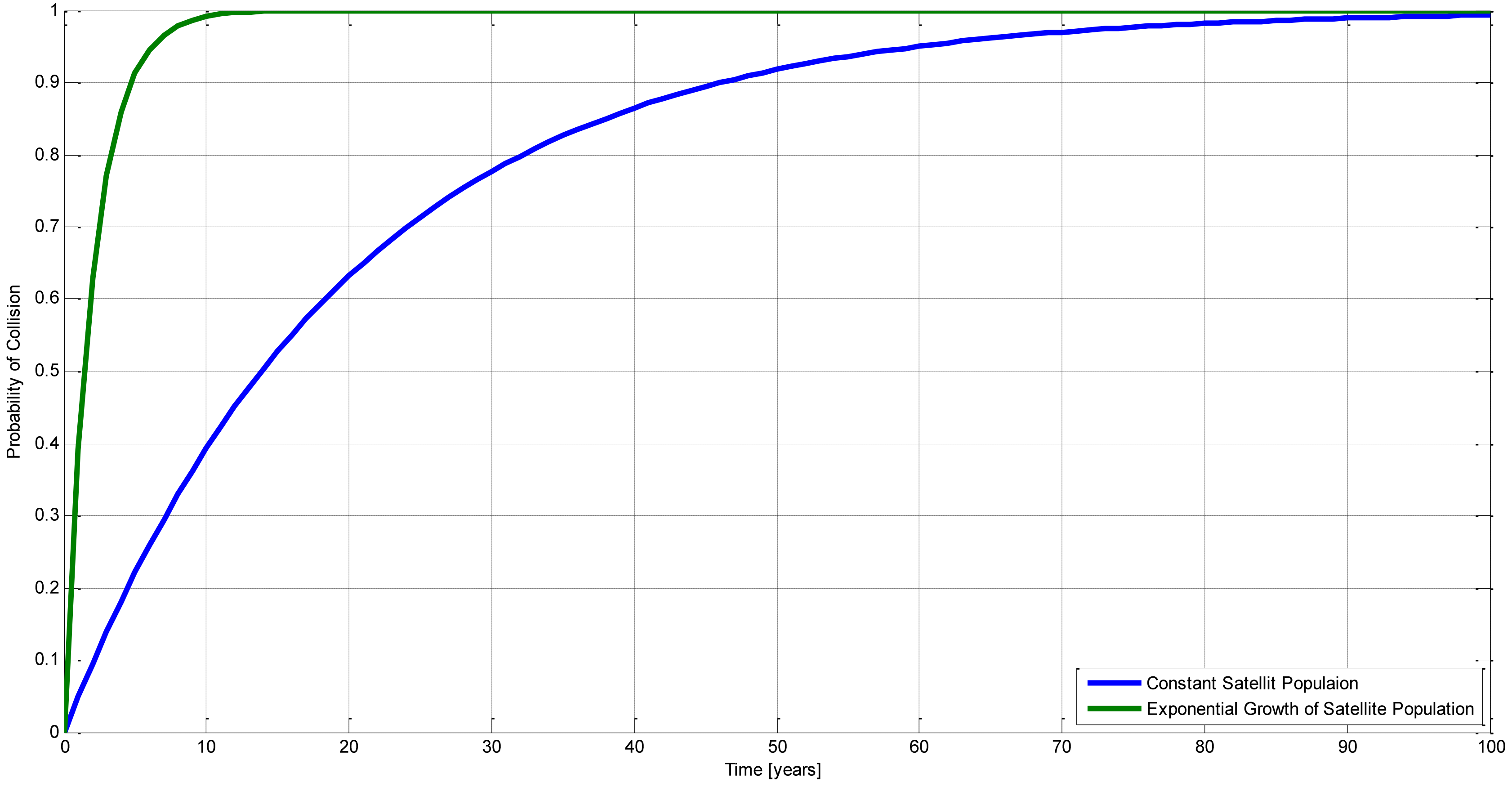
Thread to Collisions in LEO will have an additional exponentially increase (besides the already modelled one) over time due to CubeSat launches.



Metric # 1



Probability of Collision for Exponential Growth of Spacecraft Population



Warning: Numbers are arbitary

IADC Guidelines

1 Scope

The IADC Space Debris Mitigation Guidelines describe existing practices that have been identified and evaluated for limiting the generation of space debris in the environment.

The Guidelines cover the overall environmental impact of the missions with a focus on the following:

(1) Limitation of debris released during normal operations

(2) Minimisation of the potential for on-orbit break-ups

(3) Post-mission disposal

(4) Prevention of on-orbit collisions.

IADC-02-01
Revision 1
September 2007

INTER-AGENCY SPACE DEBRIS COORDINATION COMMITTEE

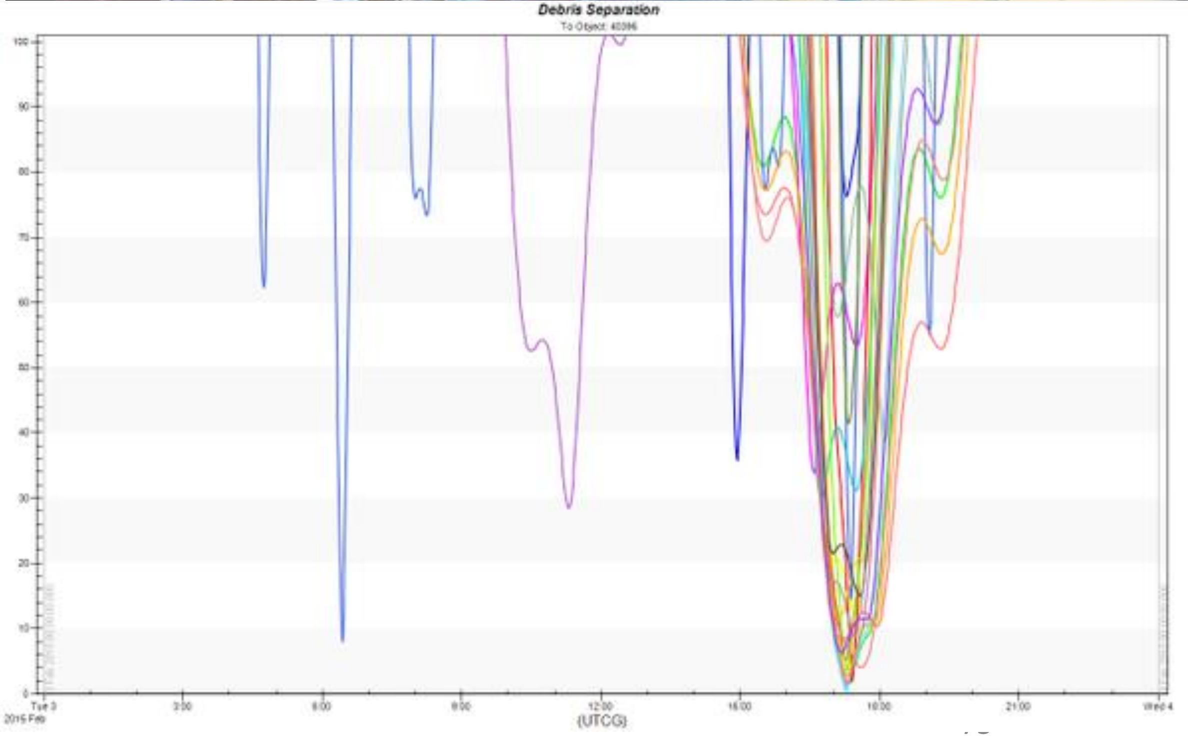
IADC Action Item number 22.4

IADC Space Debris Mitigation Guidelines

Issued by Steering Group and Working Group 4

Just from the News …

- A 20 year old military weather satellite exploded in-orbit on 3 February 2015 creating at least 43 pieces of debris



And will continue …