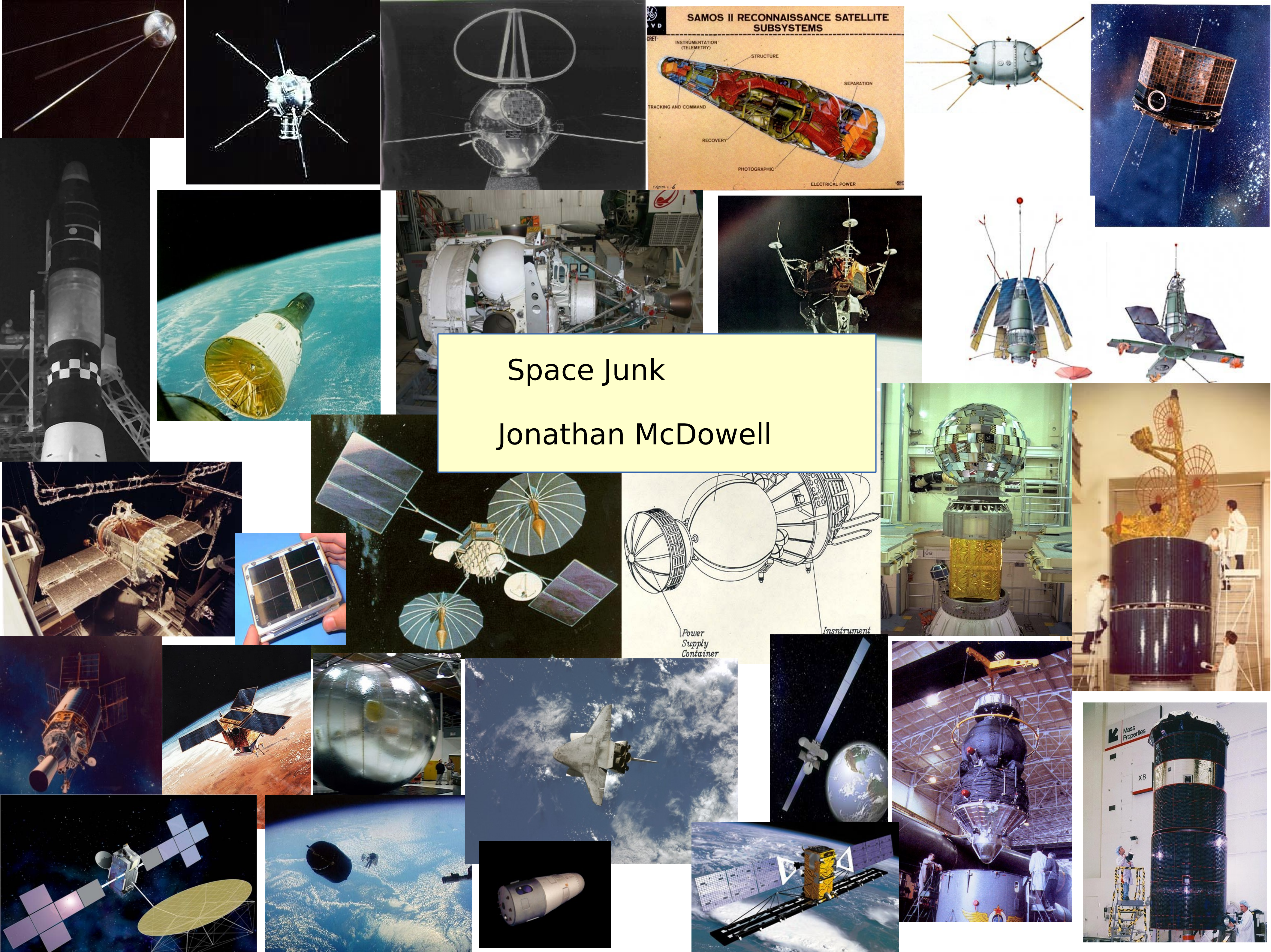
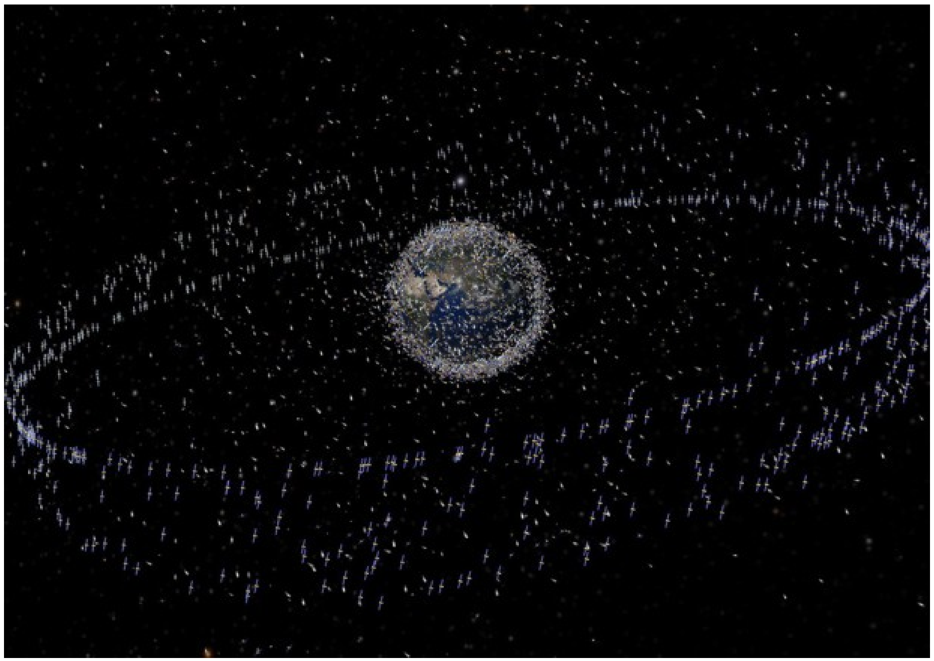


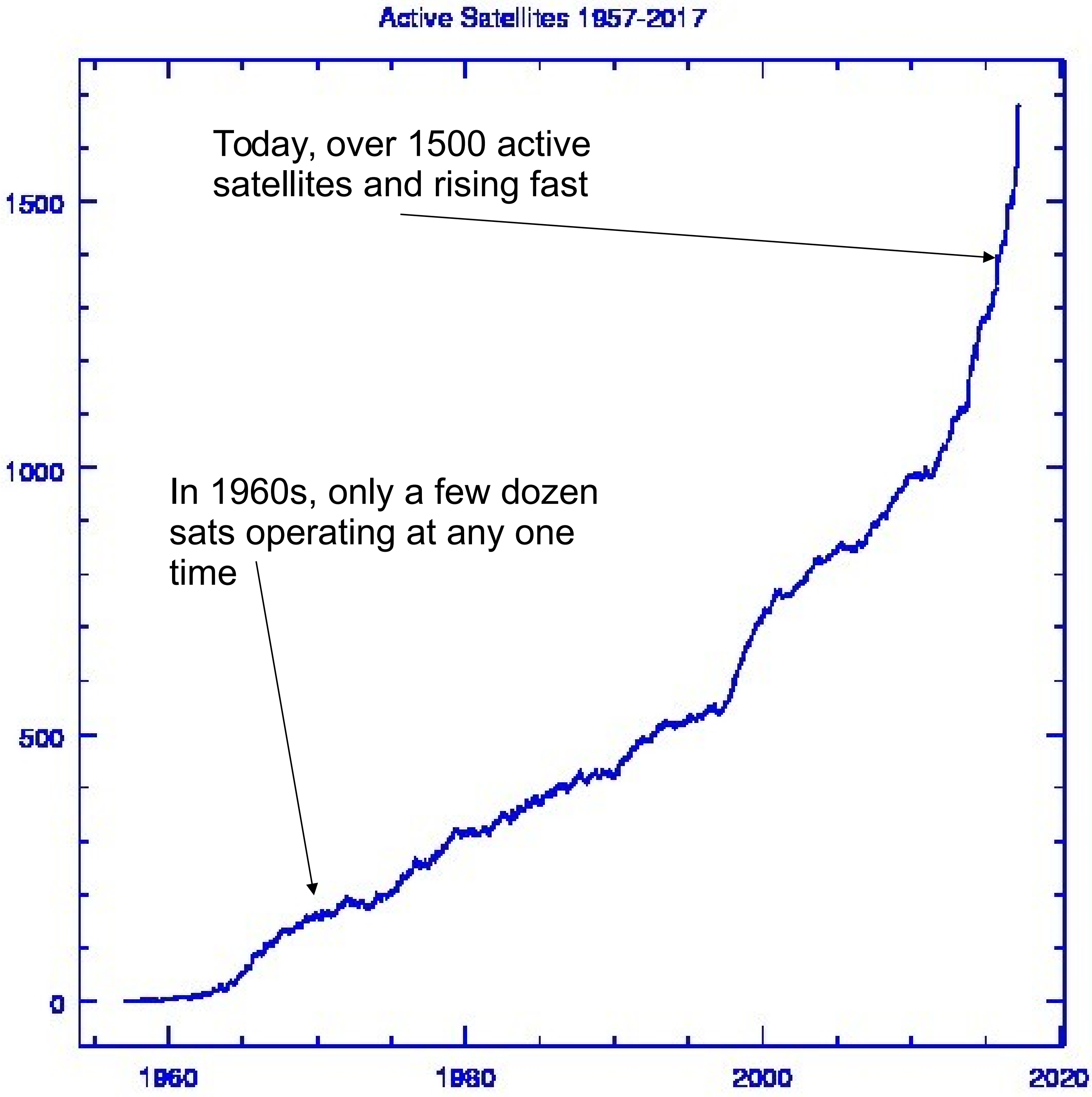
Space Junk

Jonathan McDowell



About 1500 satellites currently operating
Some in low orbit skimming just outside the atmosphere, mostly going from pole to pole

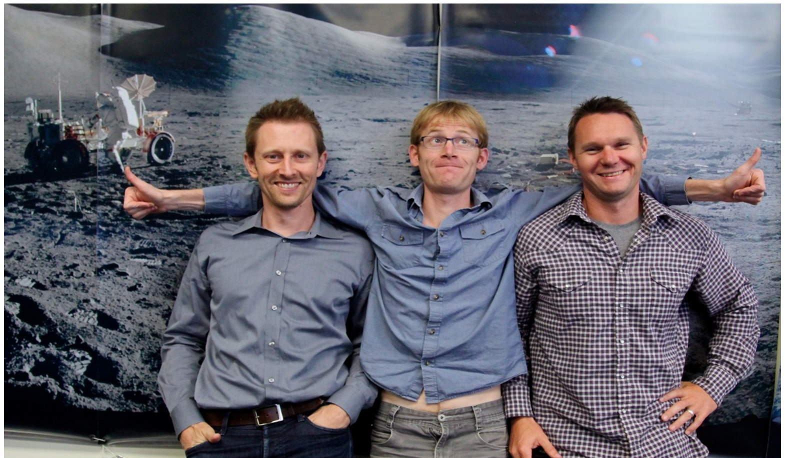
Some In 'geostationary orbit' in a ring high above the equator

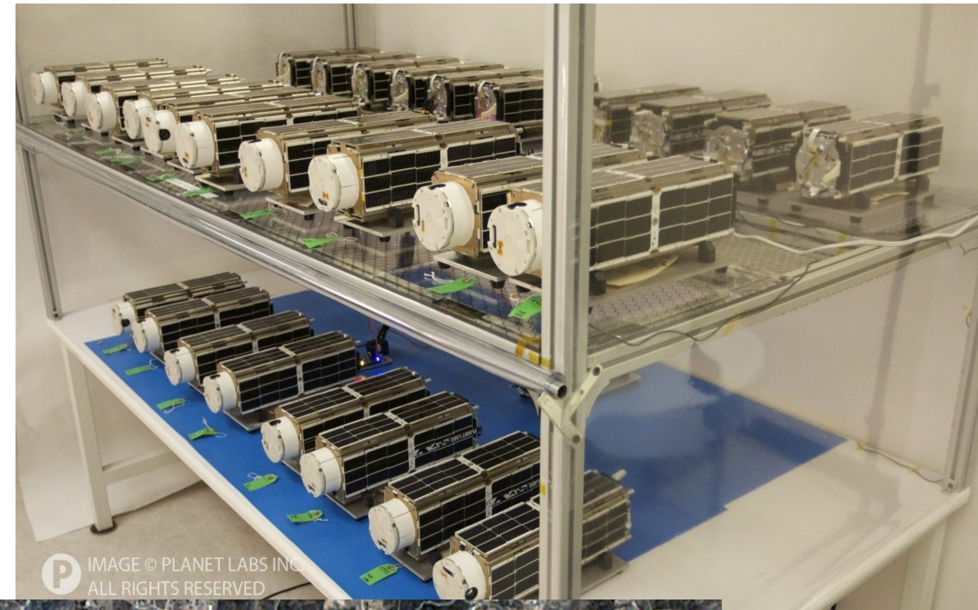


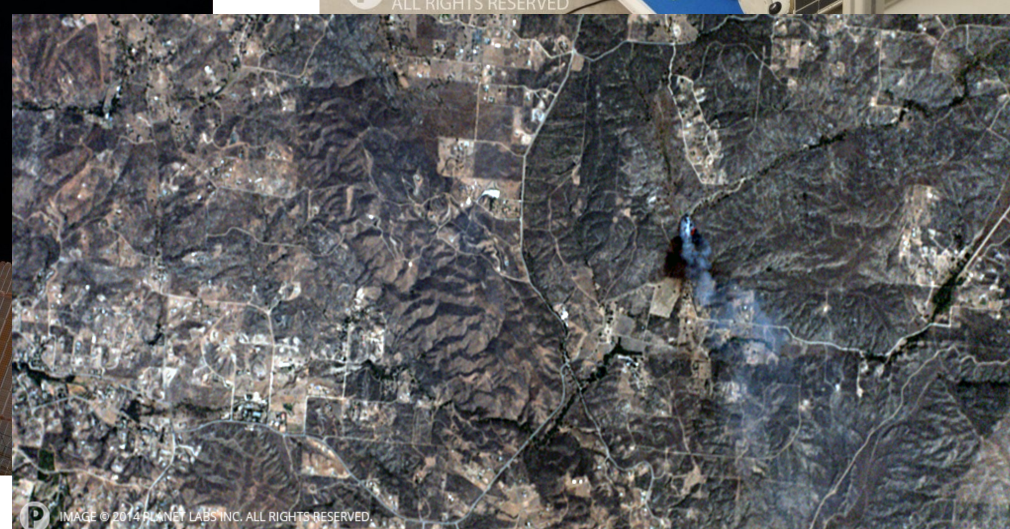
Active Satellites 1957-2017
Today, over 1500 active satellites and rising fast
In 1960s, only a few dozen sats operating at any one time
1500
1000
500
0
1960
1980
2000
2020

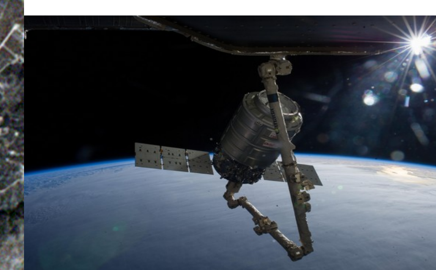
2013: CUBESAT EXPLOSION!

99 Cubesats launched Jun 2003-Feb 2013 by 63 organizations in 20 countries
120 Cubesats launched Mar 2013 – Feb 2014 by 57 organizations in 18 countries
(Cumulative: 219 Cubesats by 108 orgs in 28 countries)





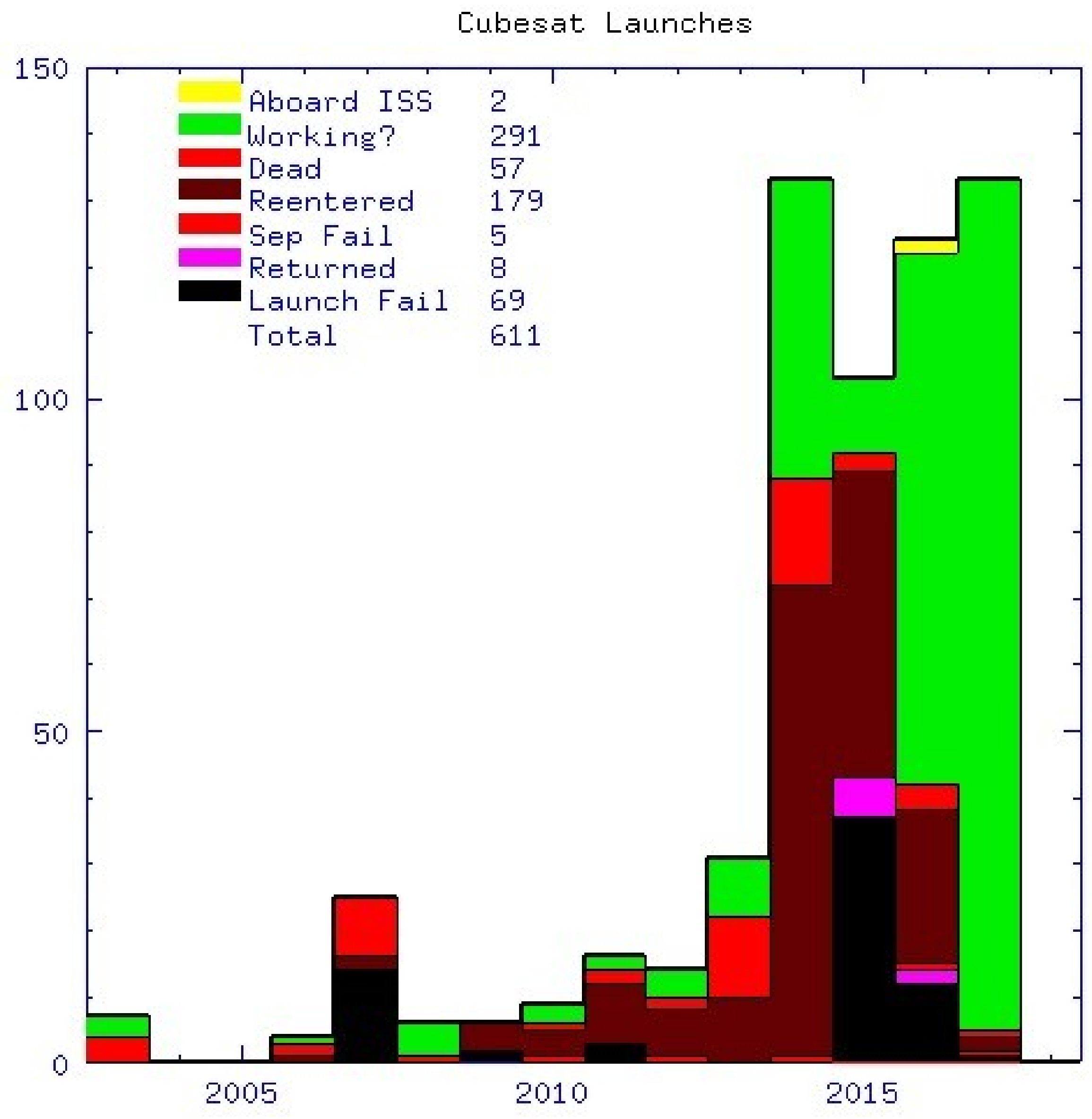


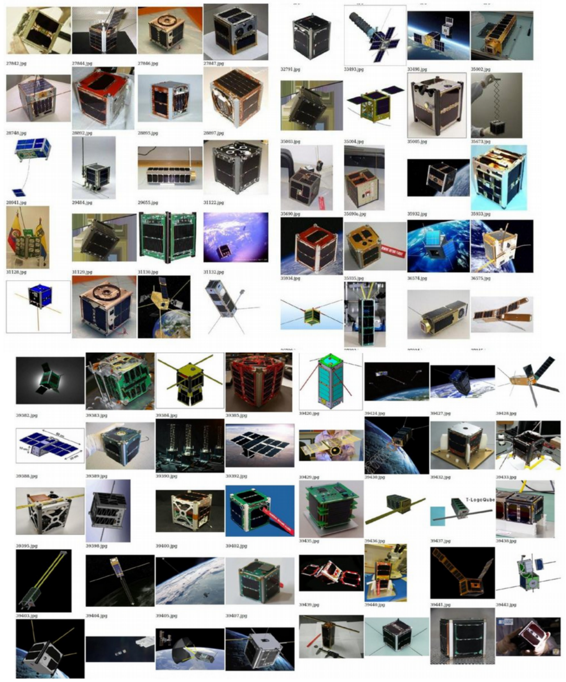


Chris, Will and Robbie left NASA to found PlanetLabs in a San Fran office building – 71 satellites launched since 2013, first big Cubesat constellation

The Cubesat Explosion: STATISTICS 2017 April

http://planet4589.org

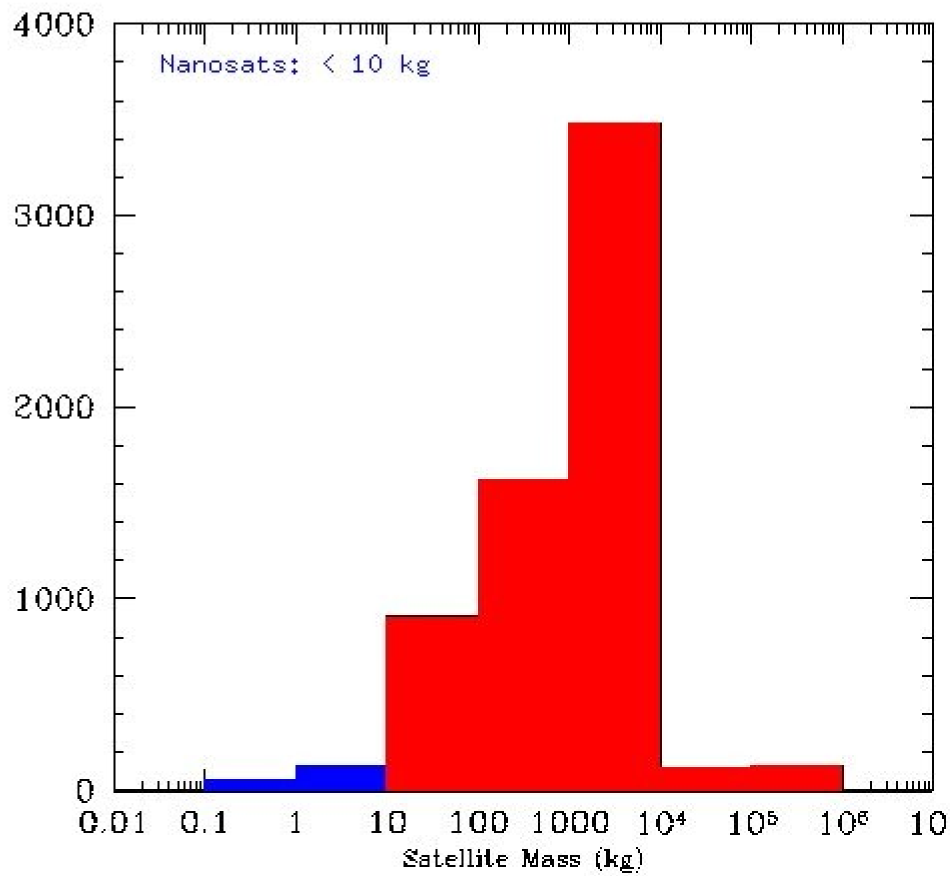


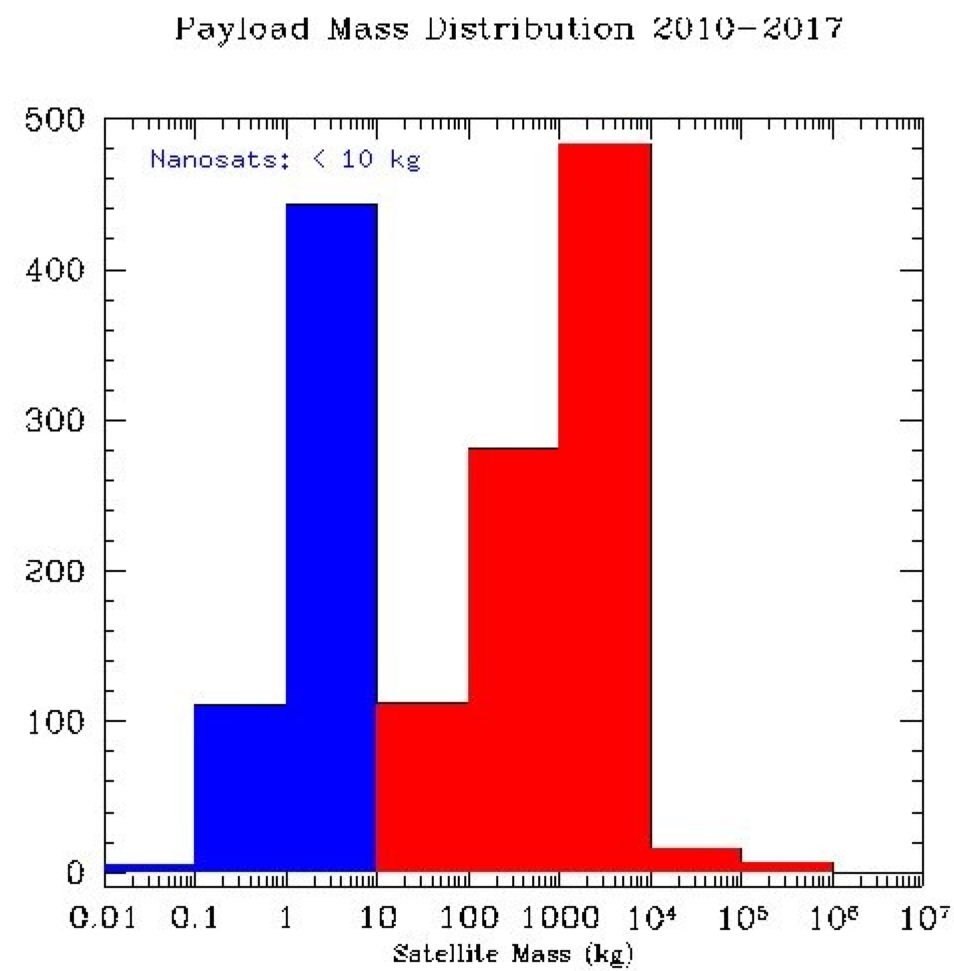


TOTAL 38 COUNTRIES:

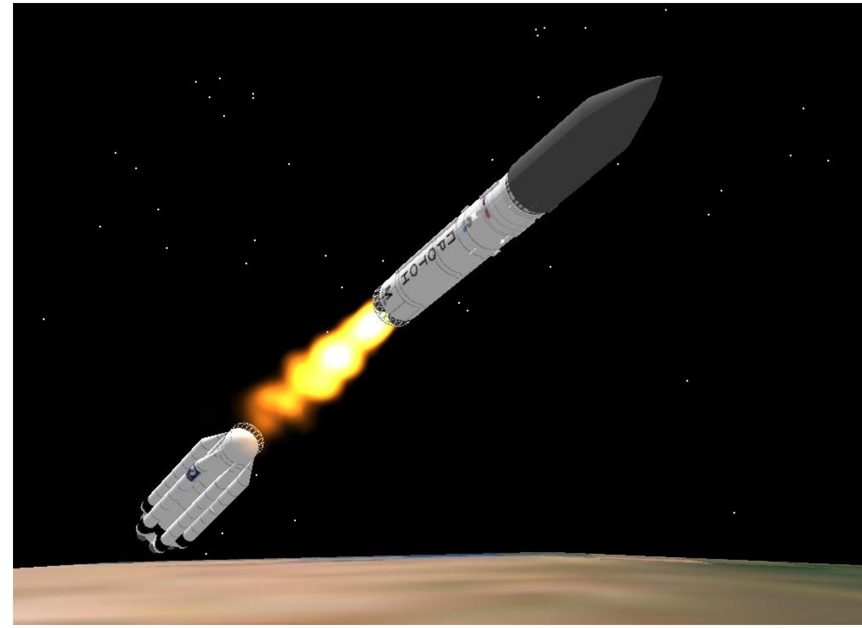
USA 478
Japan 27
Germany 10
China 10
Denmark 9
Singapore 6
Netherlands, Italy 5
S Korea, Belgium,Spain, India 4
Canada,UK,Brazil, Israel,Norway,Peru 3
Russia, Switzerland,Lithuania,Turkey,Vietnam,
Ecuador ,Argentina 2
Ukraine, France, Kazakhstan, Emirates, Uruguay,
S Africa, Algeria, Poland, Pakistan, Colombia,
Romania, Hungary,Estonia 1

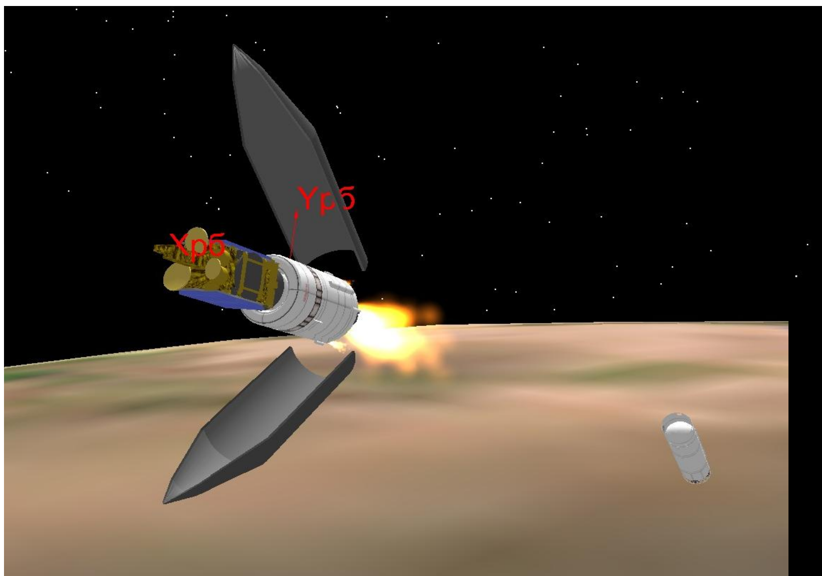
Payload Mass Distribution 1957–2009

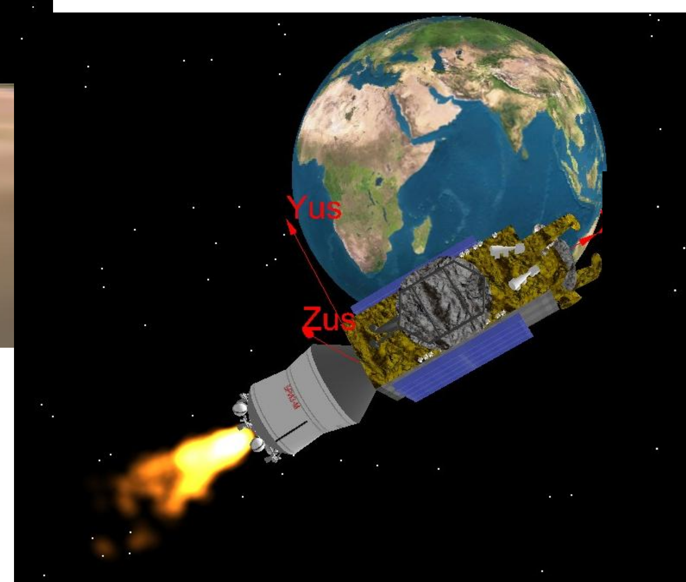


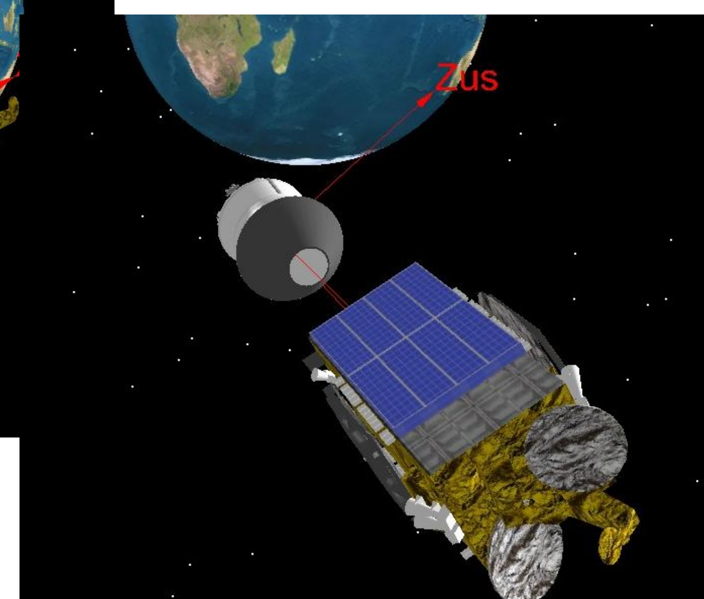


Payload Mass Distribution 2010-2017
Nanosats: < 10 kg
500
400
300
200
100
0
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
Satellite Mass (kg)



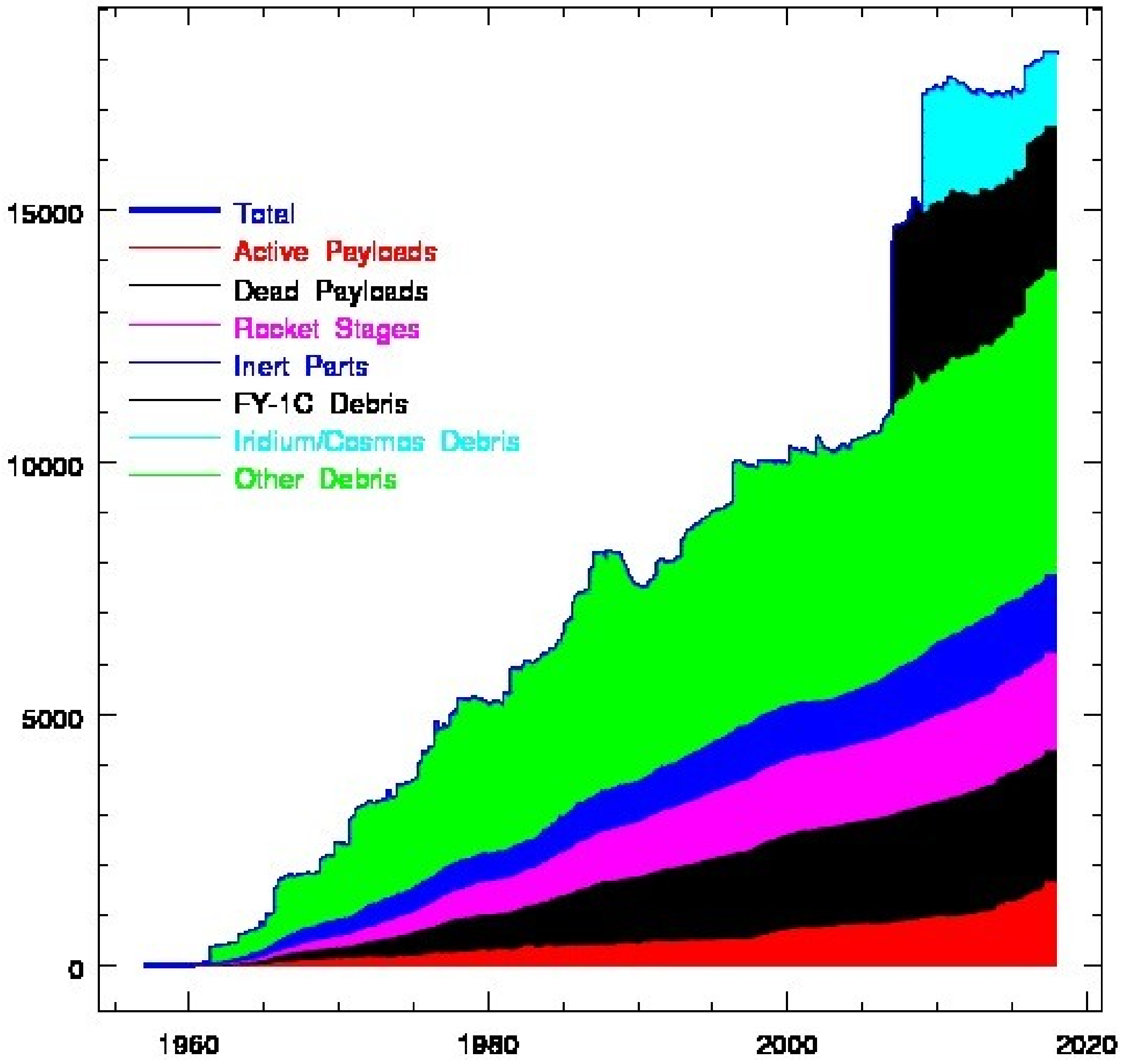




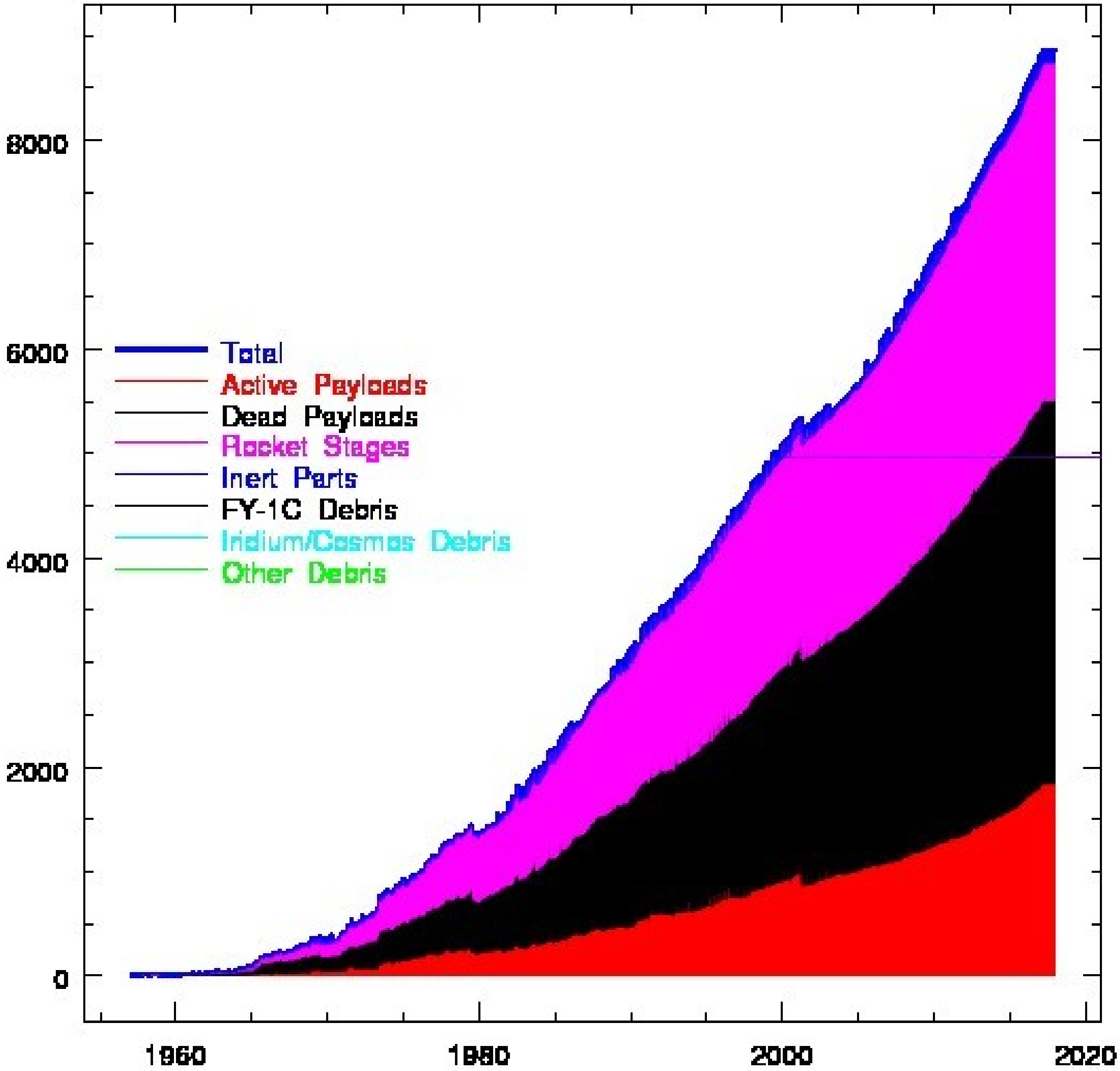


A typical satellite launch ends up with at least two objects in orbit – the satellite and the last piece (“stage”) of the rocket that got it there

The Growth of Space Junk



Space Junk - mass in metric tons



Today: 8854 tonnes

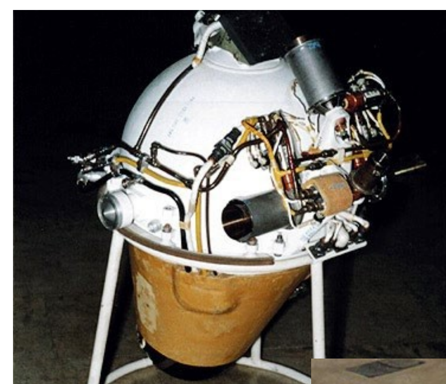
A Census of Space Debris
as of 10 Apr 2017

Total objects cataloged	42489	
Objects still in Earth orbit	18124	
Active payloads	1500?	
Dead payloads	2796?	
Rocket stages	1930	
Adapters, jettisoned objects	1652	
2007 Chinese ASAT debris	2855)	
2009 collision	1443)	10245
Other debris	5947)	

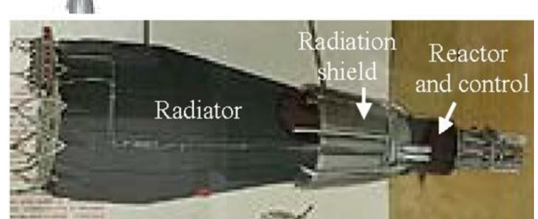
Covers, fairings	300
Jettisoned motors and tanks	170
Multi-payload adapters	141
Despin devices	131
Deployment canisters	38
Insulation blankets	36
Nuclear reactor cores	14
Misc	28
Unknown pieces	794

Residual fuel explosions	**3654**
Antisatellite weapon tests	**3247**
Accidental collision	**1458**
Battery explosion	**1315**
NaK Reactor coolant blobs	**53**
Insulation, Destruct, Other	**518**

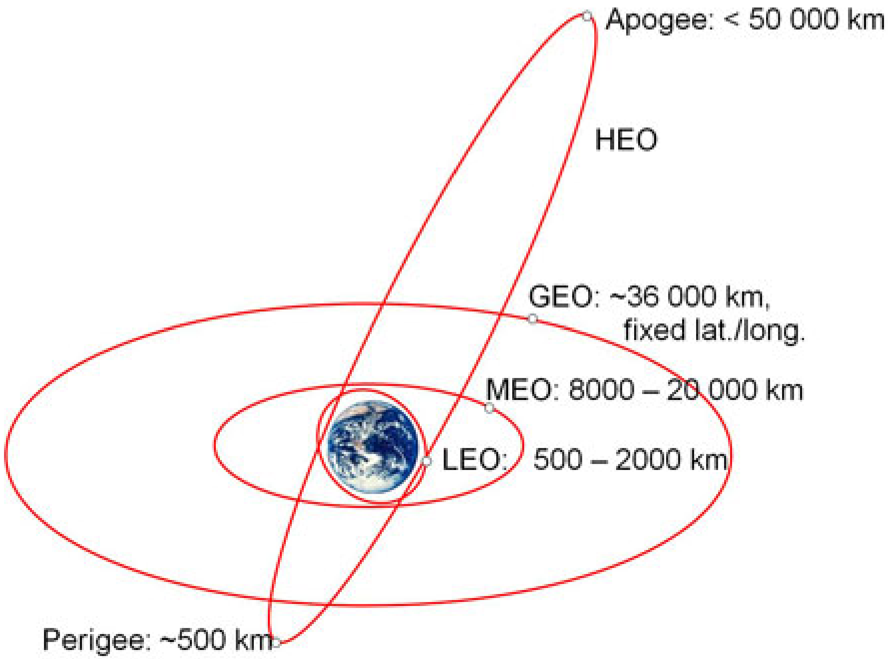






Orbitography



Low Earth Orbit

Kepler in sensible units

Newton's law of gravitation

$$V = mc^2 \left(\frac{r}{R_G}\right)^{-1}$$

Keplerian velocity

$$v/c = \sqrt{R_G/r}$$

Kepler's third law

$$T = \frac{2\pi r}{c}\sqrt{r/R_G}$$

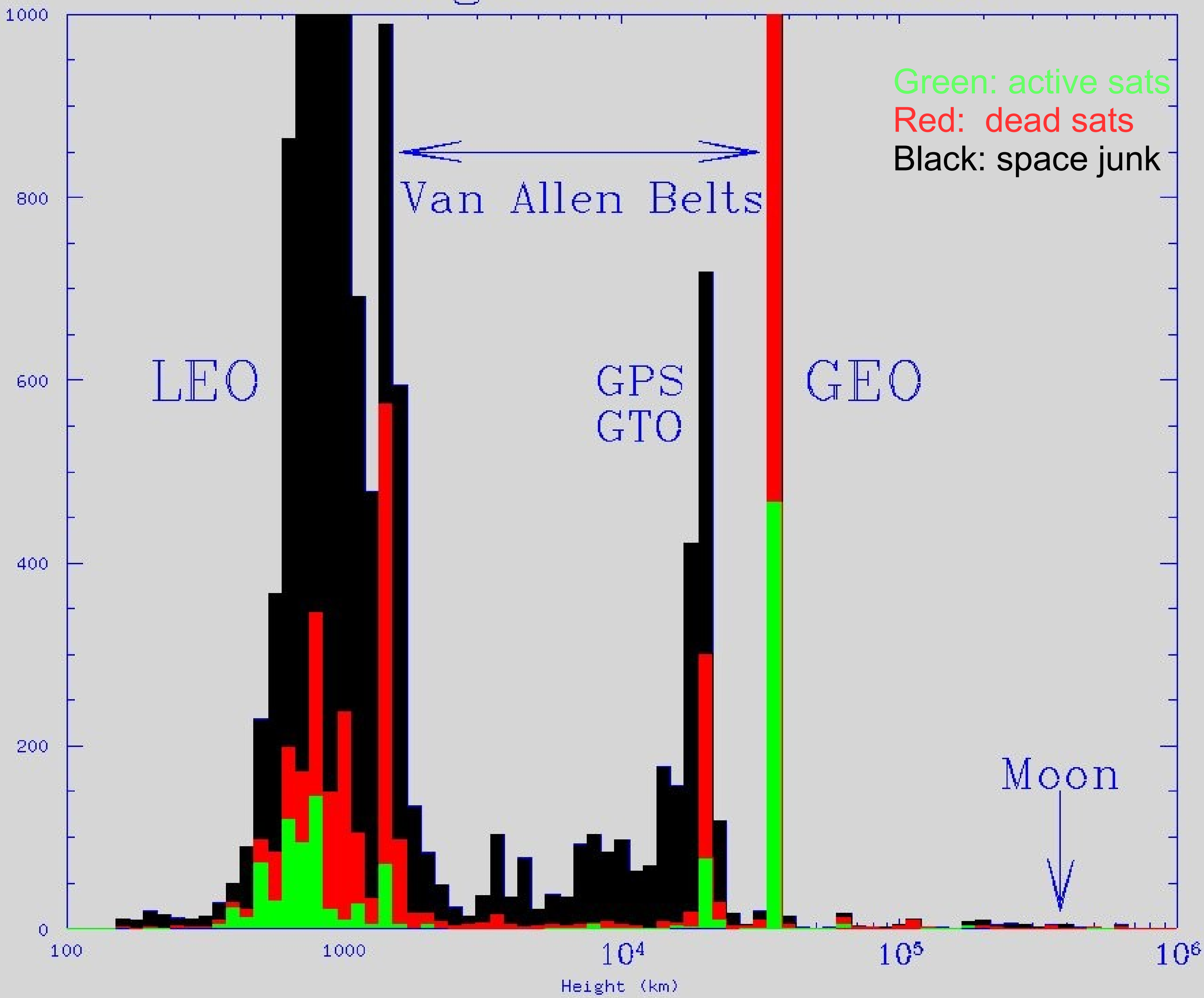
$$R_G = \frac{GM}{c^2}$$

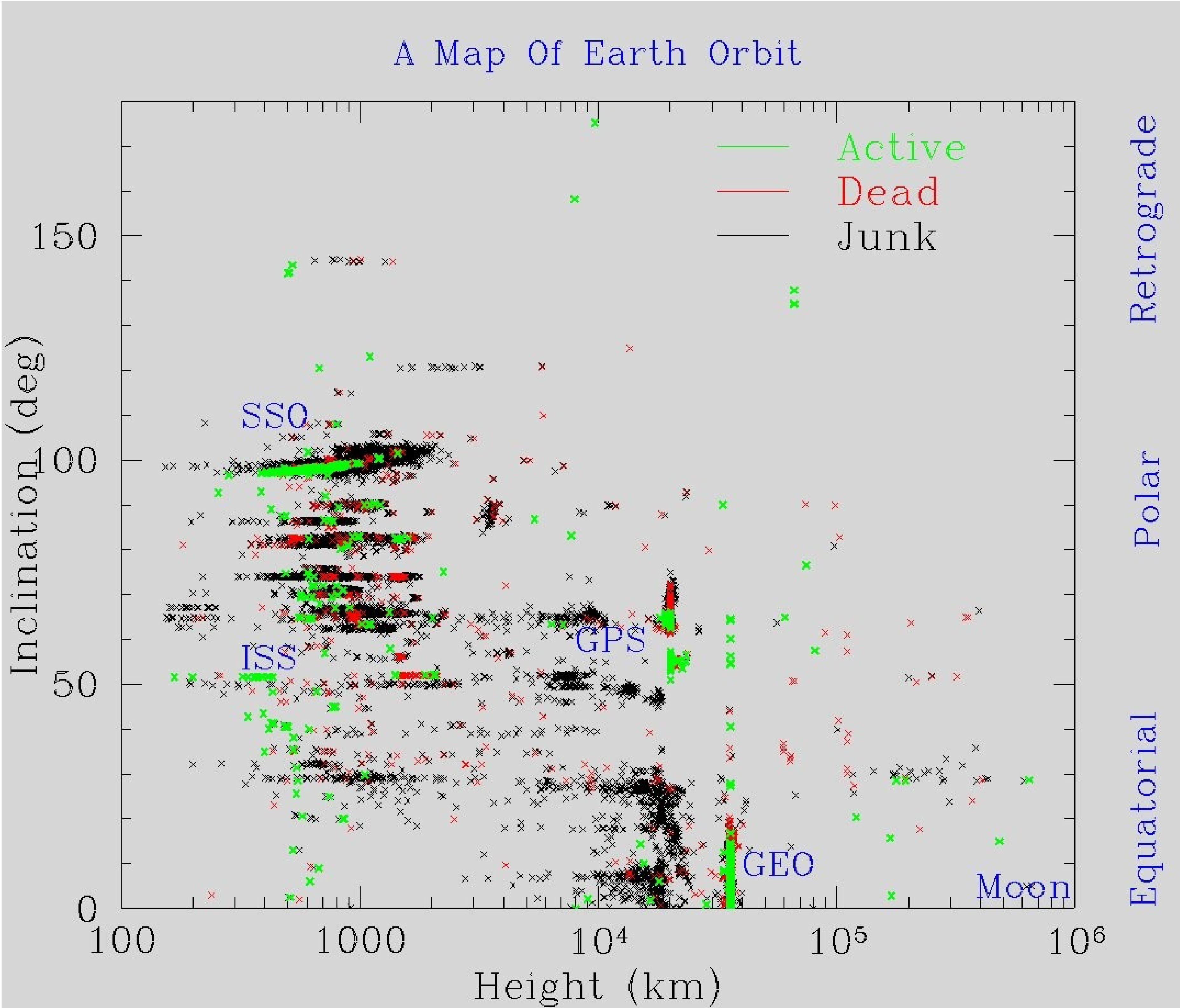
is the gravitational radius of a central mass M.

Earth surface has r = 6378 km
Space Station has height 400 km,
so r= 6778 km

This corresponds to v = 7.67 km/s
or v = 17158 mph - quite fast!!
At 400 km, orbital period is 92.5 minutes

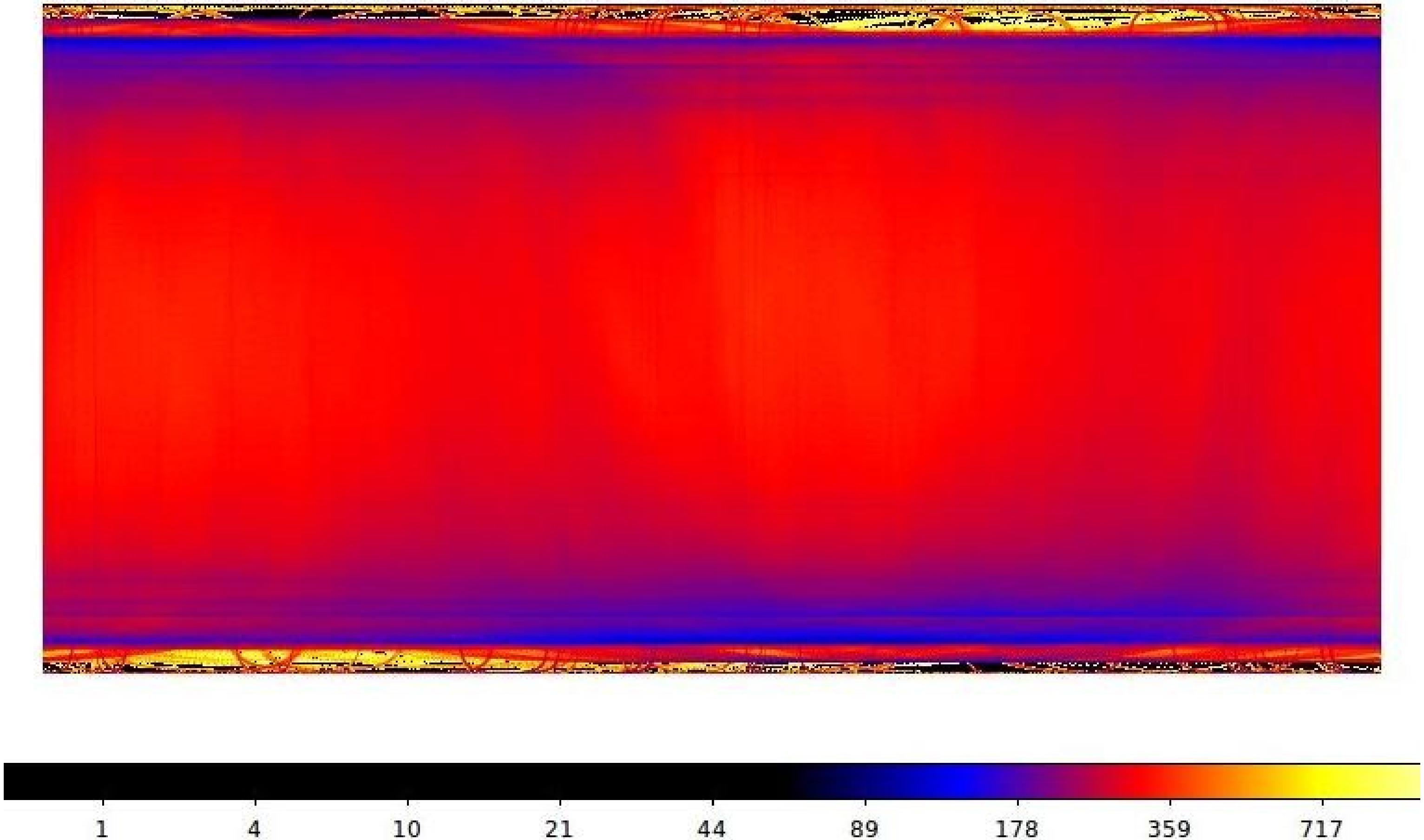
How high are satellites?



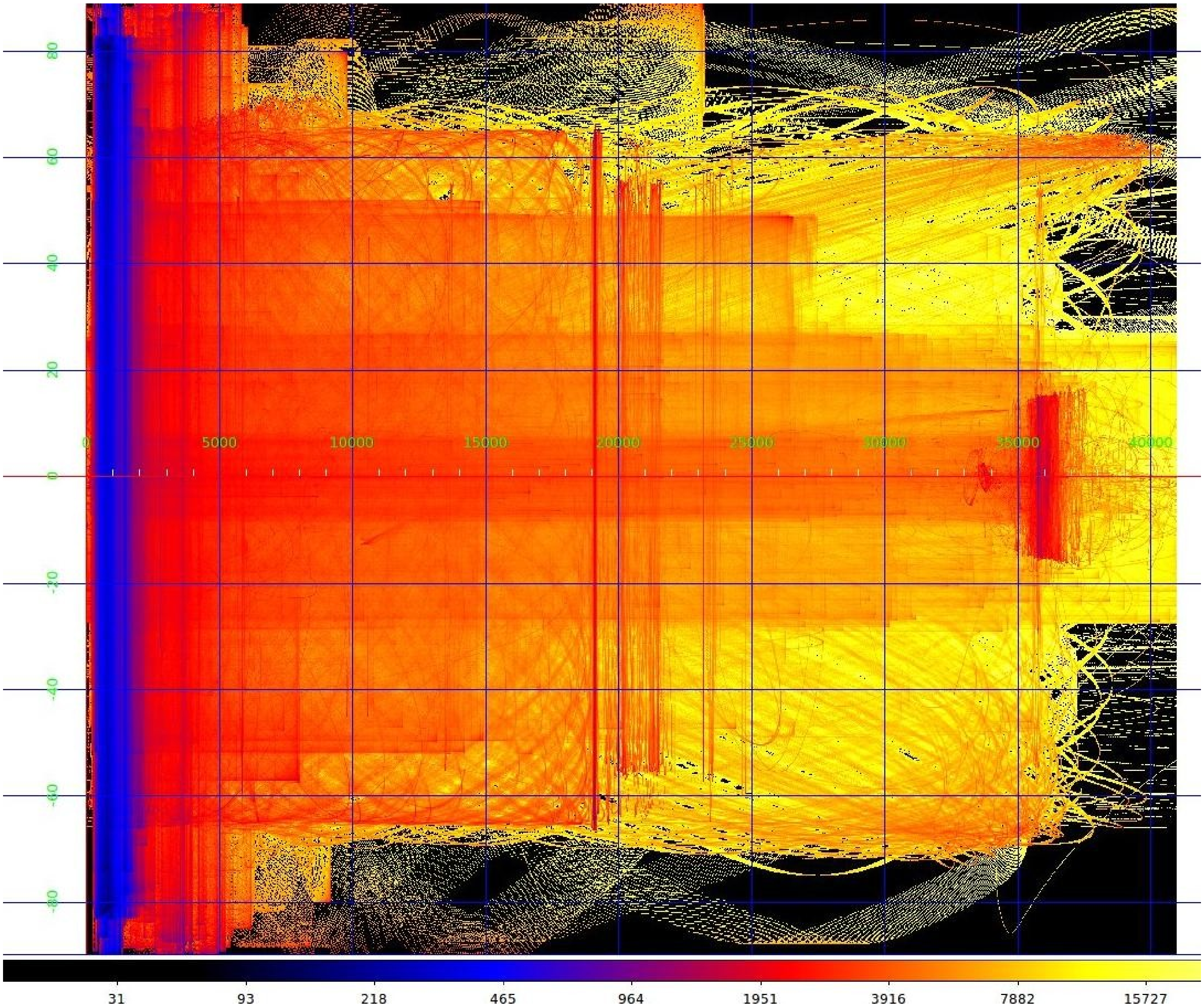

A Map Of Earth Orbit
Active
Dead
Junk
SSO
ISS
GPS
GEO
Moon
Retrograde
Polar
Equatorial
Inclination (deg)
Height (km)
0
50
100
150
100
1000
10^4
10^5
10^6

Mean free path in 800 km LEO: RA vs latitude

Calculated positions for 18000 satellites each minute for 45 day period to obtain average number density in 1 x 1 deg bins extending +-50 km in radial direction



Here is the longitude-averaged MFP as a function
of height (x axis) versus latitude (y axis)
Note the GEO and GPS belts and the horizontal structures



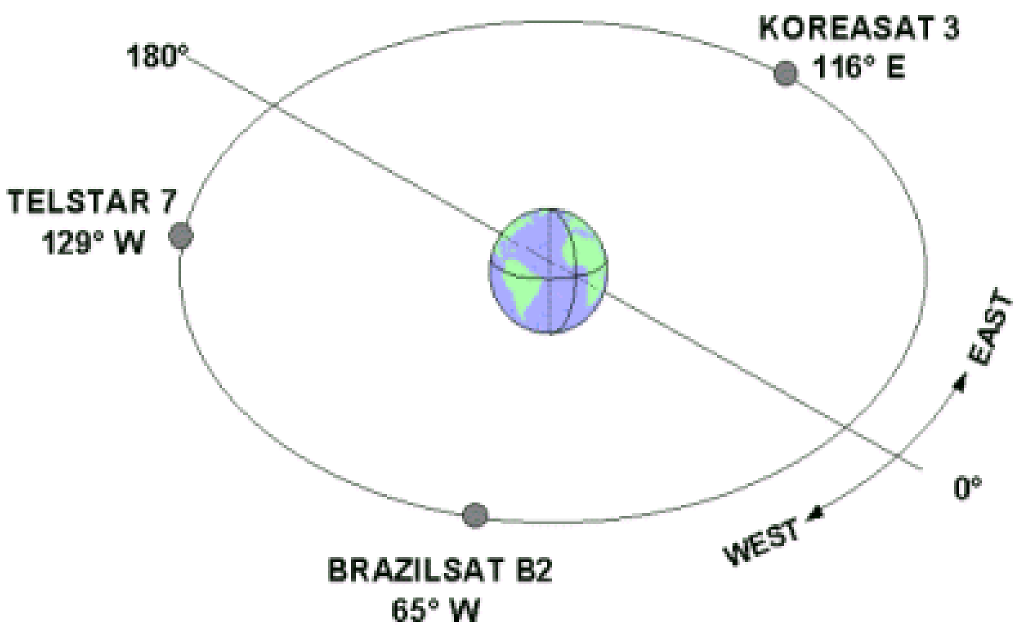
GEO: Geostationary Earth Orbit

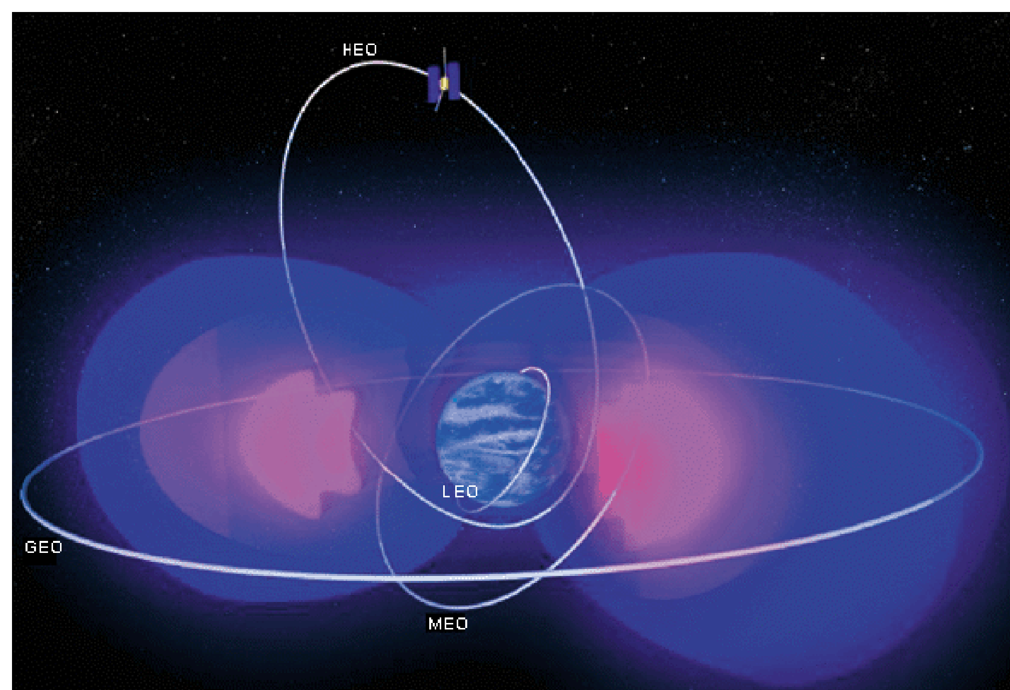
Consider a satellite whose orbit goes around the Earth's equator
Just outside the atmosphere it takes 1 ½ hours to go round the planet
Far out, at the distance of the Moon it takes a month to go round
Inbetween there is some height at which it takes exactly 23 hr 56 min

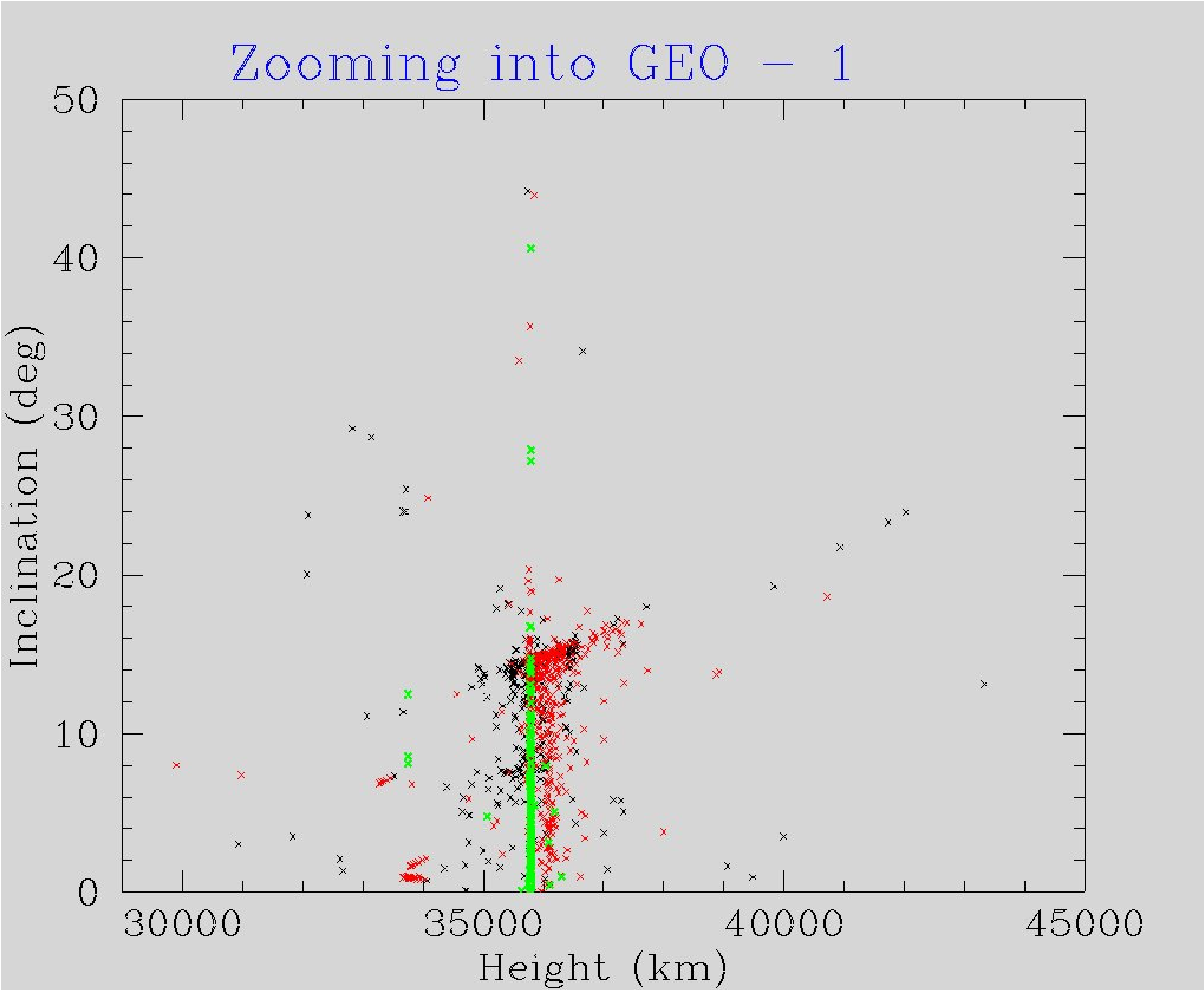
Meanwhile, the Earth spins underneath it, also taking 23 hr 56 min to complete one full rotation

So the satellite stays above the same point on the equator!

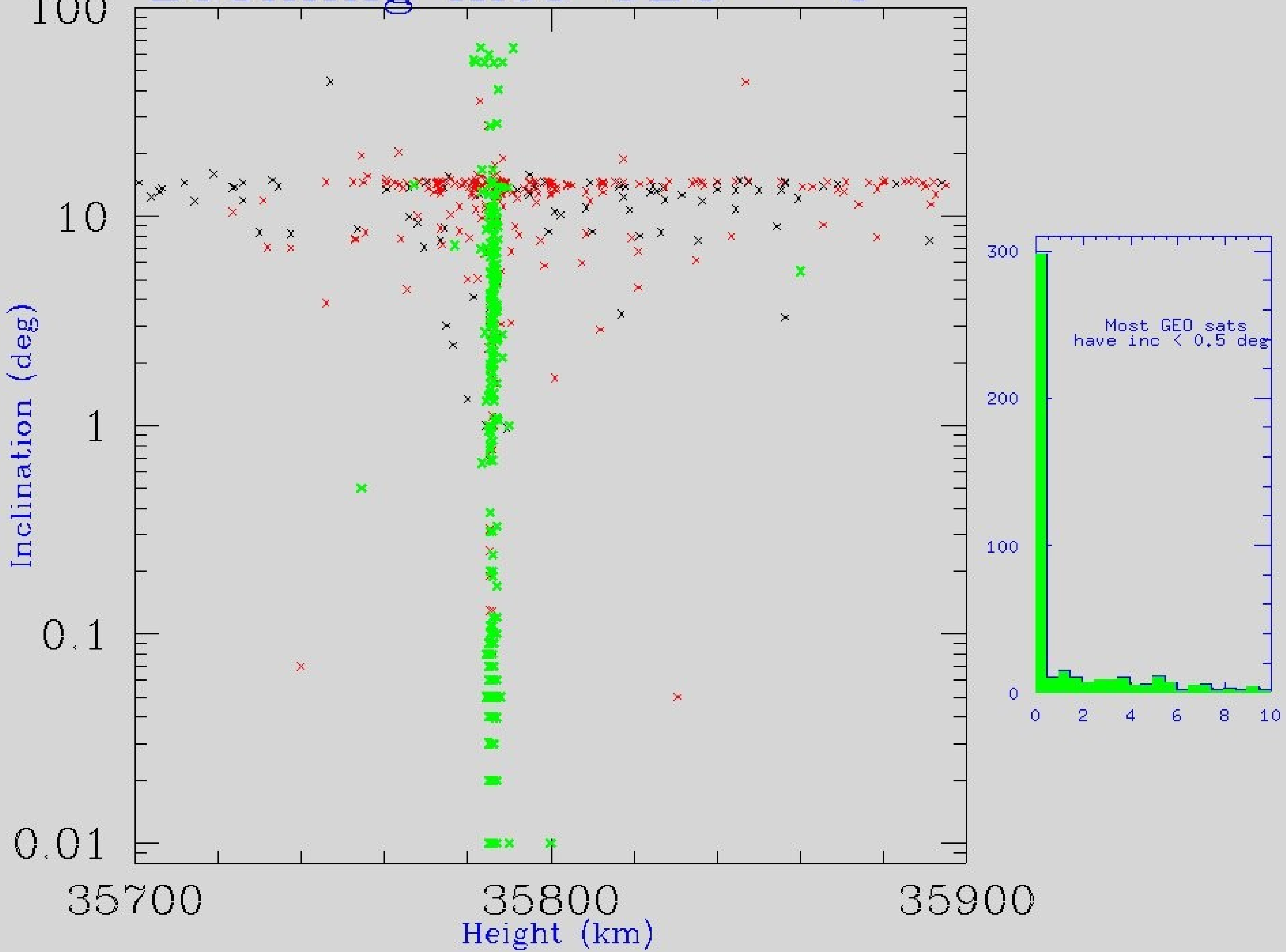
Kepler's Third Law lets us calculate the magic height: 35787 km above the Earth's surface (about 23000 miles)

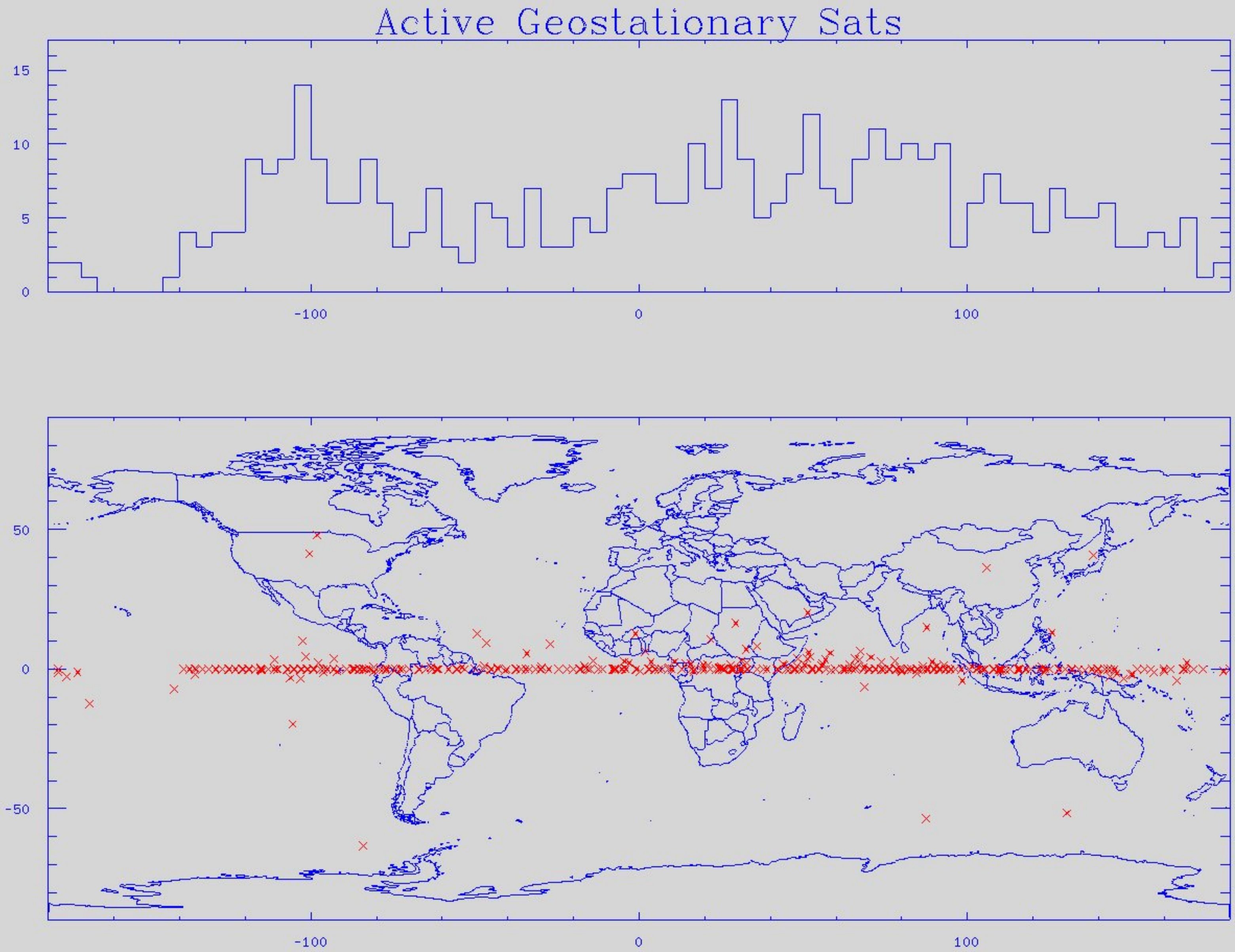





Zooming into GEO - 1
Inclination (deg)
Height (km)
0
10
20
30
40
50
30000
35000
40000
45000

Zooming into GEO - 2





Active Geostationary Sats
15
10
5
0
-100
0
100
50
0
-50
-100
0
100

Special orbits due to the oblate Earth

Actually we left something out of our math: the Earth is NOT ROUND!
It's a little squashed at the poles (polar radius is 22 km smaller than at equator)
Every time a sat goes over the poles, it gets less of a tug; over the equator it gets more.
This twists the orbit – makes it rotate in space.
By picking the orbit cleverly you can make the twist do something useful!
We consider the first term (J2) in the spherical harmonic expansion of the potential
This gives first order corrections to the orbital elements (node, arg of peri.)
- varying linearly in time

The first order orbital rotation rate for a flattened object of equatorial radius R_s

$$f_p = \frac{(3\pi J_2)\,(R_s/a)^{\frac{7}{2}}\,(1-e^2)^{-2}}{T_s}$$

where T_s is the surface orbital period

$$T_s = \frac{2\pi R_s}{c}\sqrt{\frac{R_s}{R_G}}$$

The node and perigee then rotate at

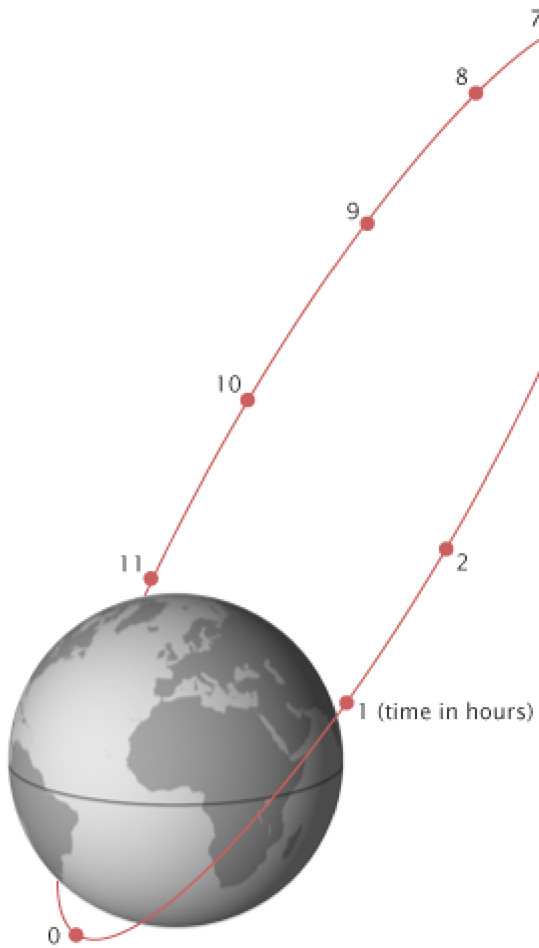
$$\dot{\omega} = f_P\left(2 - \frac{5}{2}\sin^2 i\right)$$

and

$$\dot{\Omega} = f_P \cos i$$

First let's consider the perigee rotation.

Suppose you have an elliptical inclined orbit with apogee over the northern hemisphere



The oblateness will tend to rotate the orbit in its orbital plane – soon the apogee will be in the south.

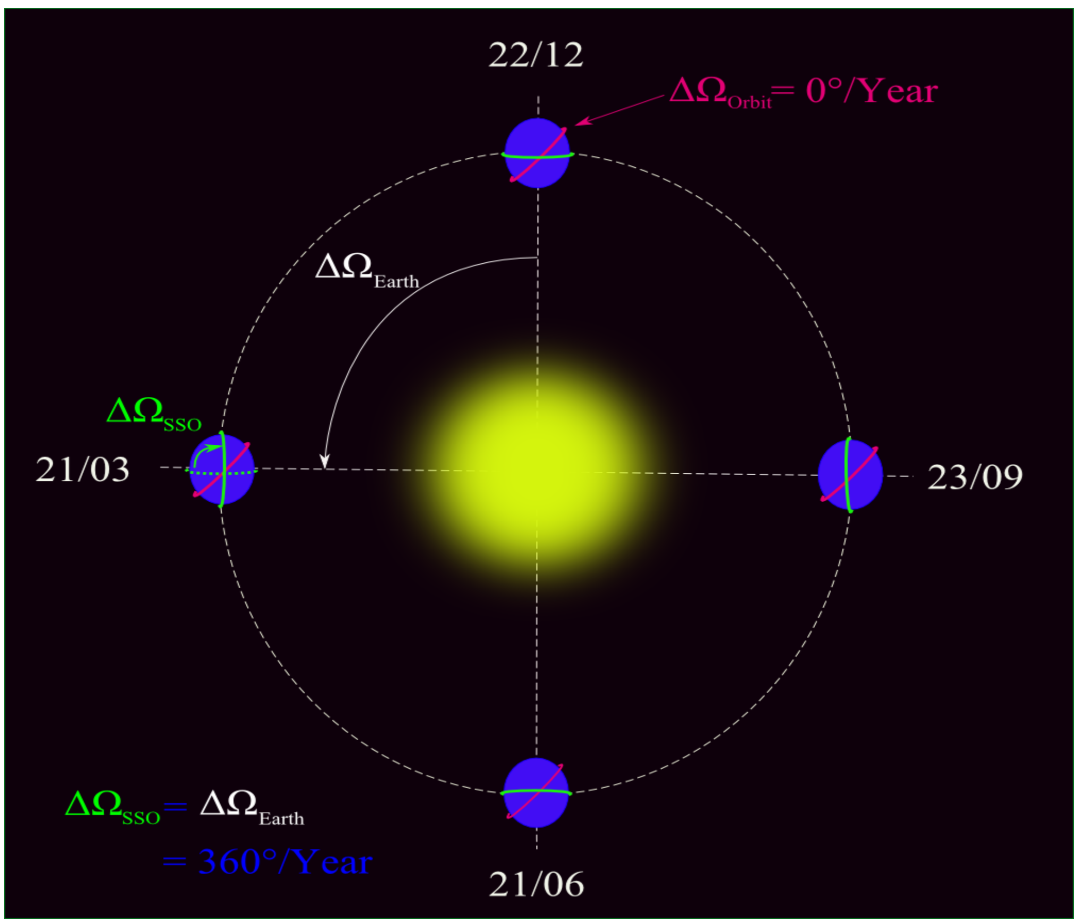
But by careful choice of inclination we can set the term 2 - 5/2 sin^2 i
to zero:
sin^2 i = 4/5
or
i = 63.43 degrees
and lock in the latitude of apogee

the "Molniya orbit" (usually T = 12 hr)

SSO: Sun Synchronous Orbit

Now let's make the ascending node term do something useful.
In perfect Keplerland, the orbit plane (and so, RA of ascending node) is fixed in inertial space. Hence, the angle between the orbit plane and the Earth-Sun line changes as the Earth orbits the sun, by about 1 degree a day.

The correct choice of altitude and inclination can induce an opposite motion in the orbit plane to keep the orbit-normal/Earth-Sun-line angle fixed.

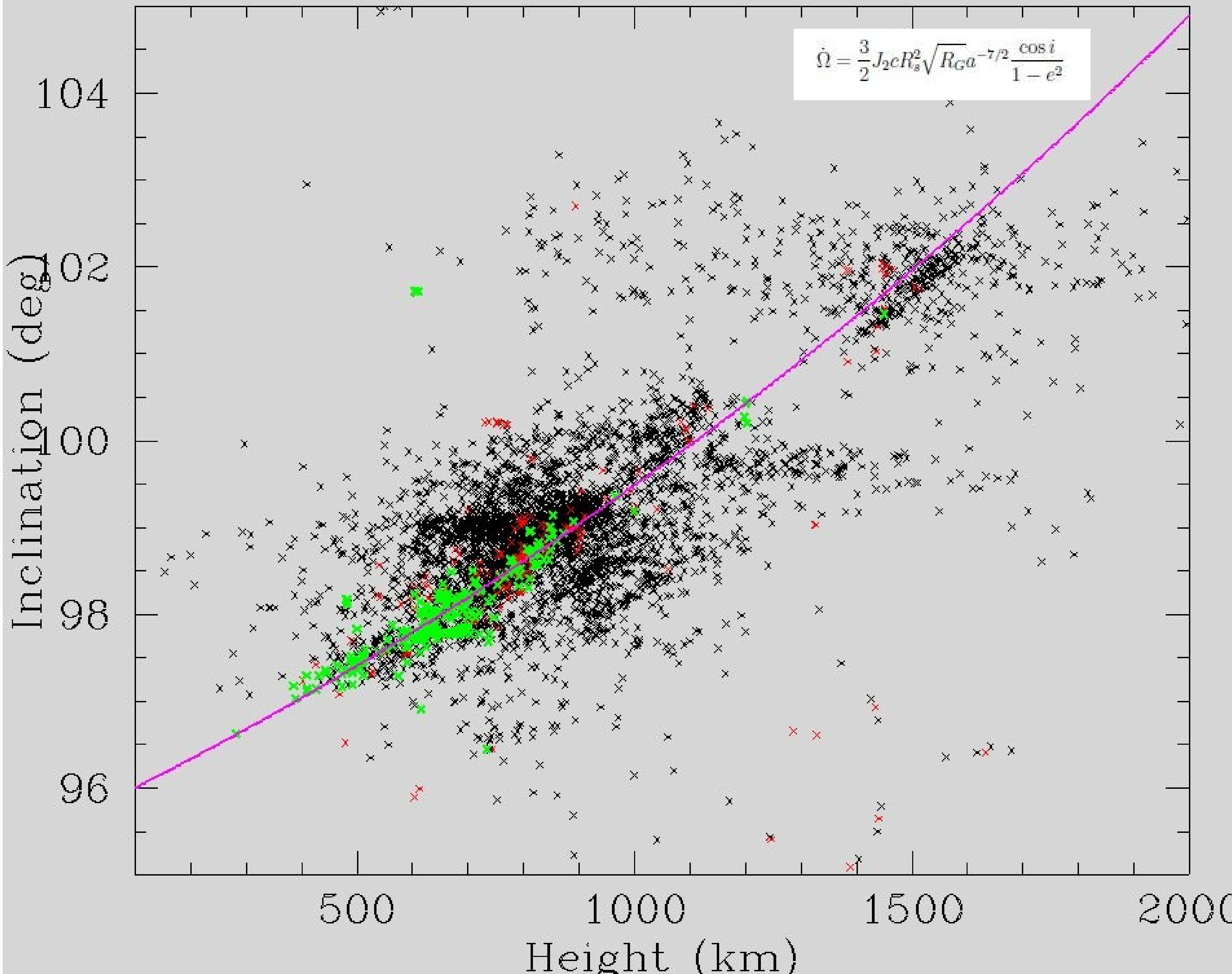


The magenta colored orbit is what you get for a perfect sphere Earth

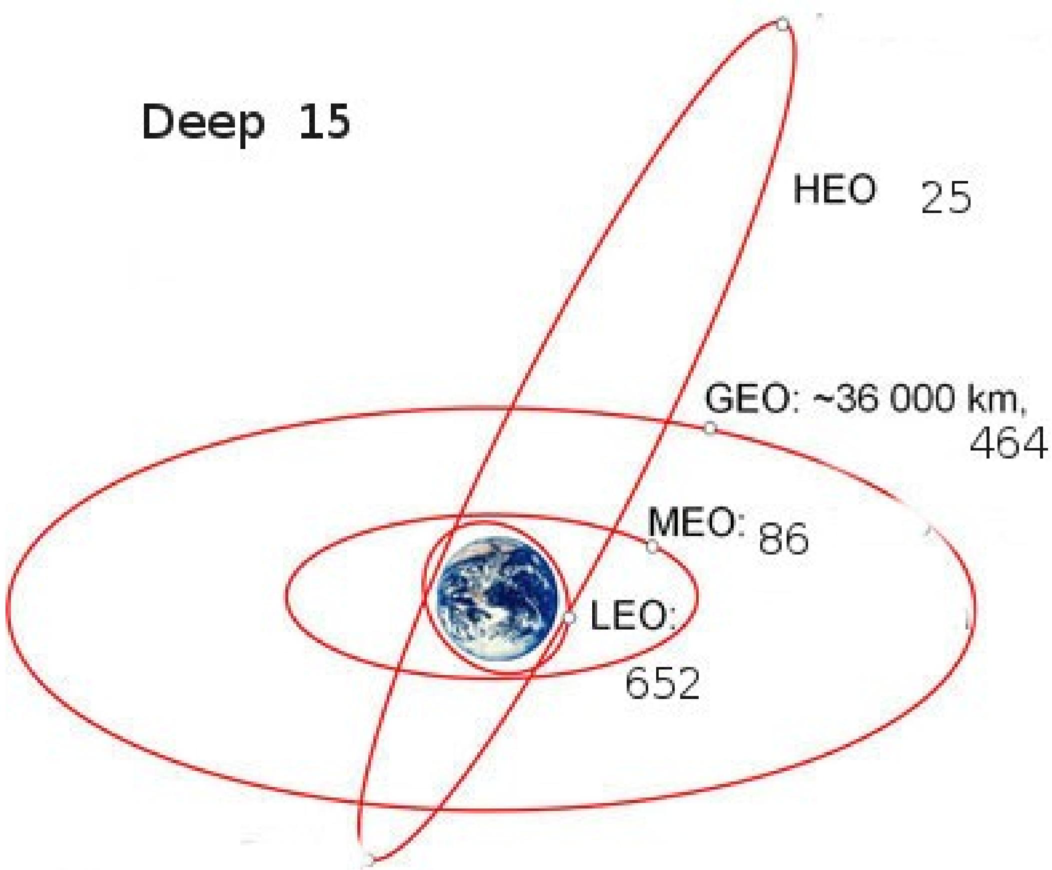
It stays fixed in space so in August (in this particular case) it is facing the sun – the satellite orbits over the dawn/dusk line
- but in May the orbit is edge on to the sun, orbiting noon to midnight.

The green colored orbit is SSO, turning so it's always facing the Sun

Zooming into SSO



Orbit Demographics (circa 2014)



Overall statistics:

	Active	Dead	Junk
LEO	652	1512	10327
MEO	86	262	758
HEO/GTO	25	151	1562
GEO	464	518	291
Deep	15	51	62

*Most satellites are either in LEO or GEO

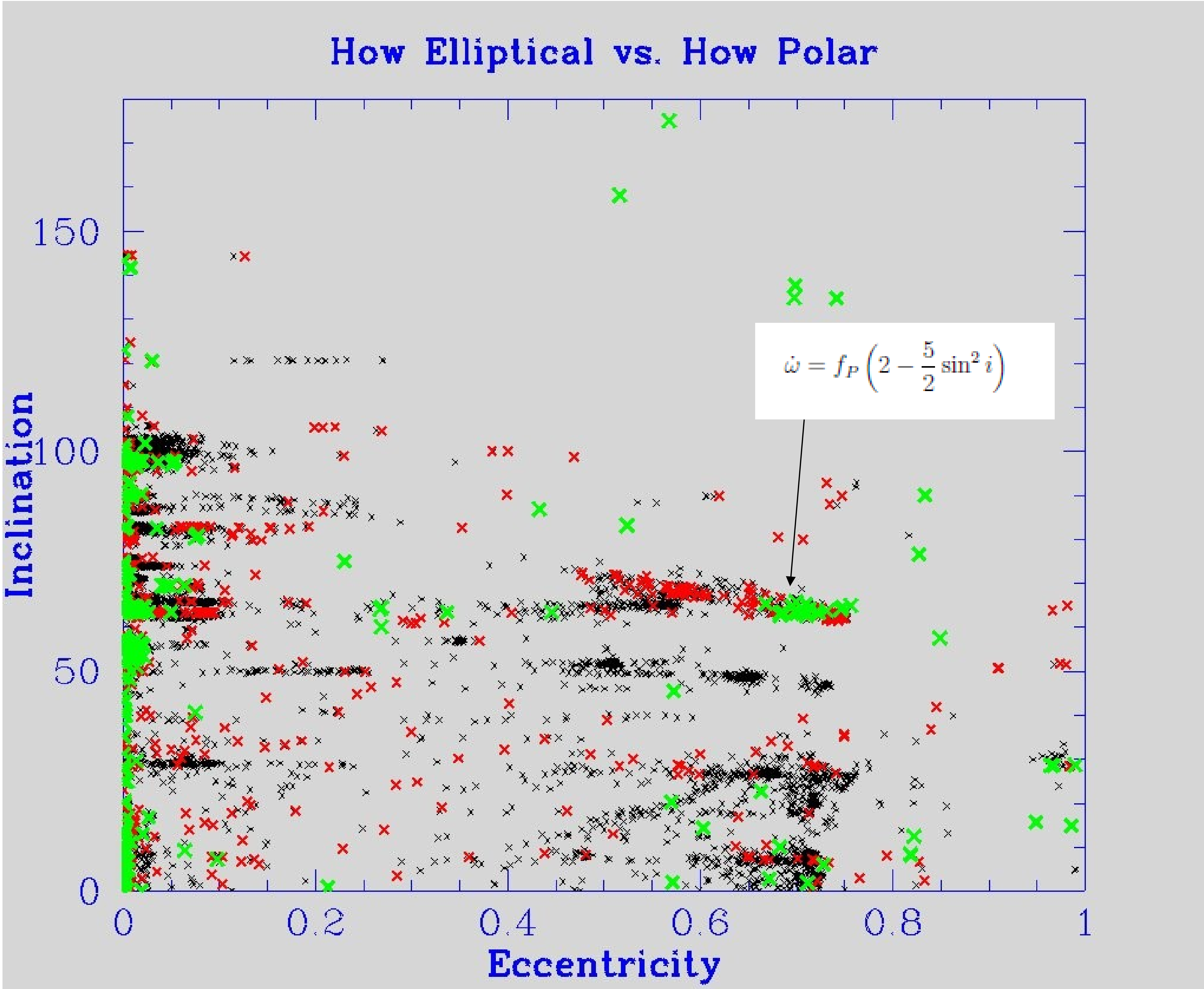
Special cases:

LEO			
- SSO	282	247	5173
- others	370	1265	4625

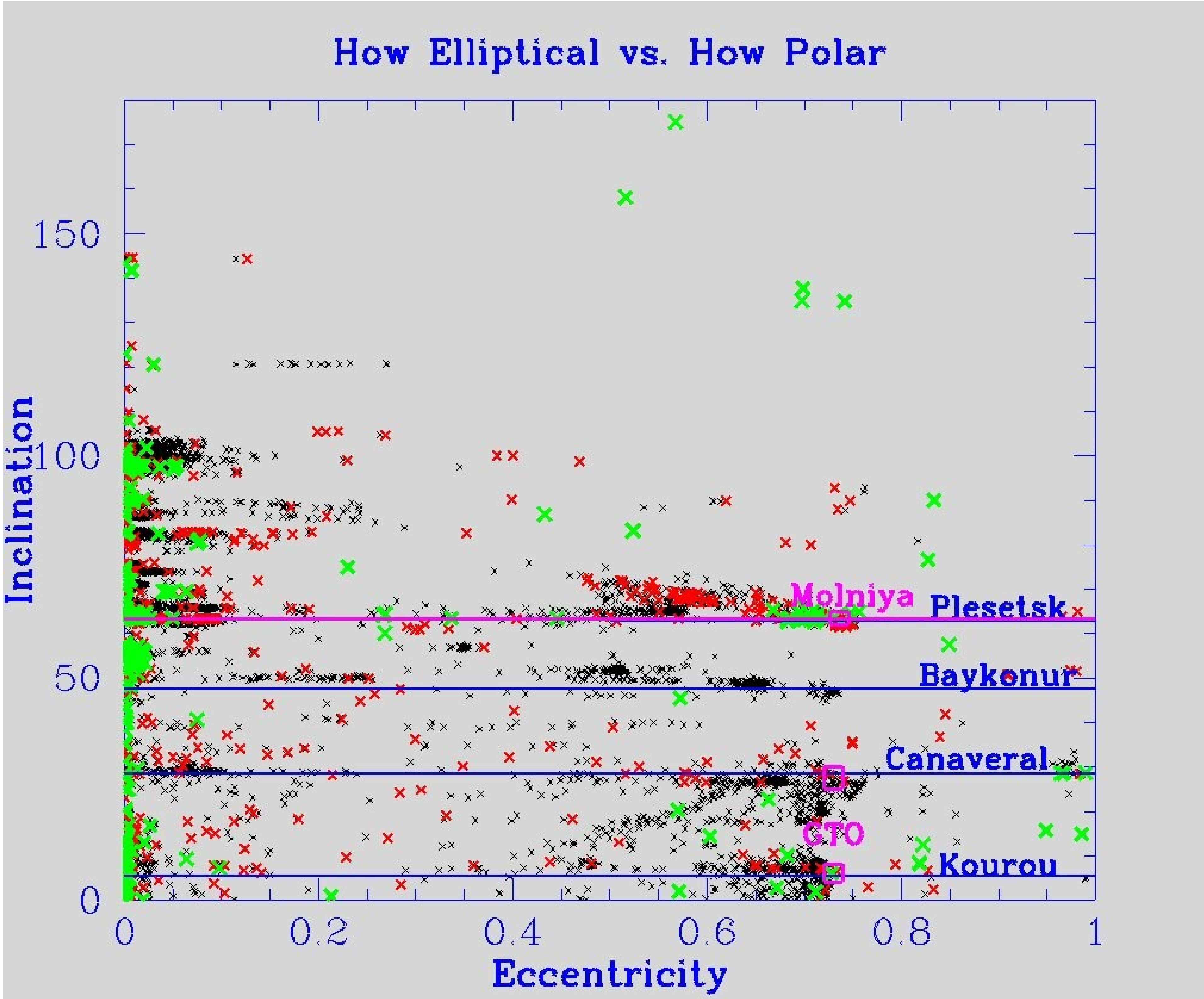
SSO is a very specific orbit, has almost half the LEO sats – and most of the debris

GEO			
Stationary	452	83	14
Graveyard	5	187	92
Drift	7	233	167
Other	1	22	57

Only 36 percent of dead GEO sats are in the graveyard



How Elliptical vs. How Polar
Inclination
Eccentricity
0
50
100
150
0
0.2
0.4
0.6
0.8
1
$\dot{\omega} = f_P\left(2 - \frac{5}{2}\sin^2 i\right)$



How Elliptical vs. How Polar
Inclination
Eccentricity
0
50
100
150
0.2
0.4
0.6
0.8
1
Molniya
Plesetsk
Baykonur
Canaveral
GTO
Kourou

Collisions

In LEO: Most likely collision over the poles, where SSO orbits in different planes intersect.

Example: 2009 Iridium/Strela collision

SSN 24946 Iridium 33, launched 1997 for Iridium LLC. Dry mass 556 kg

SSN 22675 Strela-2M 56, launched 1993 for Russian MoD. Dry mass 800 kg
  Codename Kosmos-2251; retired 1995

Collision Feb 10 1656 UTC at

97.9E 72.5N Alt. 776 km over the Siberian Arctic

Sat 1: 7.465 km/s 12 deg E of N
Sat 2: 7.470 km/s 14 deg S of E

Relative velocity 11.64 km/s

KE of Strela in Irid frame 54 GJ
(Comparison: 1 ton truck @ 100mph = 1 MJ)
Some damage was done...

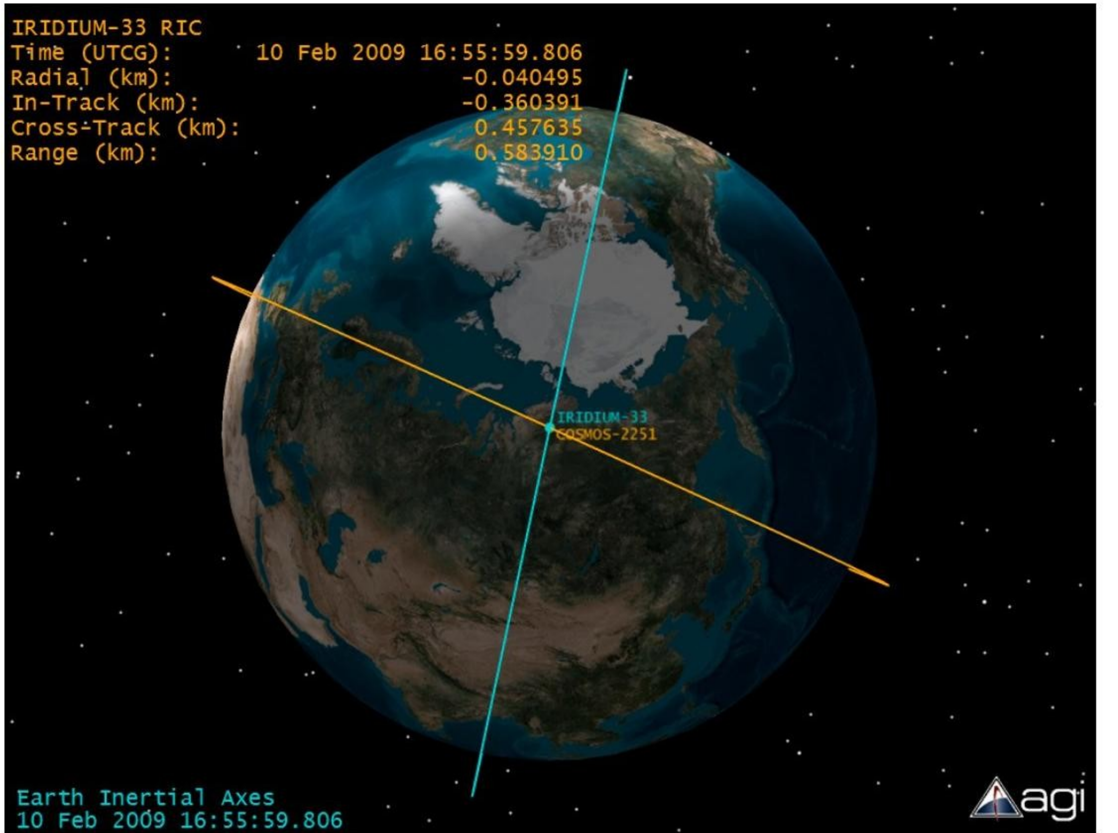
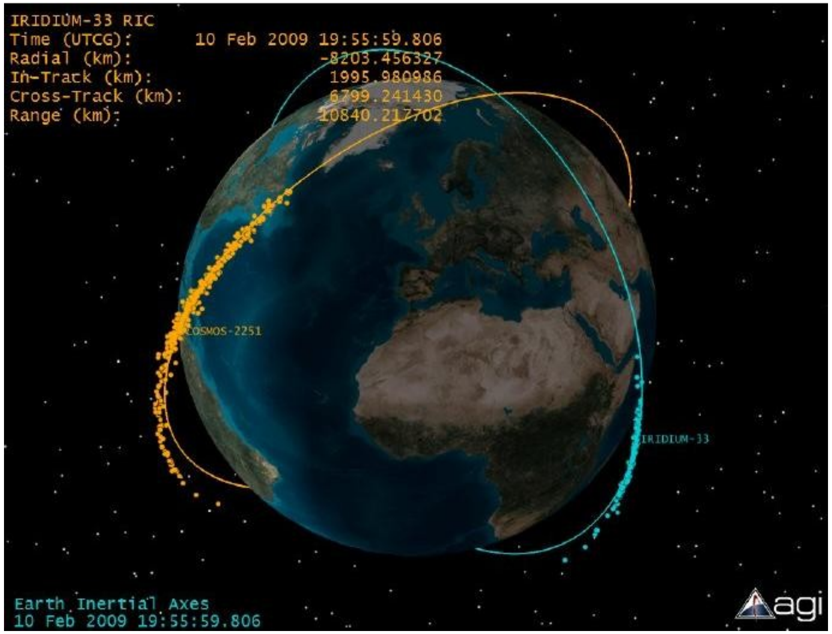
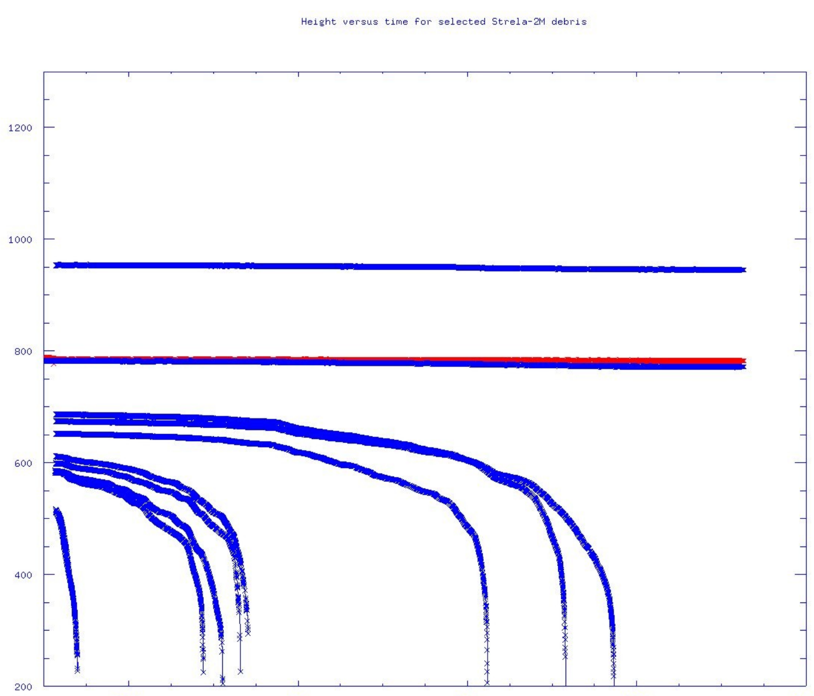


Figure from Kelso 2009





3 hours post collision (image from Kelso 2009) the debris spreads out along the orbit of each satellite

(compare meteor streams along comet orbits)

Eventually debris objects spread in RA due to differential orbital precession to make a shell

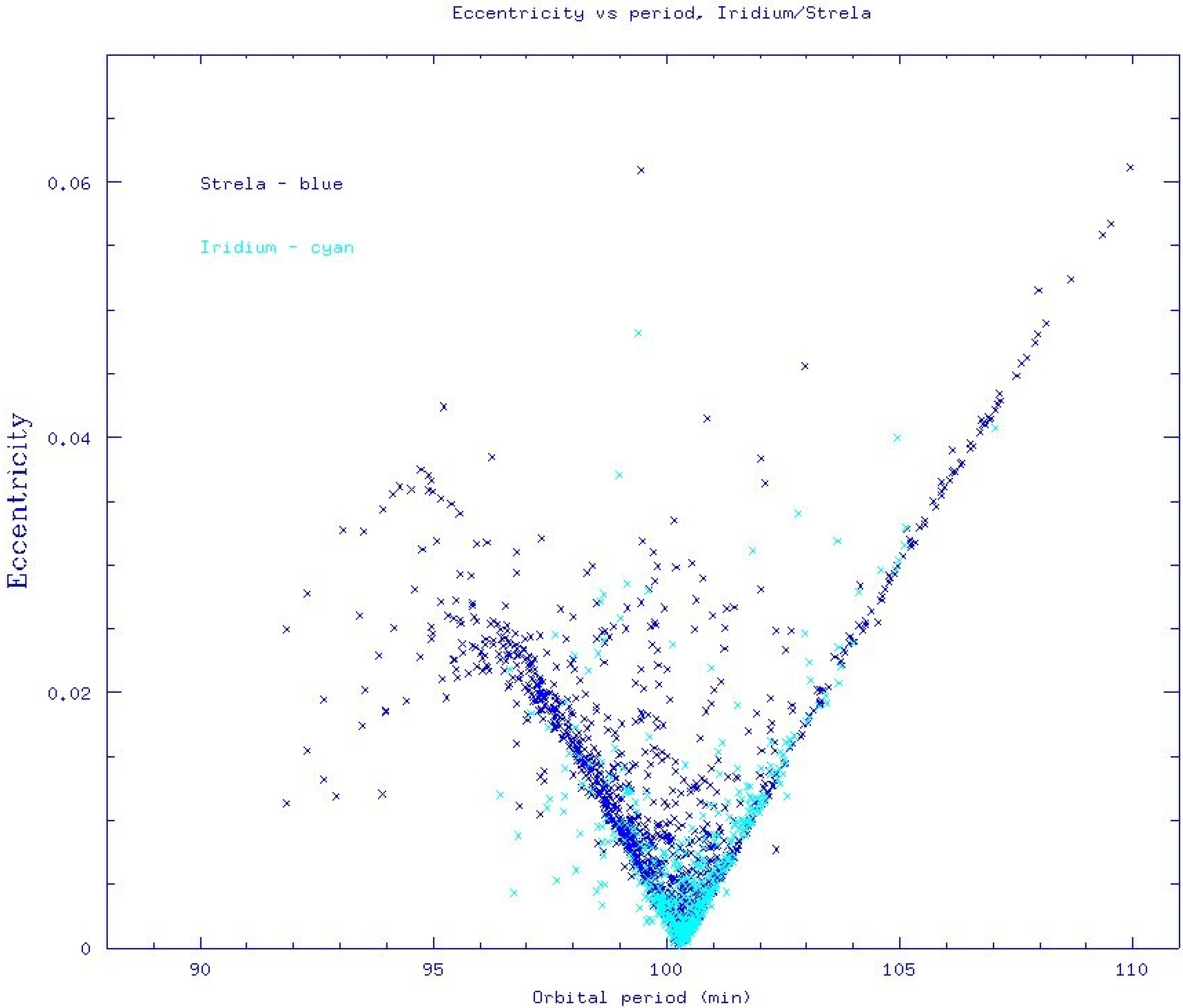
Also spread in altitude due to varying A/m ratio and hence drag coefficient

For small, light debris objects, atmospheric drag significant even at these altitudes (altitude data derived from NORAD/USSTRATCOM orbital elements via Space-Track.Org)

Current status:

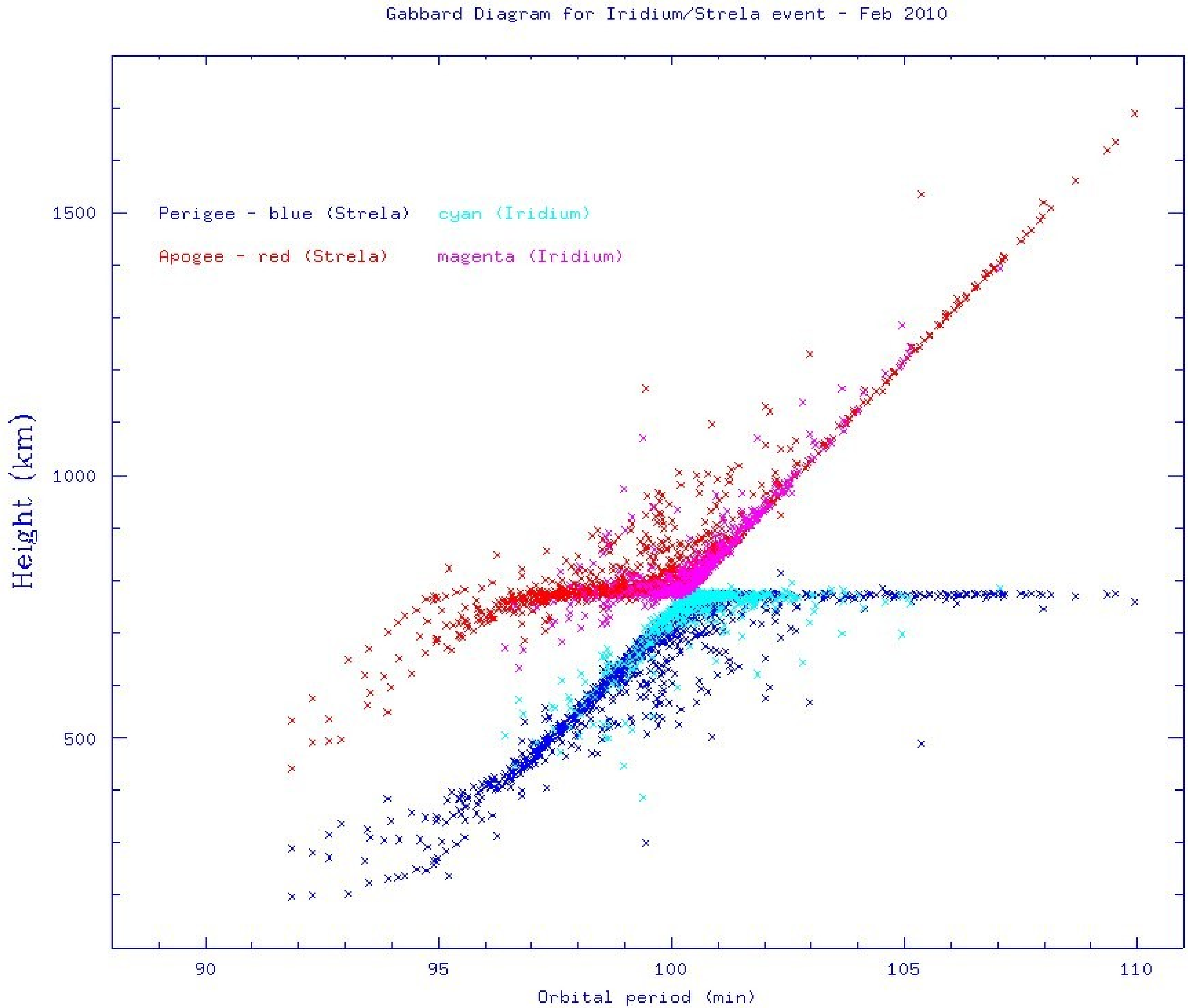
Iridium debris - 629 cataloged 286 reentered

Strela debris: 1667 cataloged 566 reentered

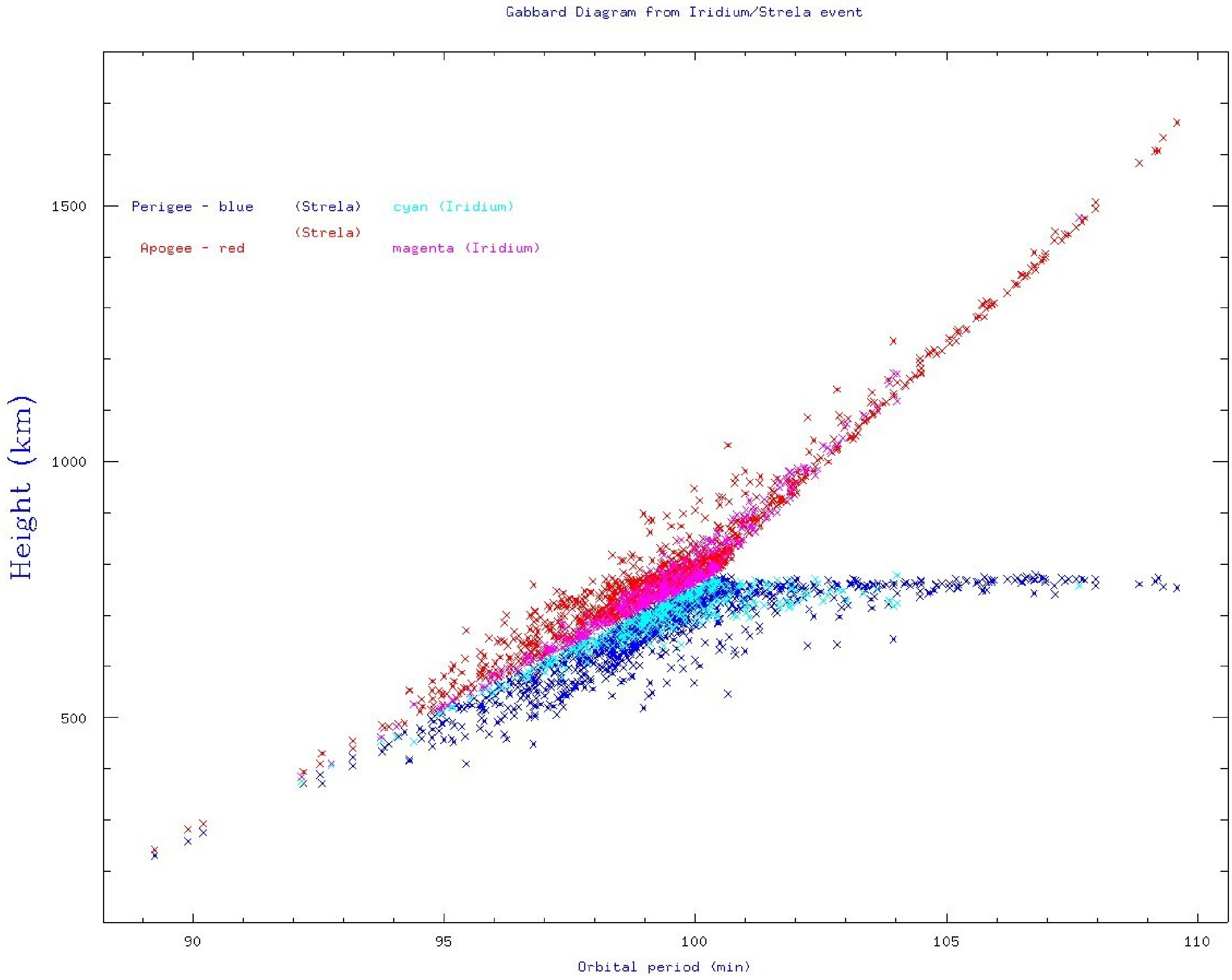


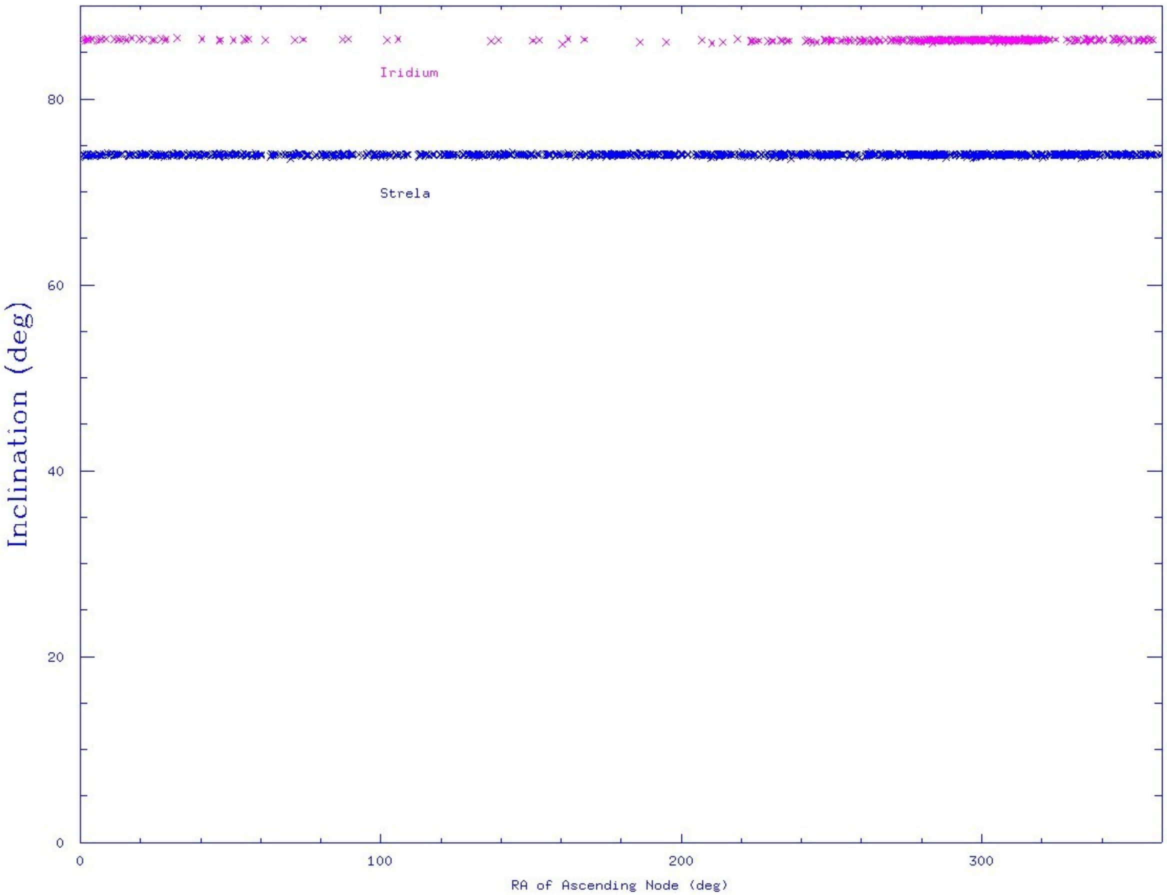
Eccentricity vs period, Iridium/Strela
Strela - blue
Iridium - cyan
Eccentricity
0.06
0.04
0.02
0
90
95
100
105
110
Orbital period (min)

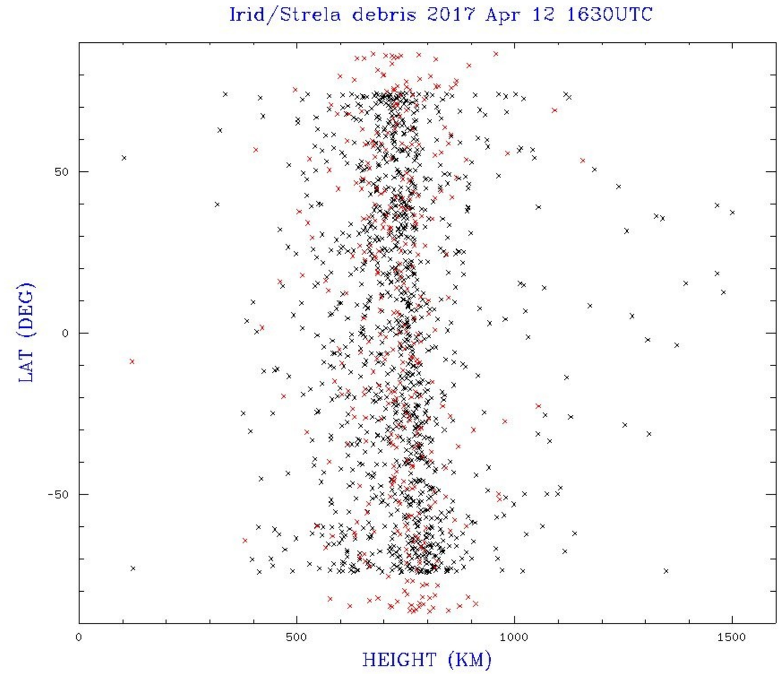
Gabbard Diagram (developed by NORAD's J. Gabbard in 1960s) shows perigee, apogee vs orbital period
Can see different ejection energies of debris objects

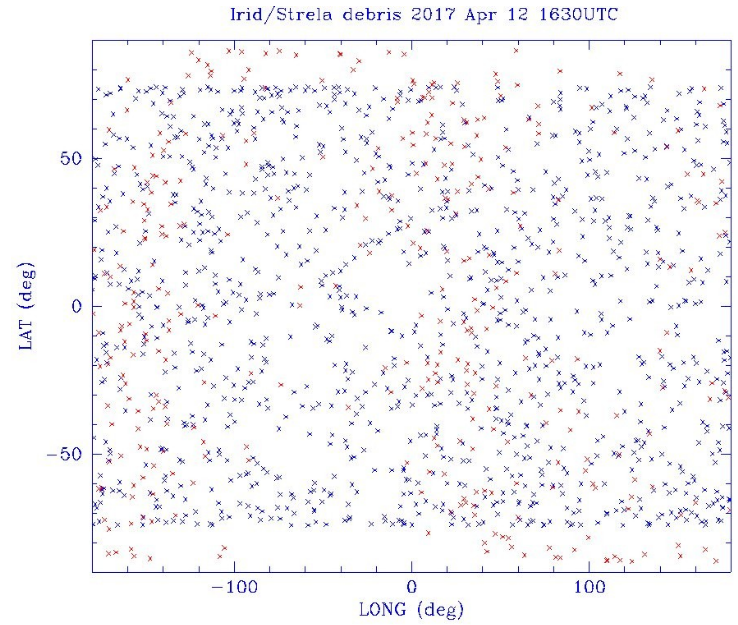


Gabbard Diagram for same event, updated to Apr 2017
Orbital decay has circularized low period objects









8 years after collision, remaining objects have spread around the Earth - all ascending node longitudes filled. But inclinations retain imprint of original two satellites.

GEO debris

GEO collisions are not so bad -   r/R is 6 times larger so Keplerian velocity is sqrt(6) times smaller.

All GEO payloads going the same way round at same inclination so relative velocities are small: typically < 0.1 km/s or less for a relocating satellite

The real debris problem is from exploded rockets in GTO (Geostationary Transfer Orbit, typically 250 x 35700 km with 5 to 50 degree inclination)

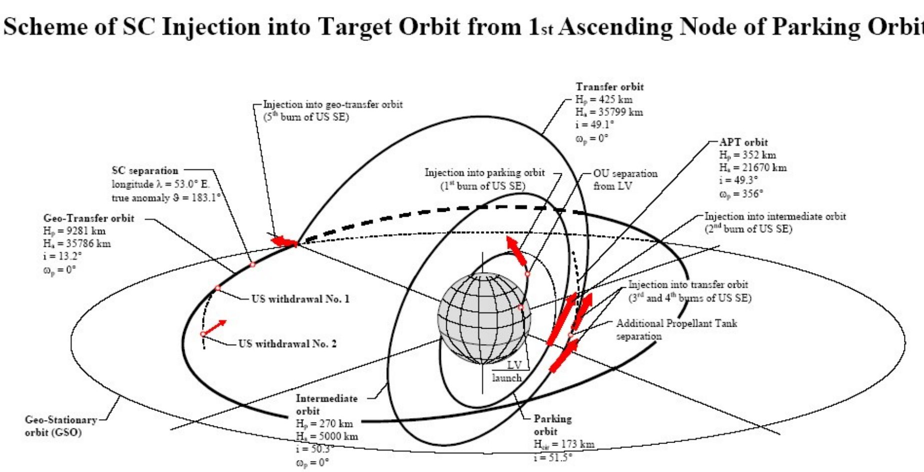
Catalog incompleteness for these is high; some data from optical telescopes, little from radars due to r**-4 dependence

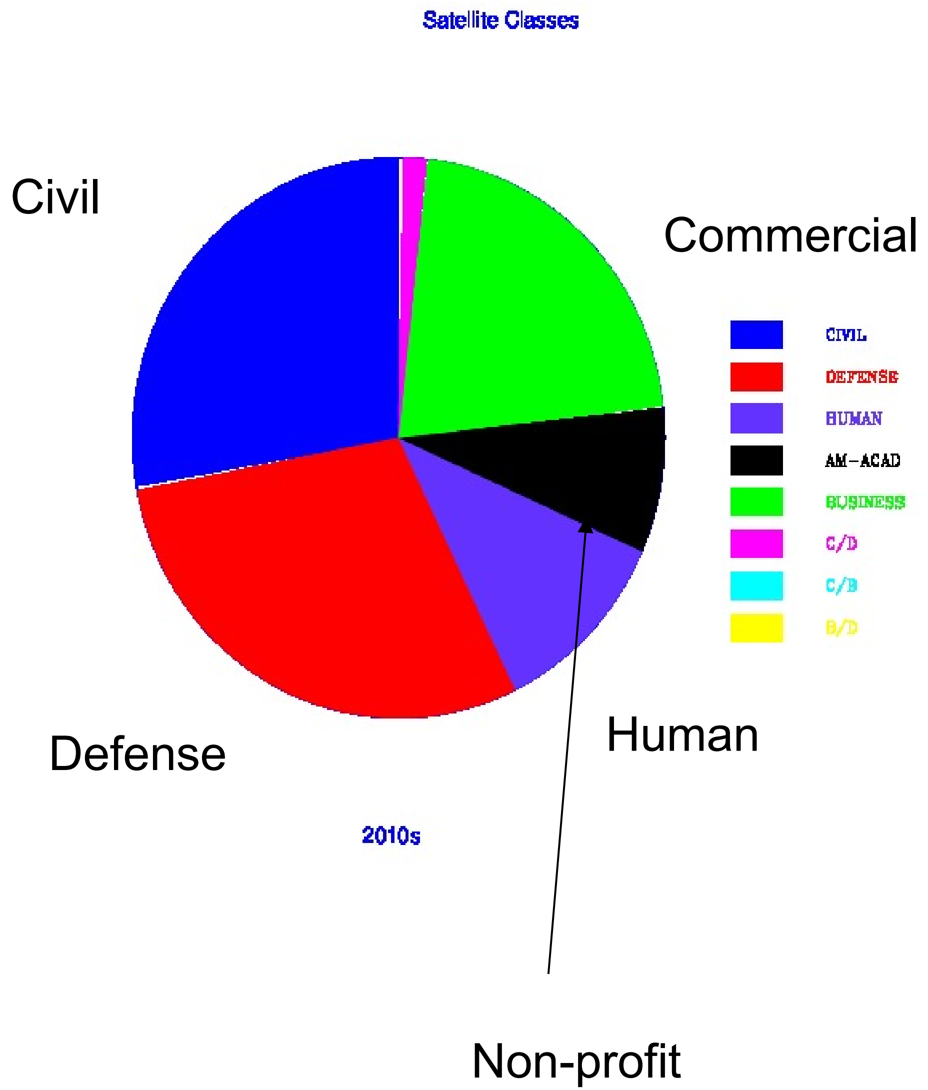
Consider Falcon 9 second stage from Jan 2017 launch of Echostar satellite.
Current orbit is 180 x 35767 km x 22.5 deg.
Apogee velocity is 1.60 km/s

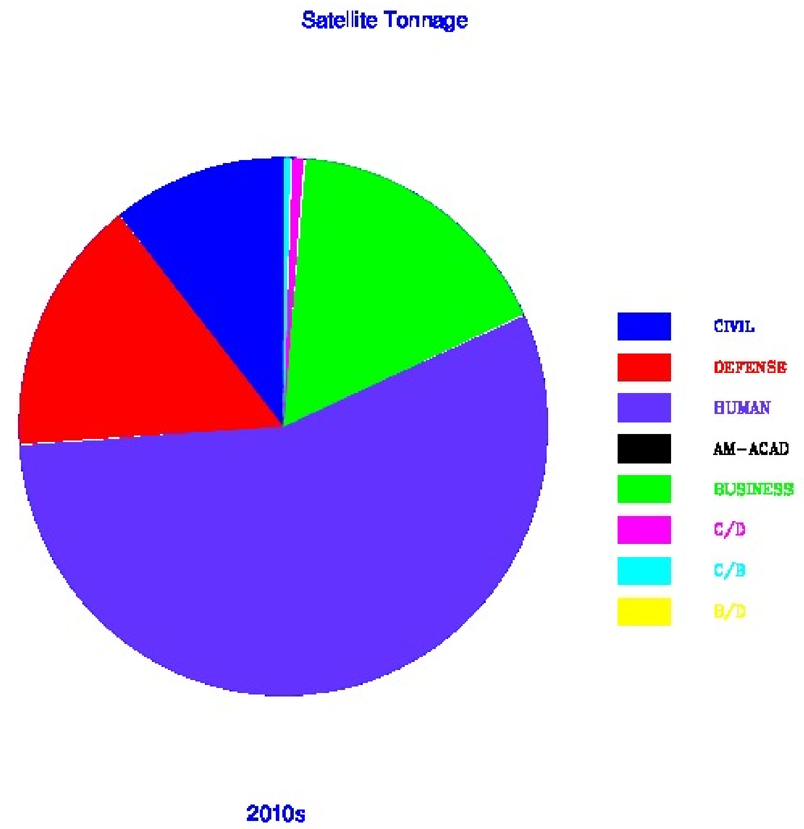
Echostar 23 payload is in 35777 x 35795 km x 0.1 deg orbit
Orbital velocity is 3.07 km/s

If they collided relative velocity would be (doing the vector math) 1.7 km/s
- 47 times less KE/kg than the Iridium-Strela event

Proton launch profile for Turksat-4B
(Khrunichev)



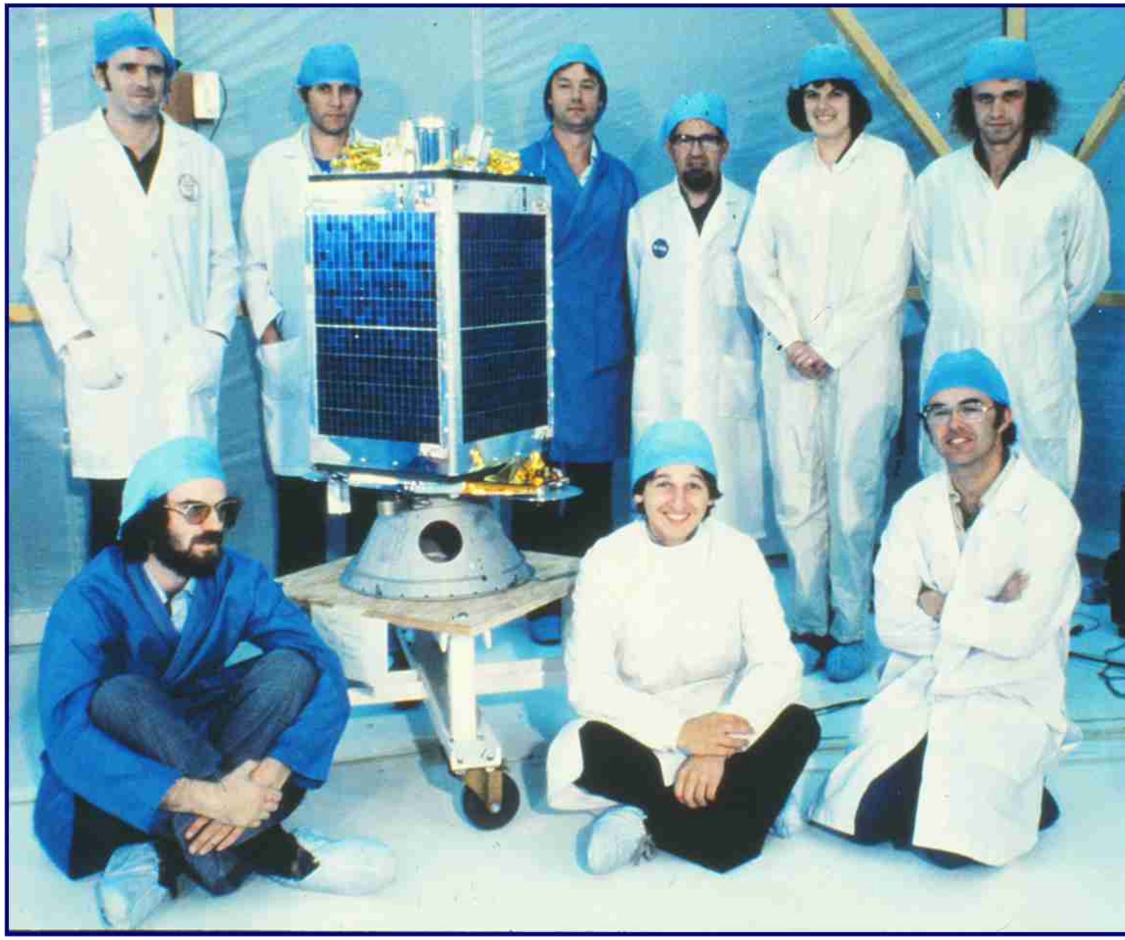




Lump all countries together – division between military, civilian and commercial is about even if you exclude human spaceflight (most of the tonnage, and money)

Non-profit an important sector by number of satellites, but tonnage is negligible

Guildford, 1981: University of Surrey team (under Martin Sweeting) builds amateur radio satellite UoSat-1
It becomes the basis of a series of cheap commercial satellites affordable by developing countries

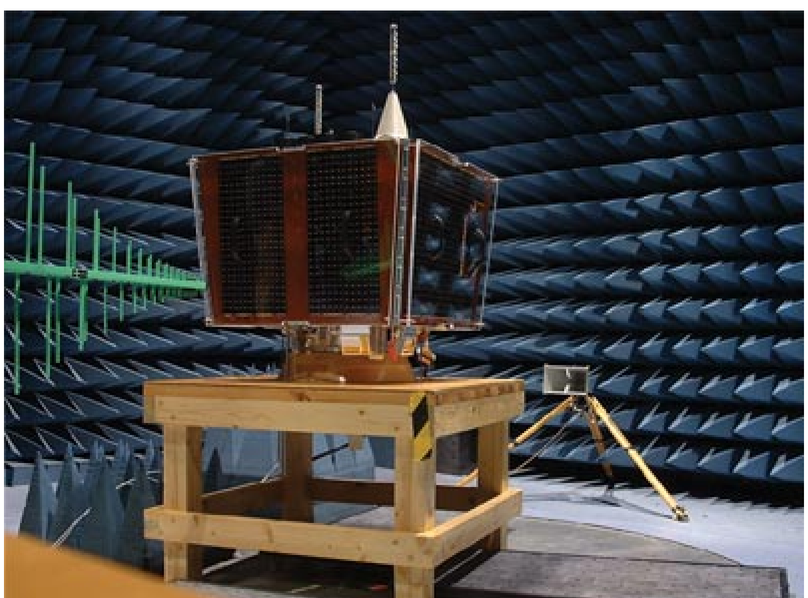


Alsat (Algeria) 2002

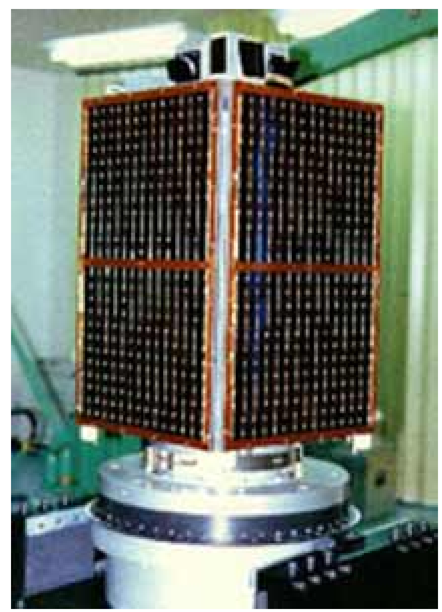
Tiungsat (Malaysia) 2000

Fasat (Chile) 1998

Posat (Portugal) 1993



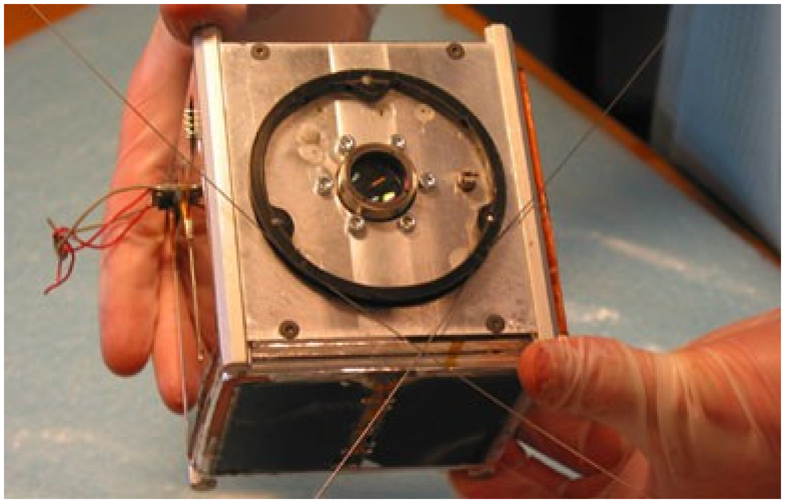
Bilsat (Turkey) 2003



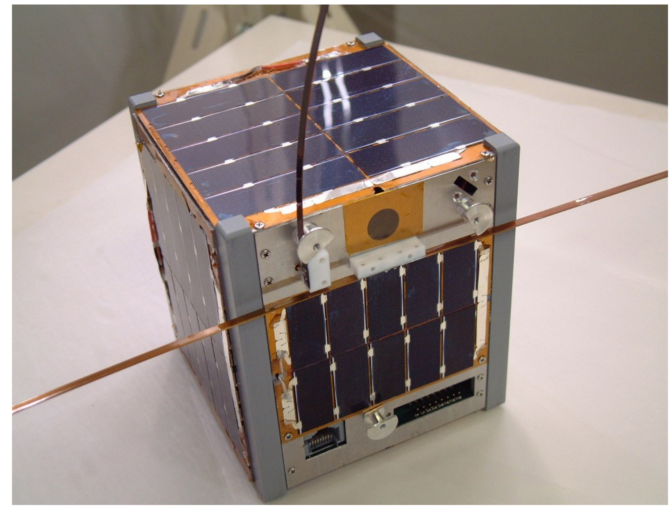
Uribyol
S Korea 1992

Nigeriasat-2 2011

Cubesats: 1 kg, 10 cm (2 lb, 4 in for the metric impaired)
Standard kit for universities to make students build sats in engineering courses
Can also make '3U' cuboids 30 x 10 cm
97 Cubesats launched 2003-Feb 2013 by 66 organizations in 20 countries



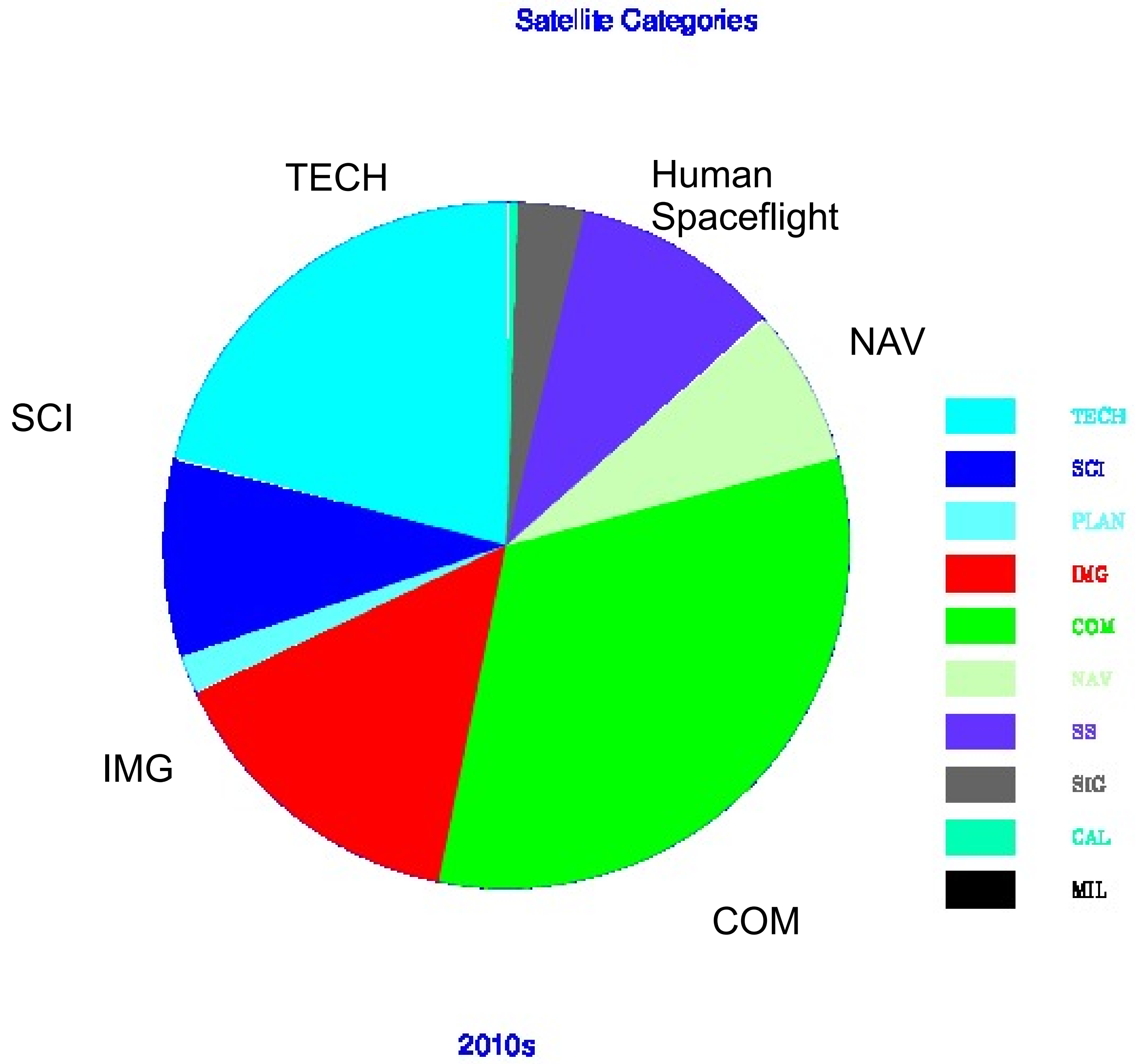
Aalborg U. 2003



Univ. of Tokyo, 2003

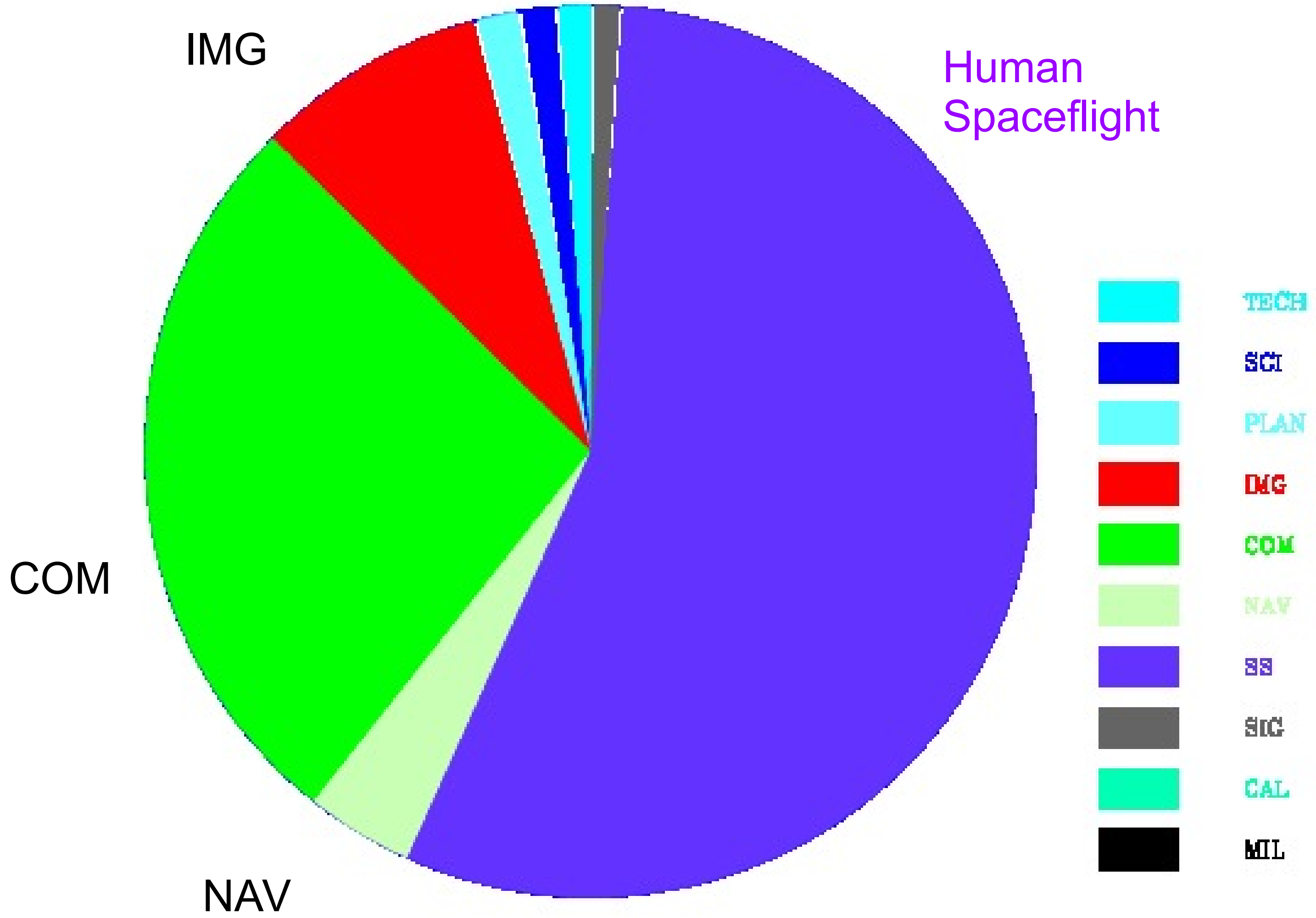
Cubesat deploy from ISS, 2012

Triple-cube Quakesat, Stanford 2003



In the 2010s, most sats are either communications or imaging; technology development (including student satellites) also a big sector

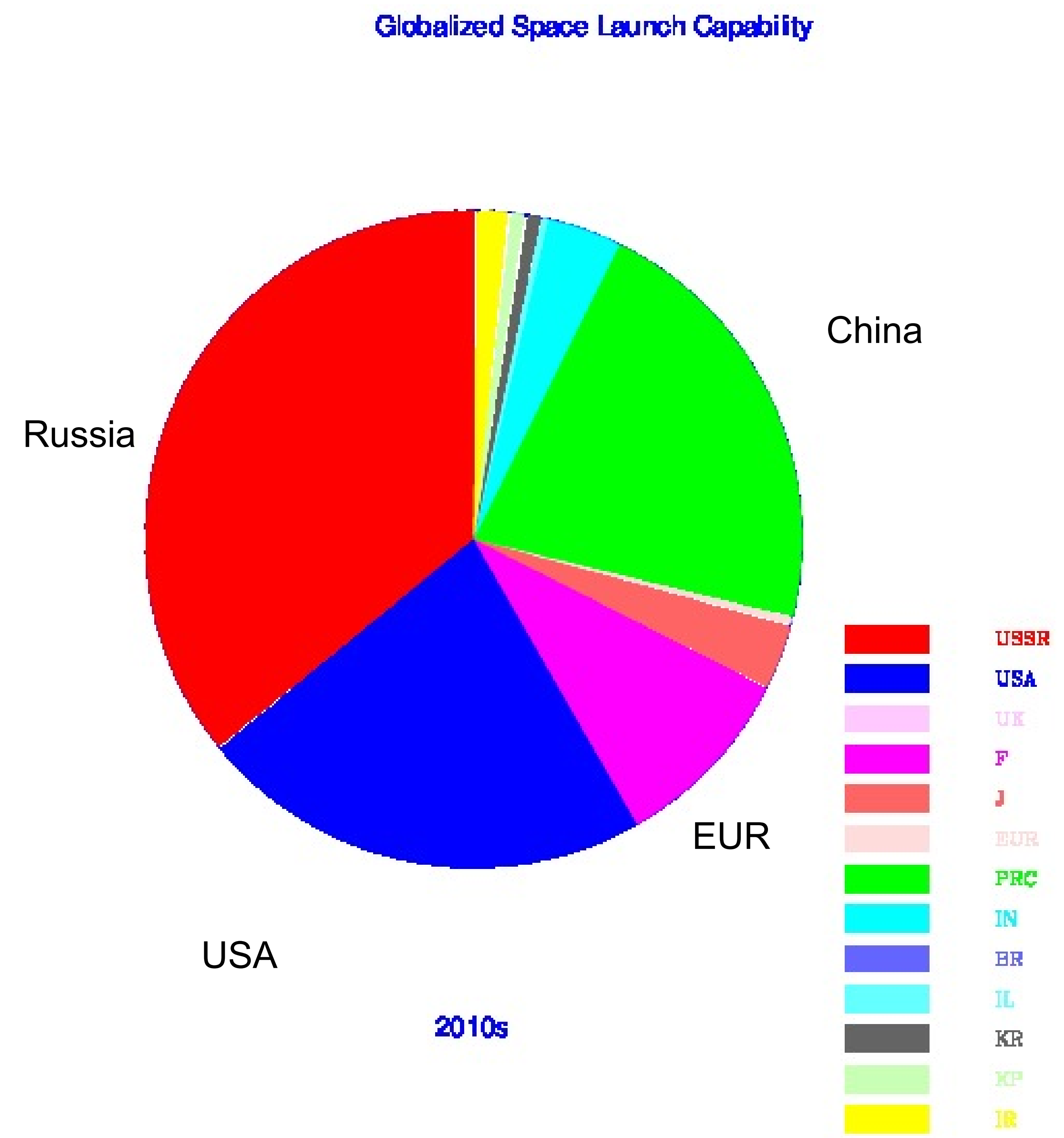
Satellite Tonnage (including human spaceflight)



2010s

By mass however, human spaceflight dominates – comms still next
Tech/student satellites vanish, they are mostly little cubesats which don't weigh much

4-yr total 900 t robotic, 1100 t 6 x Shuttle + ISS/PRC

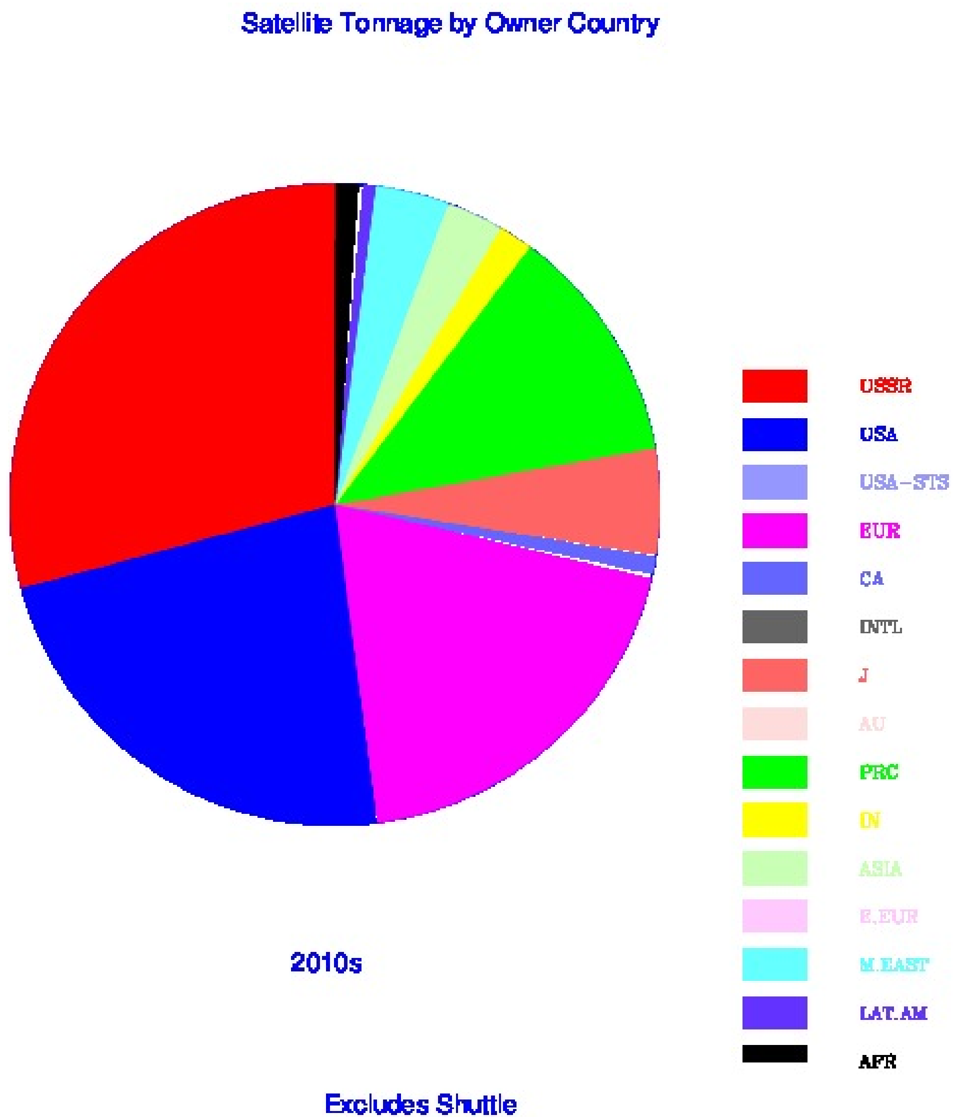


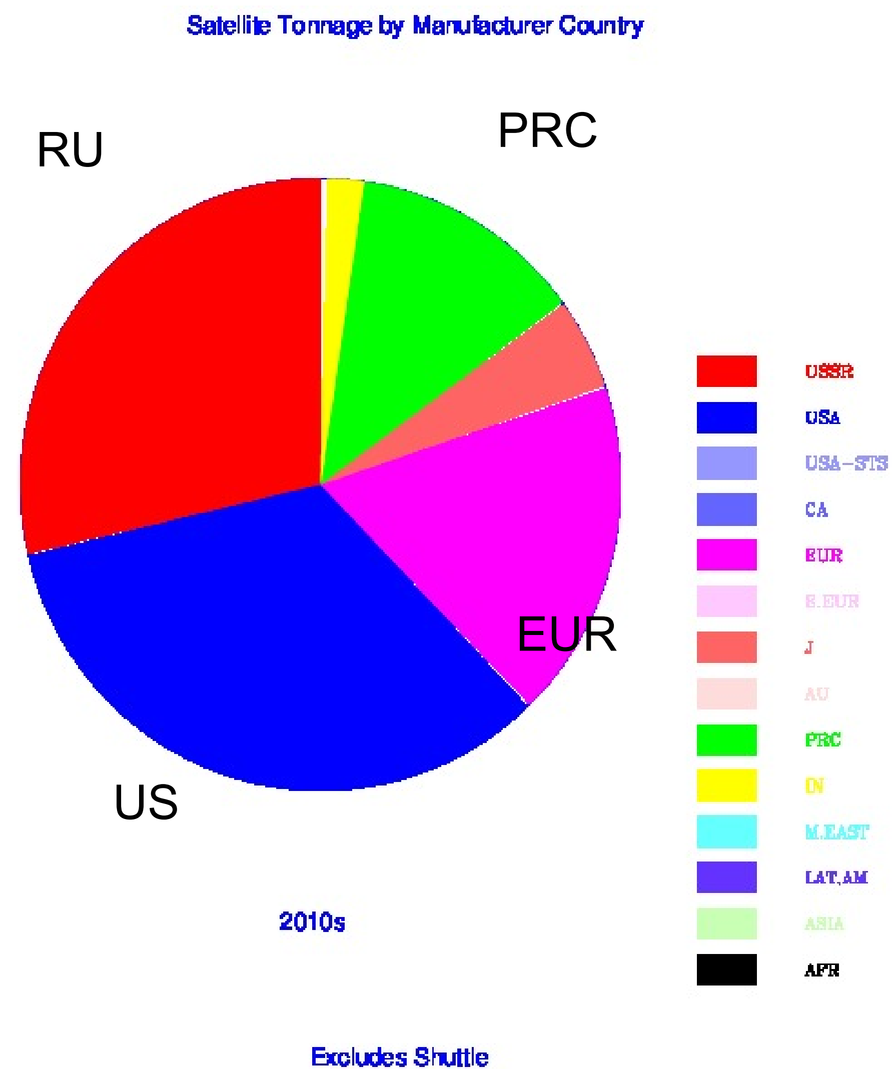
Today the space launch market has many more players

In 2012 China had as many orbital launch attempts as the US

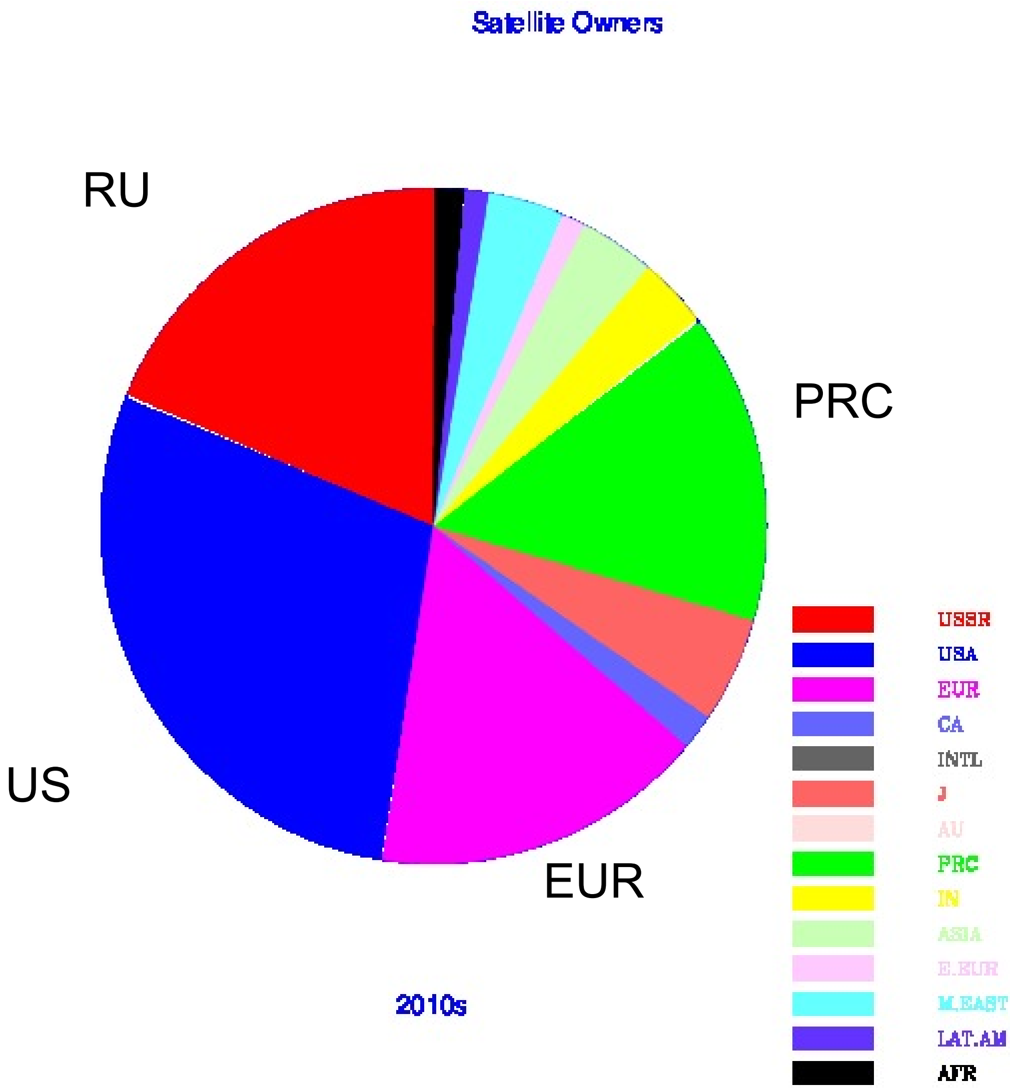
12 countries plus ESA/Arianespace have launched satellites; Brazil has also tried but failed.

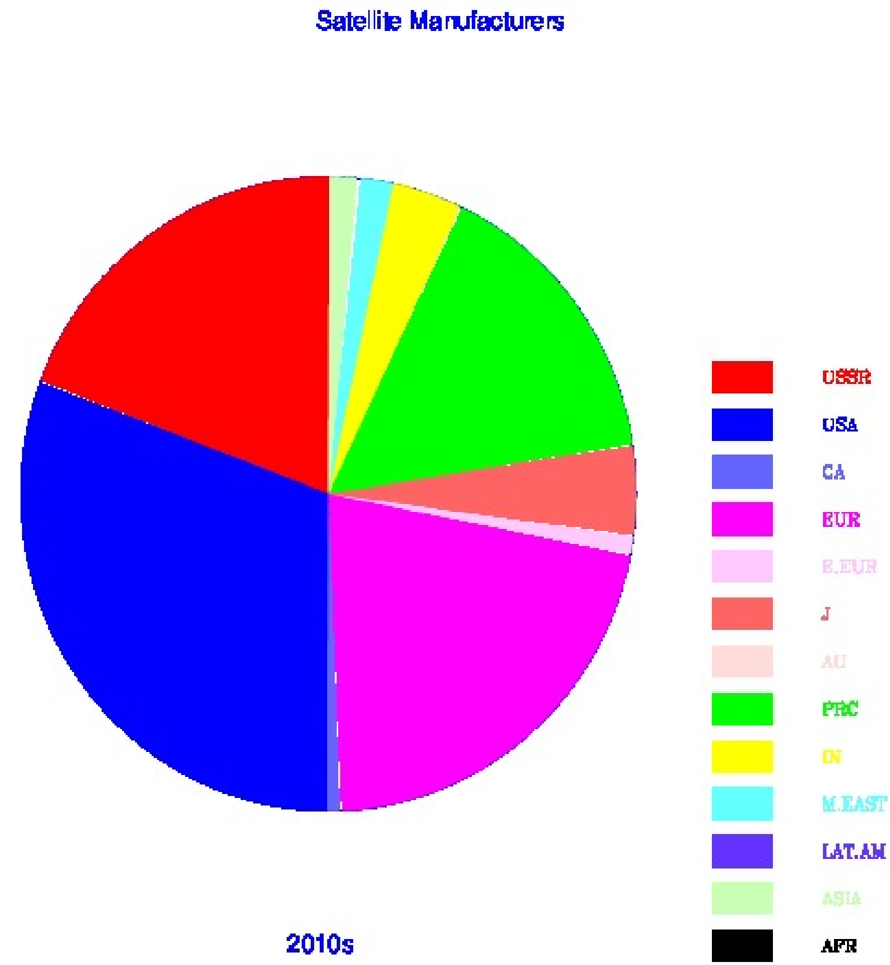
North and South Korea are the latest members of the club





The 'other' countries almost vanish when considering tonnage -
Their satellites are usually tiny cubesats





Lots of countries OWN satellites – too many to show on the chart, so I grouped together E. Europe (pink), Africa (black), Latin America (dark purple), and Asia-other-than-China/India/Japan (light green)

Russia, US, W. Europe and China dominate; next Japan (orange), and India (yellow)