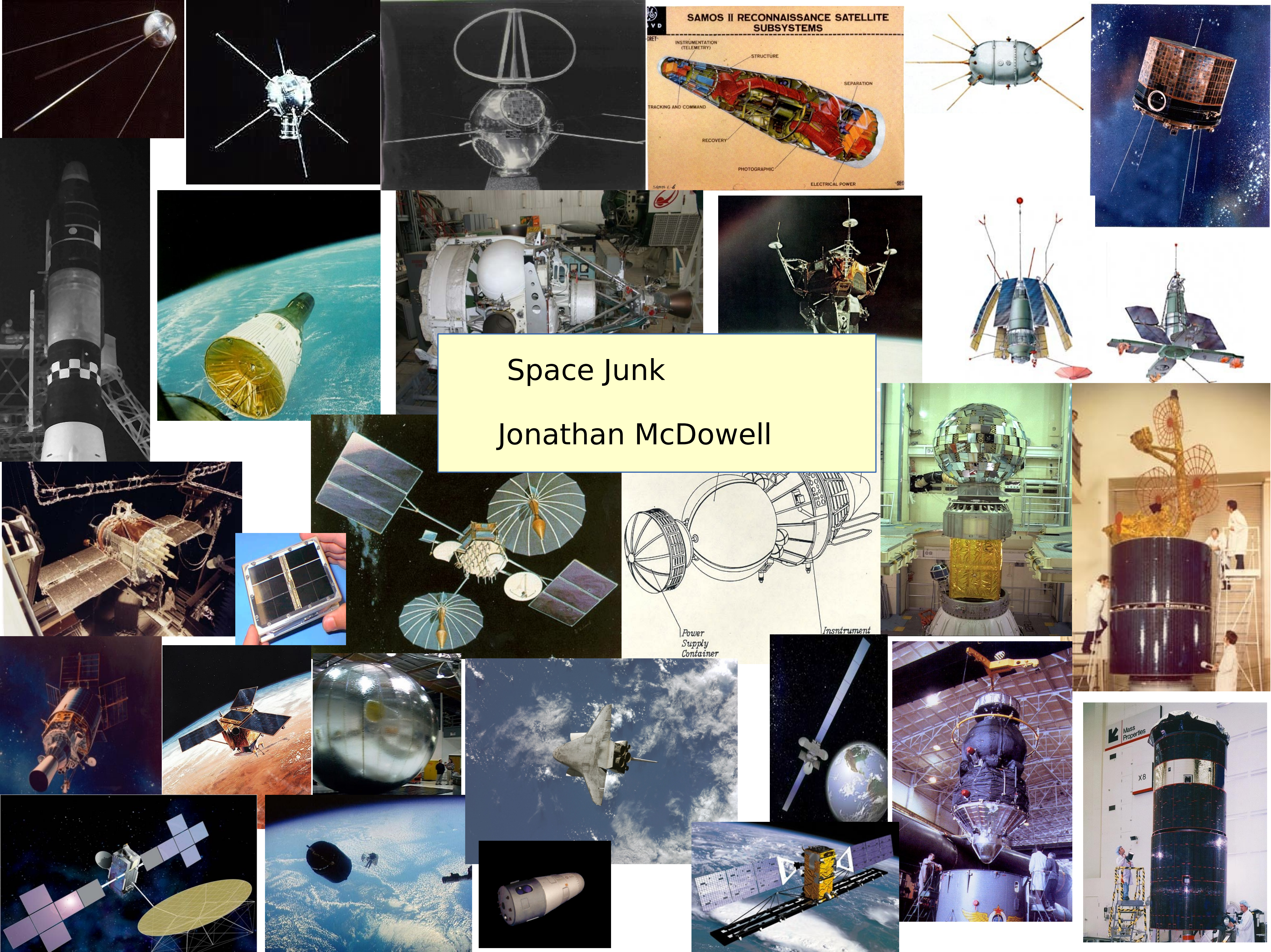
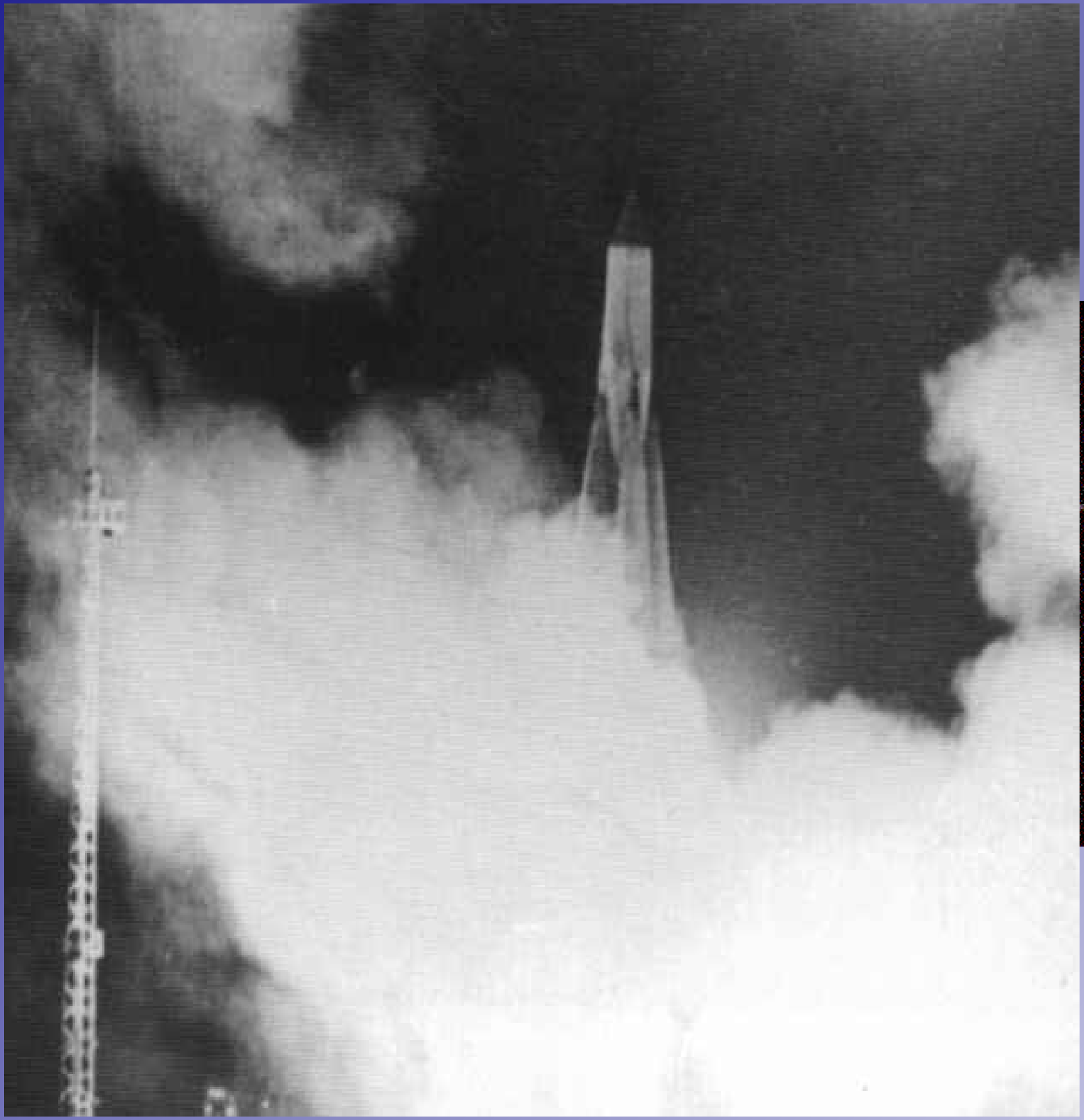
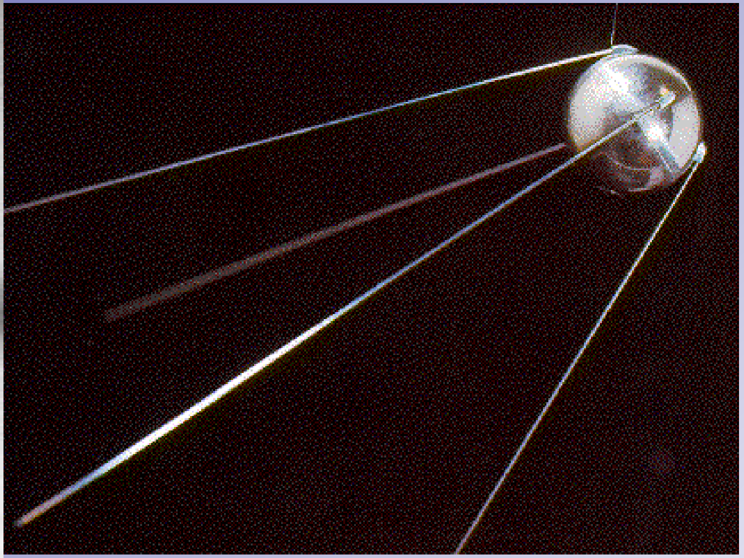
Space Junk

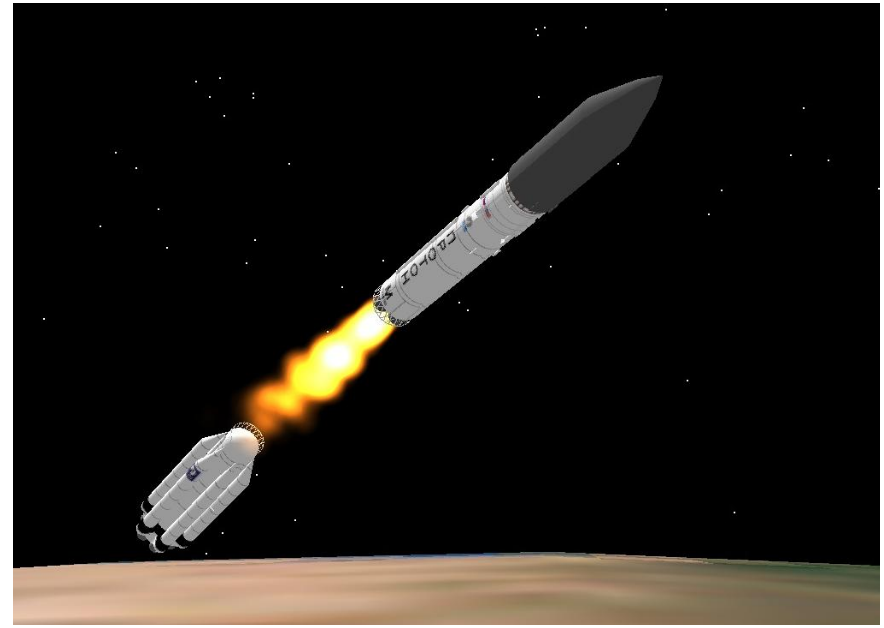
Jonathan McDowell

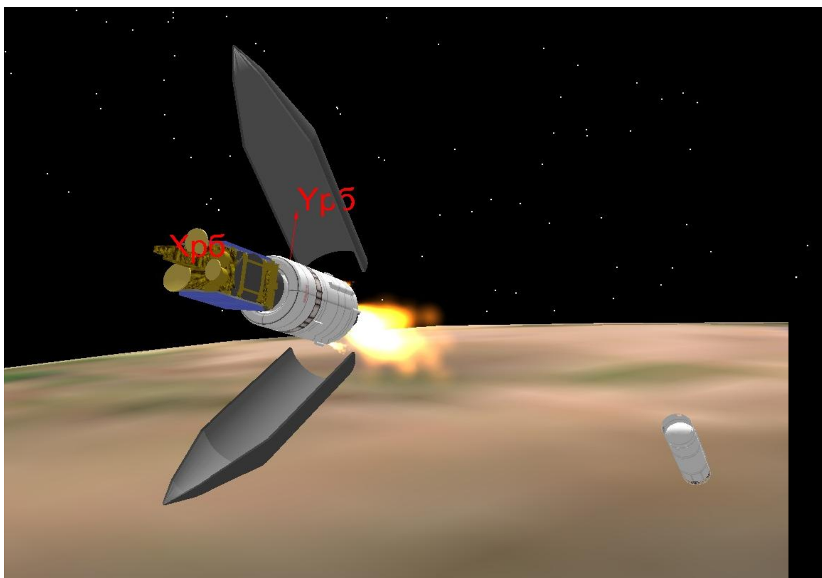


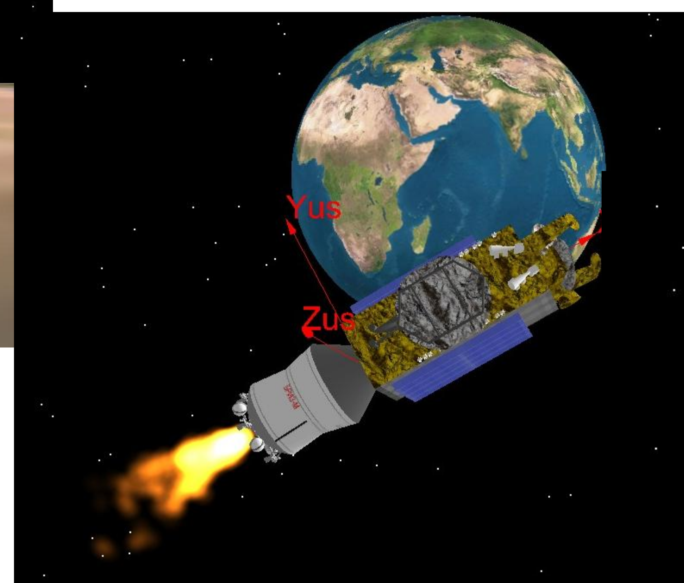
October 1957: Sputnik

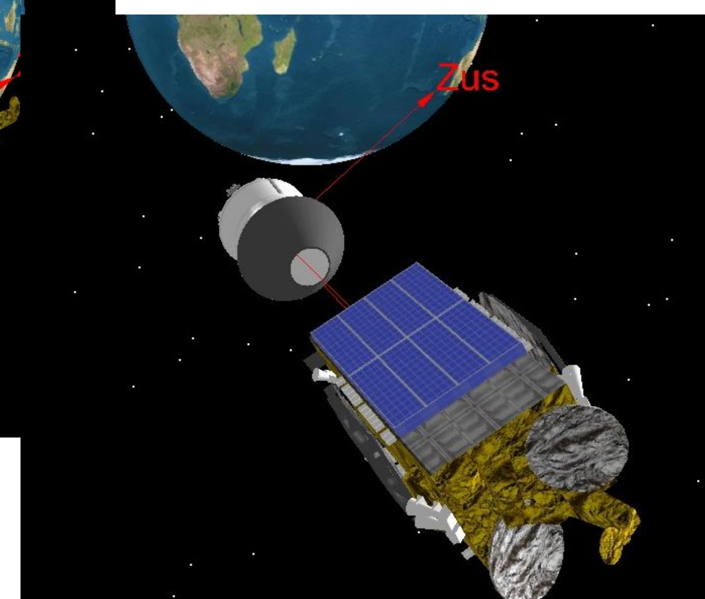












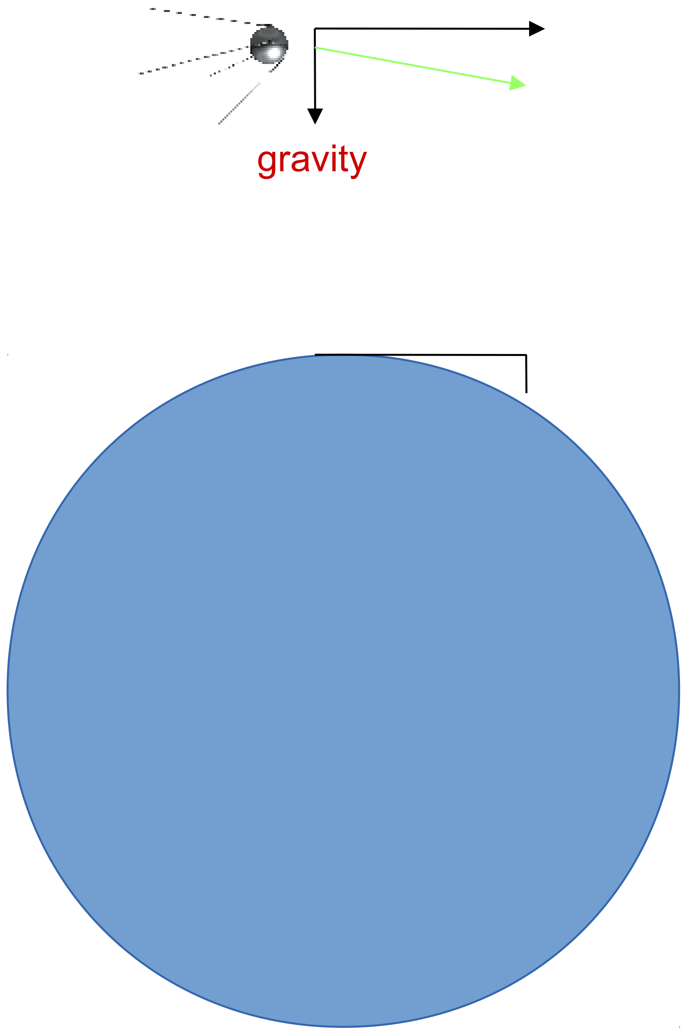
A typical satellite launch ends up with at least two objects in orbit – the satellite and the last piece (“stage”) of the rocket that got it there

Credit: Khrunichev

WHAT IS “ORBIT” ?

In 1 second:
Moves sideways 5 miles
Falls 30 feet

ORBIT: 200 miles up
Moving sideways at
7.7 km/s
(17259 mph)

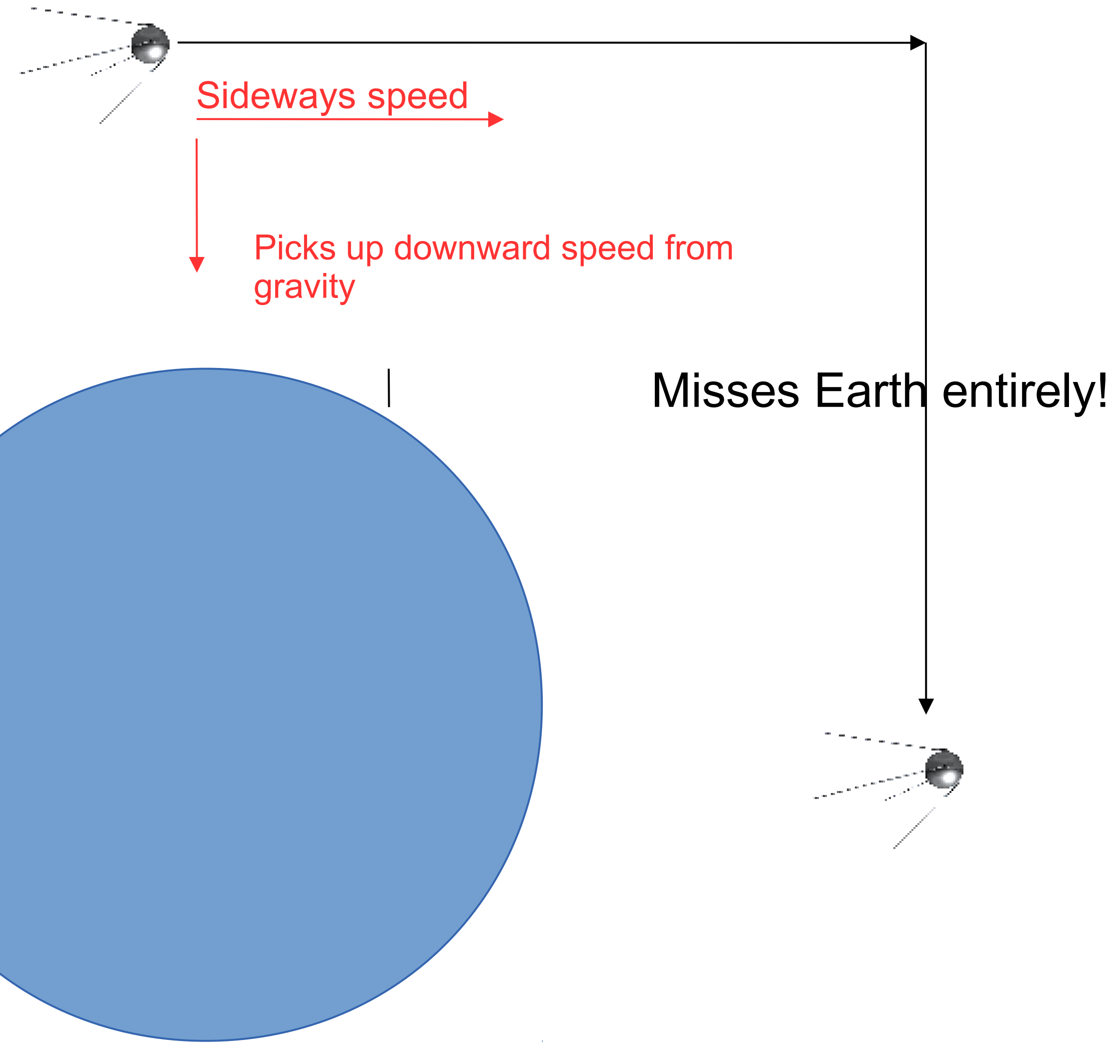


In that 5 miles,
Earth curves away
from you by 30 feet!

End up the same height above the Earth -
Fall all the way around the Earth in a circle

In 23 minutes, falls 4000 miles
BUT: moves sideways 4000 miles too!

ORBIT: 200 miles up
Moving sideways at
7.7 km/s
(17259 mph)



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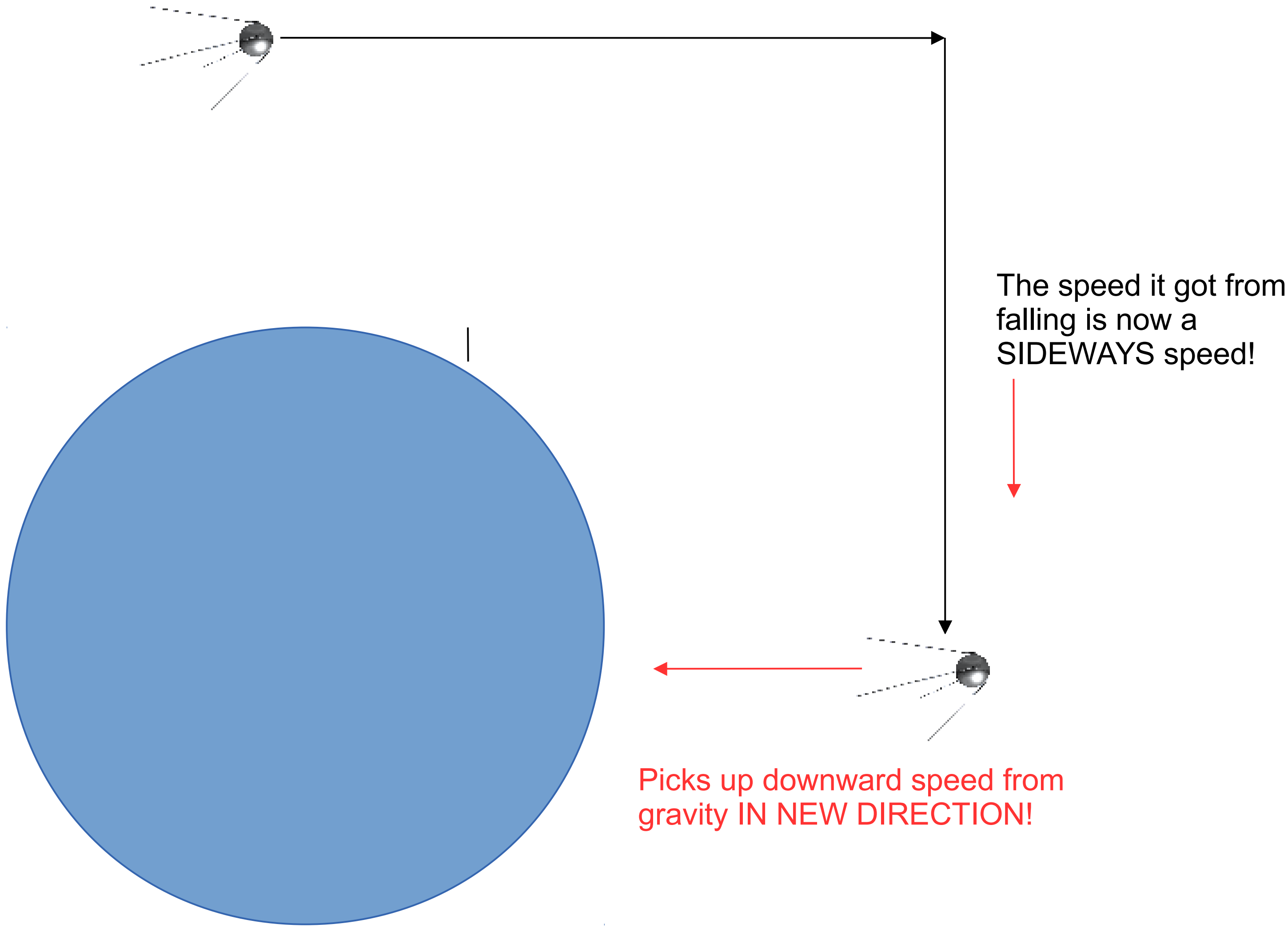

Fall around and around the Earth, always missing it!
SIDEWAYS speed makes you miss the Earth
FALLING speed becomes the new sideways speed once you turn the corner...
No rocket engine needed to keep you up! [* Offer may not apply in presence of atmosphere]

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.

Space Station ISS has height 400 km (250mi) above Earth,
so distance from ISS to center of Earth is r= 6778 km (4124 mi)

This corresponds to v = 7.67 km/s
or v = 17158 mph - quite fast!!
At 400 km, orbital period is 92.5 minutesEarth surface has radius r = 6378 km (3964 mi)

Low Earth Orbit

Newton’s Gravitation law
(e.g. asteroid or satellite of mass m and Sun or Earth with mass M)

$F = - G m M / r^2$

$V = G M m / r$

Orbital (Kepler) speed

$v = \mathrm{sqrt}(GM / r)$

Kepler’s third law
$T^2 = (4 \pi^2/GM) r^3$

Space Station ISS has height 400 km (250mi) above Earth,
so distance from ISS to center of Earth is r= 6778 km (4124 mi)

This corresponds to v = 7.67 km/s
or v = 17158 mph - quite fast!!
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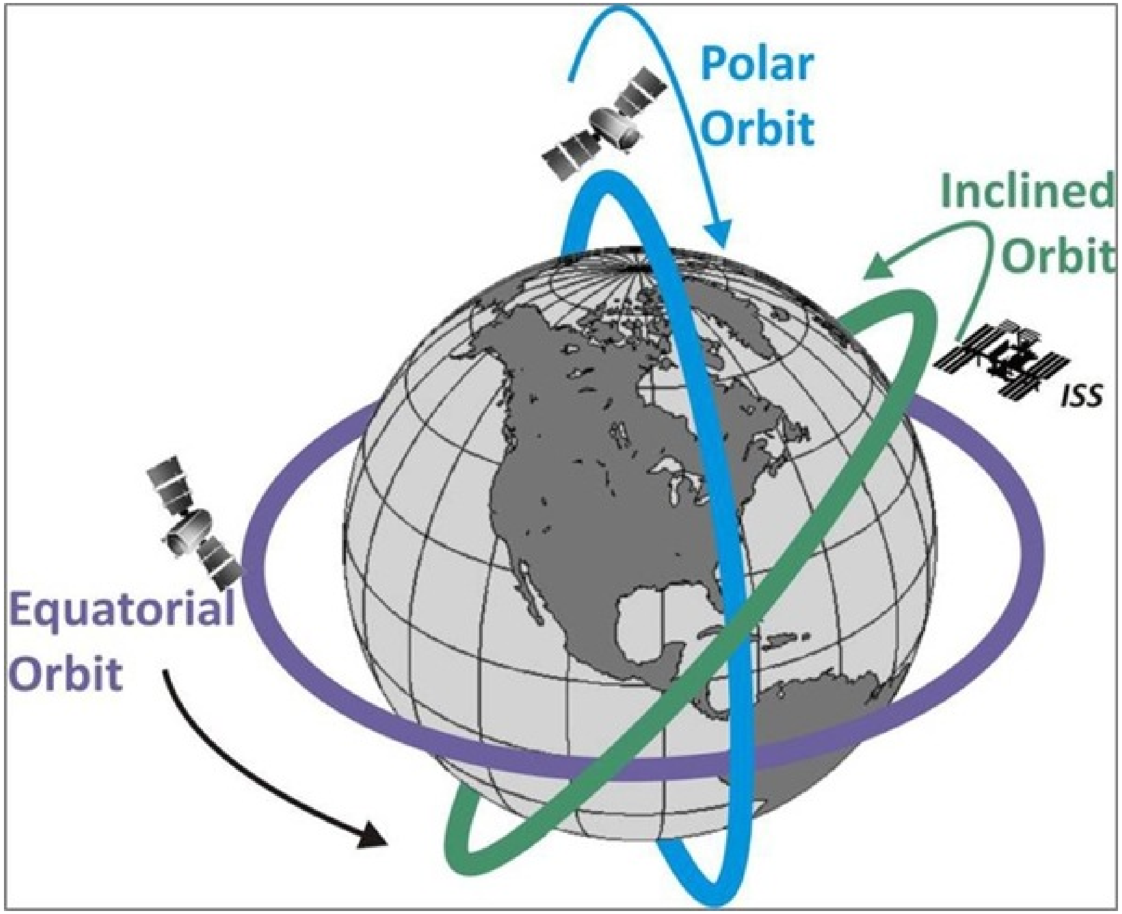
Inclination:

Does the orbit go around the equator, or from pole to pole, or something inbetween?



i = 0 degrees
Equatorial

i = 90 degrees
Polar

Station (ISS) is at
i = 51.6 degrees

Means that it orbits between
51.6 deg North and
51.6 deg South

Image:
hamradioschool.com

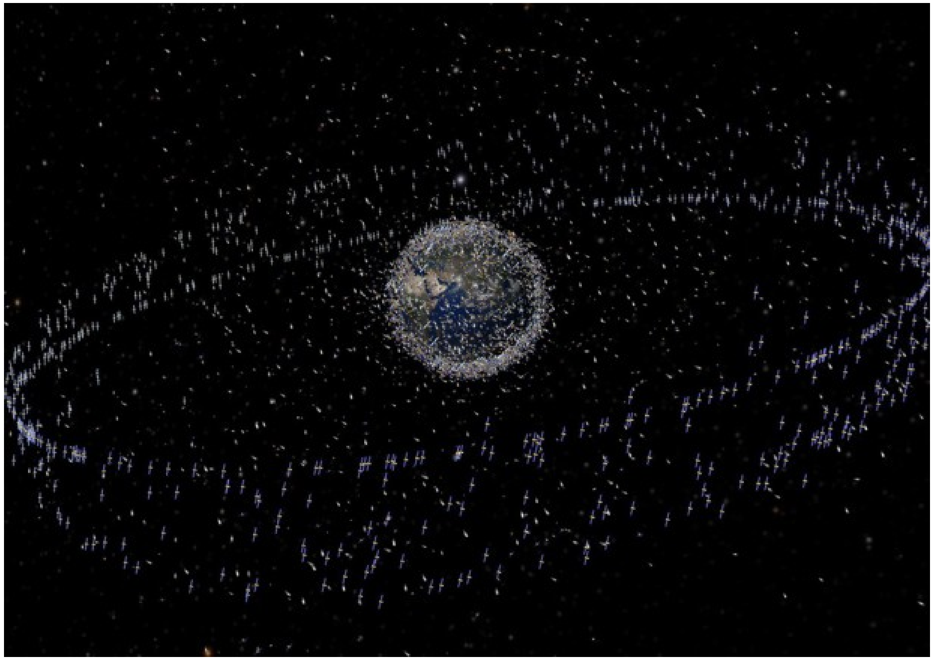
Orbit plane must contain the center of the Earth
Can't orbit in a "small circle" like the yellow line!

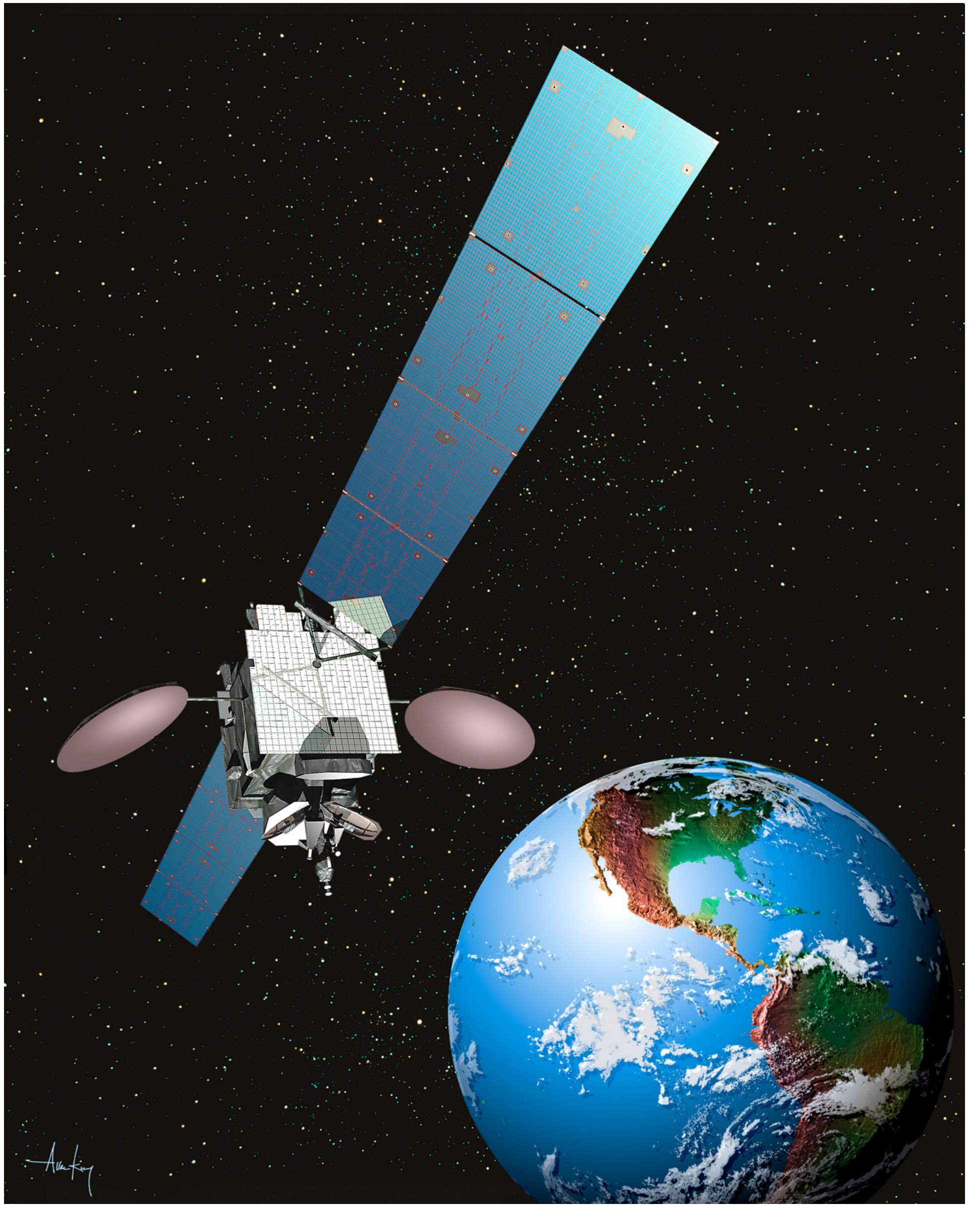
Image: Wikibooks.org

Earth spins to the east
At the equator, the ground is moving eastwards at 1040 mph!
So if you launch your rocket east, you get a free 1040 mph boost
Even at 28 degrees North (Cape Canaveral), free speed is 914 mph
Unless you NEED to go to polar orbit, you'll launch due east and get the free boost
Launching backwards (to the west) is super rare

Image: educationwithfun.com

Earth has its own ‘asteroid belts’
made of artificial objects



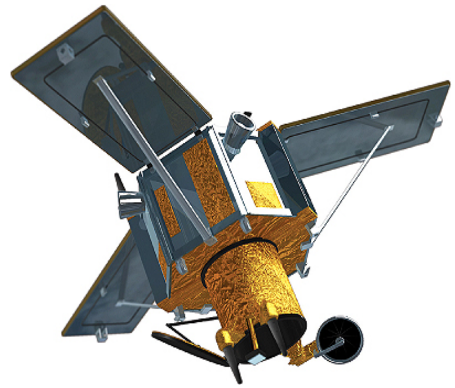


About 2000 satellites currently operating
Some in low orbit skimming just outside the atmosphere, mostly going from pole to pole

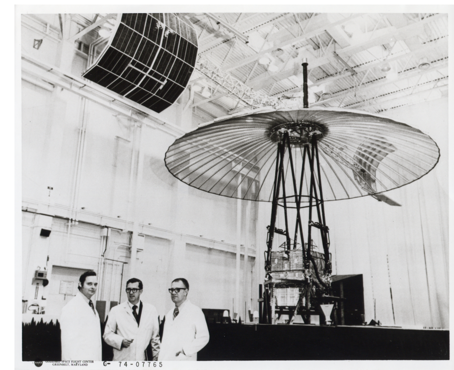
Some In 'geostationary orbit' in a ring high above the equator

Most of what humanity does in space is done with robots -
“artificial satellites”
boxes of electronics with big solar-power-generating wings, commanded from Earth

Communications



Earth Imaging



Signals intelligence

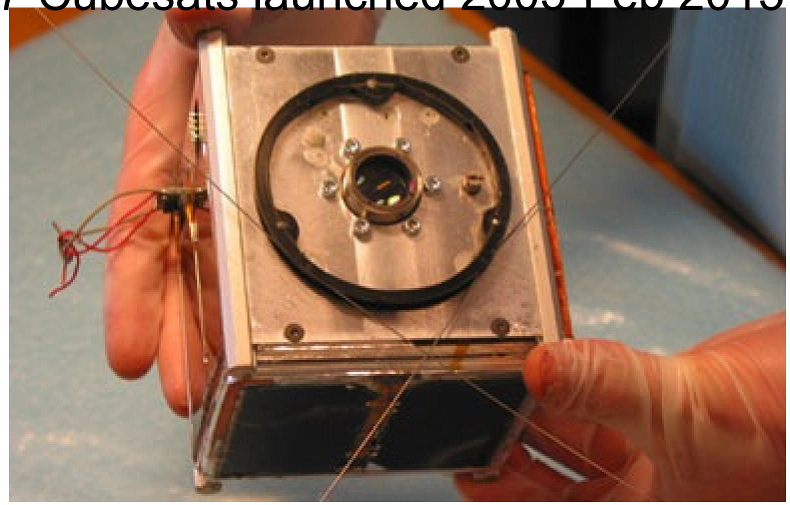
Technology and training

Navigation (GPS)

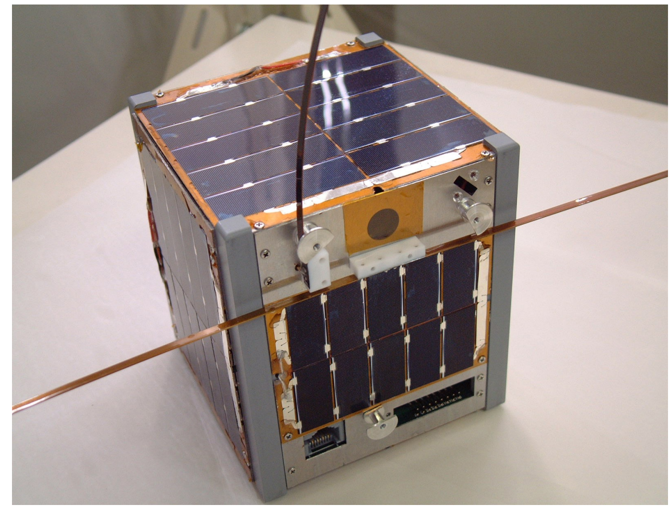
Science
(e.g. astronomy)

Human spaceflight

Satellites can be REALLY TINY:
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



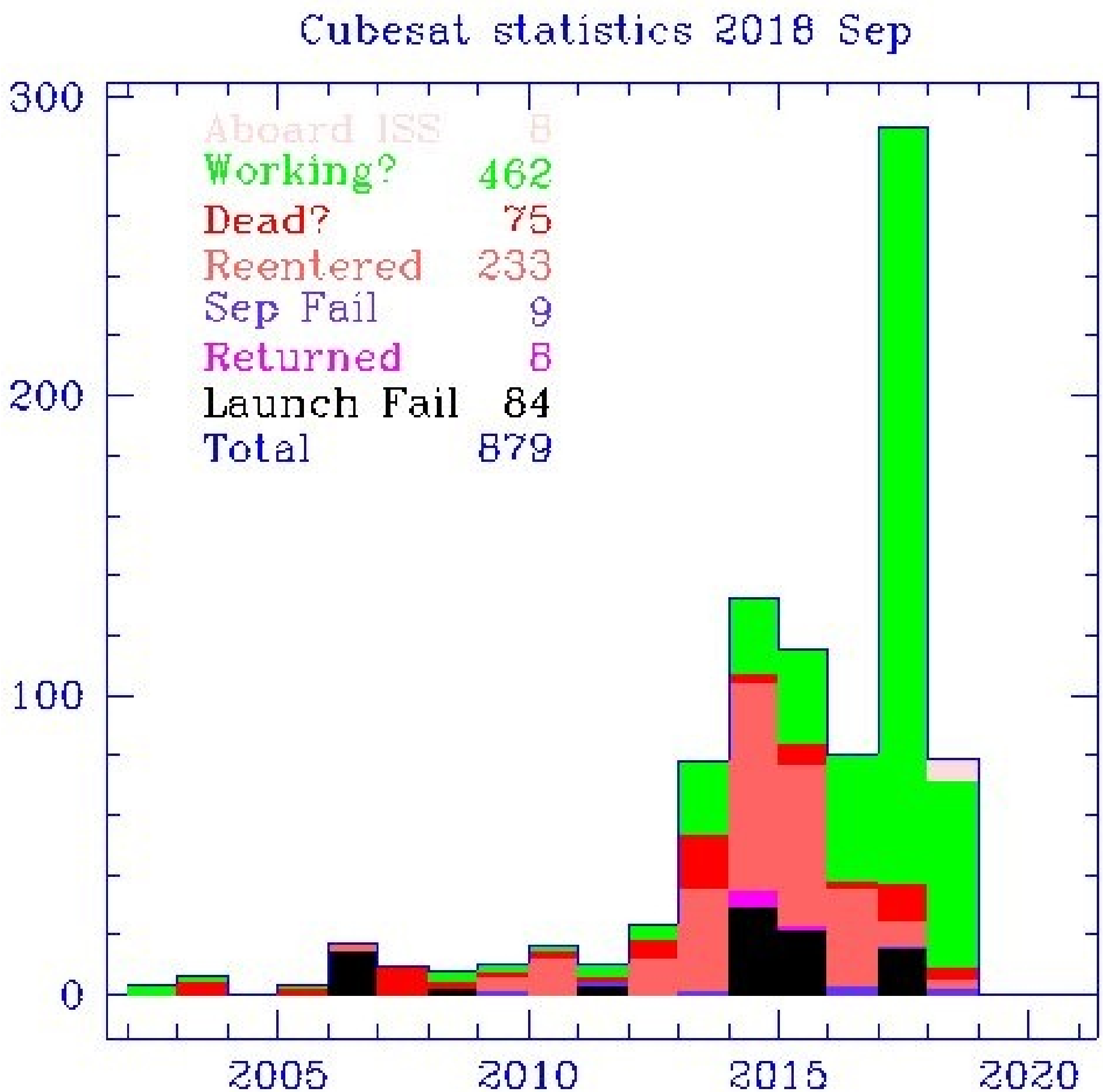
Univ. of Tokyo, 2003

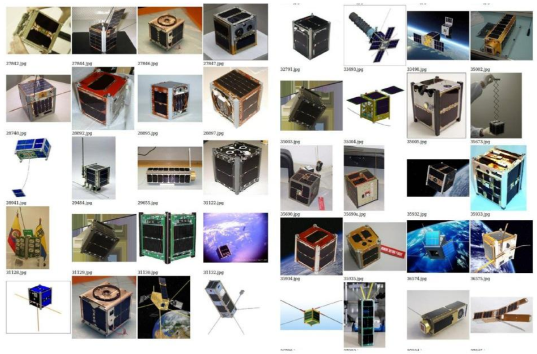
Cubesat deploy from ISS, 2012

Triple-cube Quakesat, Stanford 2003

The Cubesat Explosion

http://planet4589.org

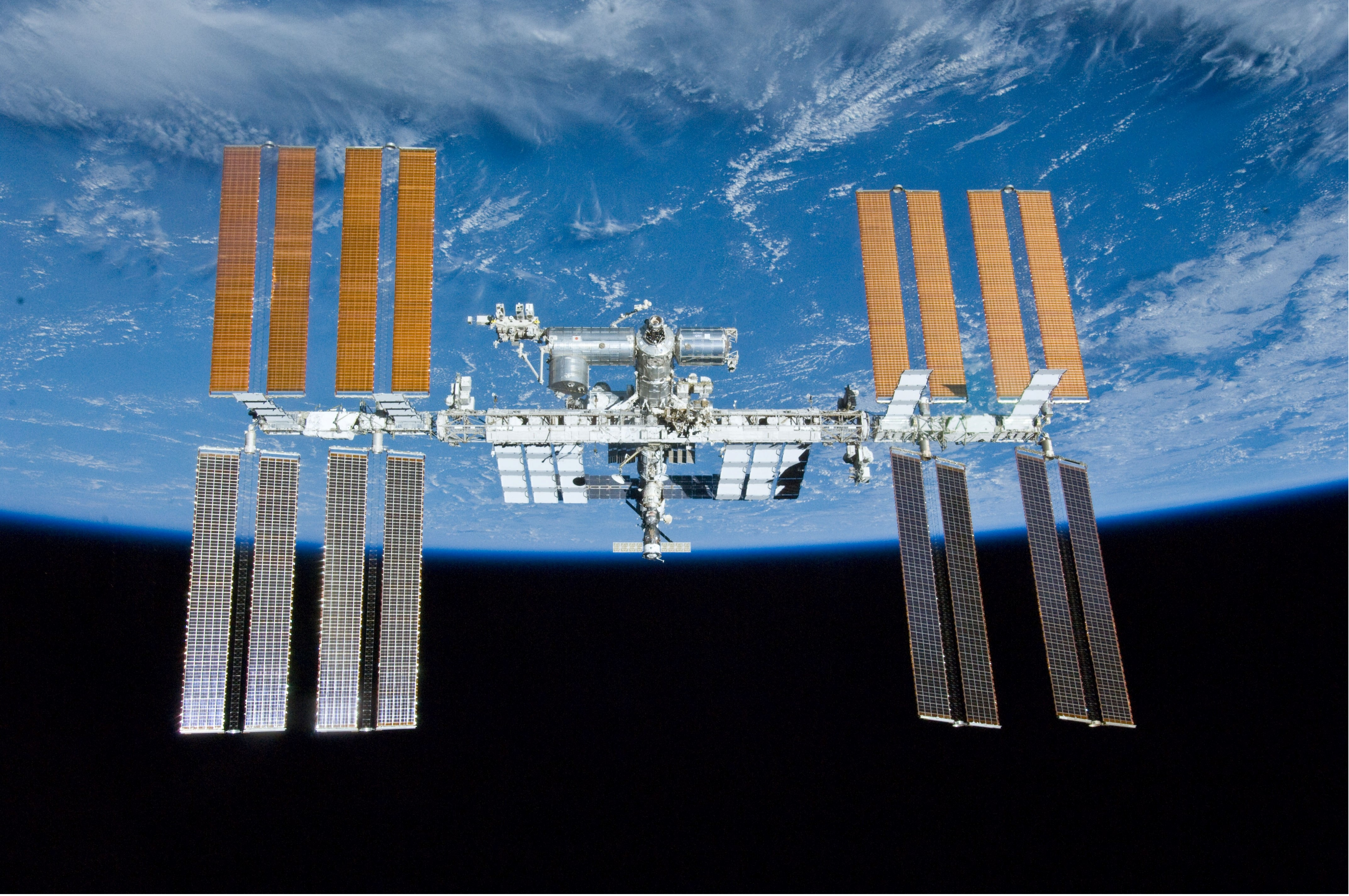




TOTAL 57 COUNTRIES:

USA 652
Japan 32
China 21
Germany 14
S Korea, Russia 13
Denmark 11
UK 10
Italy, Singapore 7
Canada 6
Netherlands, Spain, France,Turkey 5
Belgium,India,Australia,Israel 4
Brazil, Norway,Peru,Lithuania, S Africa 3
Switzerland,Vietnam,Ukraine,
Ecuador ,Argentina,Austria,Switzerland, Finland,
Greece, Sweden 2
Kazakhstan, Emirates, Uruguay, UAE,
Algeria, Poland, Pakistan, Colombia,
Romania, Hungary,Estonia, Bangladesh,
Bulgaria, Bhutan, Chile, Costa Rica, Czechia,
Ghana, Kenya, Mongolia, Malaysia, Nigeria,
Phillipines, Pakistan, Poland, Slovakia, Taiwan 1

Includes 33 startup commercial companies



The biggest artificial Earth satellite: the International Space Station
420 ton habitat in orbit

WHY IS ORBITAL DEBRIS A PROBLEM ?

Meet “Iridium 33”, a half-ton communications satellite launched in 1997.

It happily orbited the Earth for almost 12 years until...

... one Tuesday afternoon it met this satellite:

Kosmos-2251, a Strela-2M class communications satellite which operated from 1993 to 1995. Since 1995 Kosmos-2251 had been inert, just a piece of space junk...

Collision!

480 miles over the Siberian Arctic
Strela and Iridium hit each other side-on at 26050 mph

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

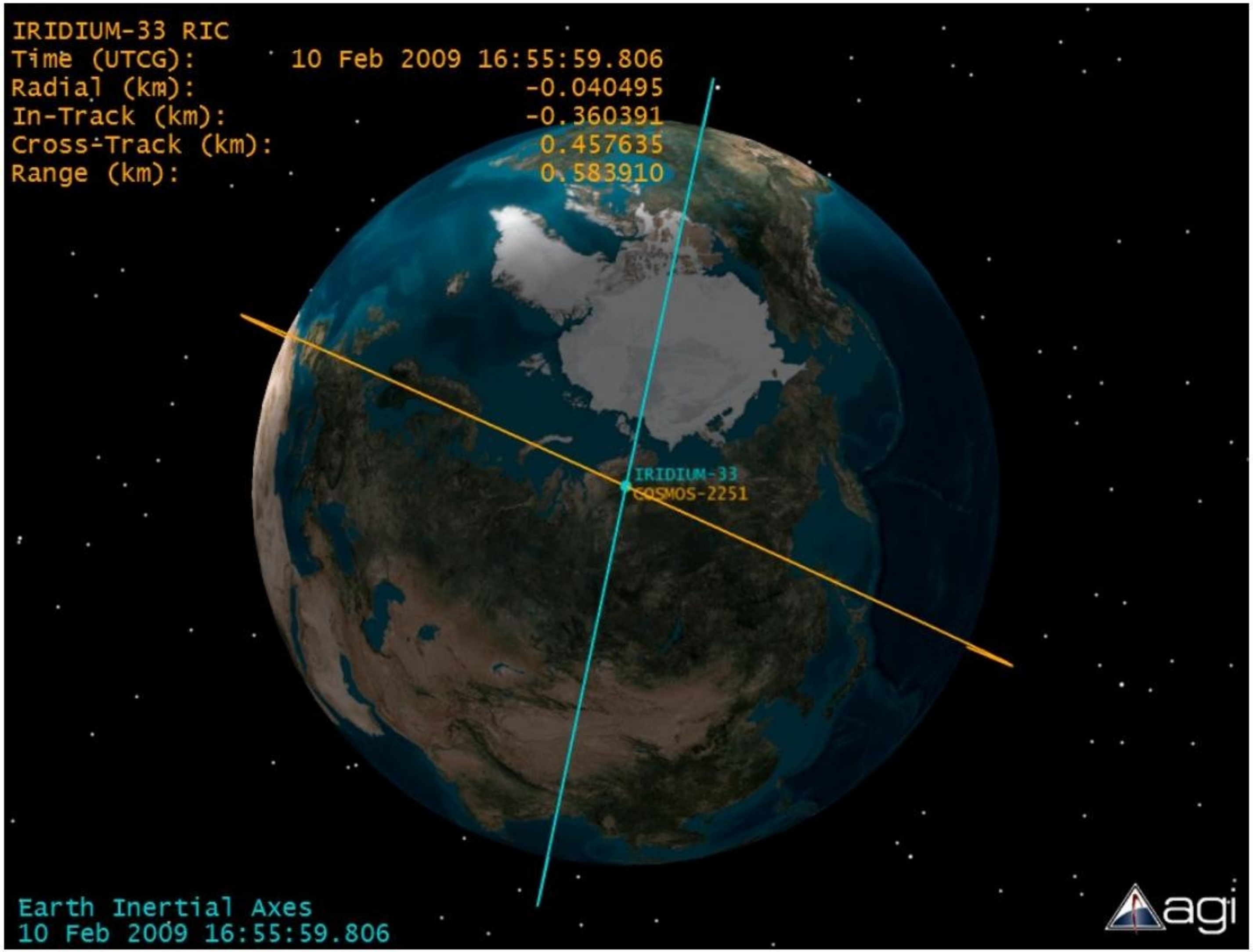
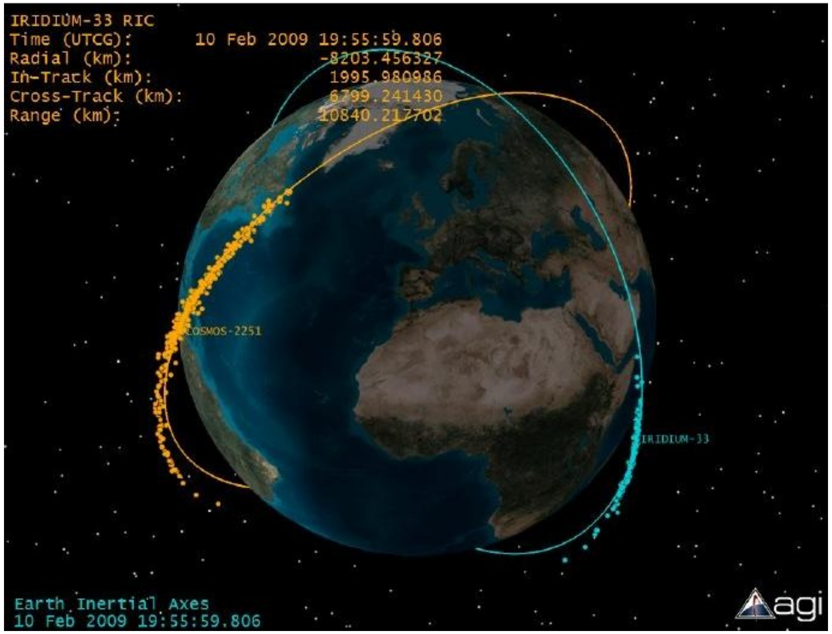
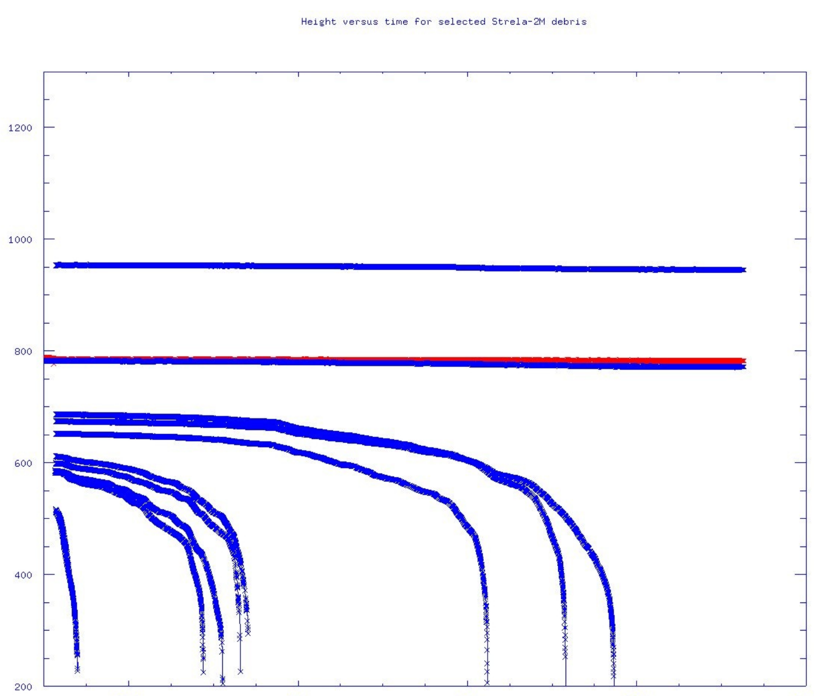


Figure from Kelso 2009





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

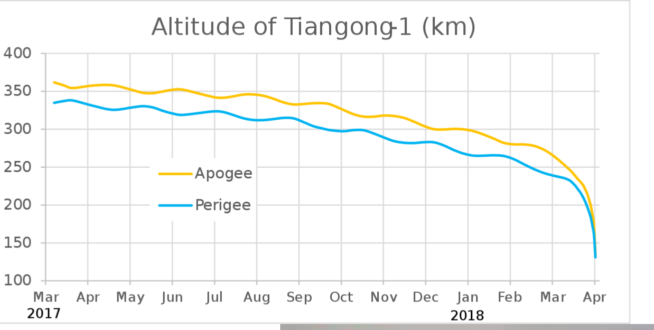
For small, light debris objects, atmospheric drag significant even at these altitudes (altitude data derived from NORAD/USSTRATCOM orbital elements via Space-Track.Org)

Current status:

Iridium debris - 629 cataloged 286 reentered

Strela debris: 1667 cataloged 566 reentered

Satellite's Nemesis: Atmospheric Drag



Try cycling into the wind – you'll feel a force

Force depends on the air density and the square of the speed

F = C rho v^2
(C is a number typically around 2, depends on your shape)

10 times as dense -   10 times bigger force
10 times as fast -   100 times bigger force
Same force acts on satellites:
out in space the atmosphere is tiny but not zero

rho is TINY (and getting smaller fast as you go upwards)
but
v is HUGE
v^2 is HUGE SQUARED

Low orbit satellites slow down and reenter in weeks to months (200 km), years (at 500 km up), centuries (1000 km up)

Even small pieces of debris are dangerous.

Kinetic (motion) energy = (1/2) mass times velocity-squared

A 4-inch piece of space junk typically weighs about 2 lb (1 kg)

How much of a punch does it make?
Equivalent kinetic energy: a 1 ton truck at 1000 mph
Like being hit by a missile

Jul 24, 1996

French Defense Ministry satellite "Cerise" hit by a small piece of space junk – luckily only minor damage

You might worry that space junk can crash to Earth and be a threat to us here down on the ground.

But when you enter the atmosphere at 17000 mph or so, you get VERY HOT and usually melt.

A few pieces of space debris hit the ground each year. In 1979 the 75 ton Skylab reentered over the Indian Ocean and some big pieces of it hit the Australian desert.

But nowadays almost all the largest spacecraft are carefully deorbited over empty regions of the South Pacific; the smaller ones burn up.

So it's not a huge problem. At the moment.

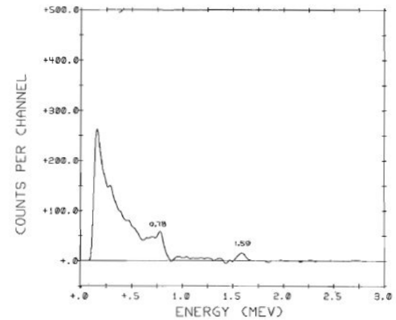


Figure 24.3 The spectrum above is the cumulative addition of individual spectra recorded over the anomaly of Figure 24.4, with local background either side subtracted. The small peak at 1.59 meV is from the fission product ^{140}La and confirmed the evidence of Figure 24.4. The single overflight by the spectrometer thus provided conclusive proof of the presence and the nature of the radioactive debris on the lake.

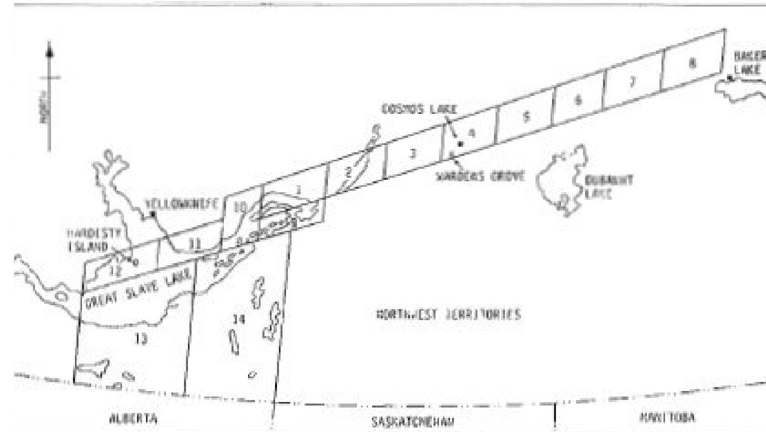


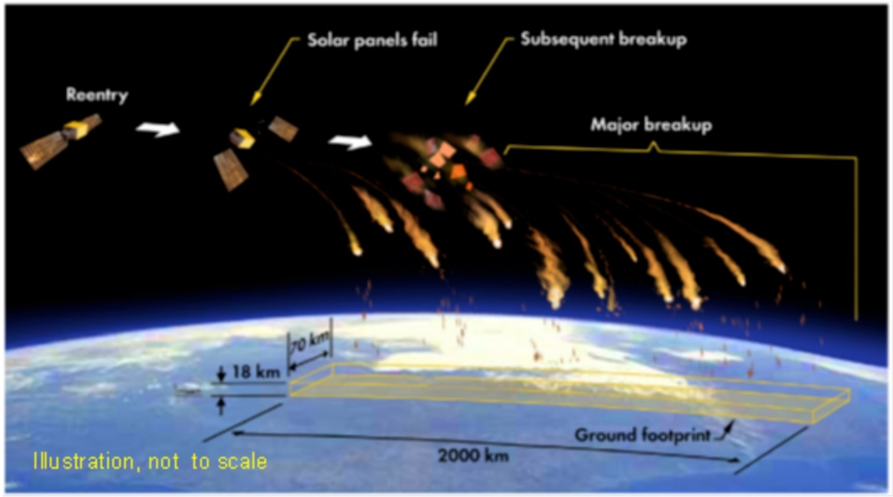
Figure 24.1 The impact trajectory of the satellite stretches from Great Slave Lake northeast toward Baker Lake. Sectors 13 and 14 were established with wind borne material in mind.

Kosmos-954:
Nuclear reactor falls on Canada, Jan 1978

Lottie Williams of Tulsa, OK with the melted, twisted piece of space debris that fell out of the sky and hit her on Jan 22, 1997.

She wasn’t hurt – the atmosphere had slowed down the space junk from 18000 mph to probably just a few mph

She remains the only person known to have been hit by space junk



Images: Aerospace Corp.

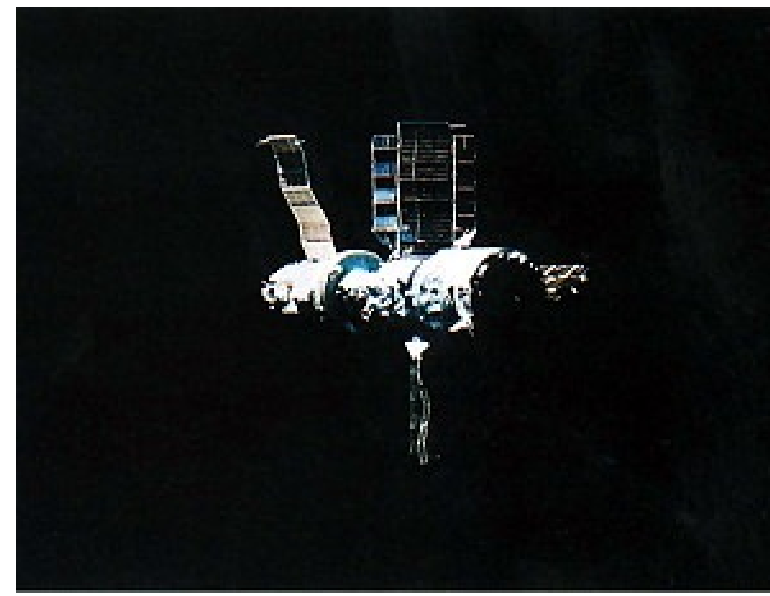
Biggest uncontrolled reentries

1979 SKYLAB 76 tons

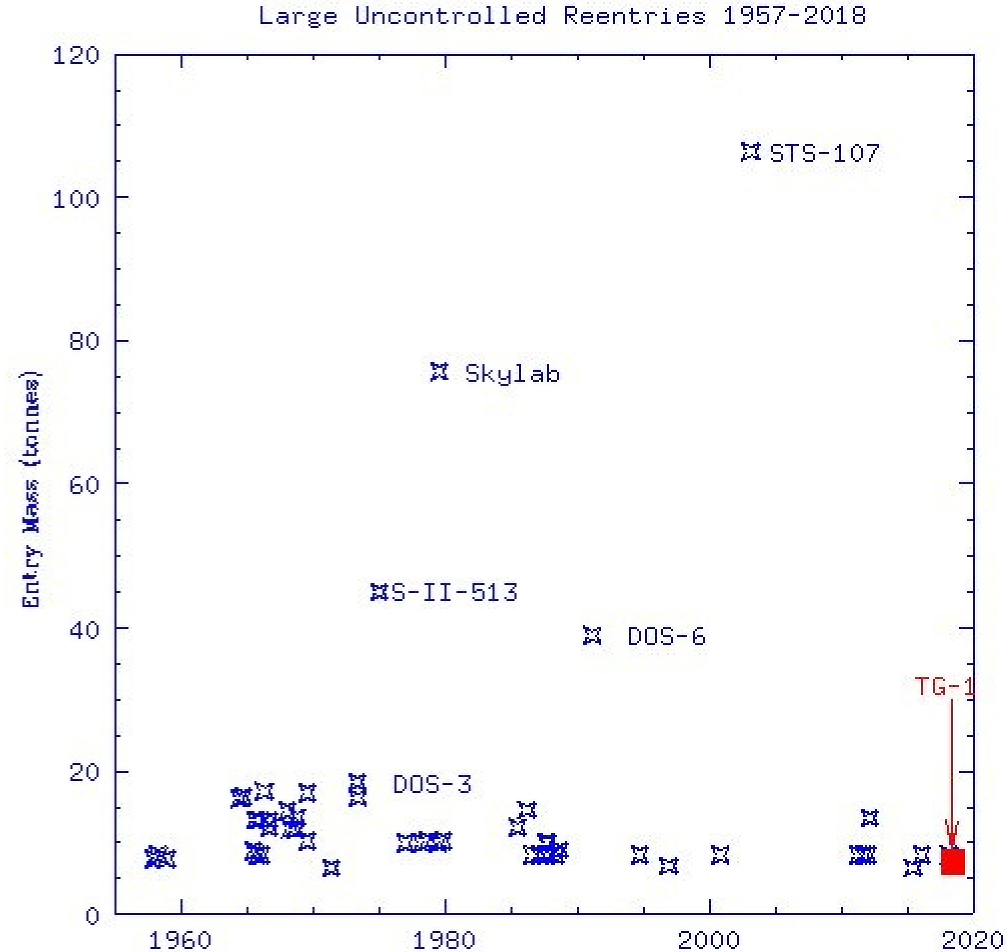
1975 SKYLAB ROCKET 49 tons

1991 SALYUT 39 tons

This past April:
TIANGONG-1 – lots of press, but only 8 tons



Something this big about once every 3-5 years




```
#
# Spacecraft                                               Reentry mass - tonnes   Date          Location
#
#-- The biggest uncontrolled reentries --
# Note: STS-107 was controlled until its breakup but had similar consequences to an uncontrolled reentry.
#
 1  OV-102 Columbia (STS-107)                              106.4              2003 Feb  1   Texas/Louisiana
 2  Skylab space station                                    75.7              1979 Jul 11   Australia
 3  Saturn S-II-13 (Skylab rocket)                          45.1              1975 Jan 11   Atlantic Ocean (w of Madeira)
 4  DOS 6 space station/TKS-M module (Salyut-7/Kosmos-1686) 39.0?             1991 Feb  7   Argentina
 5  DOS 3 space station (Kosmos-557)                        18.5              1973 May 22   Indian Ocean
 6  Saturn SA-5 rocket/Jupiter nosecone                     17.2              1966 Apr 30   Brazil
 7  N-6 No. 1 satellite (Proton-4)                          17.0              1969 Jul 24   Unknown
 8  Apollo BP-15/Saturn SA-7                                16.4              1964 Sep 22   Indian Ocean
 9  Almaz-1 space station (Salyut-2)                        16.3              1973 May 28   Pacific Ocean near Fiji
10  Apollo BP-13/Saturn SA-6                                16.2              1964 Jun  1   Pacific Ocean
11  Tselina-2 No. 3L/Zenit-2 11S772 rocket (Kosmos-1714)    14.6              1986 Feb 27   Pacific Ocean?
12  Saturn S-IVB-204 (Apollo 5 rocket)                      14.5              1968 Jan 23   Off coast of Australia
13  Saturn S-IVB-205 (Apollo 7 rocket)                      13.6              1968 Oct 18   Indian Ocean
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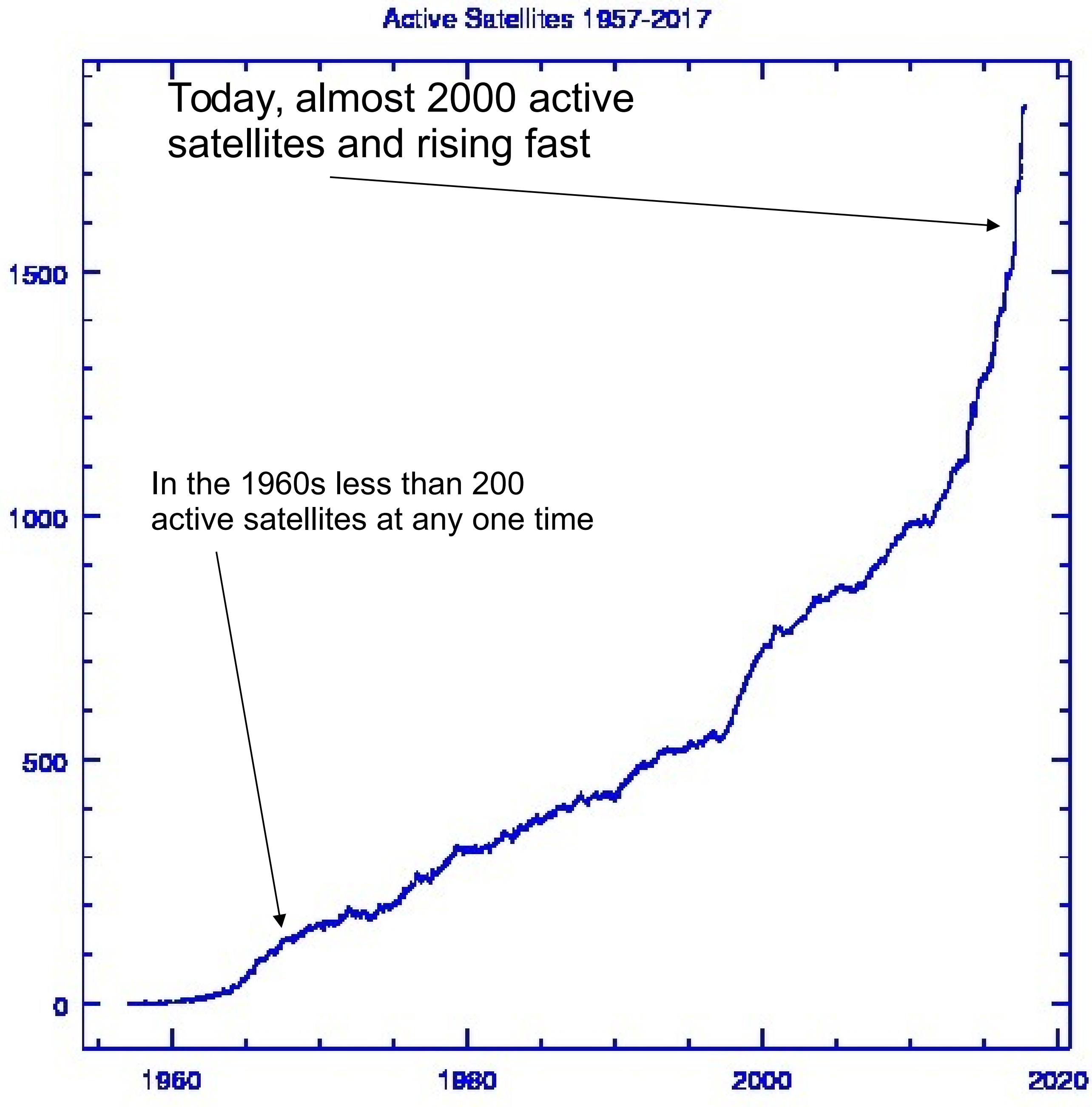
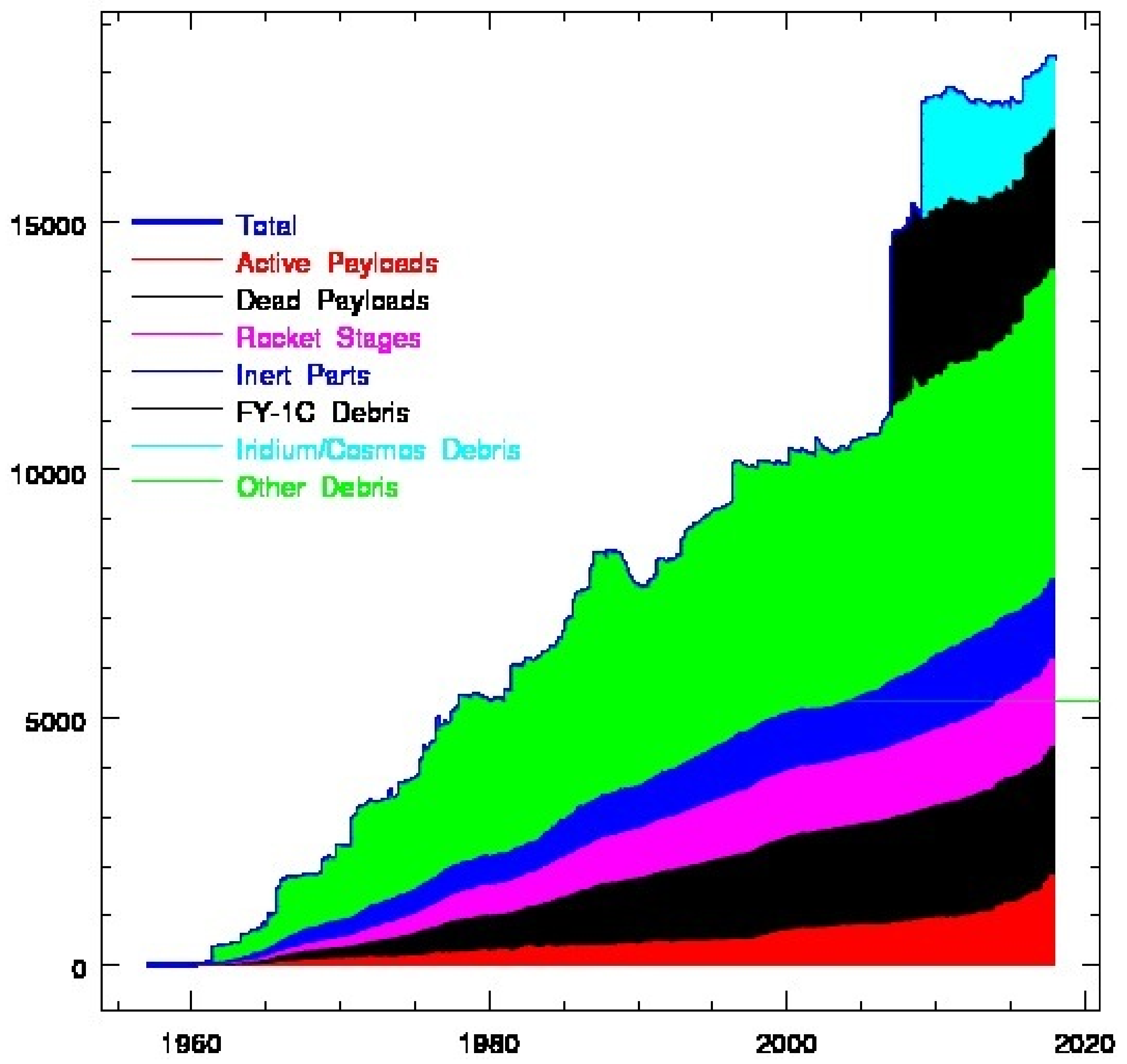
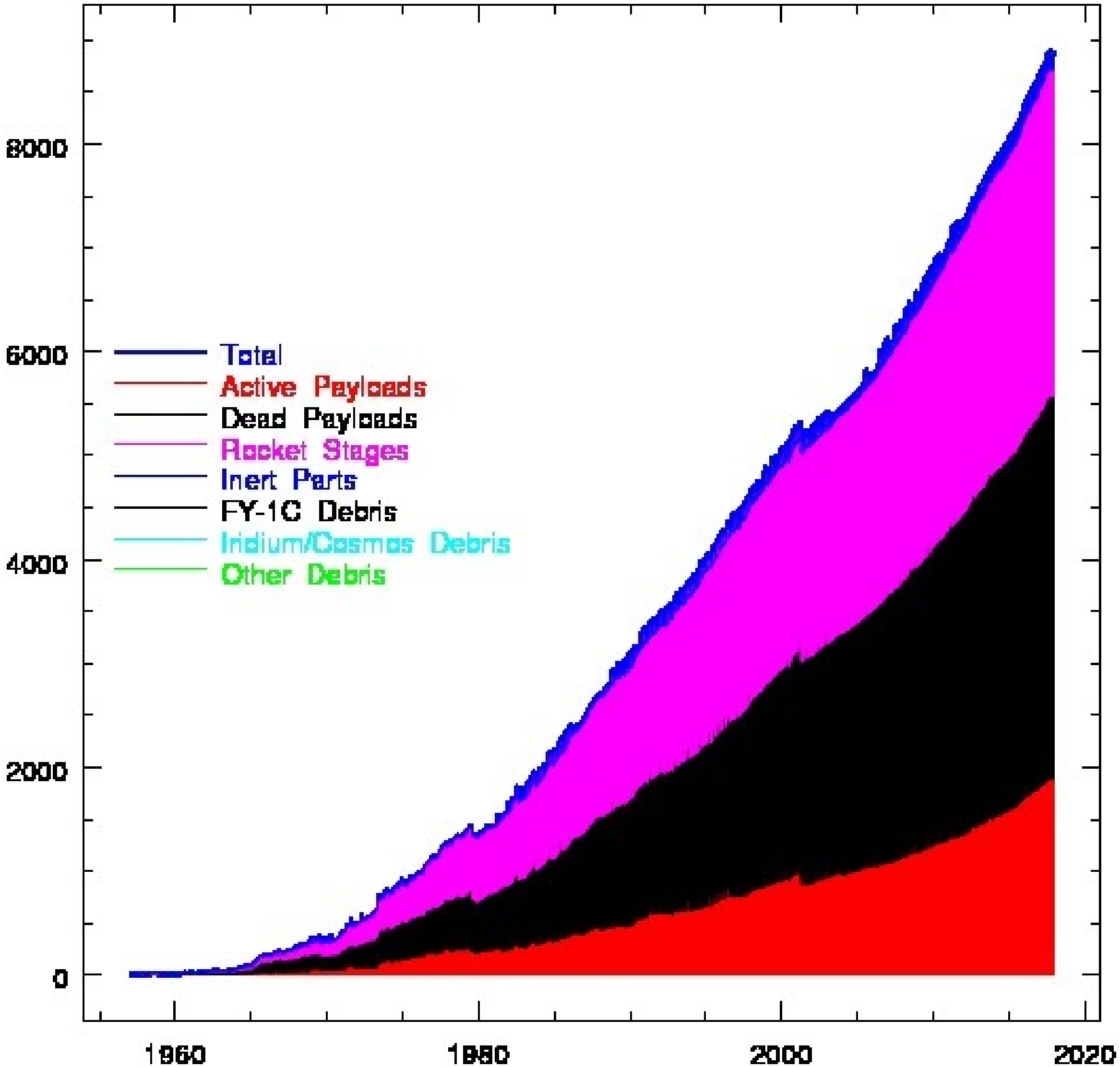
HOW MUCH JUNK?


Active Satellites 1957-2017
Today, almost 2000 active satellites and rising fast
In the 1960s less than 200 active satellites at any one time
1500
1000
500
0
1960
1980
2000
2020

The Growth of Space Junk



Space Junk - mass in metric tons

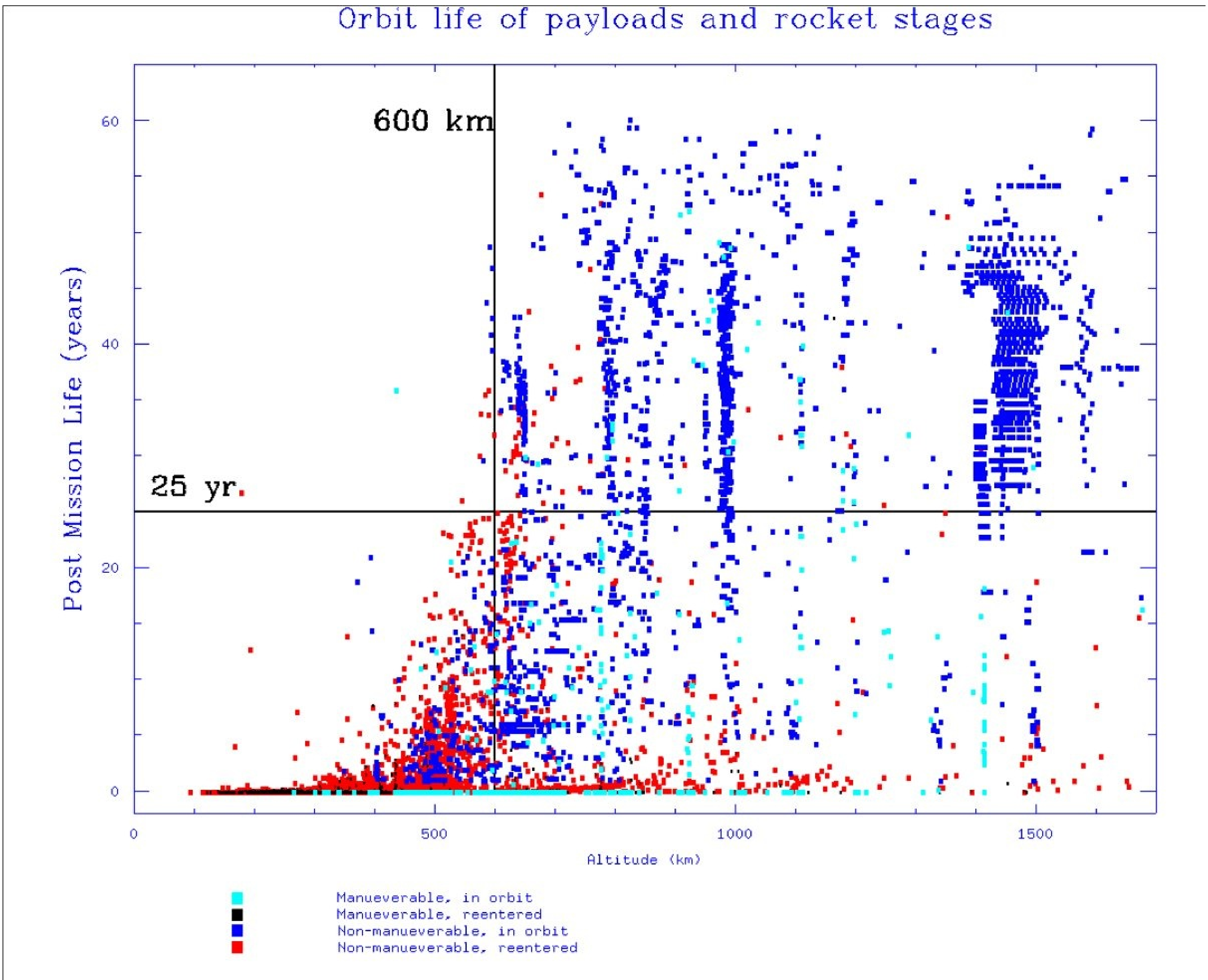


As of today:

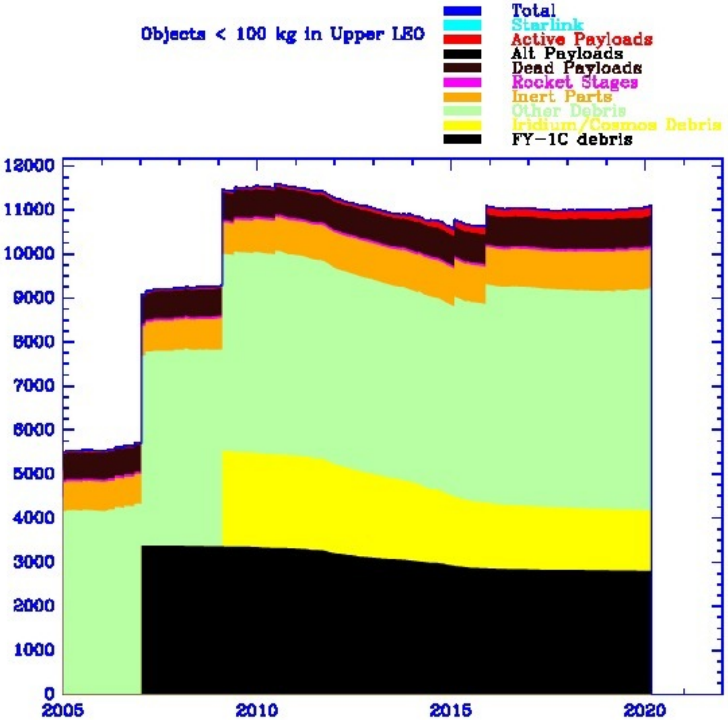
8873 metric tons of stuff in orbit

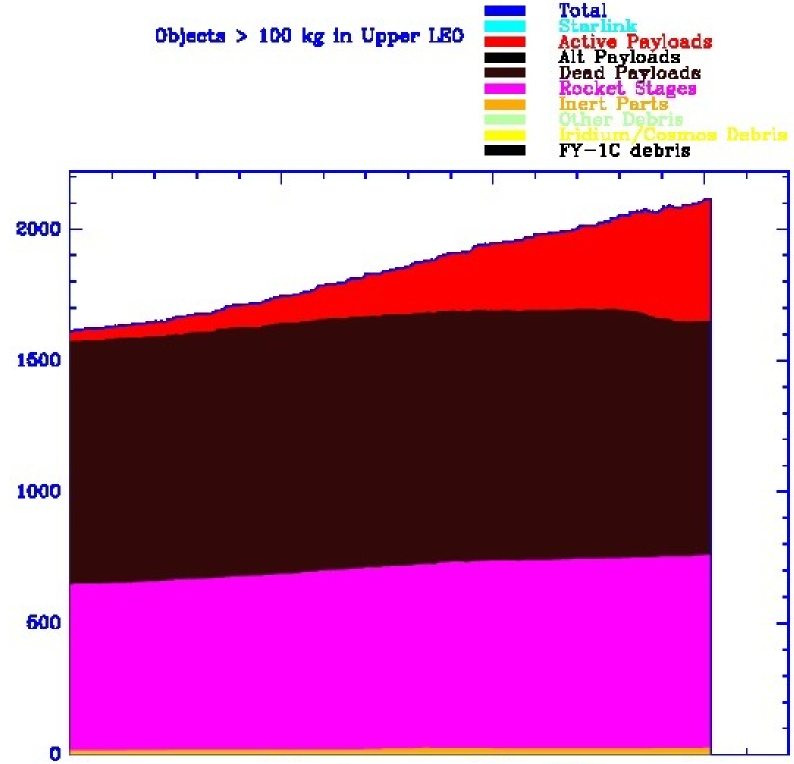
6991 tons of that is junk

(78% by mass)



Orbit life of payloads and rocket stages
600 km
25 yr.
Post Mission Life (years)
60
40
20
0
0
500
1000
1500
Altitude (km)
Manueverable, in orbit
Manueverable, reentered
Non-manueverable, in orbit
Non-manueverable, reentered


Objects < 100 kg in Upper LEO
Total
Starlink
Active Payloads
Alt Payloads
Dead Payloads
Rocket Stages
Inert Parts
Other Debris
Iridium/Cosmos Debris
FY-1C debris
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
2005
2010
2015
2020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Iridium/Cosmos Debris
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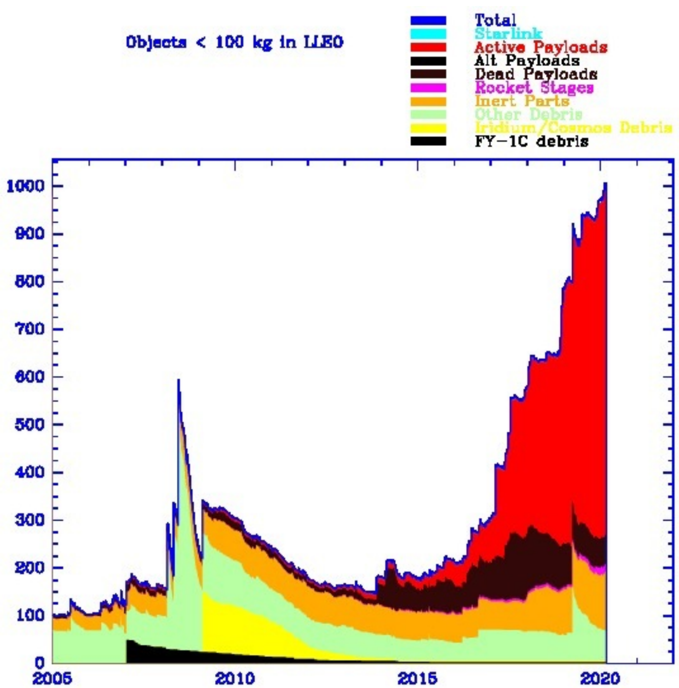
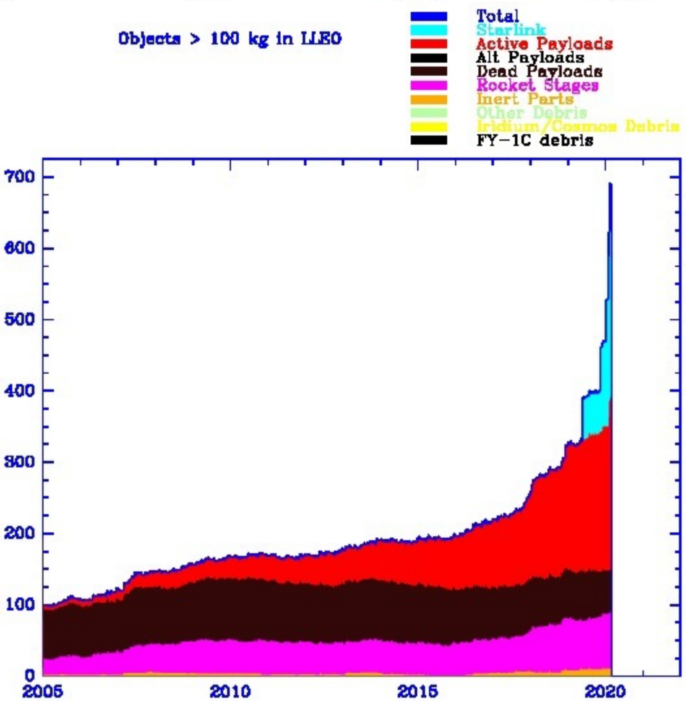
2000
1500
1000
500
0


Objects < 100 kg in LLEO
Total
Starlink
Active Payloads
Alt Payloads
Dead Payloads
Rocket Stages
Inert Parts
Other Debris
Iridium/Cosmos Debris
FY-1C debris
1000
900
800
700
600
500
400
300
200
100
0
2005
2010
2015
2020


Objects > 100 kg in LLEO
Total
Starlink
Active Payloads
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Other Debris
Iridium/Cosmos Debris
FY-1C debris
700
600
500
400
300
200
100
0
2005
2010
2015
2020

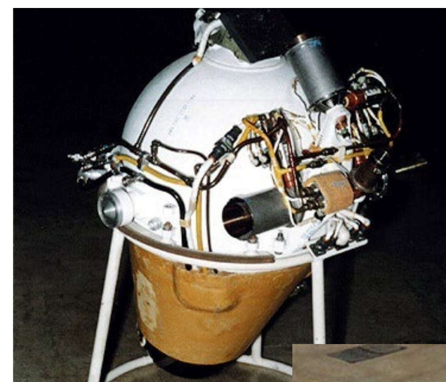
A Census of Space Debris

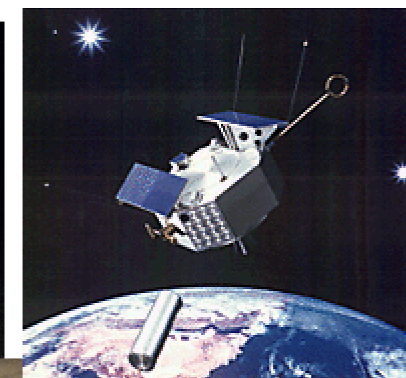
as of 12 Apr 2017

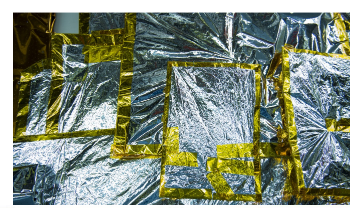
Total objects cataloged	42661	
Objects still in Earth orbit	18296	
Active payloads	1500?	
Dead payloads	2796?	
Rocket stages	1930	
Adapters, jettisoned objects	1652	
2007 Chinese ASAT debris	2855)	
2009 collision	1443)	10417
Other debris	6119)	

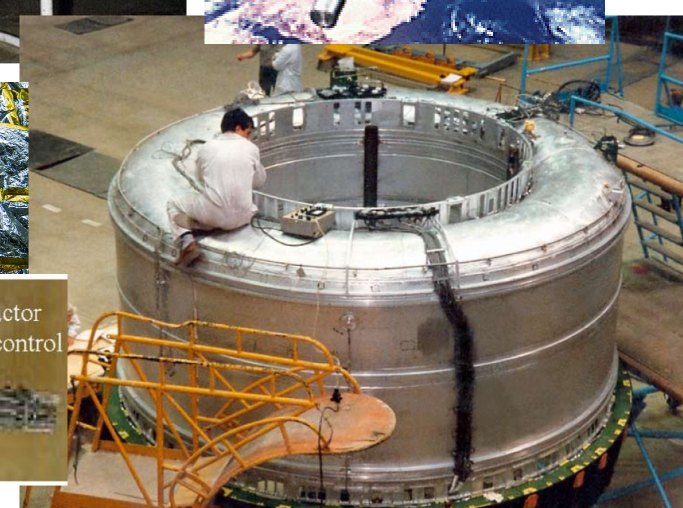
Covers, fairings	300
Jettisoned motors and tanks	170
Multi-payload adapters	141
Despin devices	131
Deployment canisters	38
Insulation blankets	36
Nuclear reactor cores	14
Misc	28
Unknown pieces	794

Residual fuel explosions	**3826**
Antisatellite weapon tests	**3247**
Accidental collision	**1458**
Battery explosion	**1315**
NaK Reactor coolant blobs	**53**
Insulation, Destruct, Other	**518**





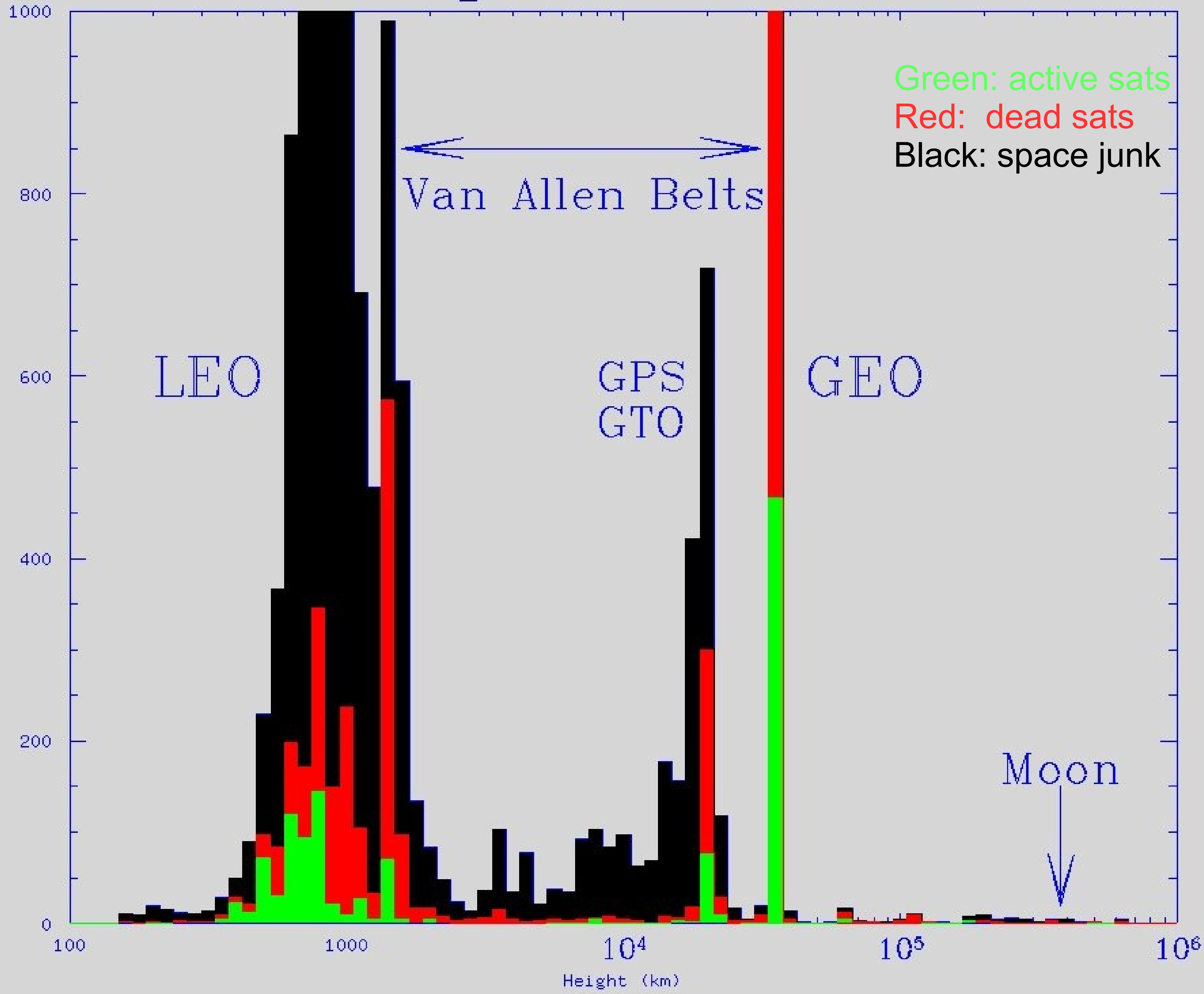


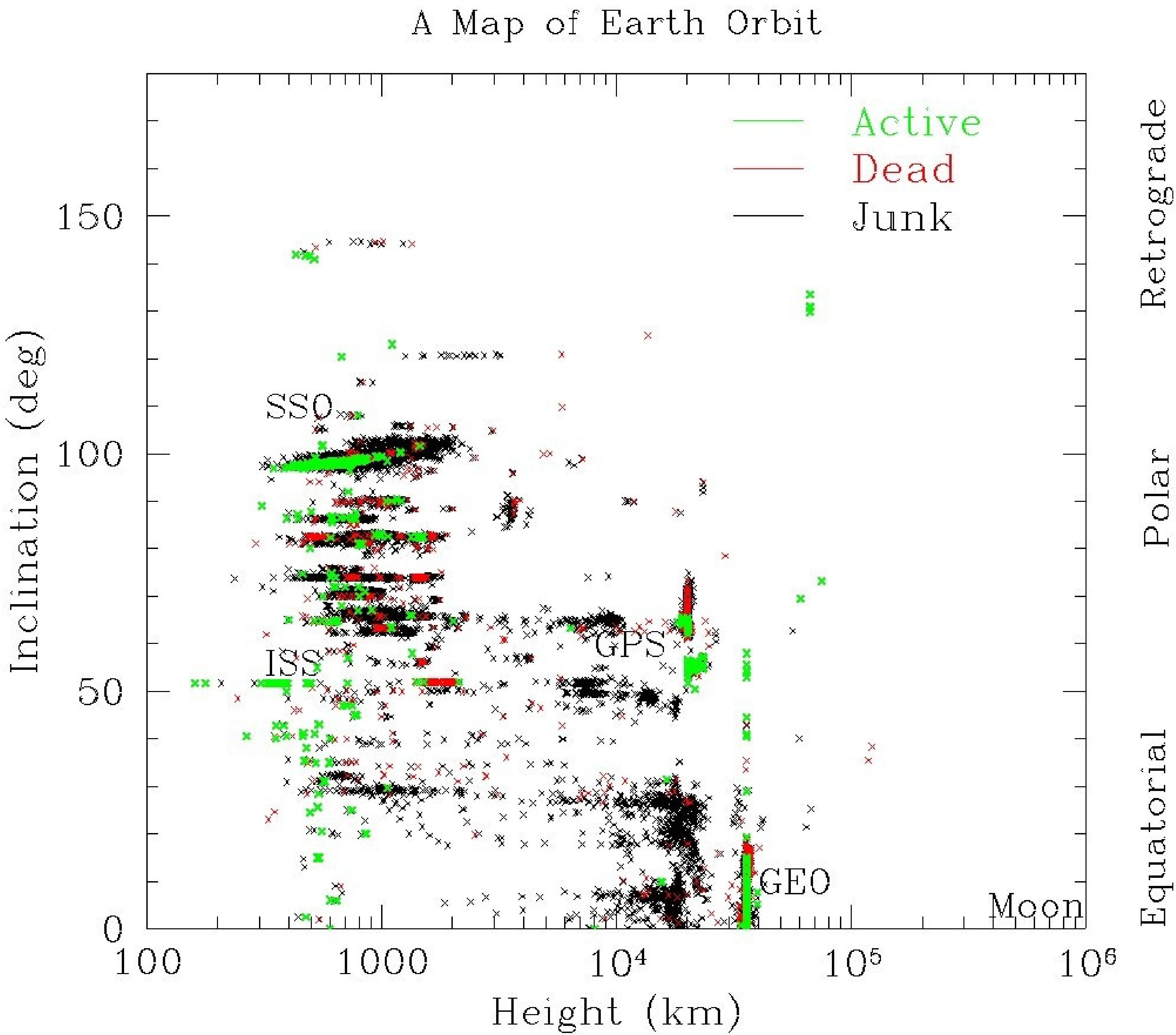


Credit: Roskosmos, NASA, Arianespace, Khrunichev; El Genk 2009 (Buk)

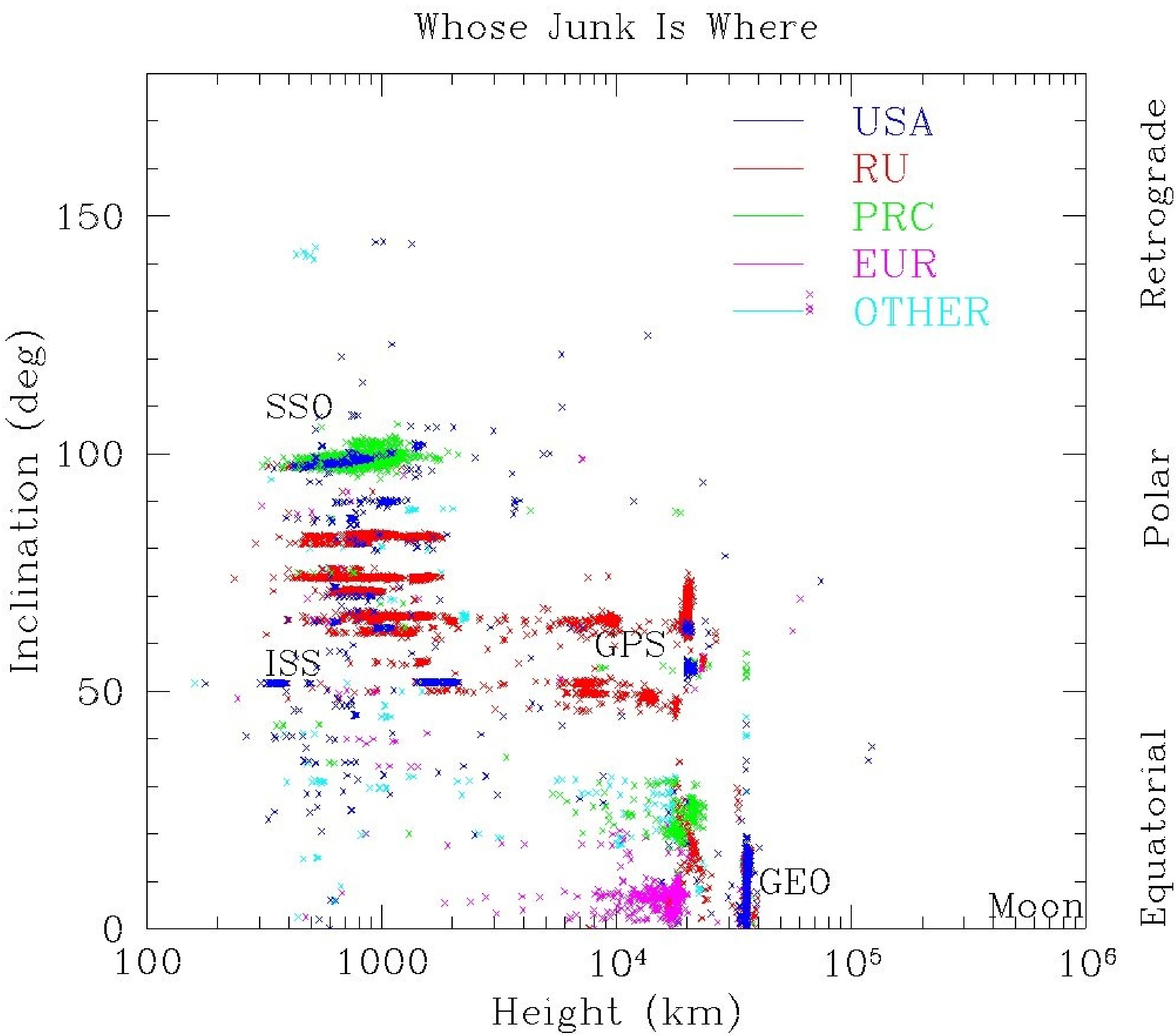
WHERE IS THE JUNK?

How high are satellites?

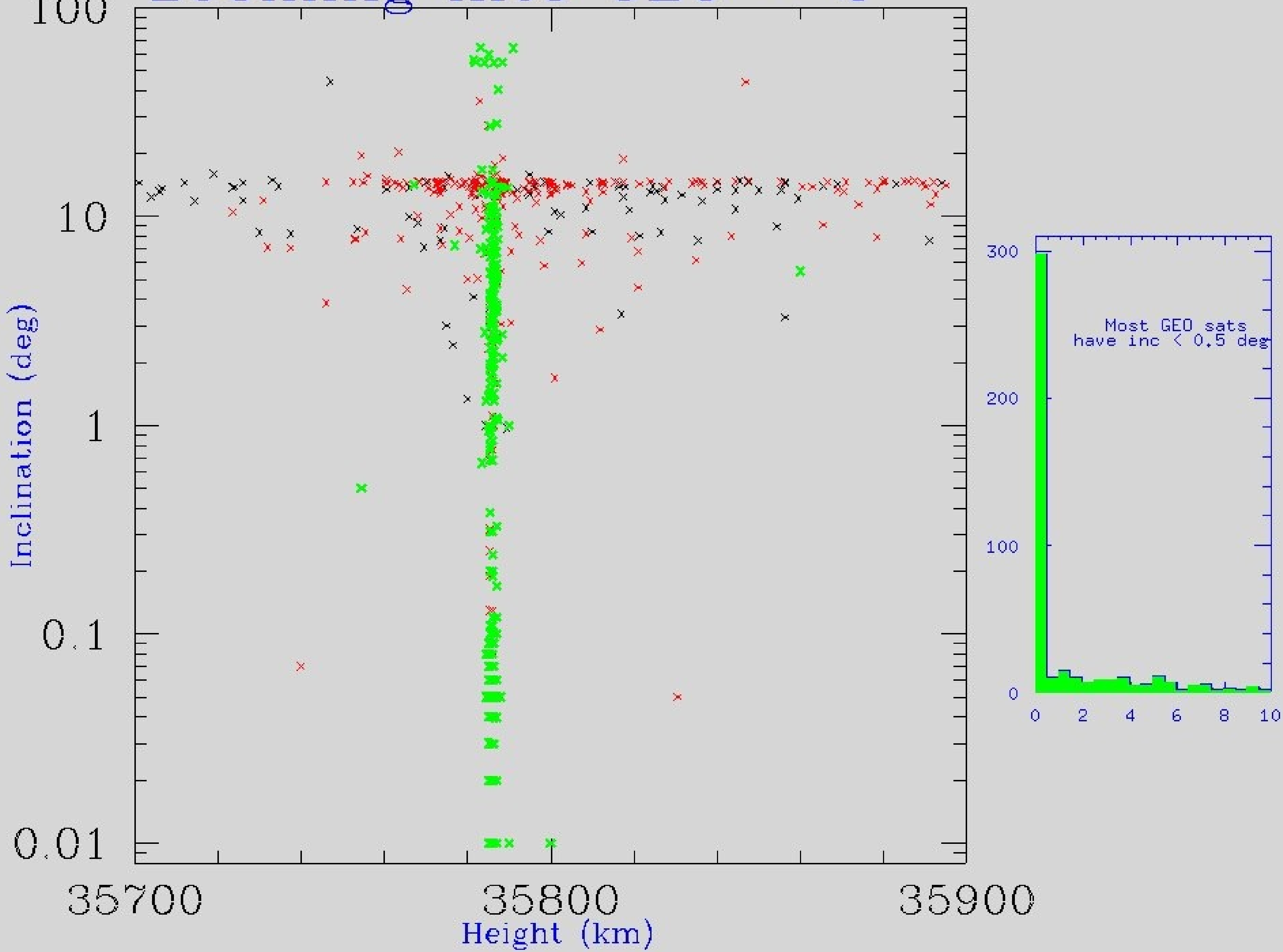




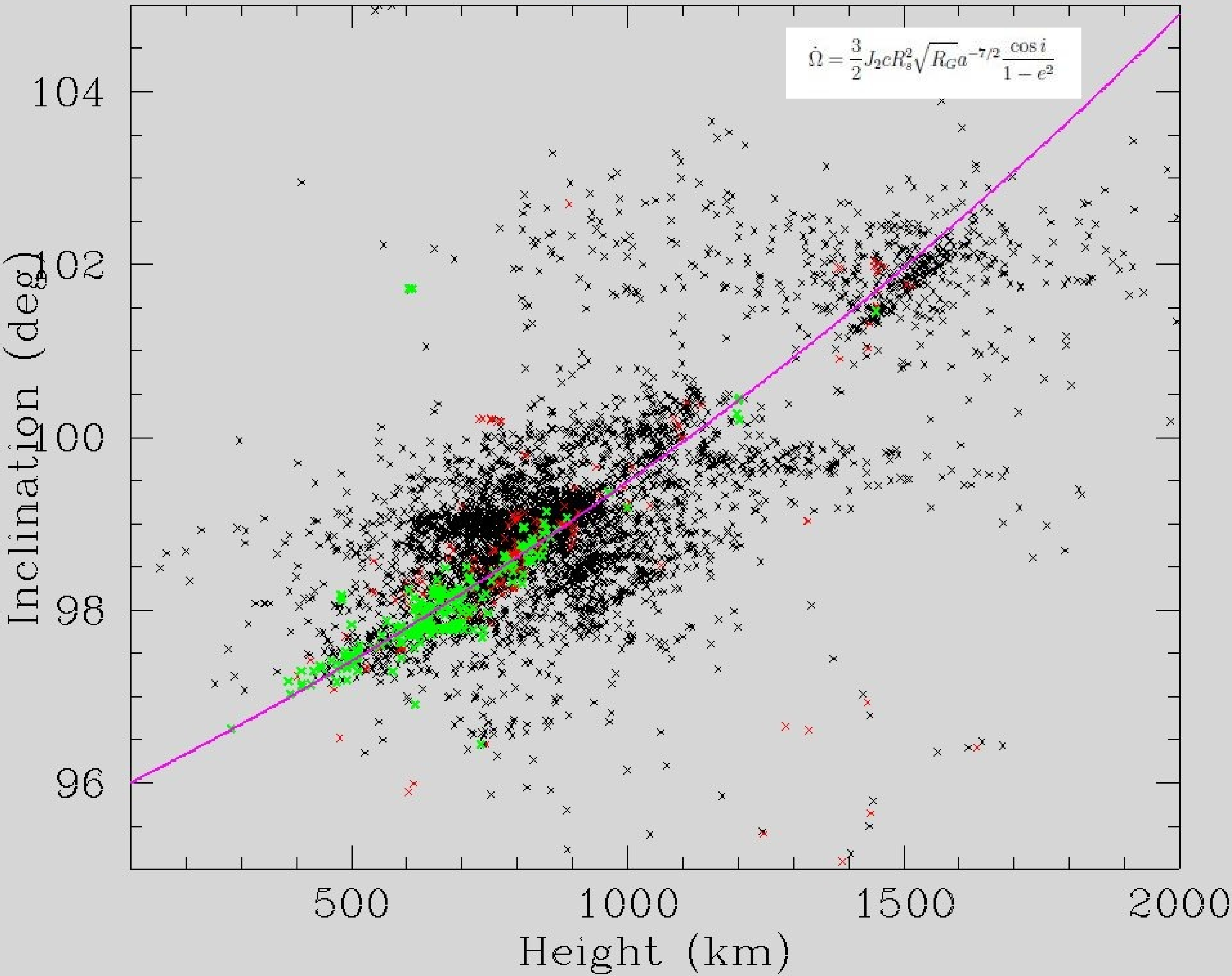
A Map of Earth Orbit
Active
Dead
Junk
Retrograde
Polar
Equatorial
Inclination (deg)
Height (km)
150
100
50
0
100
1000
10⁴
10⁵
10⁶
SSO
ISS
GPS
GEO
Moon


Whose Junk Is Where
USA
RU
PRC
EUR
OTHER
SSO
ISS
GPS
GEO
Moon
Retrograde
Polar
Equatorial
Inclination (deg)
Height (km)
0
50
100
150
100
1000
10^4
10^5
10^6

Zooming into GEO - 2



Zooming into SSO



FIXING THE PROBLEM

Rocket stages:

- add restartable engine
- bring stage back down after deploying satellite,
  either for destructive reentry over ocean ...   or recovery!

(SpaceX now recovering suborbital first stages;
recovering orbital upper stages is a task for the – near? - future)

Dead satellites:

1970s satellites mostly didn’t have their own rocket engines

medium and large 2010s satellites (with mass above 100 kg or so) mostly do

So – dump low orbit sats in the ocean at the end of their mission
or at least lower orbit so they don’t stay up so long

High orbit sats can be moved to a less busy orbit – too hard right now to bring them down.

In the future: maybe tax satellite operators to fund a fleet of space garbage trucks?

Dual satellite launch
(European Ariane 5)
4 objects end up in orbit -
two satellites, two pieces of junk

Top satellite

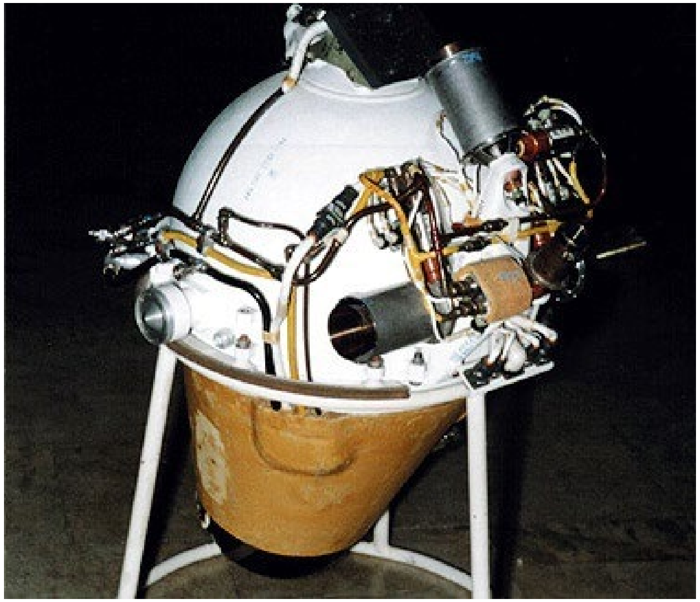
‘Adapter’: Container for lower satellite

Lower satellite

Rocket stage

- Lens caps and so on, put them on hinges instead of ejecting them

- Adapters for multiple satellites: could do the same thing, but isn’t done yet



SOZ:
an auxiliary rocket motor used by Russian ‘Proton’ rockets

Two of these jettisoned on each of the older-style Proton launches

Contain some left over fuel

Tend to blow up after several years in orbit

Solution:

Make sure all fuel is used up or vented during the mission!

Battery explosions

The NOAA and DMSP civilian and military weather satellites seem particularly prone to exploding batteries

Some Soviet navigation satellites have issues too

Solution:

Vent all battery fluids, fully deactivate

USSR Oko missile warning satellite
Configuration during active use

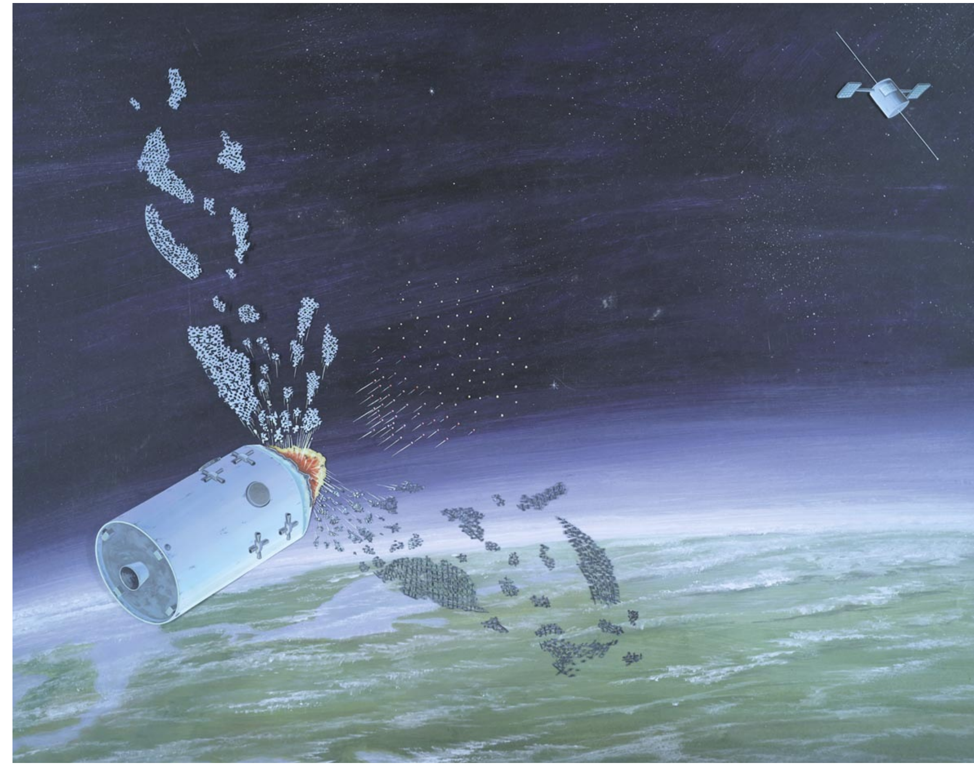
Self-destruct systems

The USSR really, really didn't want its stuff falling into US hands...

Configuration after activation of APO self destruct device

Solution: Don't do that!

F-15 ASAT, 1985



Kosmos-249, 1968

USA, USSR and China all have tested antisatellite weapons

These leave a lot of space debris in orbit

Solution: Really don’t do that!!

Debris:

- Propellant explosions
  Make the rocket stage restartable, deplete all fuel

- Battery explosions
  Design battery to be vented of all energetic materials at end of mission

- Self-destruct systems (used by Soviet missions to prevent others recovering their technology)

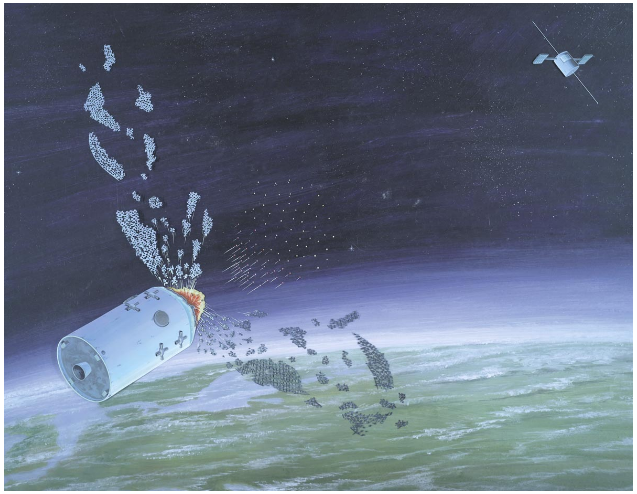
  Don't do that

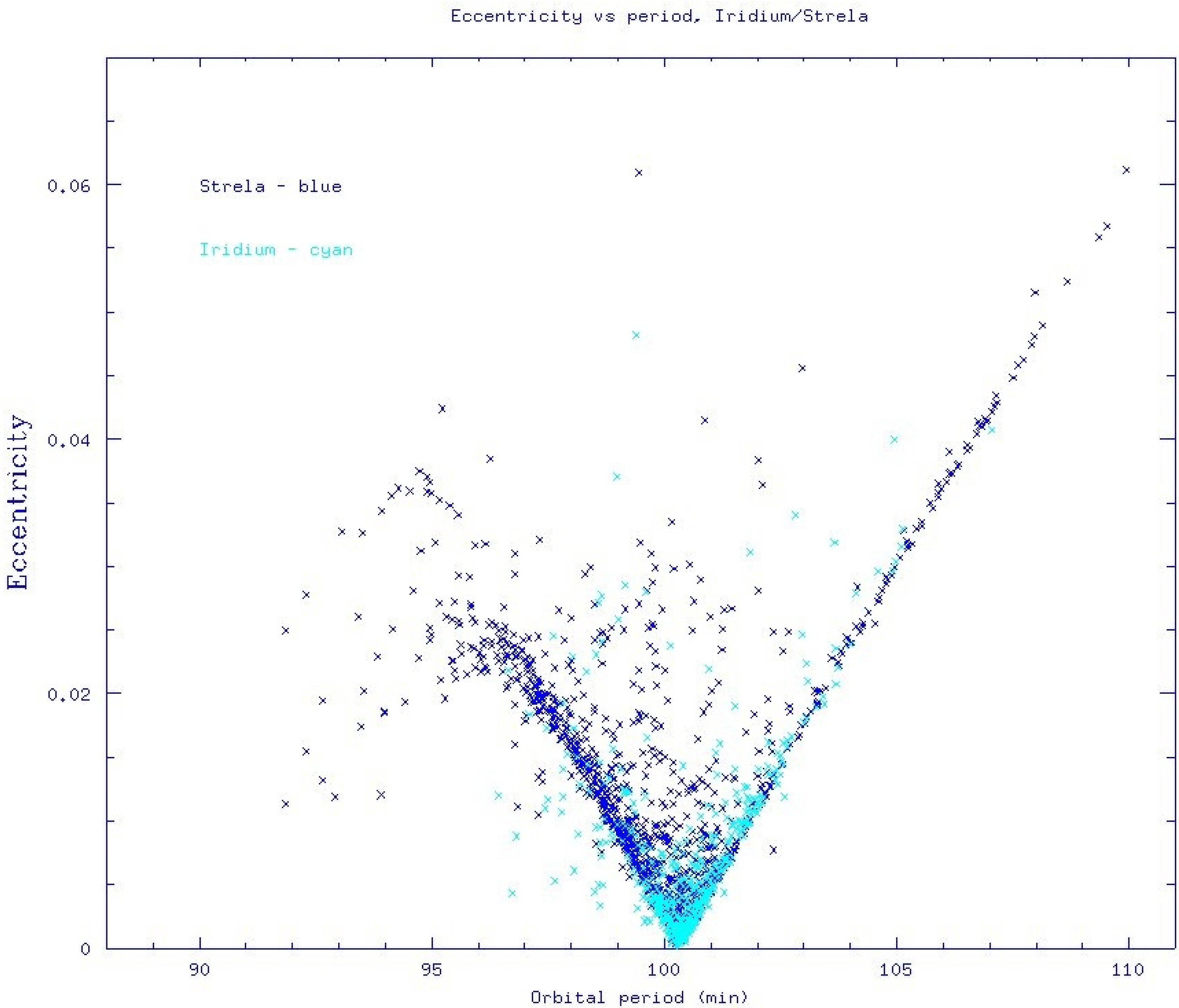
- Antisatellite weapons

  Really don't do that

- Collisions

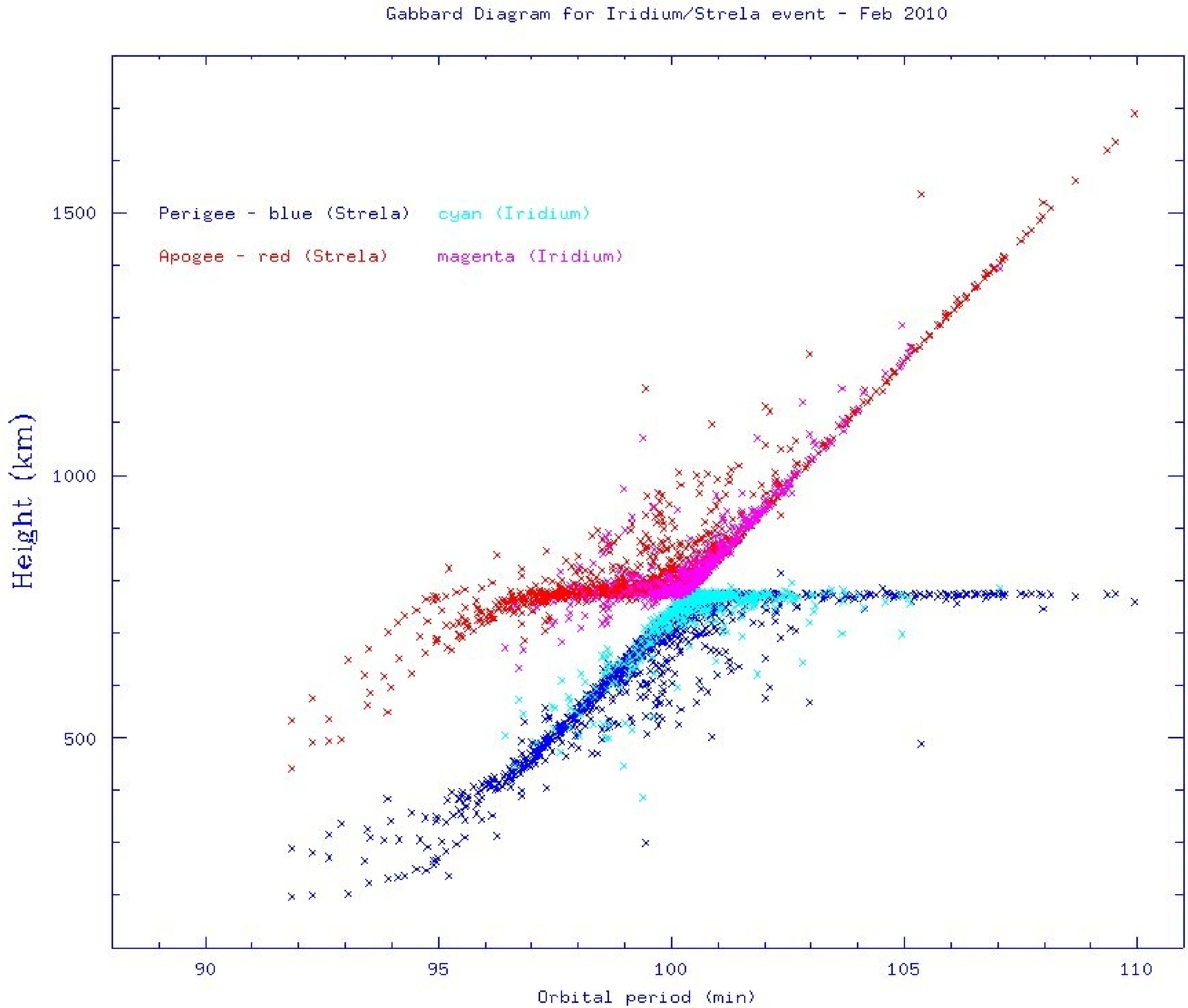
  Reduce total amount of debris



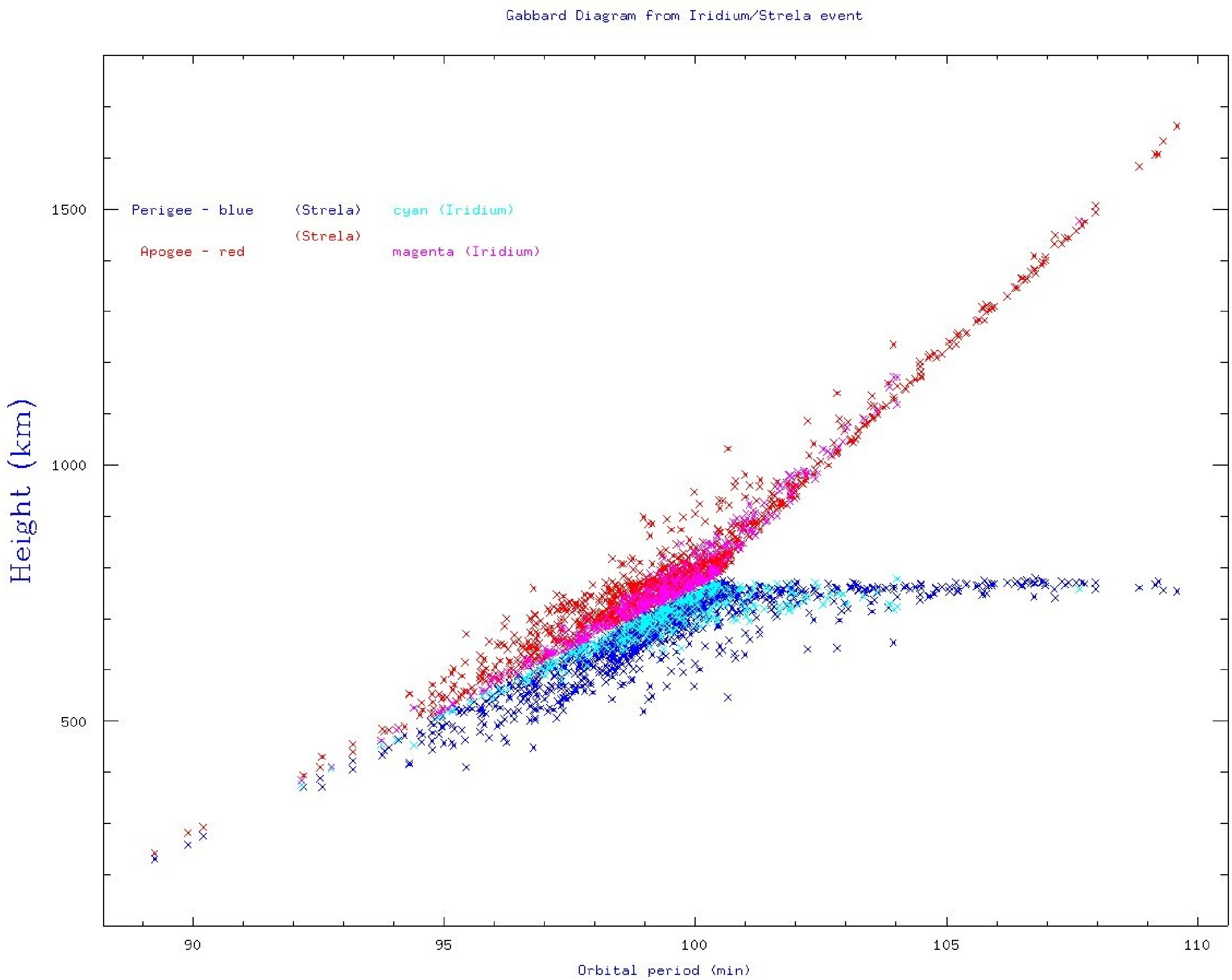


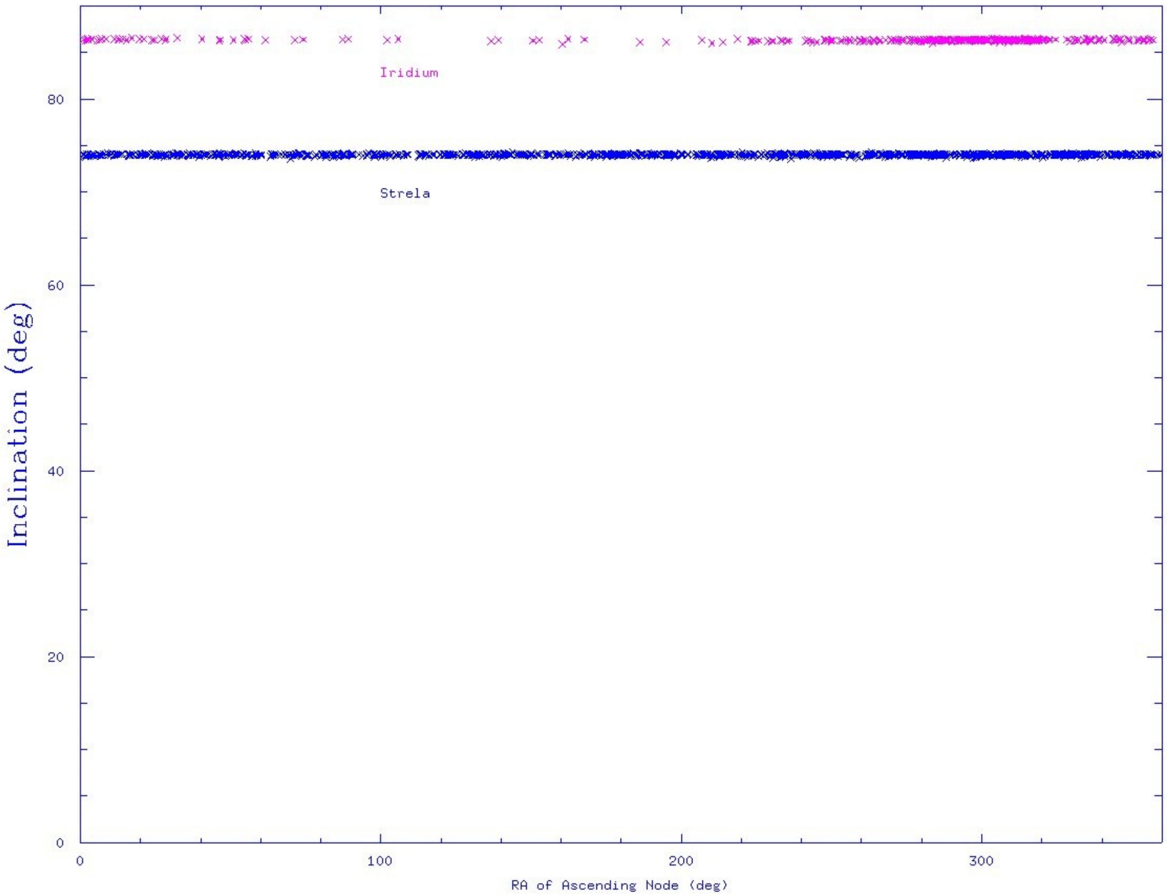
Eccentricity vs period, Iridium/Strela
Strela - blue
Iridium - cyan
Eccentricity
0.06
0.04
0.02
0
90
95
100
105
110
Orbital period (min)

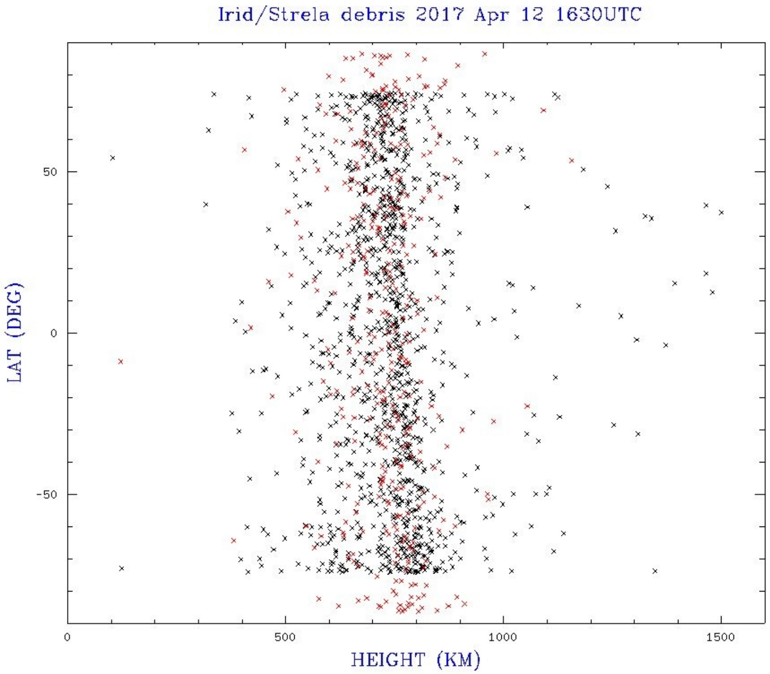
Gabbard Diagram (developed by NORAD's J. Gabbard in 1960s) shows perigee, apogee vs orbital period
Can see different ejection energies of debris objects

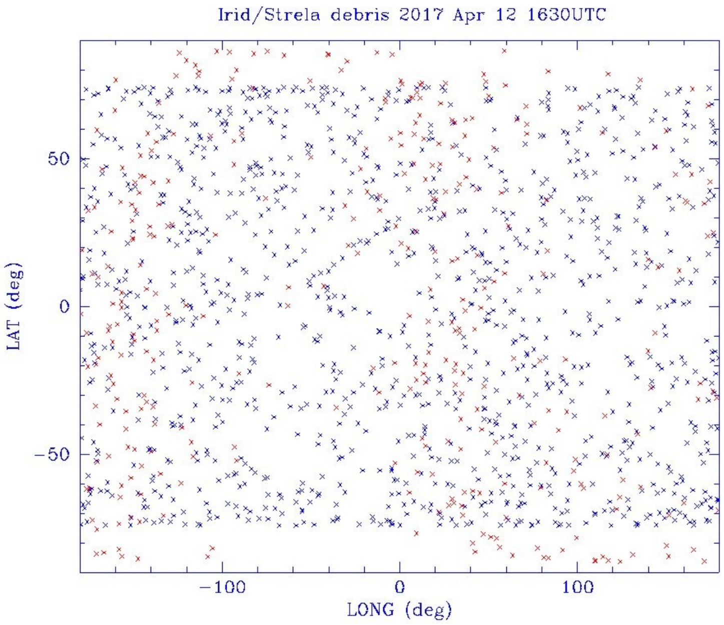


Gabbard Diagram for same event, updated to Apr 2017
Orbital decay has circularized low period objects









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

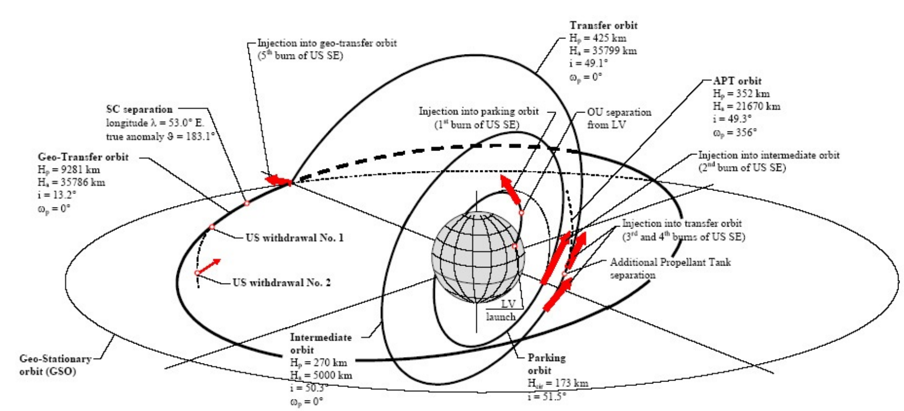
Consider Falcon 9 second stage from Jan 2017 launch of Echostar satellite.
Current orbit is 180 x 35767 km x 22.5 deg.
Apogee velocity is 1.60 km/s

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 (Credit: Khrunichev)

Scheme of SC Injection into Target Orbit from 1st Ascending Node of Parking Orbit



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

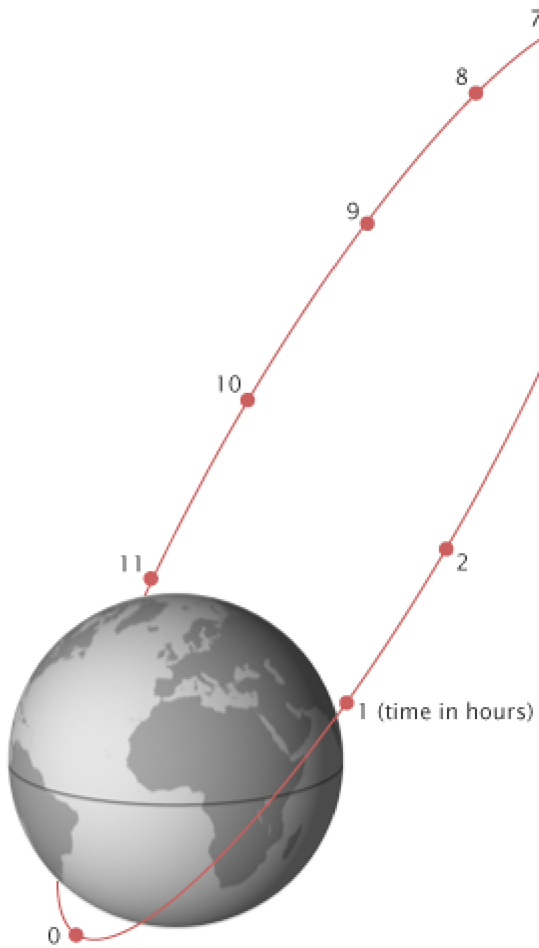
$$\dot{\omega} = f_P\left(2 - \frac{5}{2}\sin^2 i\right)$$

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

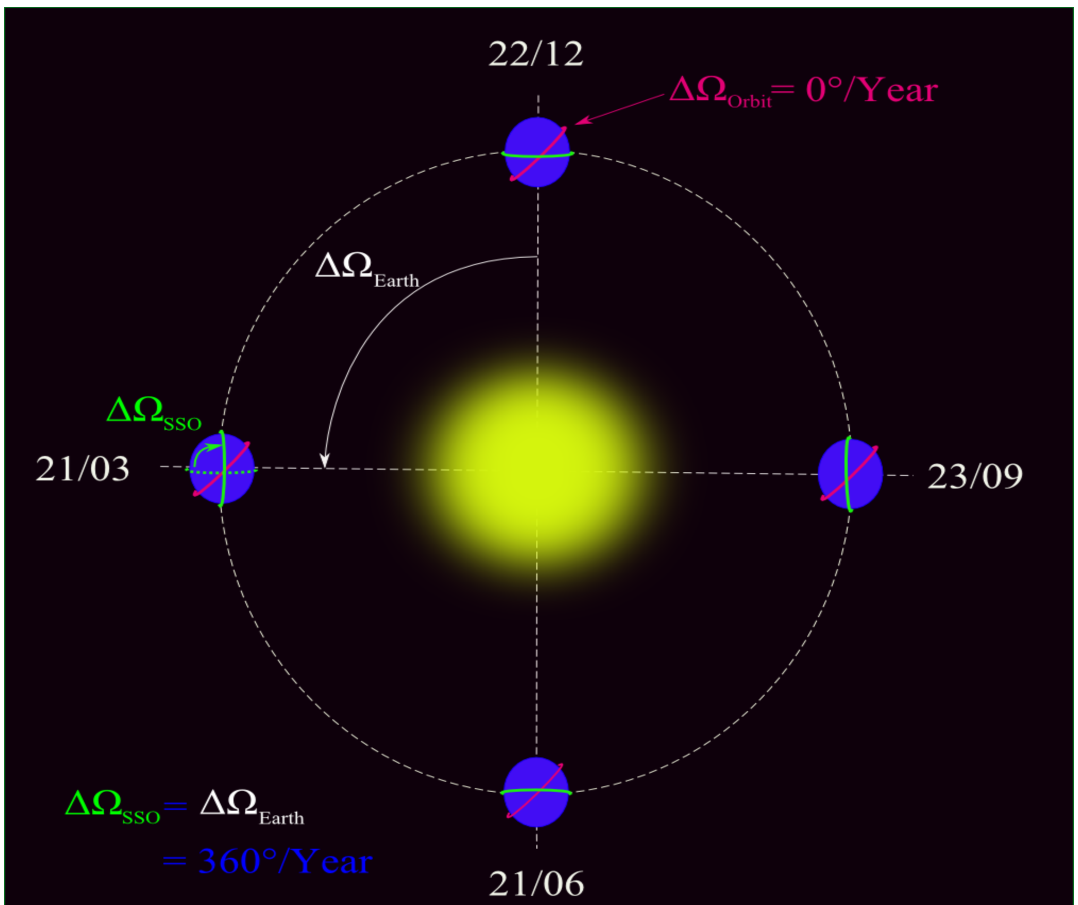
the "Molniya orbit" (usually T = 12 hr)

Credit: Wikipedia

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.



Credit: Wikipedia

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