Space debris

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Introduction to space debris

The source of space debris could be expired satellites, spent rocket upper stages, fragments from explosions and collisions, paint flakes, chunks of slag from solid rocket motors, remnants of old science experiments and a variety of small particles.

Three categories of space debris, depending on their size:

Category I (<1cm)

make significant damage to vulnerable parts of a satellite, shielding

Category II (1-10 cm)

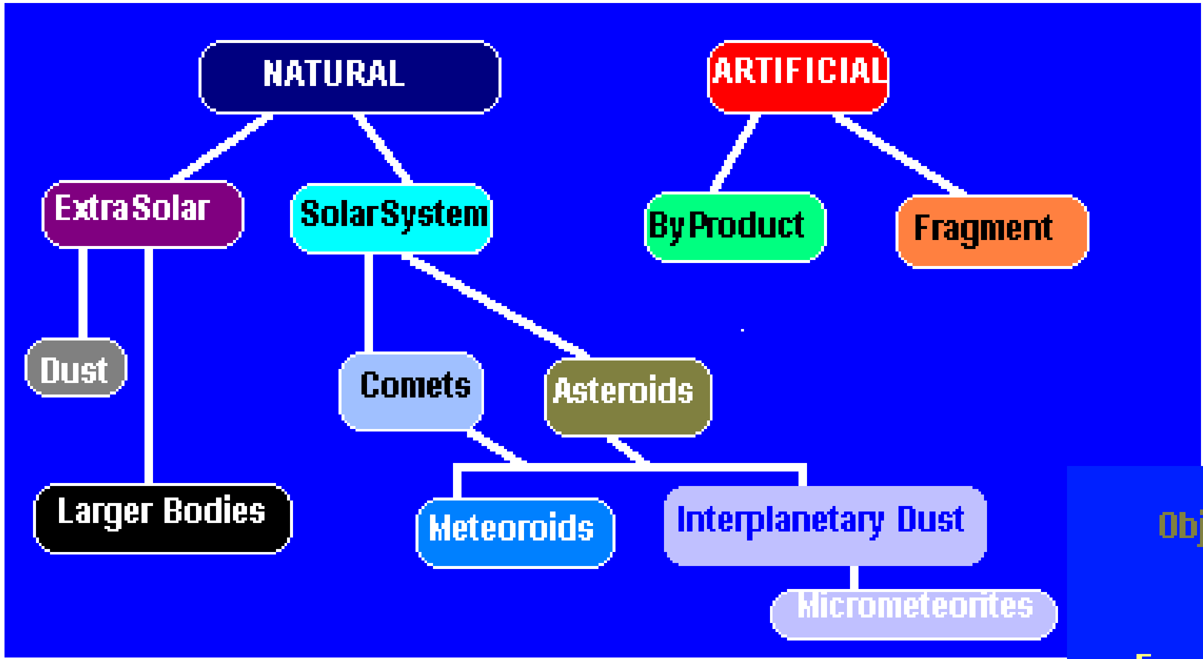
seriously damage or destroy a satellite in a collision, no effective shielding

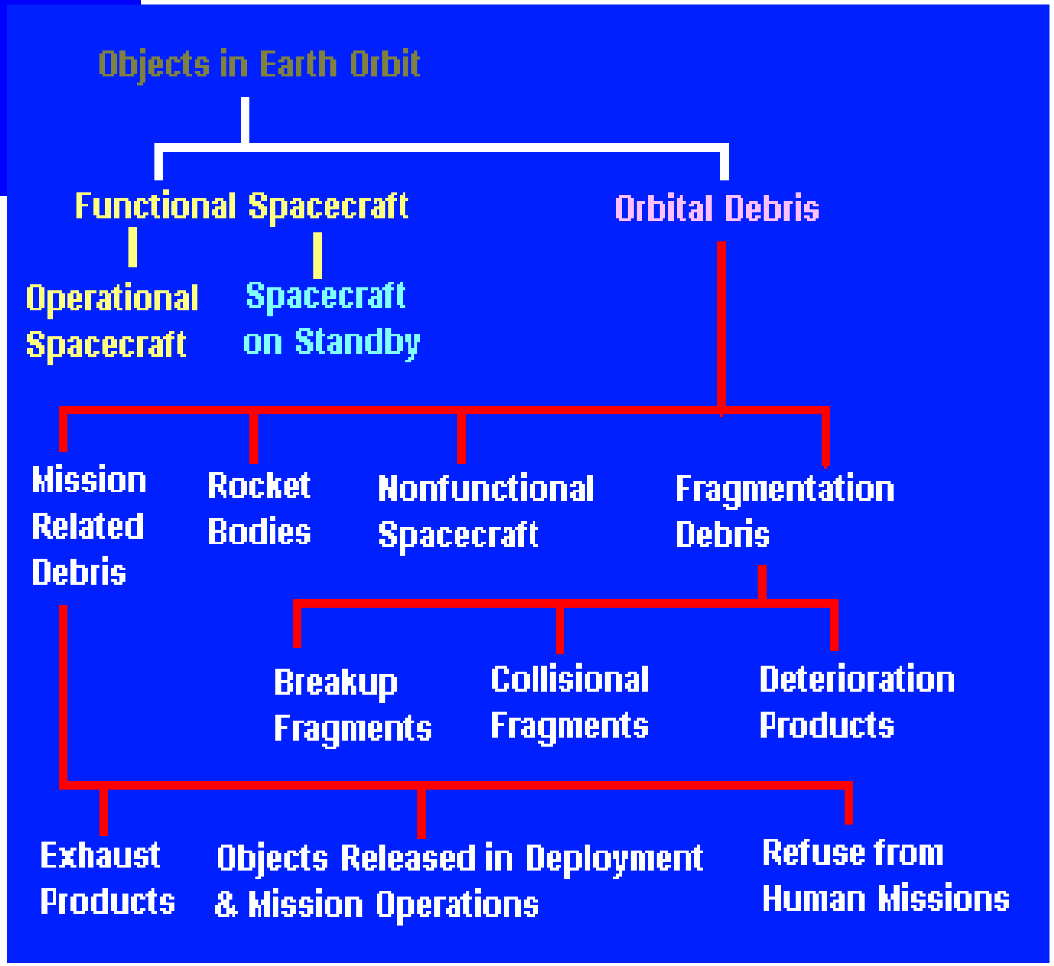
Category III (>10cm)

destroy a satellite in a collision, can be tracked(in GEO >1m), evasive maneuver

http://swfound.org/media/50909/zang_debrisremoval.pdf

Classification of debris





The first artificial space debris is the first satellite launched into space was the Soviet Sputnik-1. This was placed into low Earth orbit on 4 October 1957.

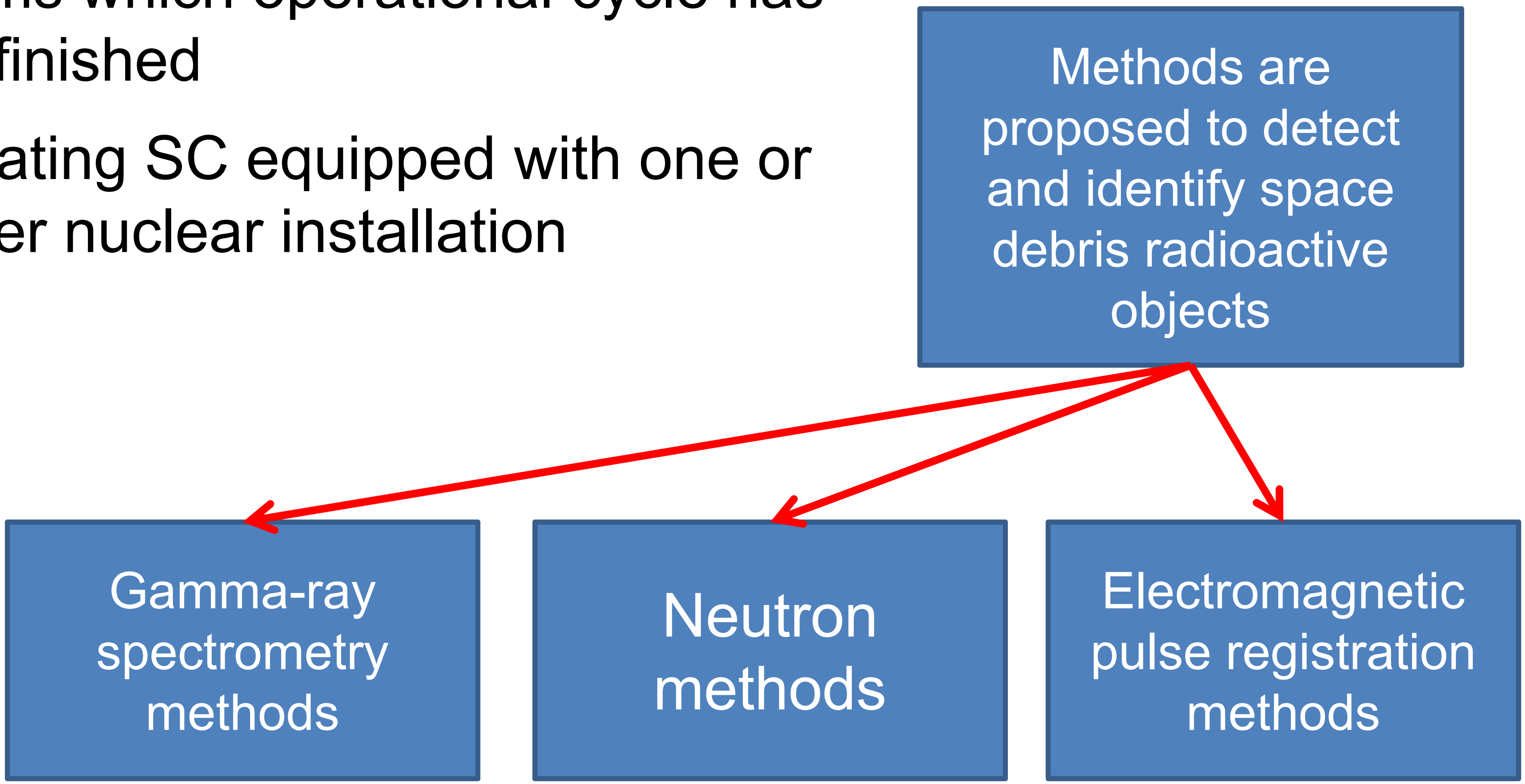
http://www.spaceacademy.net.au/watch/debris/gsd/gsd.htm#class

Radioactive space debris:

-Fragments of nuclear propulsion systems;

-Individual SC with nuclear propulsion systems which operational cycle has been finished

-Operating SC equipped with one or another nuclear installation



http://www.tsi.lv/sites/default/files/editor/science/Conferences/SPACE/anikeeva.pdf

Amount of orbital debris

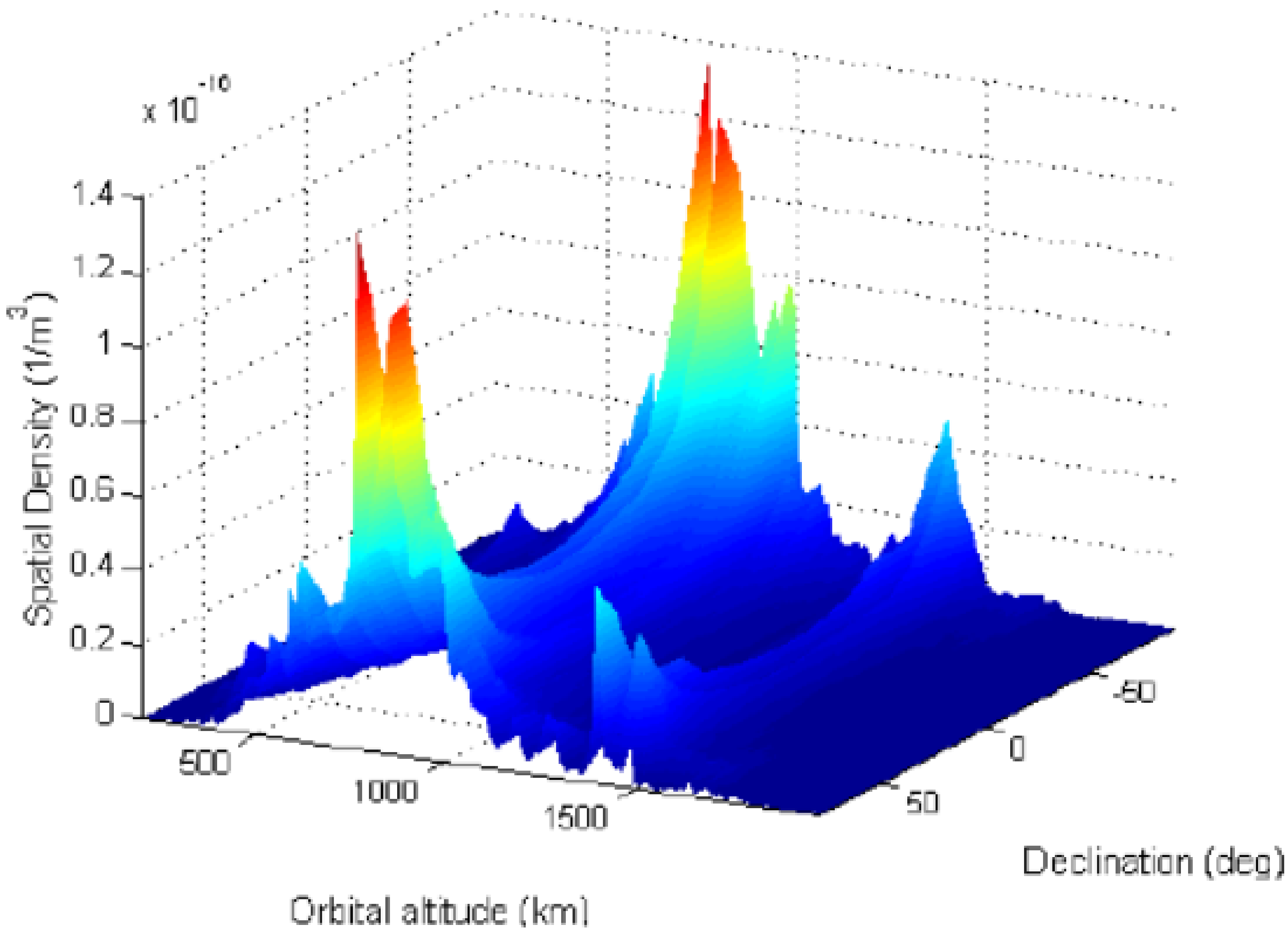
- currently more than 20,000 objects are tracked and kept in a catalog
- space debris number is much more than catalog

Debris Size	*0.1-1cm*	*1-10cm*	*>10cm*
Total Number at all altitudes	150 million	780,000	23,000
Debris in Low-Earth Orbit	20 million	400,000	15,000

Estimated amount of orbital debris, by size

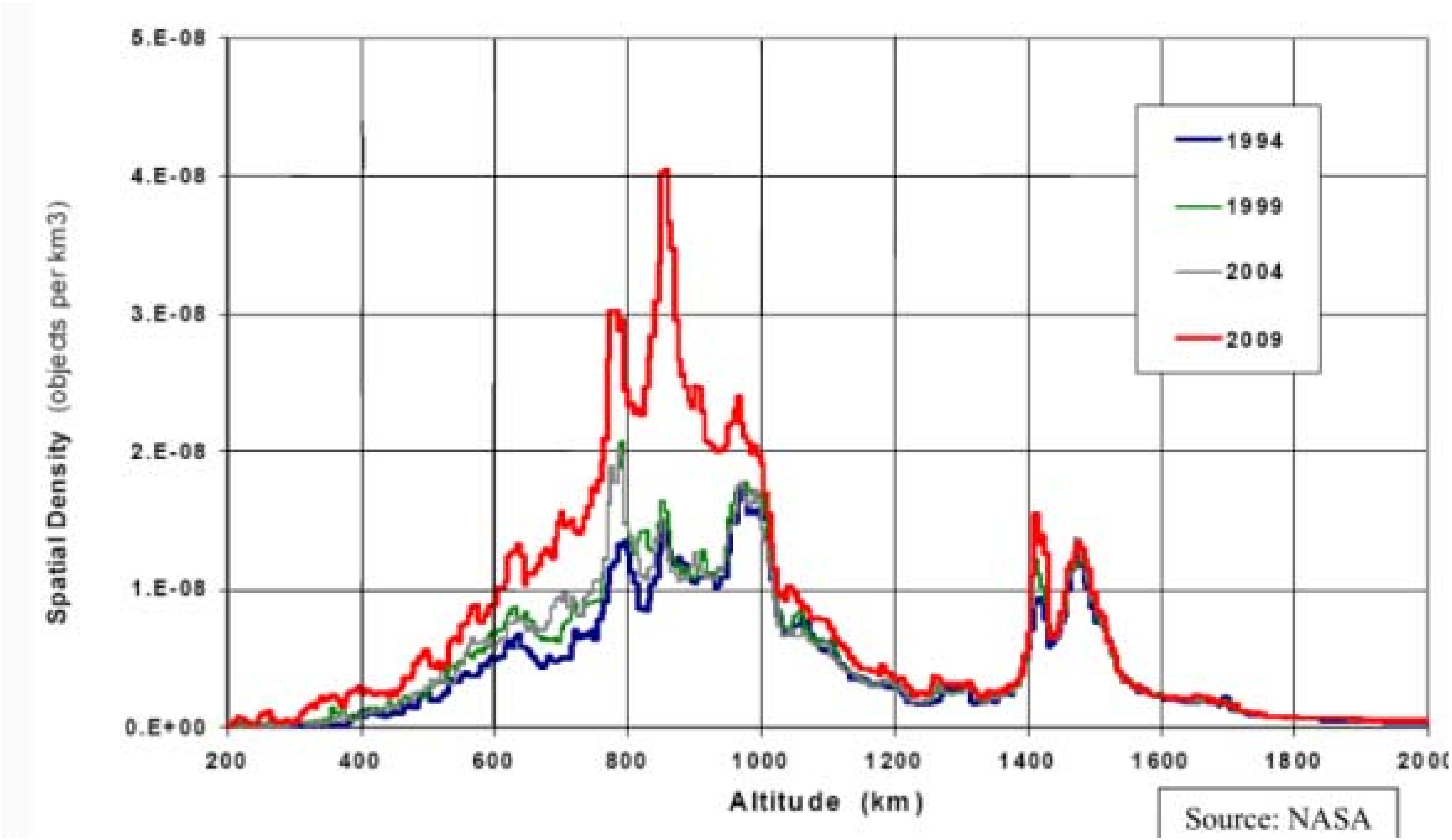
http://swfound.org/media/50909/zang_debrisremoval.pdf

Distribution of LEO debris



http://swfound.org/media/50909/zang_debrisremoval.pdf

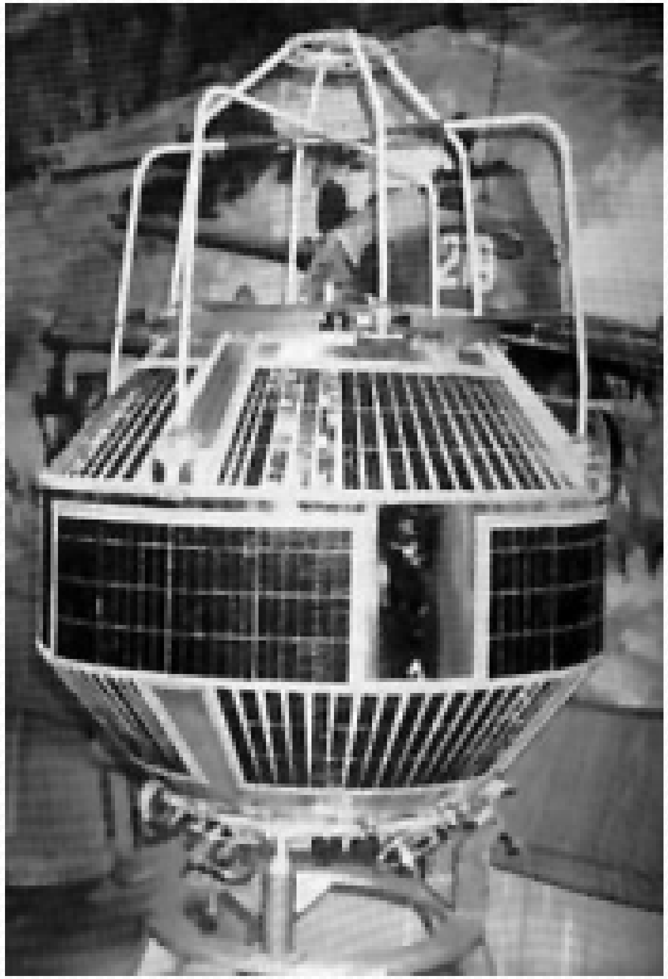
Evolution of total trackable Low-Earth Obit (LEO) object



Marshall H. Kaplan, Survey of Space Debris Reduction Methods, AIAA SPACE 2009 Conference & Exposition 14 - 17 September 2009, Pasadena, California,AIAA 2009-6619 The number of space debris increases very

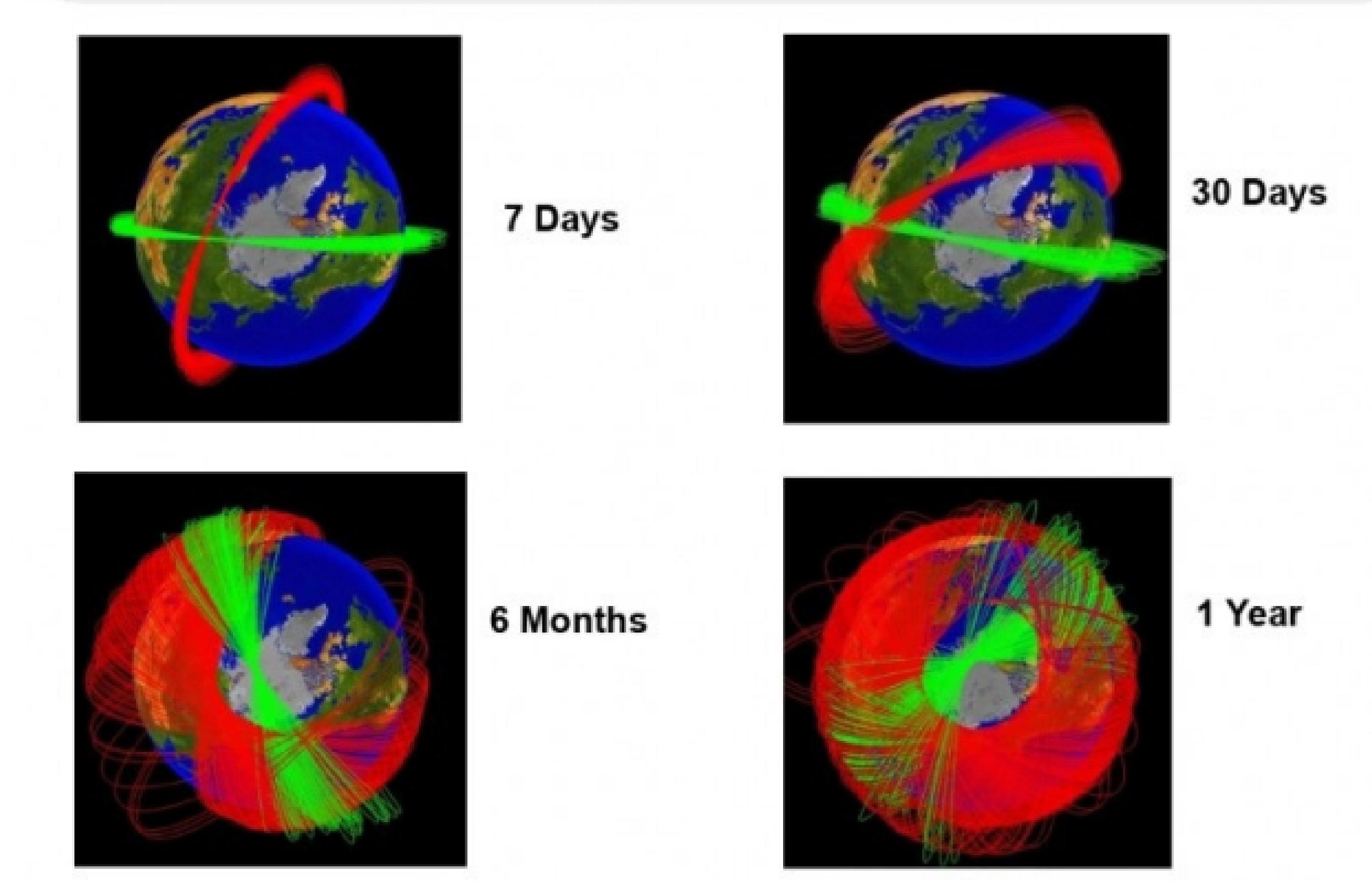
Collision of Iridium33 and Cosmos2251

In an unprecedented space collision, a commercial communications satellite (IRIDIUM 33) and a defunct Russian satellite (COSMOS 2251) impacted each other on February 9th, 2009 above Northern Siberia, creating a cloud of debris. Till now, over 1719 large fragments have been observed.



VIDEO link
https://www.youtube.com/watch?v=dtT3pTh_q-8

Spread of collision debris orbital planes



http://commons.erau.edu/cgi/viewcontent.cgi?article=1000&context=stm

Debris observation

Space object catalogues are limited to a larger objects, typically greater than 10 cm in low Earth orbits and greater than 1m at geostationary altitude

Ground based telescopes and radars can detect:
-LEO debris down to a few mm in size
-GEO debris down to 10 cm in size

In–situ impact detector (on-board spacecraft) can sense object down to a few micrometers in size
While telescopes are mainly suited for GEO and high-altitude debris observations, radars are advantageous in the low-Earth orbit (LEO) regime, below 2000 km.

http://m.esa.int/Our_Activities/Operations/Space_Debris/Scanning_observing

Radar facilities for debris observation

Table 1. Radar facilities for debris observation

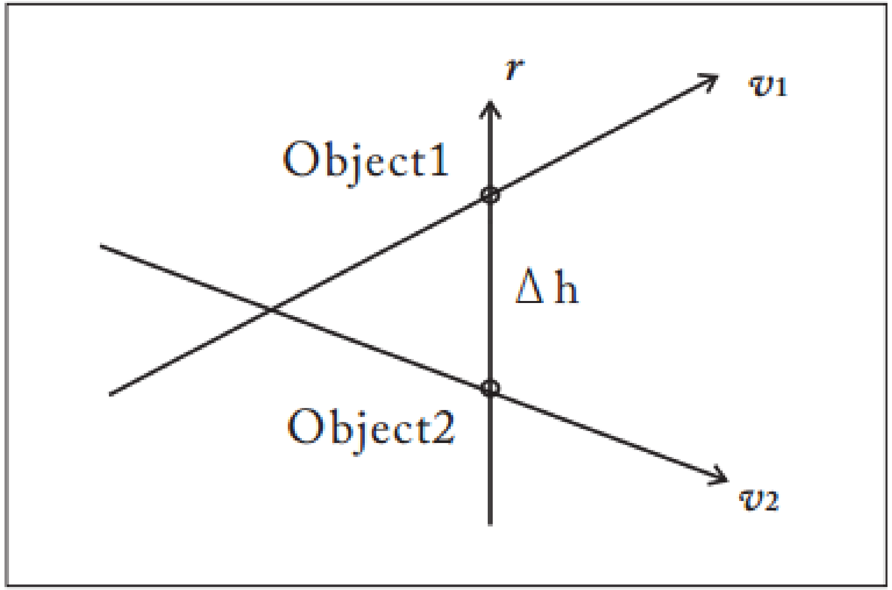
Country	*Organization*	*Facility*	*Type*	*Primary operation mode*	*Configuration*	*Field of view*	*Wave-length (m)*	*Sensitivity (diameter) (m)*	*Status*
Germany	FGAN	TIRA	Dish	Mixed	Monostatic	0.5	0.23	0.02 at 1,000 km	Operational
Germany	MPIfR	Effelsberg	Dish	Stare	Bistatic with TIRA	0.16	0.23	0.009 at 1,000 km	Experimental
Japan	Kyoto University	MU radar	Phased array	Stare	Monostatic	3.7	6.4	0.02 at 500 km	Operational
Japan	ISAS	Uchinoura	Dish	Mixed	Bistatic	0.4	0.13	0.02 at 500 km	Experimental
Japan	ISAS	Usuda	Dish	Mixed	Bistatic	0.13	0.13	0.02 at 500 km	Experimental
Ukraine/Russian Federation	. .	Evpatoria	Dish	Stare	Bistatic	0.1	0.056	0.003 at 1,000 km	Developmental
United States	NASA/ NSF	Arecibo	Dish	Stare	Bistatic	0	0.13	0.004 at 575 km	One-time experiment
United States	NASA/ DoD	Haystack	Dish	Stare	Monostatic	0.1	0.03	0.006 at 1,000 km	Operational
United States	NASA/ DoD	HAX	Dish	Stare	Monostatic	0.1	0.02	0.05 at 1,000 km	Operational
United States	NASA	Goldstone	Dish	Stare	Bistatic	0	0.035	0.002 at 500 km	Operational
United States	DoD	TRADEX	Dish	Mixed	Monostatic	0.61/ 0.30	0.23/ 0.10	0.03 at 500 km	Operational

http://orbitaldebris.jsc.nasa.gov/library/un_report_on_space_debris99.pdf

The probability of collision in the radial direction

The uncertainly the radial position is defined by a one-dimensional normal distribution with the form:

$$\rho(r) = \frac{1}{2\sqrt{\pi}\sigma_r} \exp\left\{\frac{-(r-\Delta h)^2}{2\sigma_r^2}\right\}$$



Where Δh is the difference in altitude of the two objects, and the relative error in position in the radial direction is given by:

$$\sigma_r^2 = \sqrt{\sigma_{1r}^2 + \sigma_{2r}^2}$$

Then the density function describing the probability of collision can be given by·

$$F(r) = \frac{1}{2\sqrt{\pi}\sigma_r} \int_{-\infty}^{r} \exp\left\{\frac{-(r-\Delta h)^2}{2\sigma_r^2}\right\} \mathrm{d}r$$

http://www.raa-journal.org/raa/index.php/raa/article/viewFile/1587/1442

The probability of collision in the radial direction

It can be substituted by an approximate expression with the form:

$$F(r) = \frac{\exp\left[a(r-\Delta h)\right]}{1+\exp\left[a(r-\Delta h)\right]}, \qquad \text{where } a = \frac{4}{\sqrt{2\pi}\sigma_r}$$

The result from this approximation is sufficiently accurate and does not introduce error greater than 2%.

Denoting the combined size of the objects in the radial direction as r_a, the probability of collision caused by difference in altitude can be expressed as:

$$P_R = F(x)\,|_{-\infty}^{r_a} - F(x)\,|_{-\infty}^{-r_a} = \frac{\exp\left[\frac{4(r_a-\Delta h)}{\sqrt{2\pi}\sigma_r}\right]}{1+\exp\left[\frac{4(r_a-\Delta h)}{\sqrt{2\pi}\sigma_r}\right]} - \frac{\exp\left[\frac{4(-r_a-\Delta h)}{\sqrt{2\pi}\sigma_r}\right]}{1+\exp\left[\frac{4(-r_a-\Delta h)}{\sqrt{2\pi}\sigma_r}\right]}$$

http://www.raa-journal.org/raa/index.php/raa/article/viewFile/1587/1442

Mean time between impacts

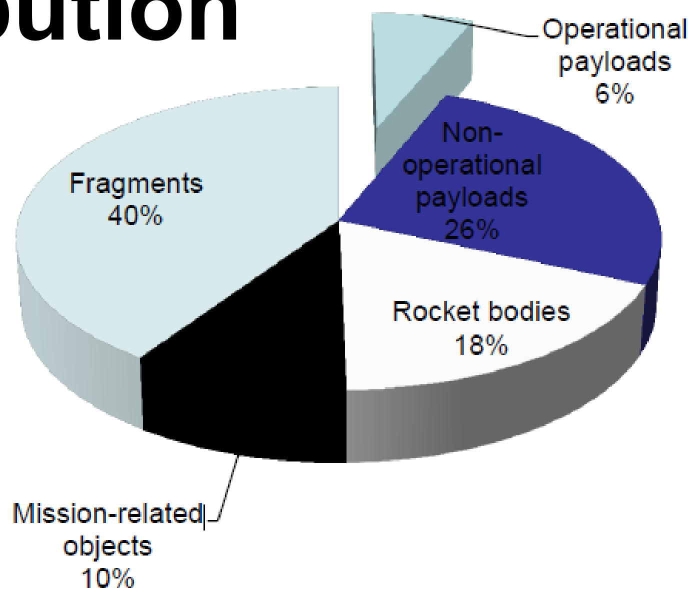
Table 5. Mean time between impacts on a satellite with a cross-section area of 10 square metres

Height of circular orbit	*Objects 0.1-1.0 cm*	*Objects 1-10 cm*	*Objects >10 cm*
500 km	10-100 years	3,500-7,000 years	150,000 years
1,000 km	3-30 years	700-1,400 years	20,000 years
1,500 km	7-70 years	1,000-2,000 years	30,000 years

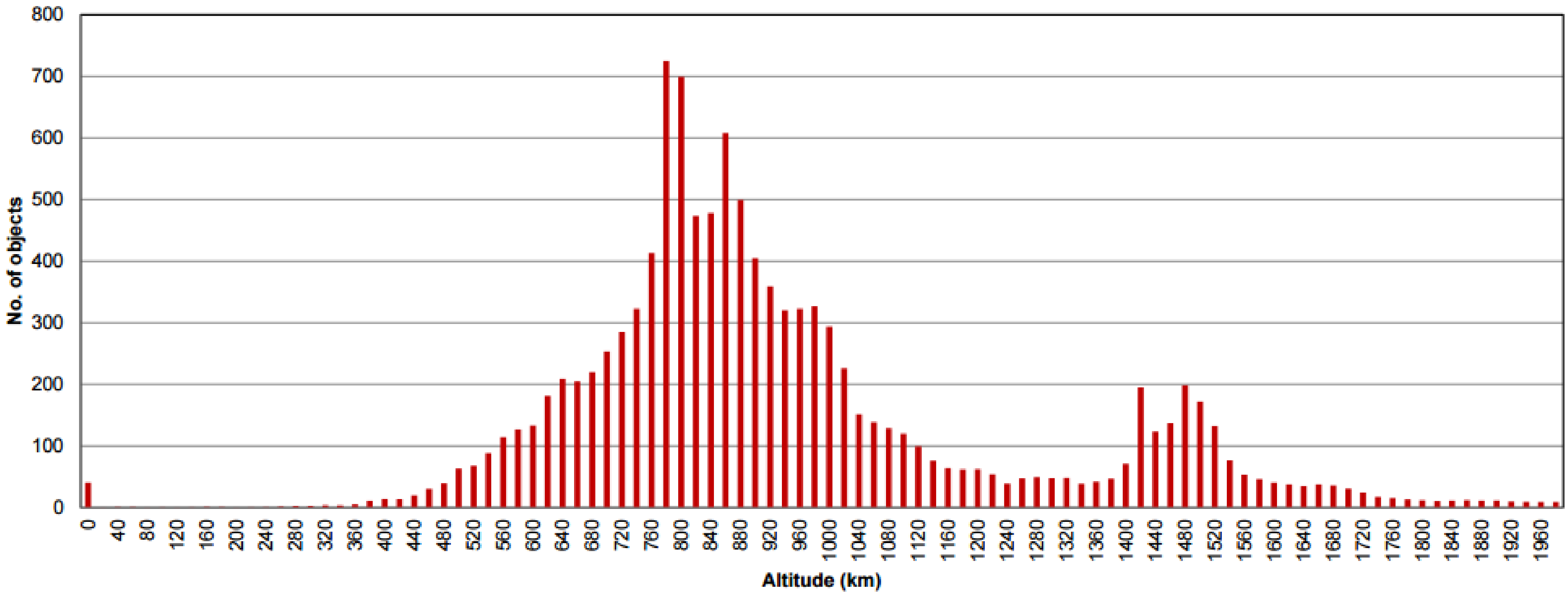
http://orbitaldebris.jsc.nasa.gov/library/un_report_on_space_debris99.pdf

Orbital Debris Distribution

- Largest portion (2/3) of orbital debris is concentrated in LEO
- Only 6% of Earth orbiting objects are operational payloads

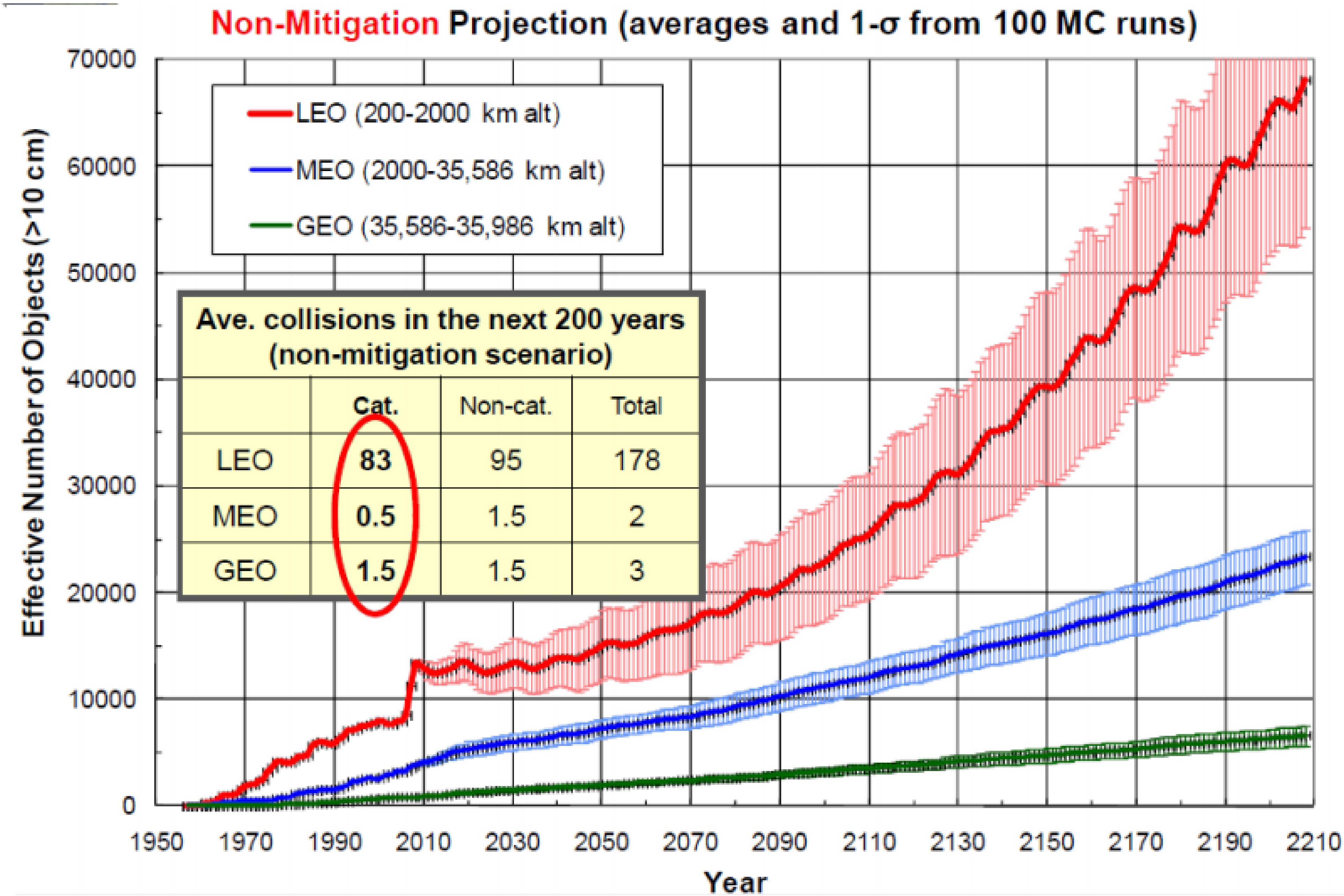


Altitude Distribution in LEO



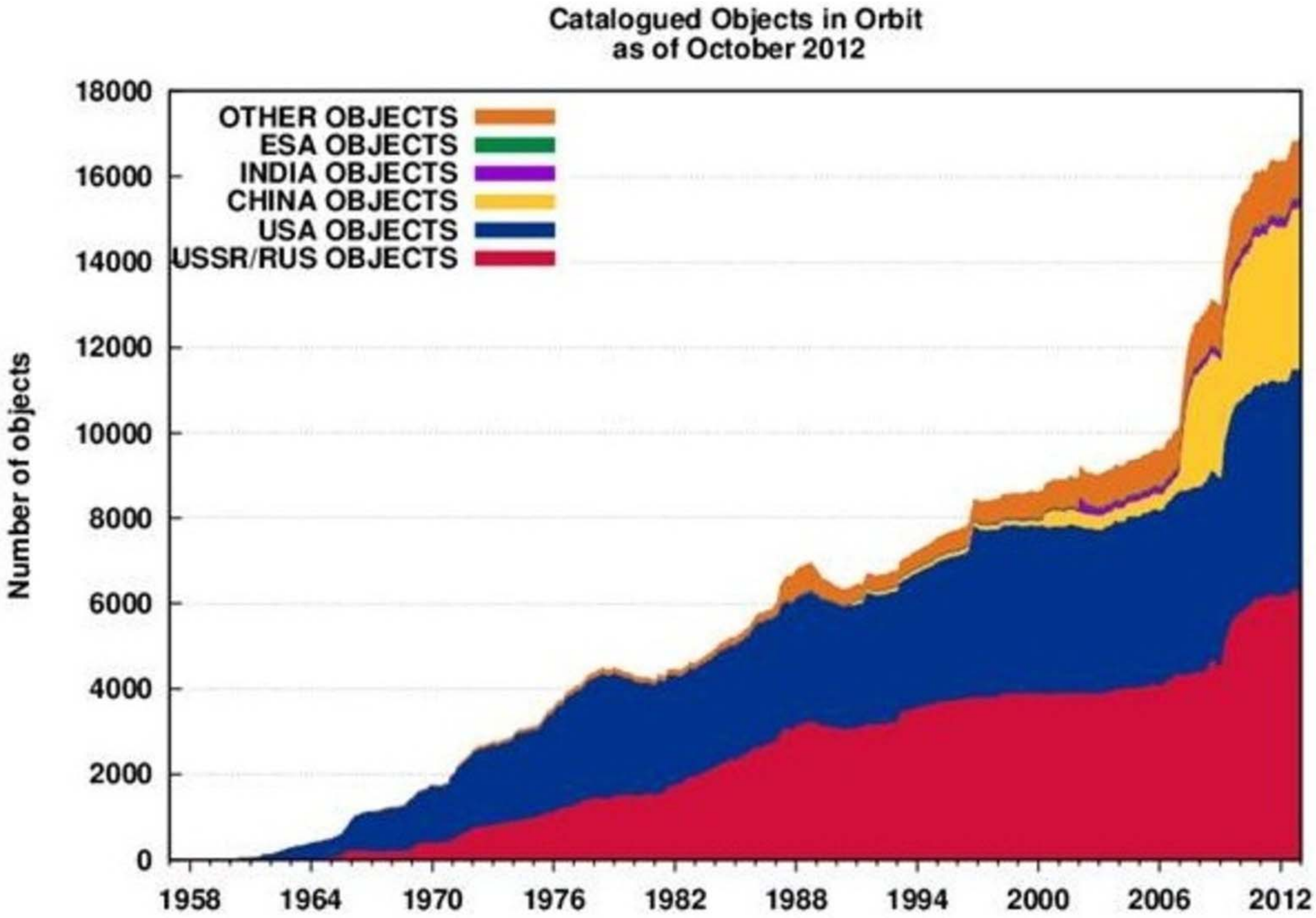
http://www.surrey.ac.uk/ssc/research/space_vehicle_control/deorbitsail/files/gsf_keynote_2012.pdf

Orbital Debris projection



http://www.surrey.ac.uk/ssc/research/space_vehicle_control/deorbitsail/files/gsf_keynote_2012.pdf

Catalogued Objects in Orbit



In almost 50 years of space activities, more than 4900 launches have placed some 6600 satellites into orbit, of which about 3600 remain in space; only a small fraction - about 1000 - are still operational today.

http://m.esa.int/Our_Activities/Operations/Space_Debris/About_space_debris

Active debris removal method

Removing debris from LEO can make the LEO environment safe for the future space activities. And clearing GEO will keep the GEO orbit resources available.

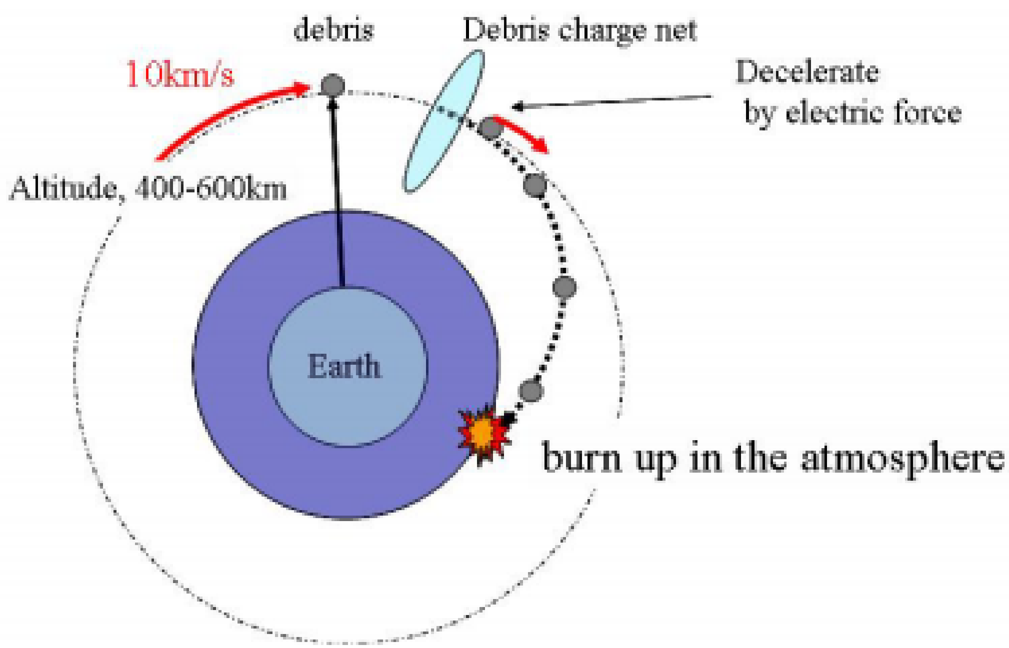
	Catalog I (Size < 1cm)	*Catalog II (Size 1cm~10cm)*	*Catalog III (Size >10cm)*
LEO orbit 160km-2,000km	Space-based Magnetic Field Generator Sweeping/Retarding Surface Space-based Laser	Ground-/Air-/Space-based Laser	Drag Augmentation Device Magnetic Sail Momentum Tethers Electrodynamic Tethers Capture/Orbital Transfer Vehicle (Space Shutter)
GEO orbit About 35,000km			Solar Sail Momentum Tethers Capture/Orbital Transfer Vehicle (Using Net or Tentacles)

VIDEO LINK- http://www.star-tech-inc.com/id121.html

http://swfound.org/media/50909/zang_debrisremoval.pdf

Space debris removal method using electrostatic force in space plasma

Debris removal method for small diameter less than 1 mm.
The debris must be decelerated in order to descend their orbit. This method employs the deceleration of debris by means of electrostatic force. Debris must be charged electrically with respect to space (usually have same potential with LEO plasma)



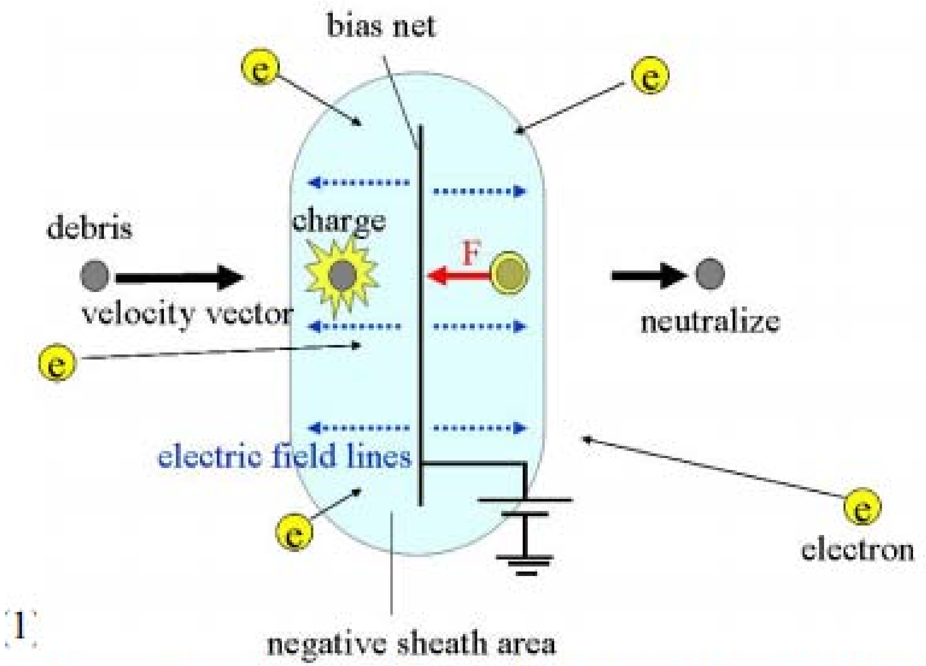


Figure 2. principle of charging and decelerating the debris.

Preliminary investigation of space debris removal method using electrostatic force in space plasma Kazuhiro Toyoda 1 , Yasunori Furukawa2 , Teppei Okumura3 , Hirokazu Masui 4 , and Mengu Cho 5

Space debris removal method using electrostatic force in space plasma

The space potential increases from plasma potential to bias potential in negative sheath area with approaching the net. The capacitance between debris and space are

$$C_d = 4\pi\varepsilon_0 a$$

The debris has a negative charge Q_d

$$Q_d = C_d\left(V_s - V_f\right) = 4\pi\varepsilon_0 a\left(V_s - V_f\right)$$

After passing through the net, the negative charged debris is pulled back in the direction of the bias net due to electrostatic force in the negative sheath. The debris loses the energy U_{dc}.

$$U_{dc} = Q_d V_{bias} = 4\pi\varepsilon_0 a V_{bias}^2$$

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Space debris removal method using electrostatic force in space plasma

During passing the biased net, it is assumed that the debris loses the energy U_{dc}, the debris velocity decreases from v_0 to v_1, and the altitude descends from h_0 to h_2

$$\frac{1}{2}mv_1^2 - G\frac{Mm}{R+h_0} = \frac{1}{2}mv_2^2 - G\frac{Mm}{R+h_2}$$

$$\frac{mv_2^2}{R+h_2} = G\frac{Mm}{(R+h_2)^2}$$

$$\frac{1}{2}mv_0^2 = \frac{1}{2}mv_1^2 + U_{dc}$$

$$h_2 = \frac{GM}{\frac{GM}{R+h_0} + \frac{6\varepsilon_0 V_{bias}^2}{\rho a^2}} - R$$

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Atmospheric drag

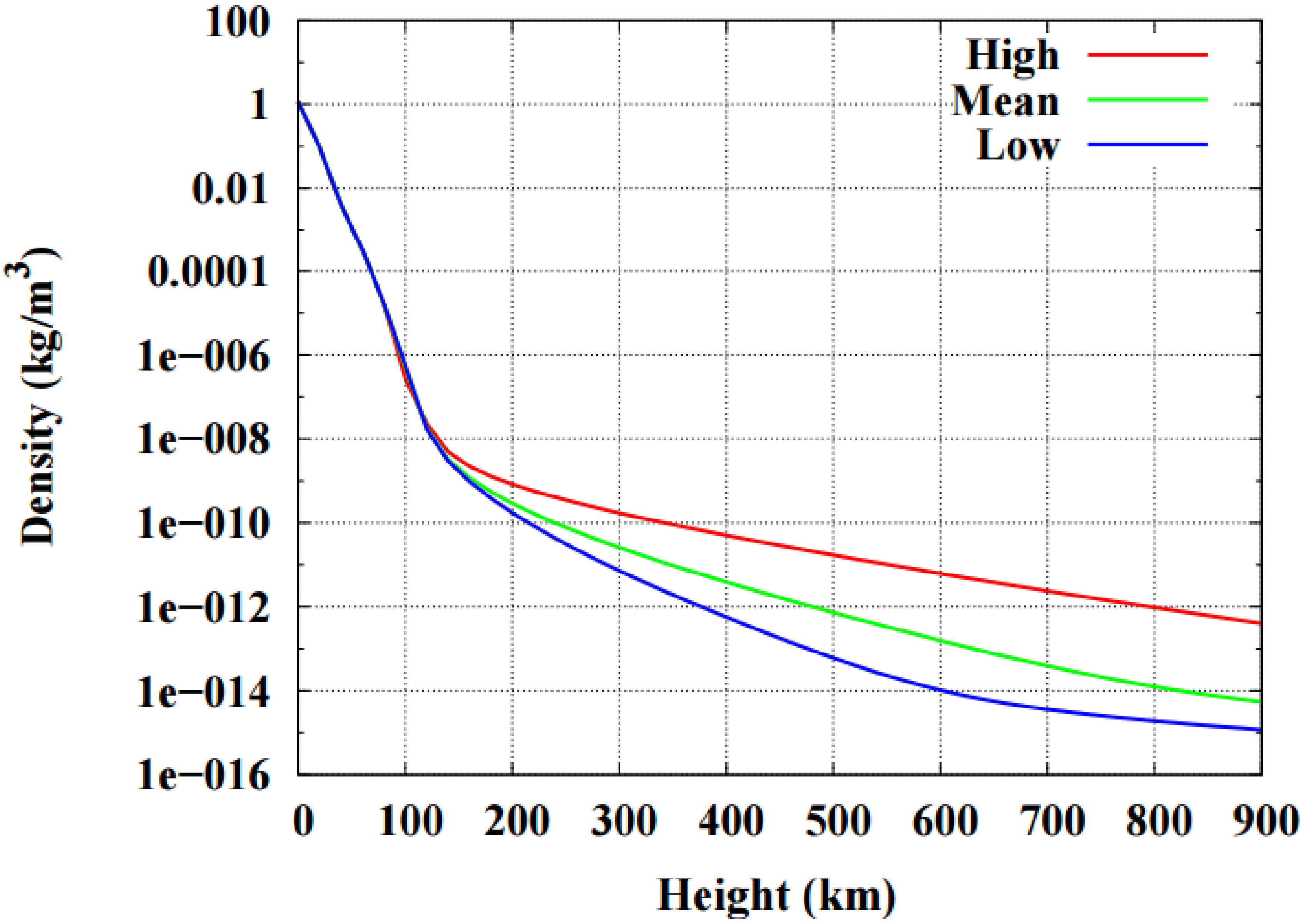
$$\mathbf{a}_D = \frac{\mathbf{D}}{m} = -\frac{1}{2}\frac{C_D A}{m}\rho\,|\mathbf{v}_{rel}|\,\mathbf{v}_{rel}$$

- $\mathbf{v}_{rel}$ Speed relative to the atmosphere ▶ Rotation, winds
- C_D Drag Coefficient: ▶ difficult to measure ▶ $C_D \sim 2 - 2.4$ (1-4)
- A Frontal area ▶ depends on attitude
- ρ Atmospheric density: ▶ $\sim$ 15% error
- $\beta = \dfrac{m}{C_D A}$ **Ballistic coefficient:** ($\beta \uparrow$, $\mathbf{a}_D \downarrow$)

Some authors use the opposite form: $\mathrm{BC} = \dfrac{C_D A}{m}$

http://ocw.upm.es/ingenieria-aeroespacial/modeling-the-space-environment/contenidos/material-de-clase/mse06_atmos.pdf

Atmospheric drag



http://ocw.upm.es/ingenieria-aeroespacial/modeling-the-space-environment/contenidos/material-de-clase/mse06_atmos.pdf

Atmospheric drag

SATELLITE ORBITAL DECAY

Calculating decay rates and orbital lifetimes of satellites in essentially circular orbits below 500 km altitude.

Mass 100.0 kg

Area 1.0 m^2

Initial Altitutde 500 km (range: 180km - 500 km)

Solar Radio Flux (F10.7) 70

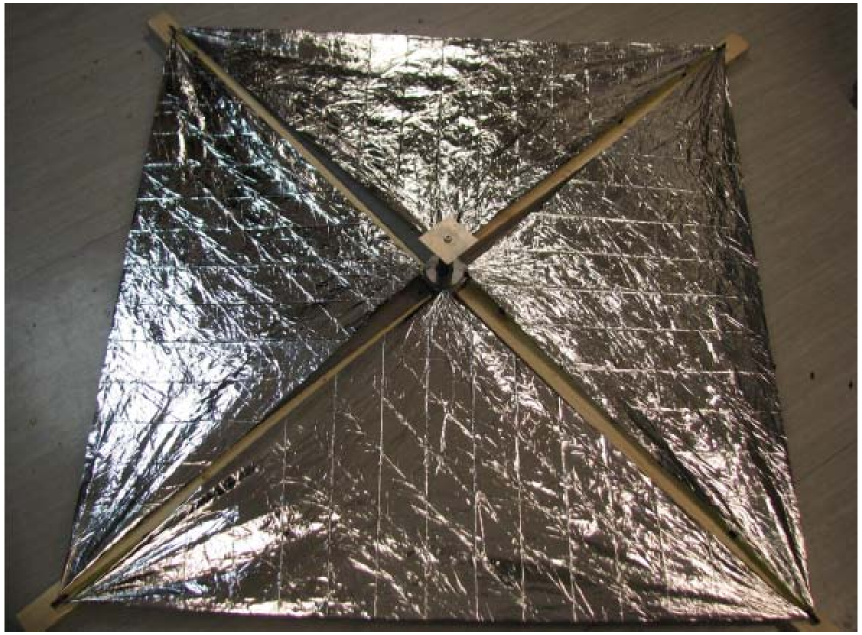
Geomagnetic Index 0 (Ap)

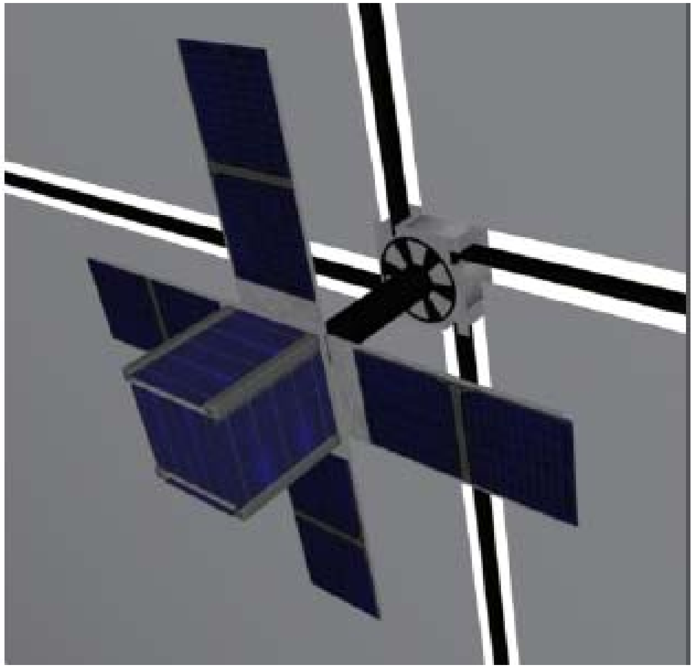
calc

TIME(days)	HEIGHT(km)	PERIOD(mins)	MEAN MOTION(rev/day)	DECAY(rev/day^2)
0	500	94.58	15.22	0
1364.09	489.99	94.39	15.25	0
2608.39	479.99	94.19	15.28	0
3605.79	469.99	93.98	15.32	0
4403.09	459.99	93.78	15.35	0
5038.8	449.99	93.57	15.38	0
5544.3	439.99	93.36	15.42	0
5945.2	429.99	93.16	15.45	0
6262.2	419.99	92.95	15.49	0.0001
6512.3	409.99	92.75	15.52	0.0001
6709.1	399.99	92.54	15.55	0.0001
6863.5	389.99	92.34	15.59	0.0002
6984.3	379.99	92.13	15.62	0.0003
7078.6	369.99	91.93	15.66	0.0004
7152	359.99	91.73	15.69	0.0005
7209	349.98	91.52	15.73	0.0007

http://www.lizard-tail.com/isana/lab/orbital_decay/

Solar sail

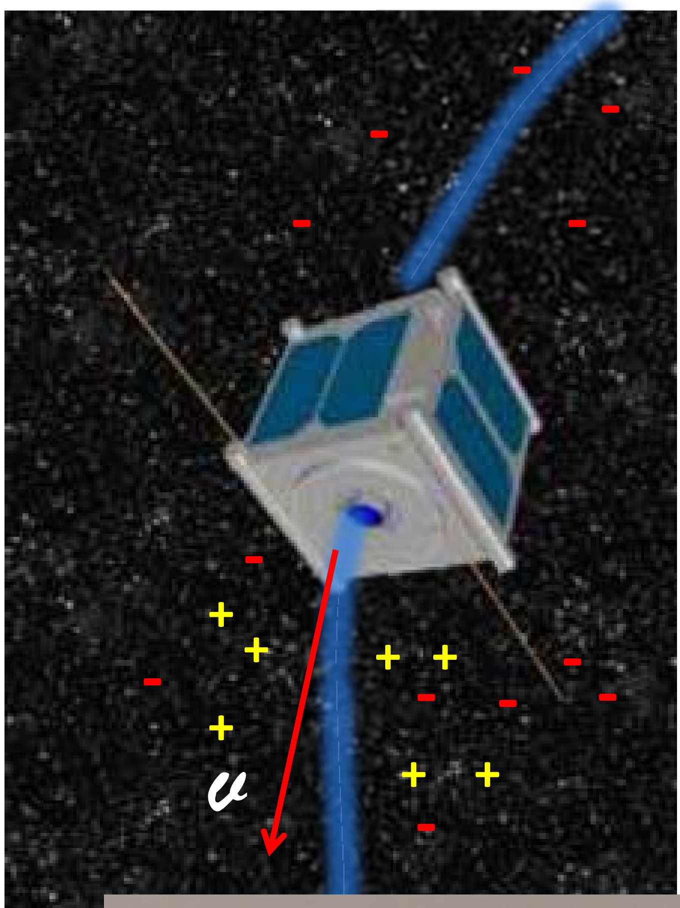




Mass (kg)	3		150		500	
Area (m^2)	0.03	25	0.8	25	1.5	25
Initial altitude (km)	t_D (years) without sail	t_D (days) with sail	t_D (years) without sail	t_D (years) with sail	t_D (years) without sail	t_D (years) with sail
600	26.5	39	42.4	2.3	73.3	5.3
650	48.1	75	85.0	3.7	146.5	13.6
700	88.5	132	159.9	6.7	282.7	24.3
750	160.5	190	299.7	14.1	521.5	37.9

http://ocw.upm.es/ingenieria-aeroespacial/modeling-the-space-environment/contenidos/material-de-clase/mse06_atmos.pdf

Satellite deorbit system based on electric propulsion



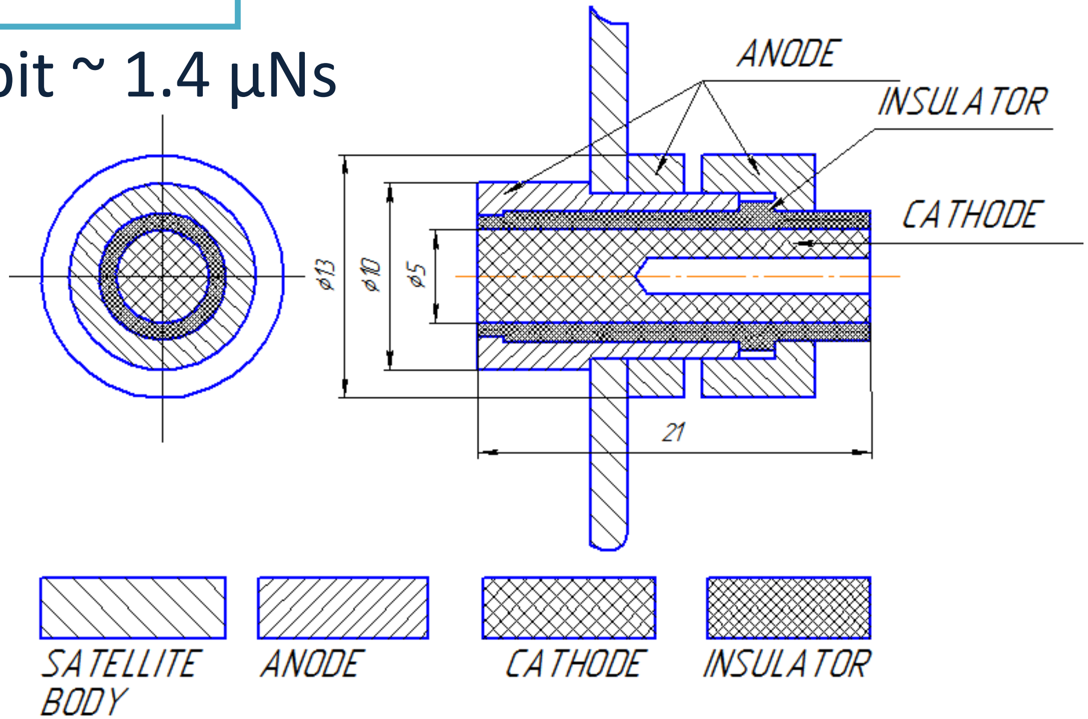
Weight : 6 gr (thruster head)
32 gr (all system)

Size : ϕ 13 mm x 21 mm

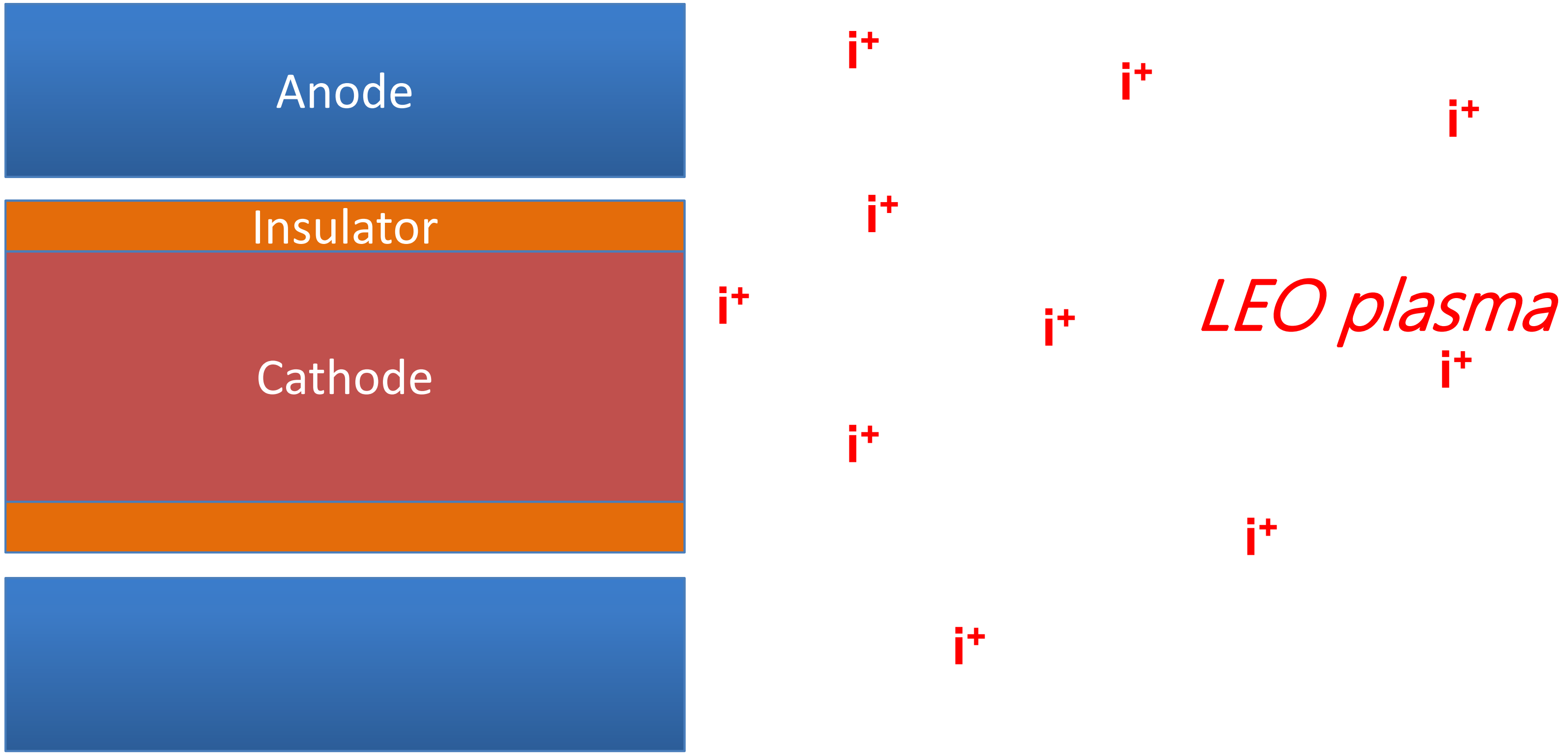
Applied voltage = 300 V…800 V (thruster head)

$$I_{SP} = 1200[s]$$

Impulse bit ~ 1.4 µNs

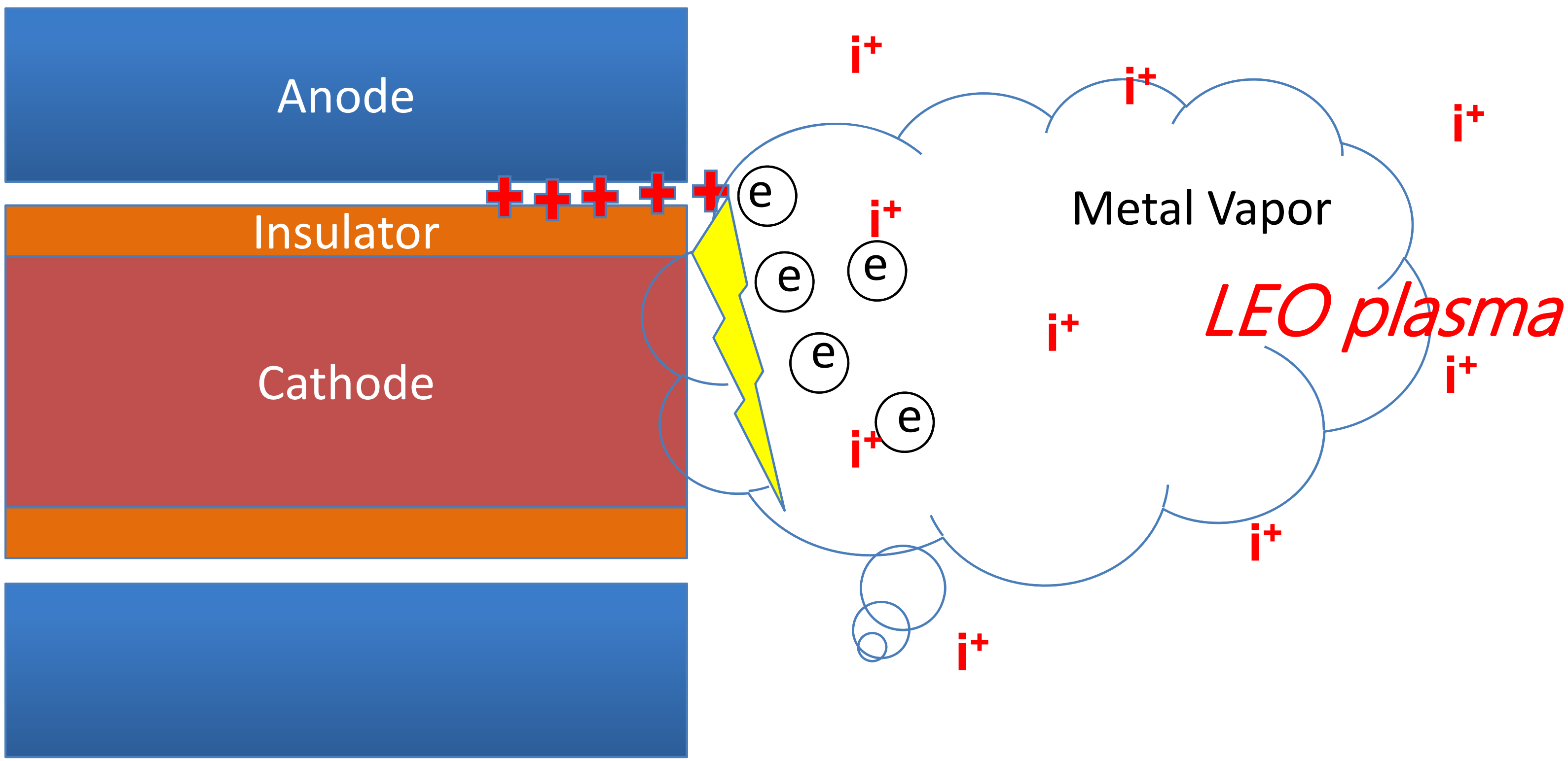


Principle of Vacuum Arc Thruster



Characteristics:
- Solid propellant;
- Metal vapor is jetted;
- 300 V direct drive;
- Firing by the micro discharge in plasma environment.

Principle of Vacuum Arc Thruster



Characteristics:
- Solid propellant;
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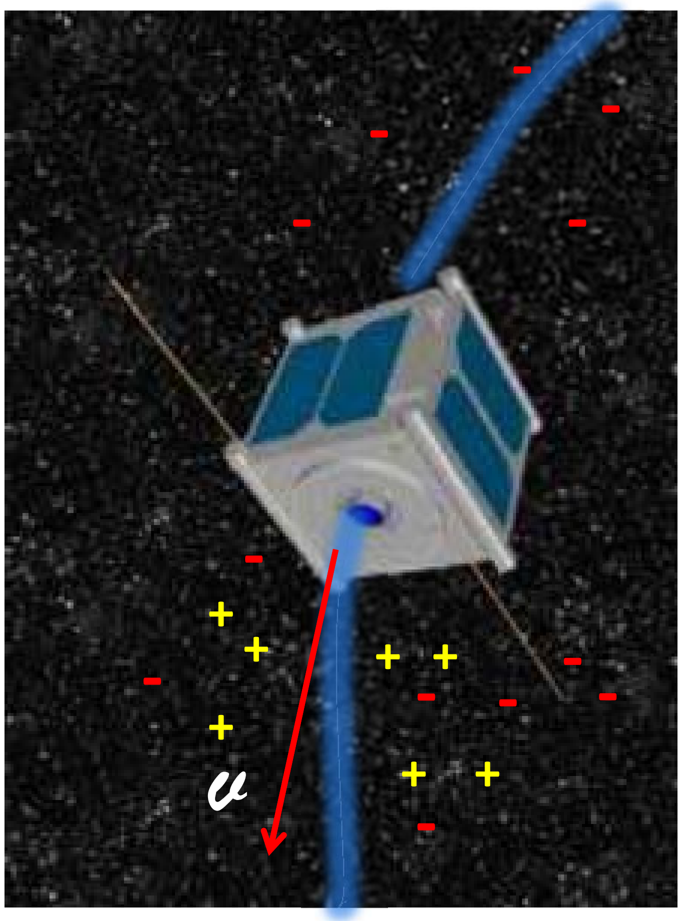
Ion concentration



$$n \cong n_0 \exp\left[-\left(\frac{V_0}{v_{th}}\right)^2 \cdot \left(\frac{R_0}{r}\right)^2\right]$$

$$R_0 = 0.05(m)$$

$$r = 0.05(m)$$

RAM side compression region would be:

$$v_{th} = \sqrt{\frac{2 \cdot k \cdot T}{m_p}}$$

$$k = 1.38 \cdot 10^{-23}$$

$$T = 2327(K)$$

$$m_p(O) = \frac{16 \cdot 10^{-3}}{6.23 \cdot 10^{23}} = 2.6 \cdot 10^{-26}(kg)$$

$$v_{th} = 1572\left(\frac{m}{\sec}\right)$$

$$n_{O^+} = 1.3 \cdot 10^{11}(m^{-3})$$

$$n_0 + n_r = n_0 \cdot \left(1 + \frac{V_0}{v_{th}}\right) = 1.3 \cdot 10^{11} \cdot \left(1 + \frac{7800}{1572}\right) = 7.75 \cdot 10^{11}(m^{-3})$$

Behind the satellite body:

$$n \cong 1.3 \cdot 10^{11} \exp\left[-\left(\frac{7800}{1572}\right)^2 \cdot \left(\frac{0.05}{0.05}\right)^2\right] = 0(m^{-3})$$

"Spacecraft environment interaction", D. Hastings, H. Garret

Satellite deorbit system based on electric propulsion

$$T_{deorbit} = \frac{N_p}{f(frequency)}$$

$$\frac{mv_1^2}{2} - G\frac{Mm}{R+h} = \frac{mv_2^2}{2} - G\frac{Mm}{R+H}$$

$$F = \frac{1}{2} \cdot C_d \cdot A \cdot \rho \cdot v_1^2 - atmospheric\_drag$$

$$v_1 = \sqrt{G\frac{M}{R+h}}$$

$$mv_1 - mv_2 = I_{bit}$$

$$v_2 = v_1 - \frac{I_{bit} \cdot N_p}{m};$$

$$N_p - number\_of\_pulses;$$

$$m - satellite\_mass$$

$$M = 6 \cdot 10^{24} [kg]$$

$$R = 6.37 \cdot 10^{6} [m]$$

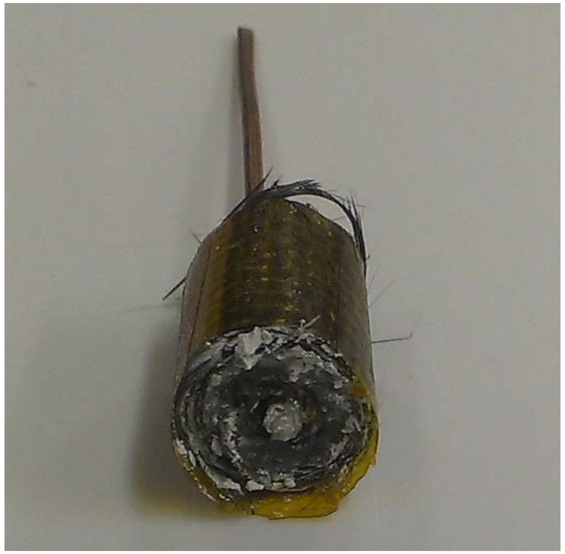
$$G = 6.67 \cdot 10^{-11} [m^3 s^{-2} kg^{-1}]$$

$$h = 600 [km]$$

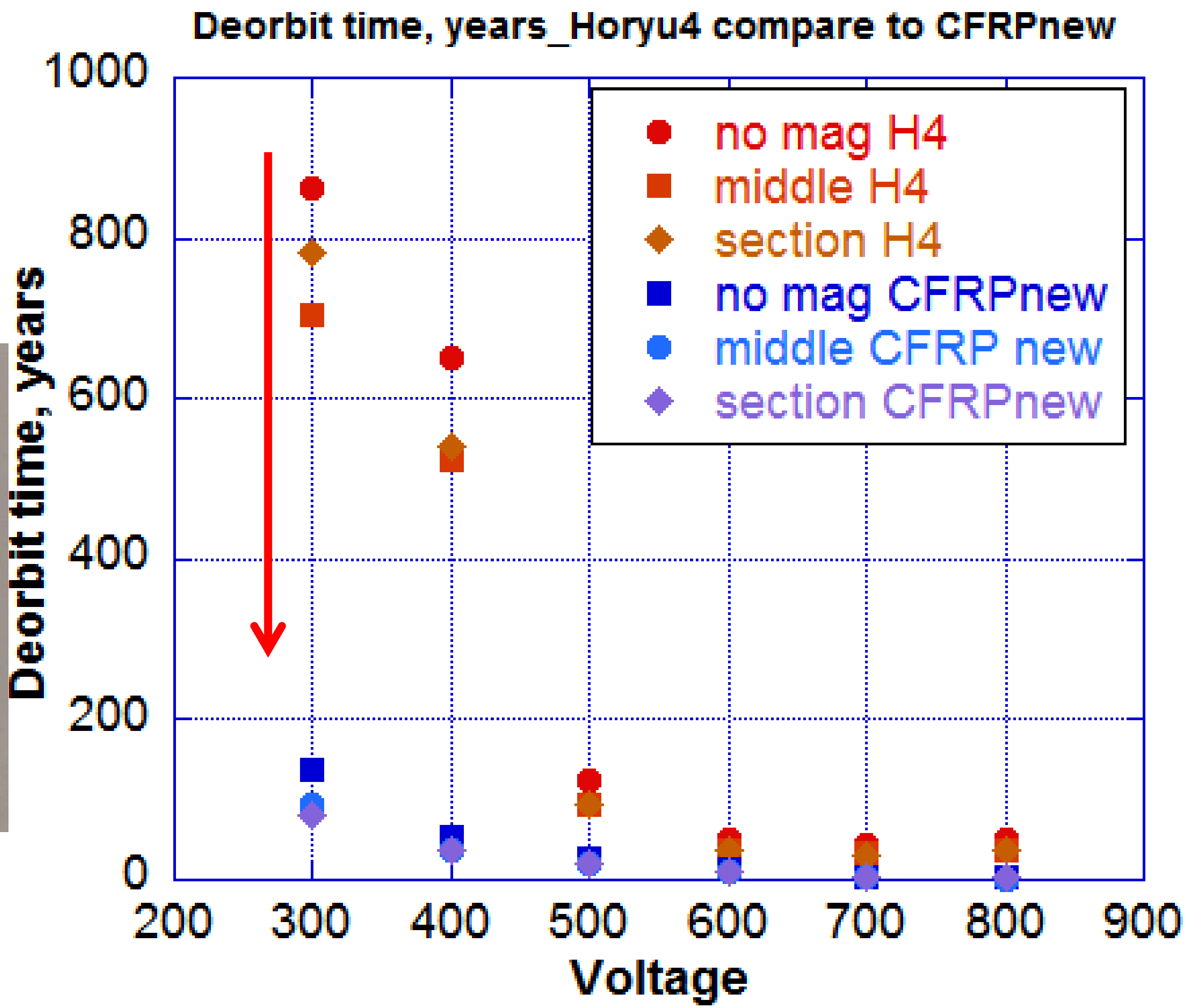
$$H = 400 [km]$$

$$N_p = \frac{m}{I_{bit}} \left[\sqrt{G\frac{M}{R+h}} - \sqrt{2 \cdot G\frac{M}{R+h} - G\frac{M}{R+H}} \right]$$

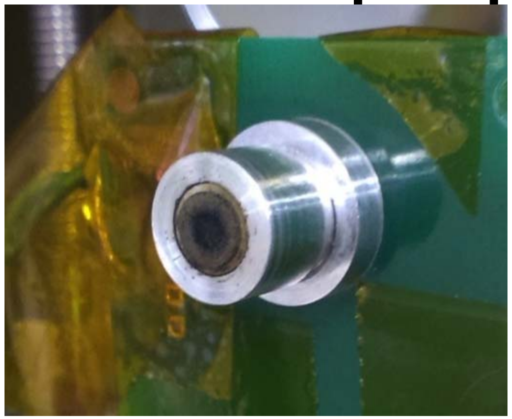
Satellite deorbit system based on electric propulsion



$$T_{deorbit} = \frac{N_p}{f(frequency)}$$

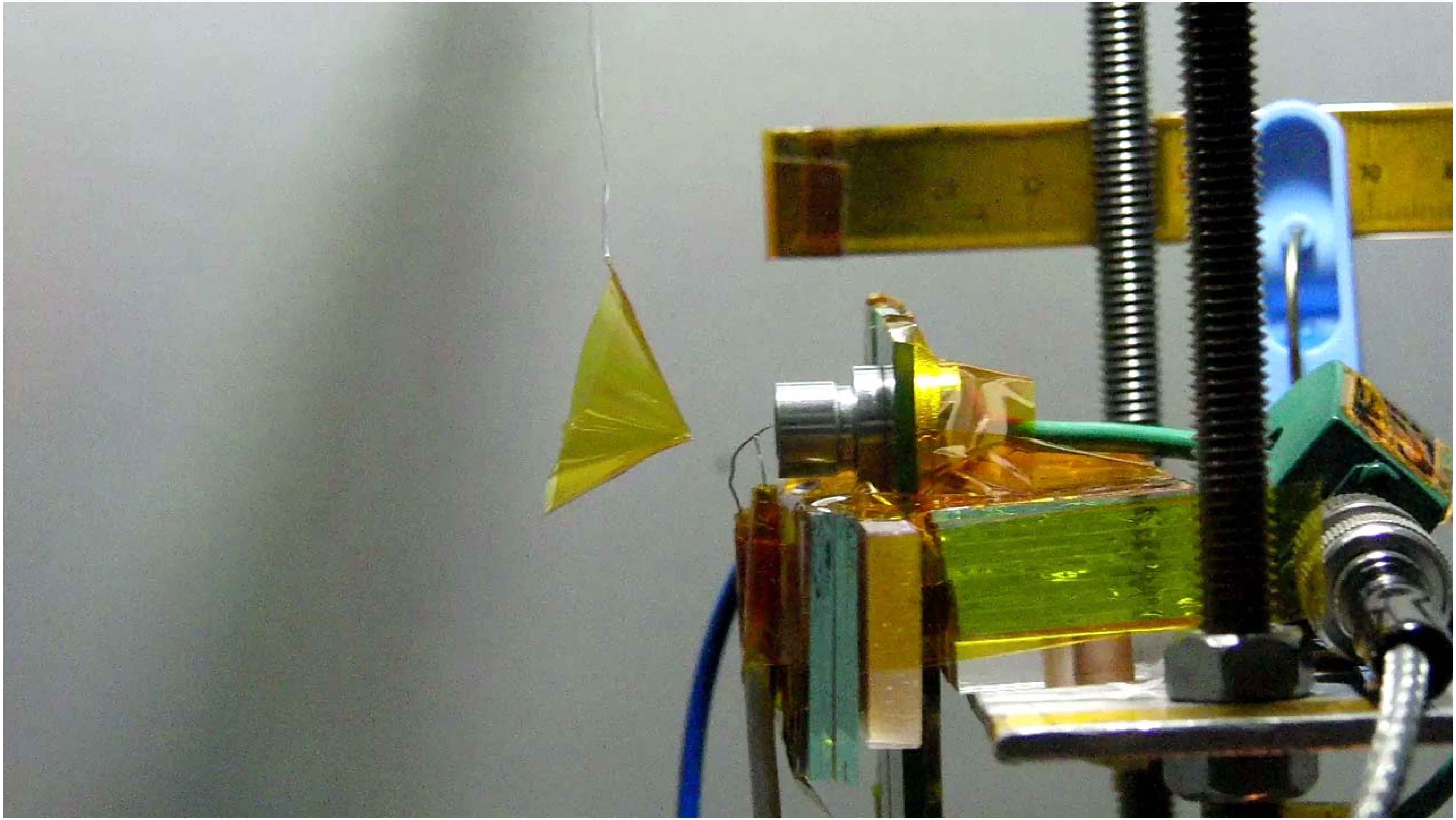


Satellite deorbit system based on electric propulsion



deorbit time, years	without magnet	NS middle	NS section
300	863	705	783
400	651	525	539
500	123	94.9	94.5
600	50.4	38.5	36.1
700	43.9	32.3	30.8
800	51.3	36.3	36.1

deorbit time, years	without magnet	NS middle	NS section
300	137	93.4	79.1
400	54.9	38.6	36.4
500	28.3	20.4	20.8
600	14.3	10.5	11.4
700	3.63	2.69	3.07
800	2.41	1.8	2.15



Debris Evolution

- Euroconsult forecast for next 10 years shows 400 out of 1200 anticipated launches will be in LEO – only includes satellites > 50kg

To have a sustainable LEO population requires:

- Implementation of commonly adopted mitigation measures
- Active Debris Removal (ADR) of 5 objects or more...

25 Year Deorbiting Requirement

- Orbital debris mitigation guidelines have been debated in great detail in the space community.
- In February 2007 and after a multi-year effort the United Nations' Committee on the Peaceful Uses of Outer Space (COPUOS) adopted a set of space debris mitigation guidelines which includes a 25 year deorbit requirement from LEO.
- The guidelines were accepted by the COPUOS in June 2007 and endorsed by the United Nations in January 2008.
- To become the law in many countries in Europe

Thank you for your attention