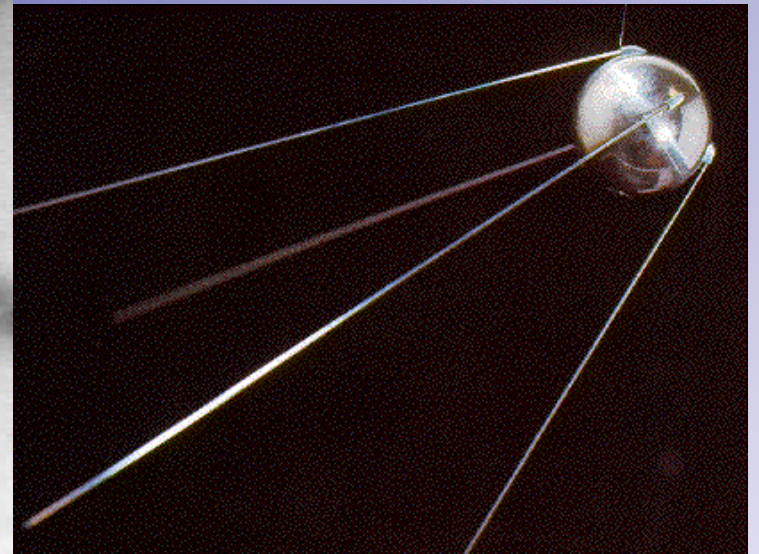
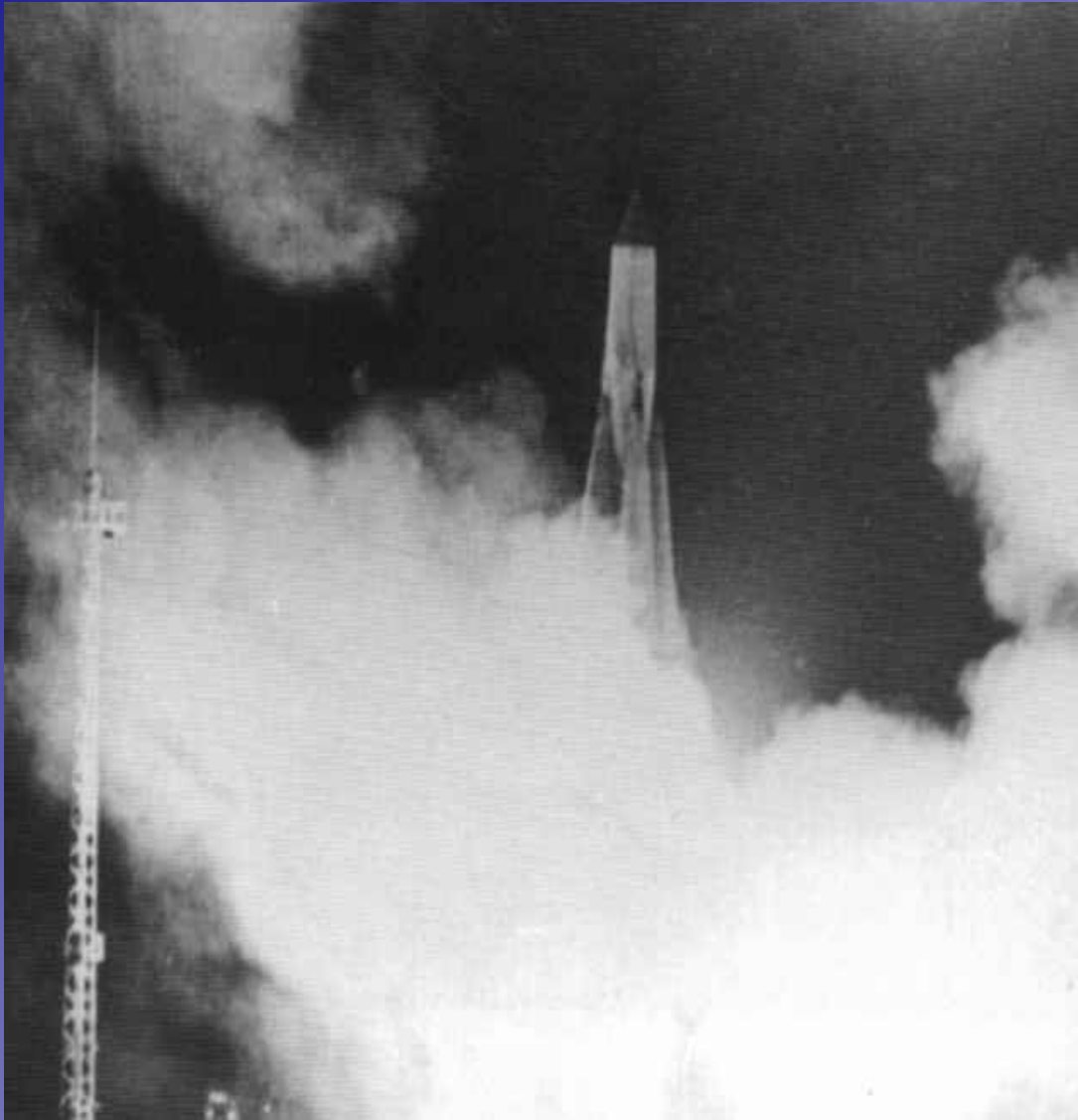
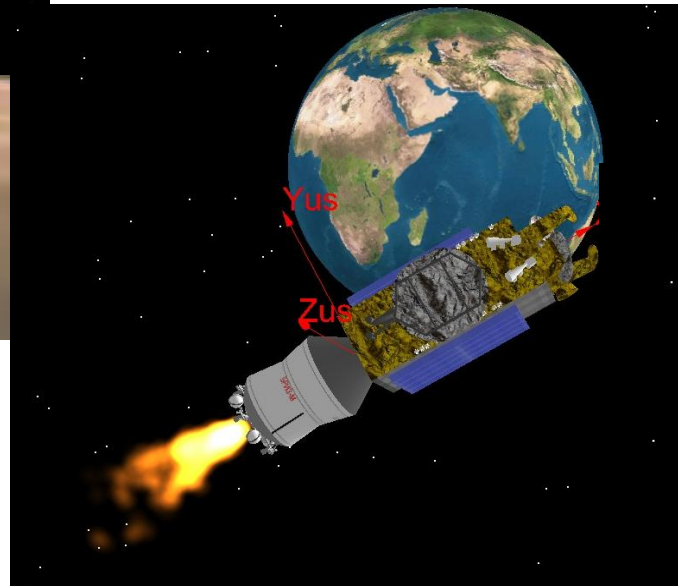
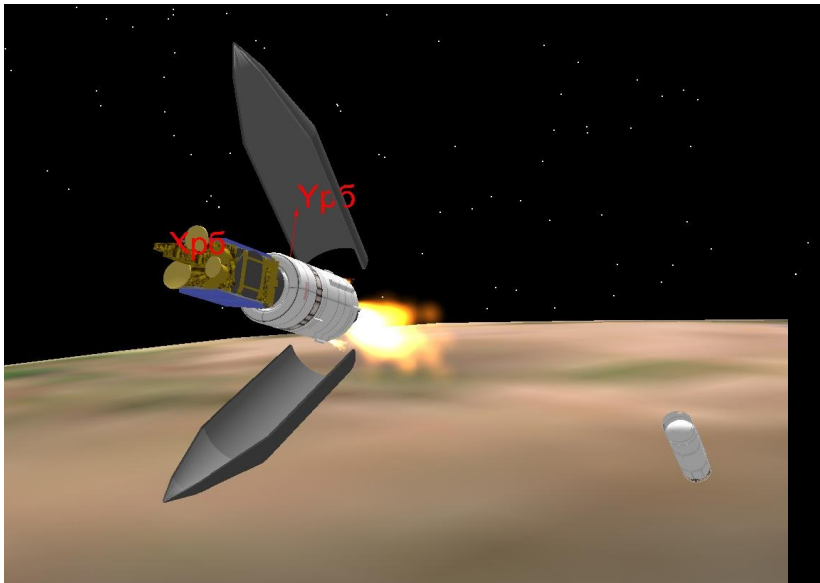
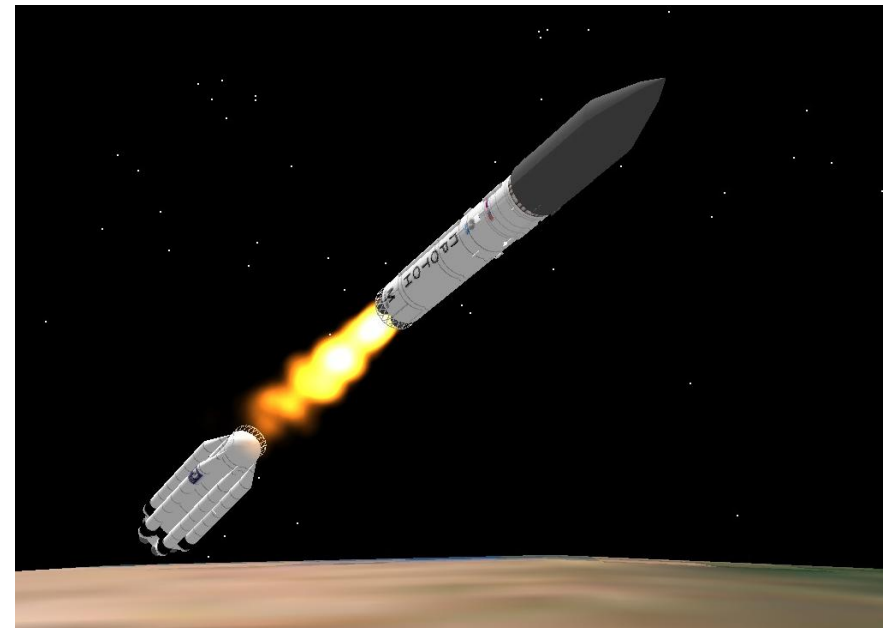


Harvard freshman seminar version, 2019 Mar 11

October 1957: Sputnik



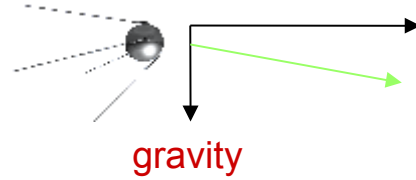


A typical satellite launch ends up with at least two objects in orbit – the satellite and the last piece (“stage”) of the rocket that got it there

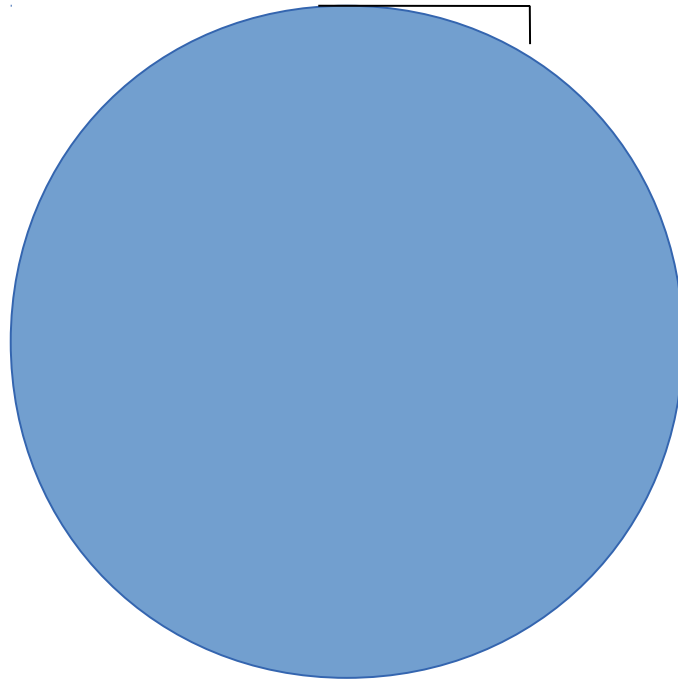
Credit: Khrunichev

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)

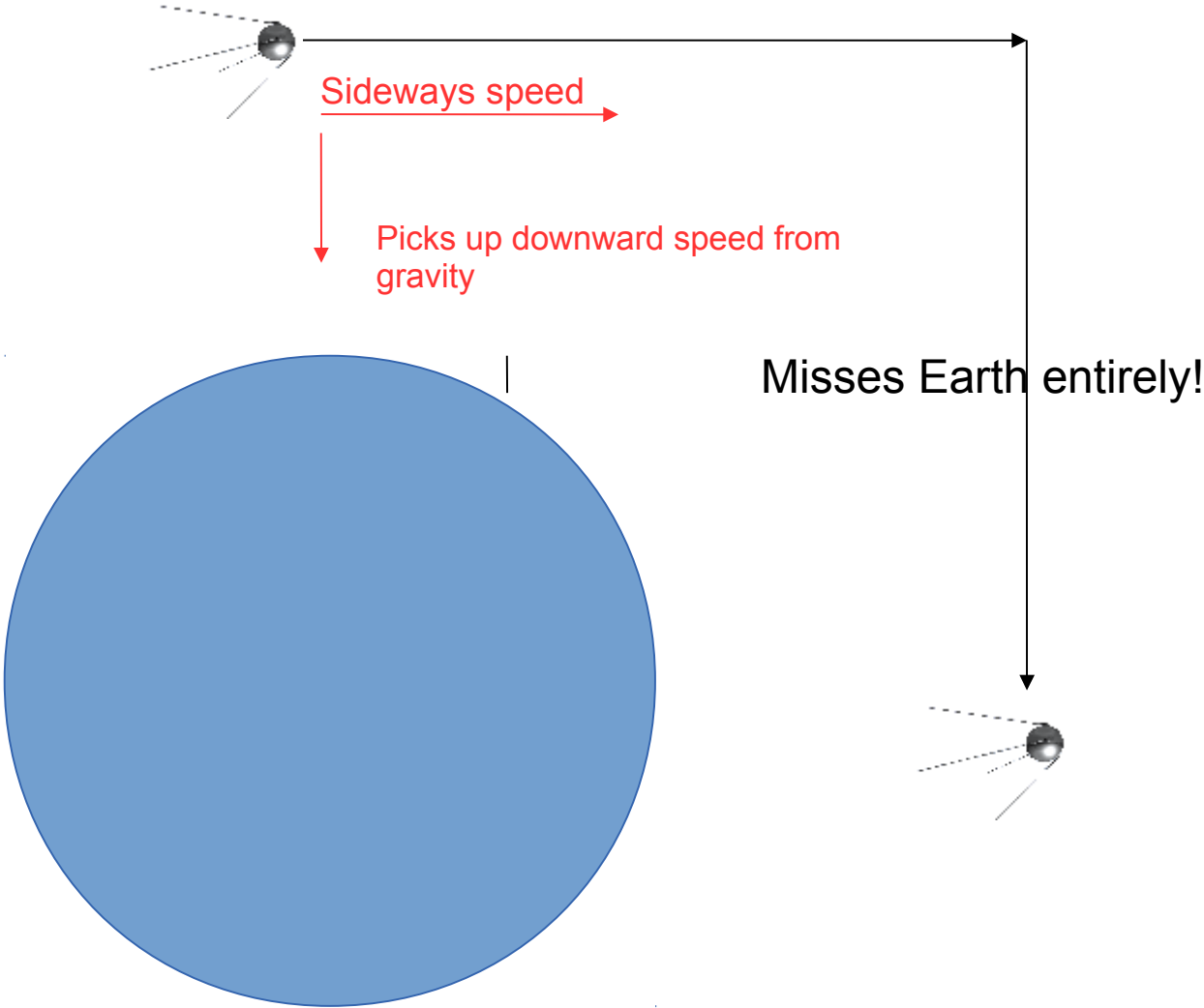


In that 5 miles,
Earth curves away
from you by 30 feet!

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

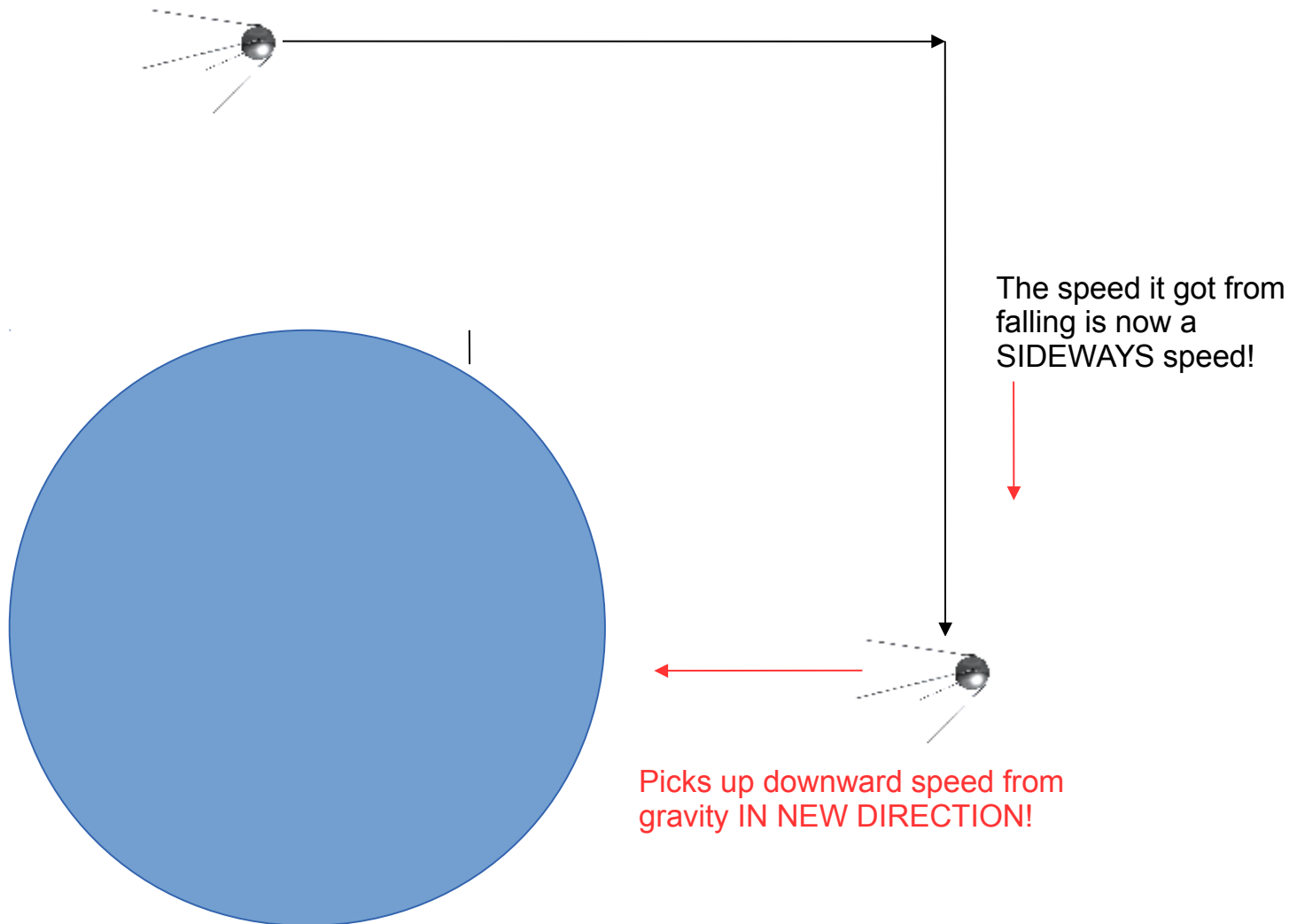
In 23 minutes, falls 4000 miles
BUT: moves sideways 4000 miles too!

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



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)



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 minutes Earth 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

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

Kepler's third law

$$T^2 = (4 \pi^2 / GM) r^3$$

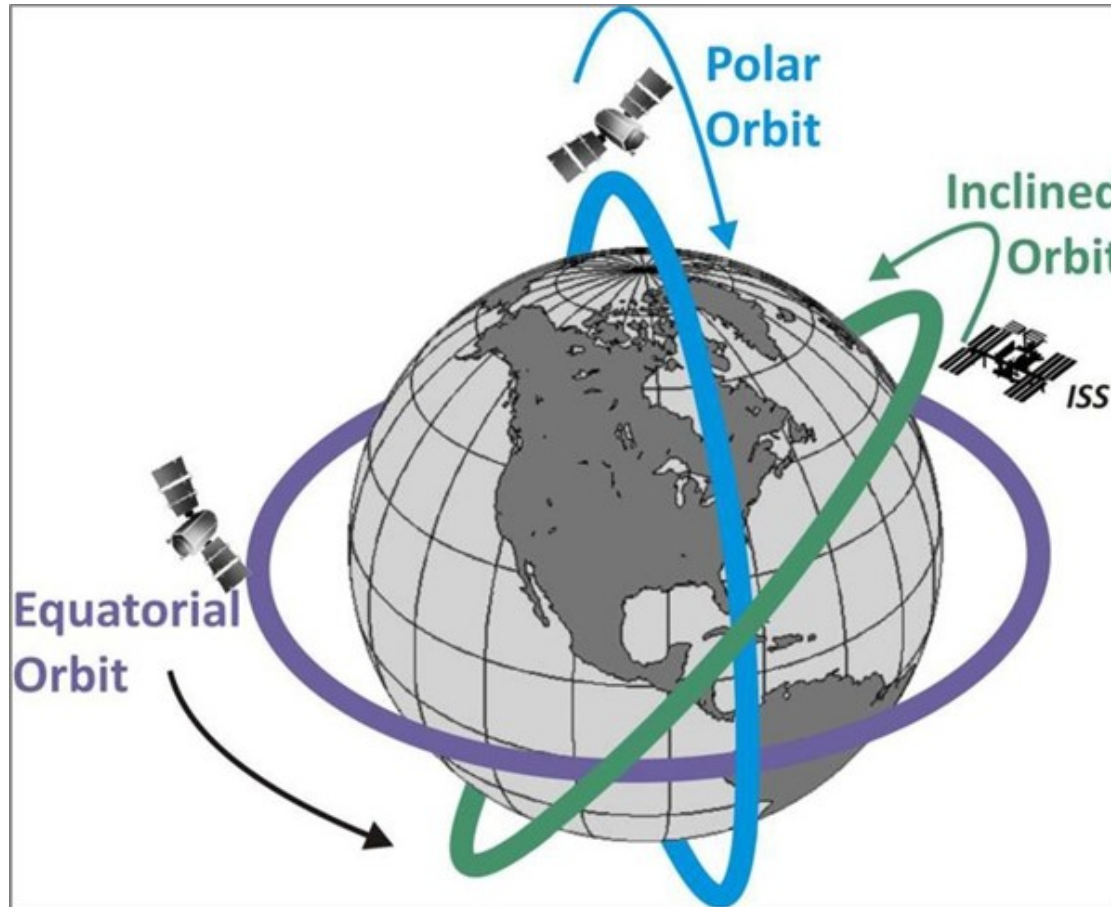
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or $v = 17158$ mph - quite fast!!

At 400 km, orbital period is 92.5 minutes Earth surface has radius $r = 6378$ km (3964 mi)

Inclination:

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



$i = 0$ degrees
Equatorial

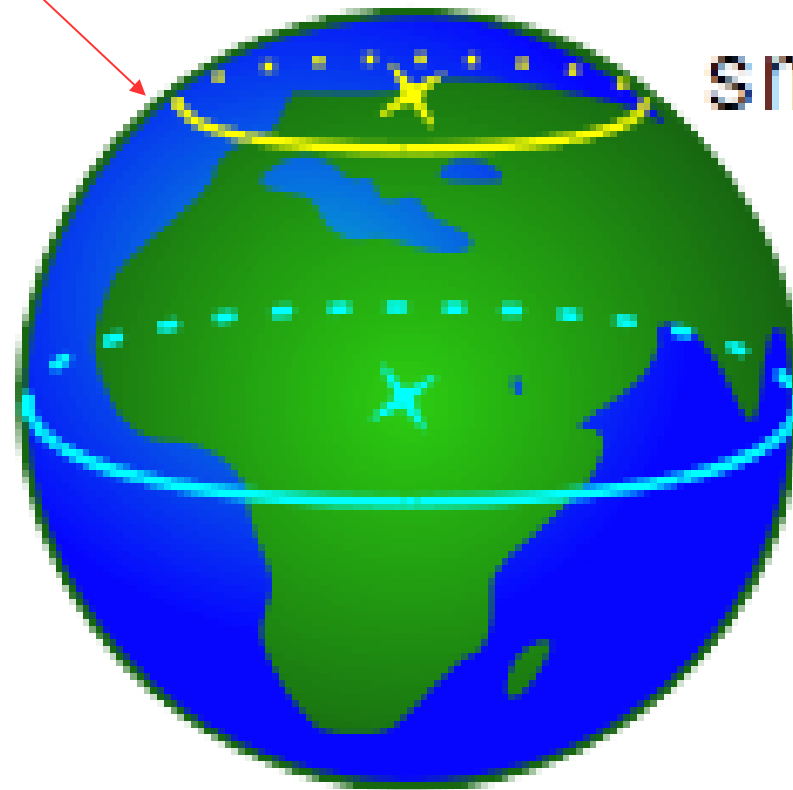
$i = 90$ degrees
Polar

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!



small circle

great circle

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”

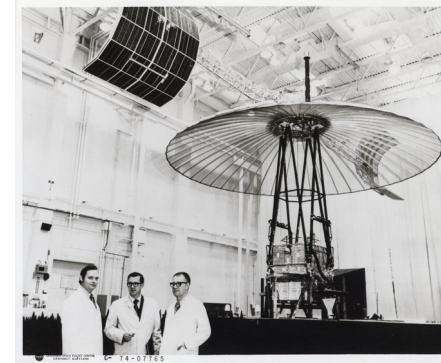
boxes of electronics with big solar-power-generating wings, commanded from Earth



Communications



Earth Imaging



Signals intelligence



Technology and training



Navigation (GPS)



Science
(e.g. astronomy)



Human spaceflight

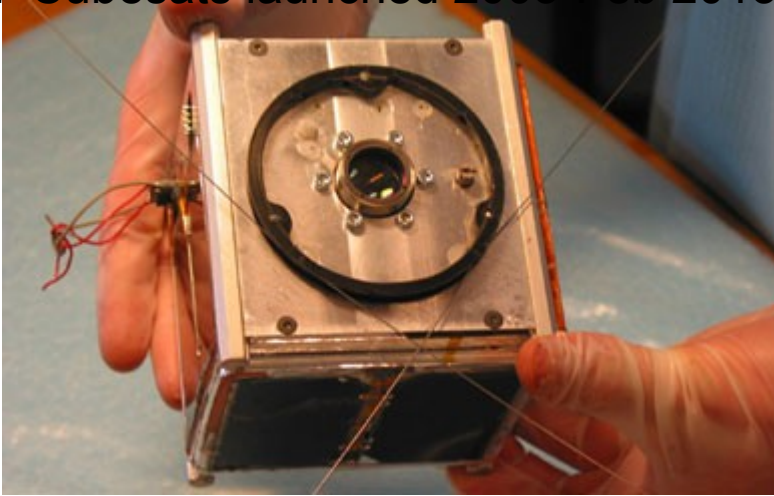
Satellites can be REALLY TINY:

Cubesats: 1 kg, 10 cm (2 lb, 4 in for the metric impaired)

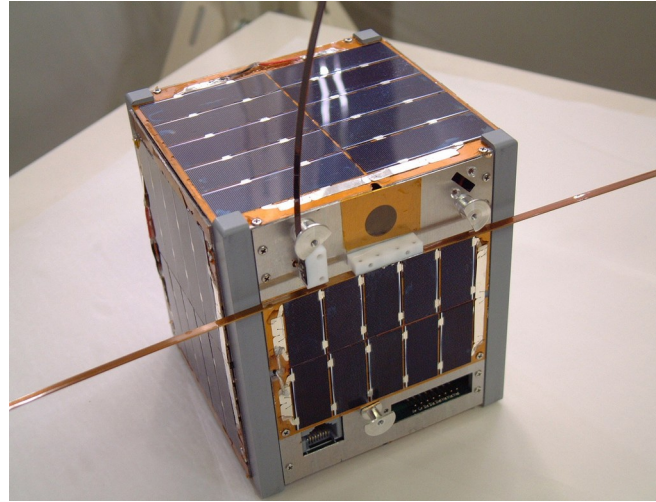
Standard kit for universities to make students build sats in engineering courses

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

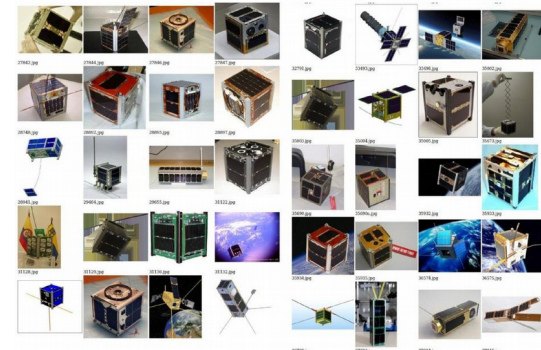
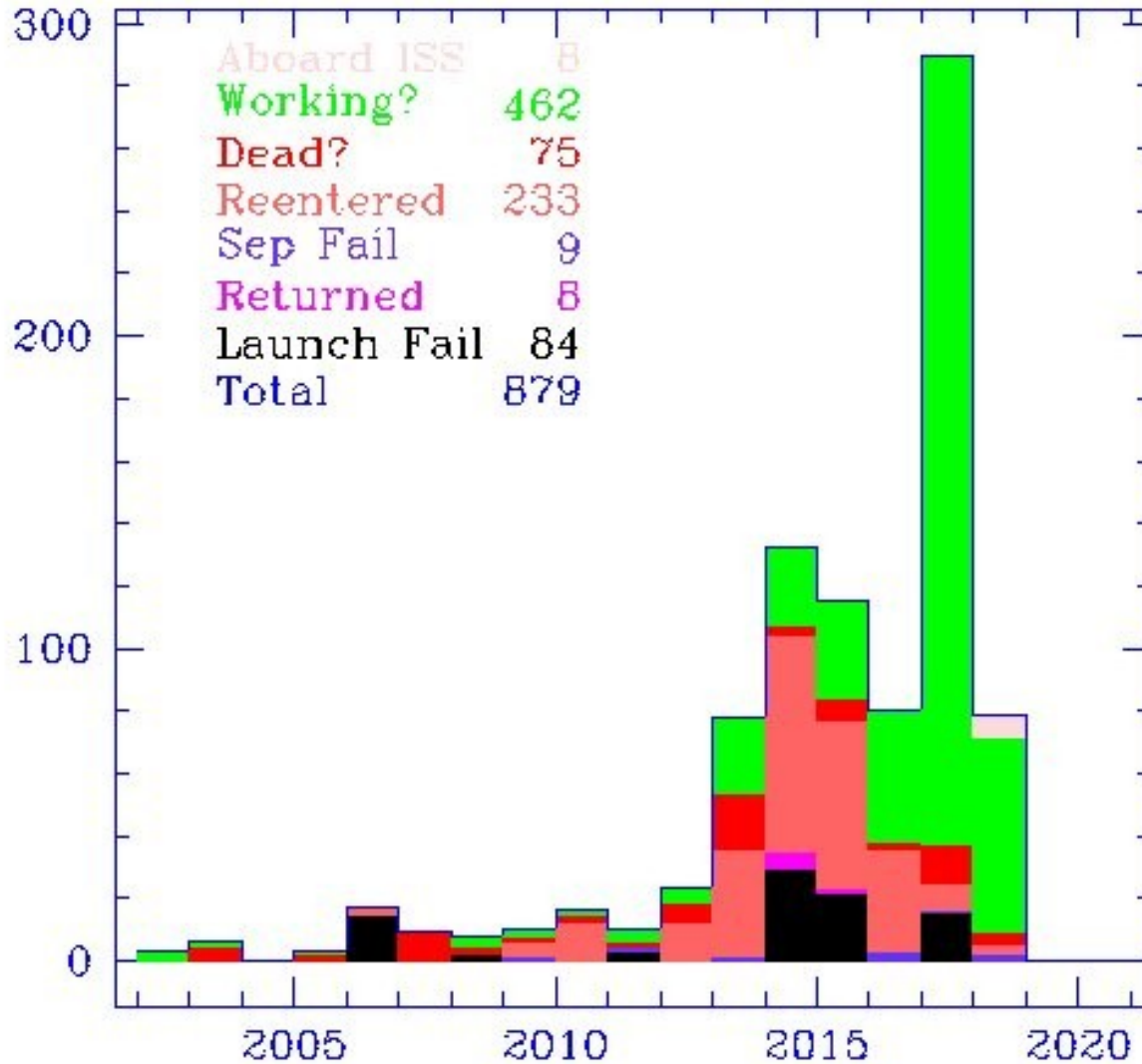


Triple-cube Quakesat, Stanford
2003

The Cubesat Explosion

<http://planet4589.org>

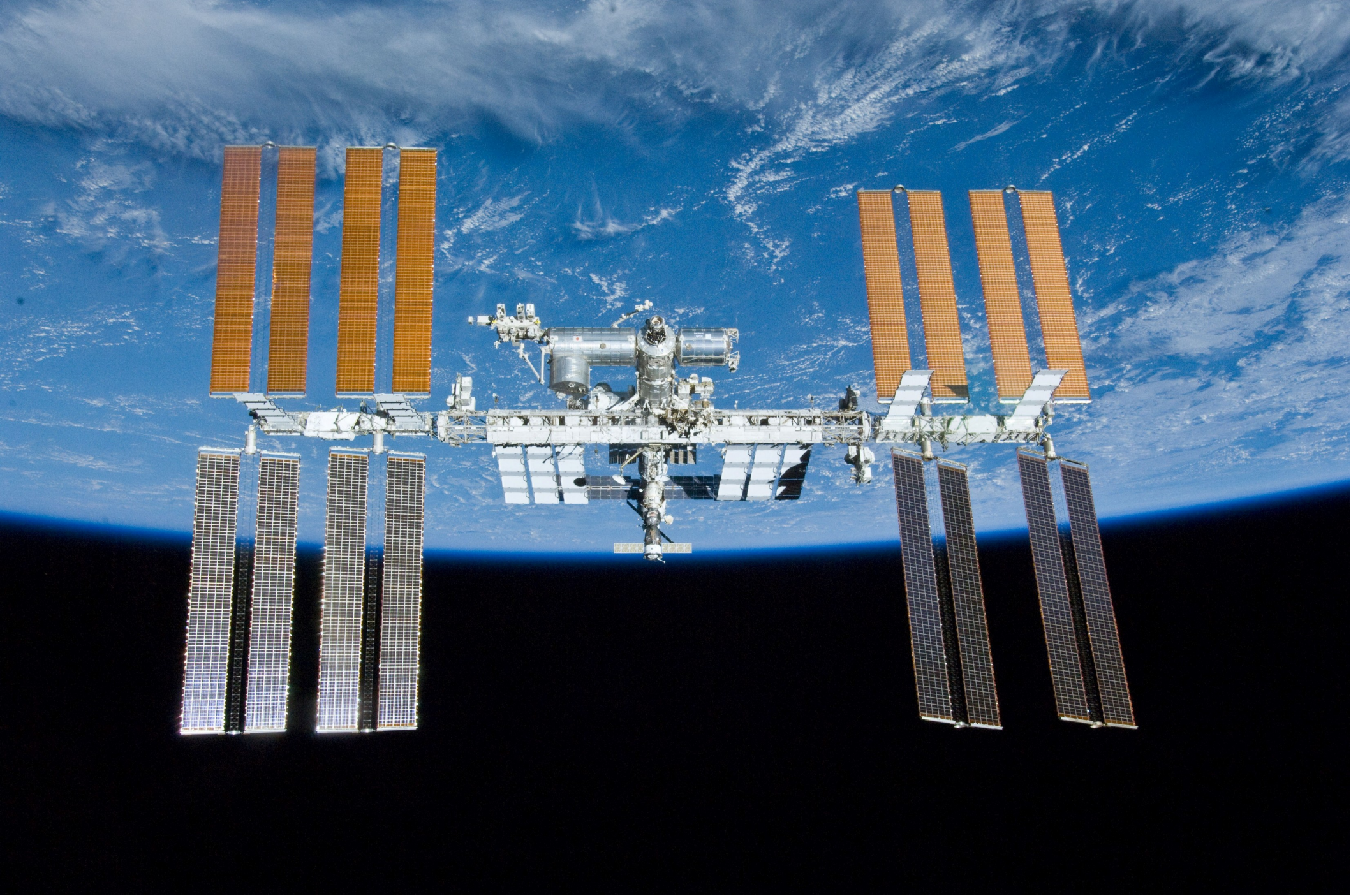
Cubesat statistics 2018 Sep



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...

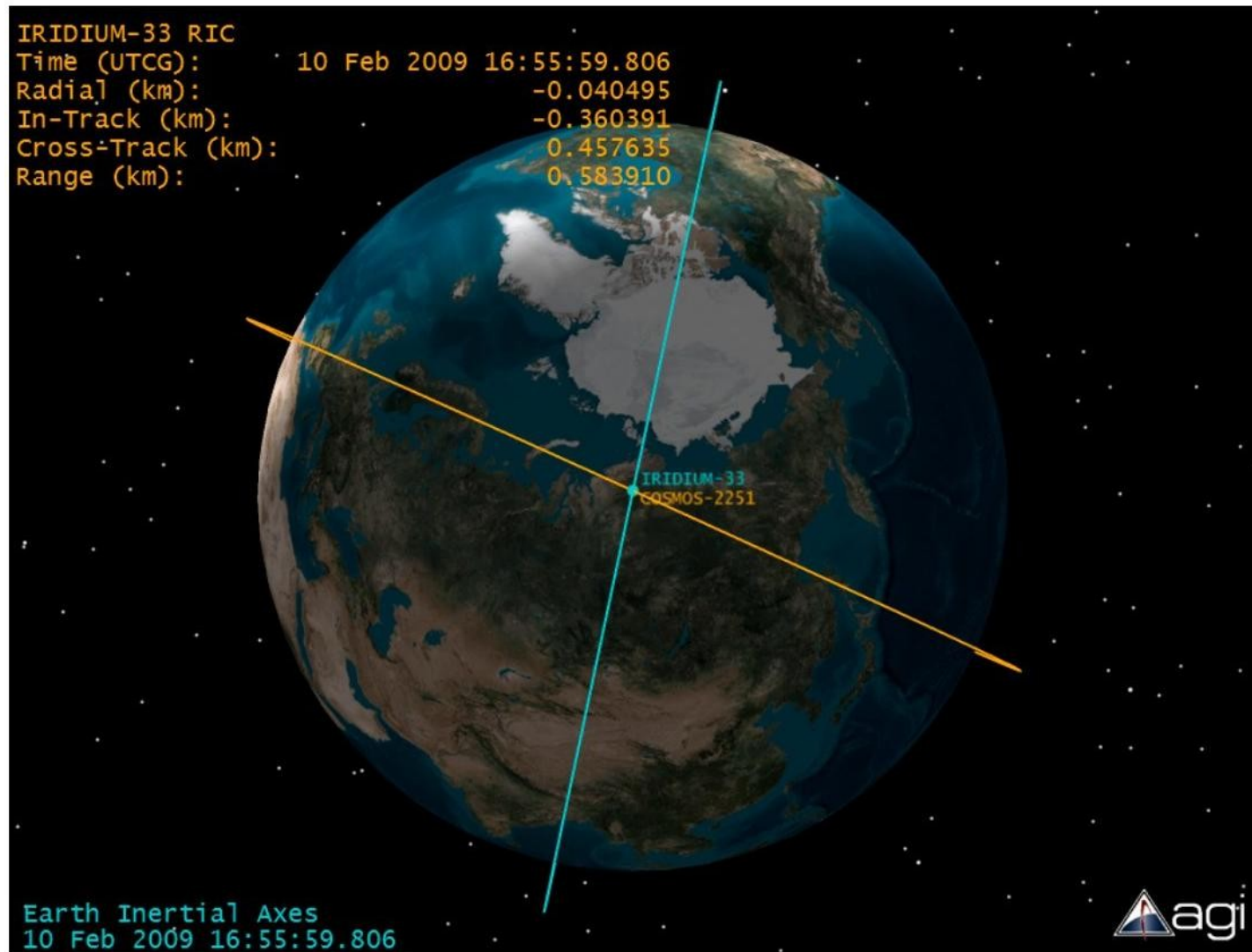
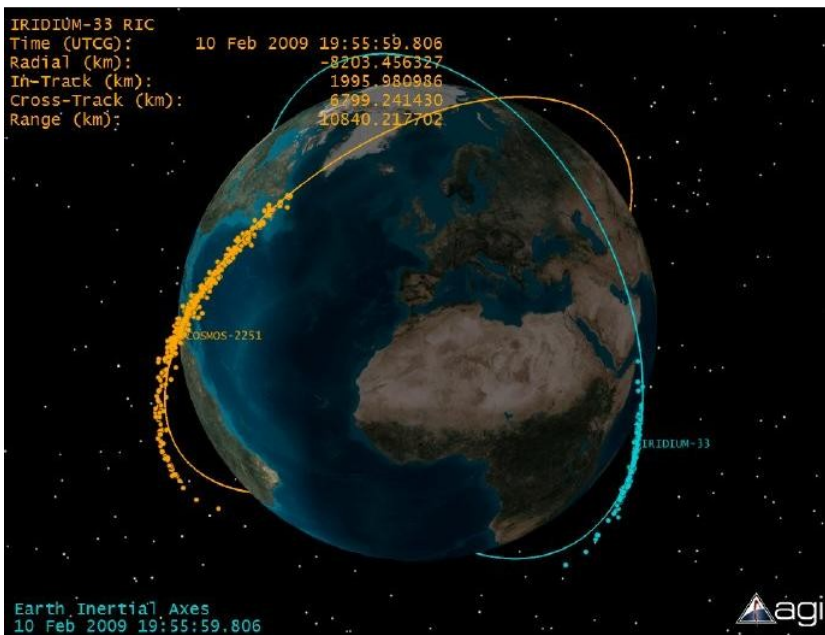


Figure from Kelso 2009



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

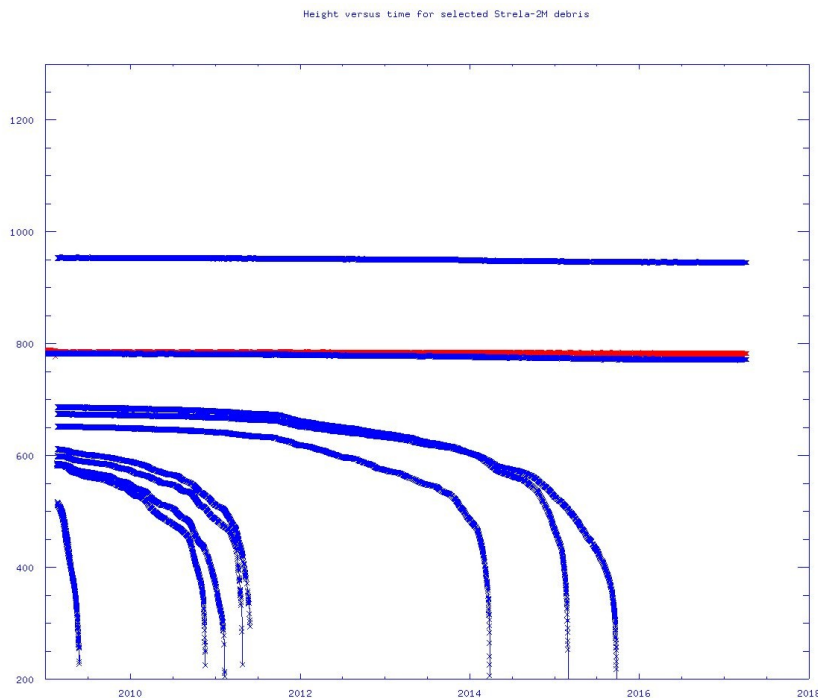
Also spread in altitude due to varying A/m ratio and hence drag coefficient

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

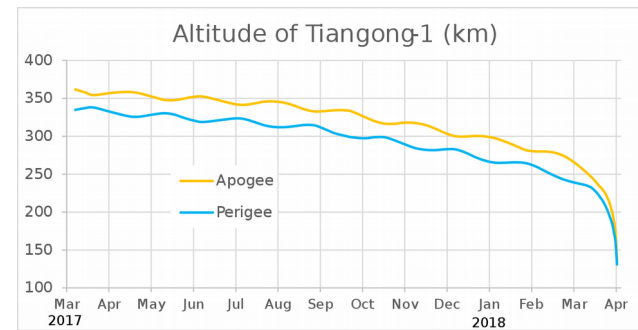
Current status:

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

v² 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.

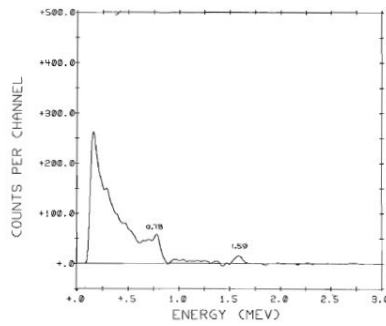


Figure 24.3 The spectrum above is the cumulative addition of individual spectra recorded over the anomaly of Figure 24.4, with local background either side subtracted. The small peak at 1.59 MeV is from the fission product ^{139}La and confirmed the evidence of Figure 24.4. The single overflight by the spectrometer thus provided conclusive proof of the presence and the nature of the radioactive debris on the lake.

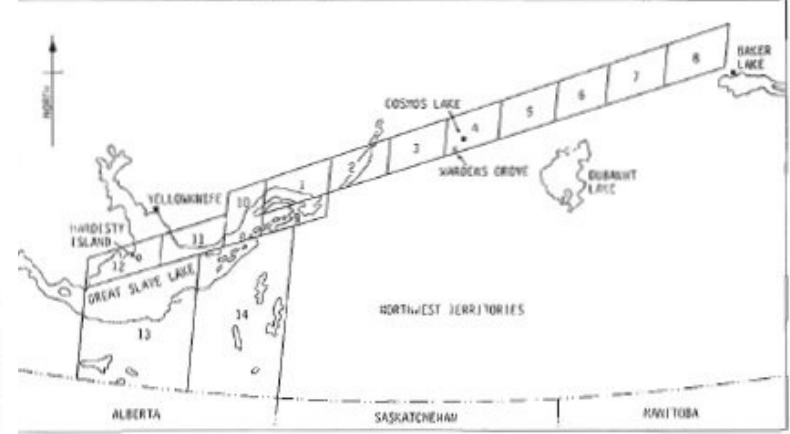


Figure 24.1 The impact trajectory of the satellite stretches from Great Slave Lake northeast toward Baker Lake. Sectors 13 and 14 were established with wind borne material in mind.

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



Radioactive debris being prepared for removal. In general, the materials were wrapped in plastic film to prevent dust or any dust or fine particles. The more radioactive elements were then manipulated into special shielded crates for safe transport.

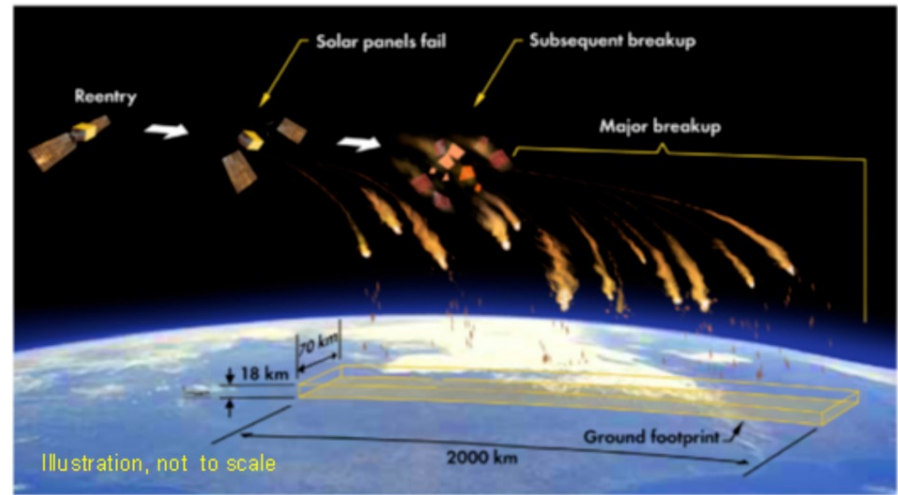




Lottie Williams of Tulsa, OK with the melted, twisted piece of space debris that fell out of the sky and hit her on Jan 22, 1997.

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

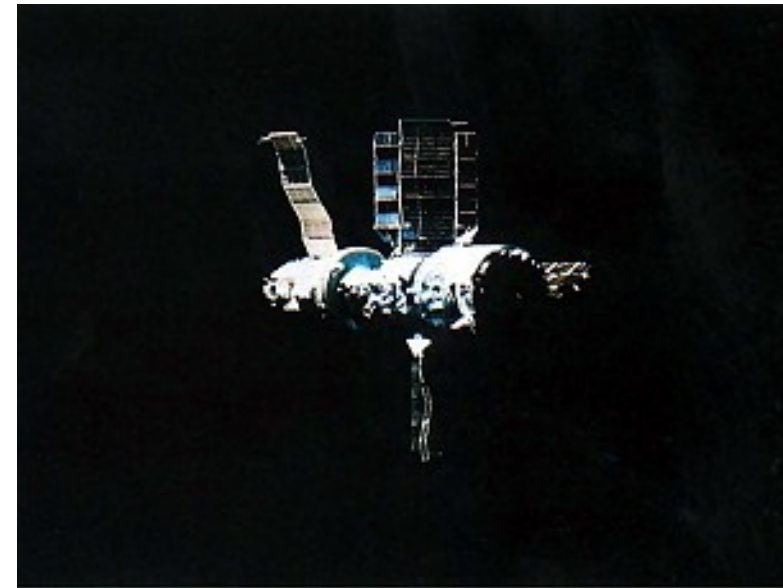
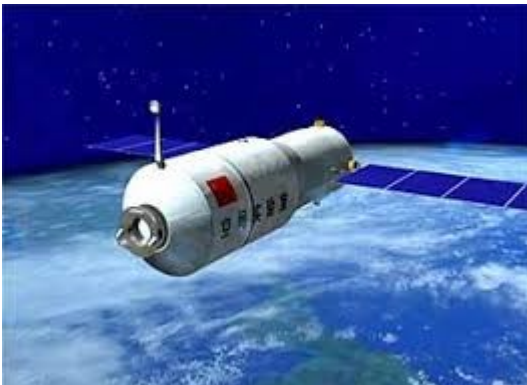
1975 SKYLAB ROCKET 49 tons

1991 SALYUT 39 tons

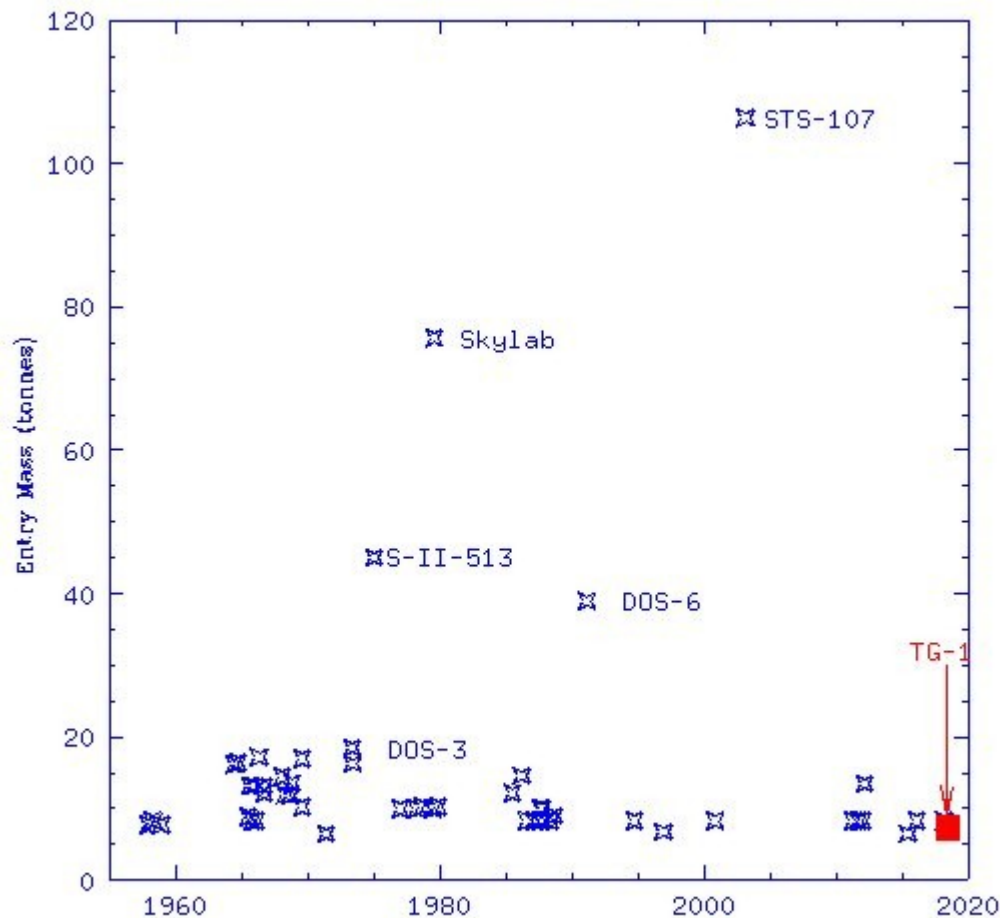


This past April:
TIANGONG-1 – lots of press, but only 8 tons

Something this big about once every 3-5 years



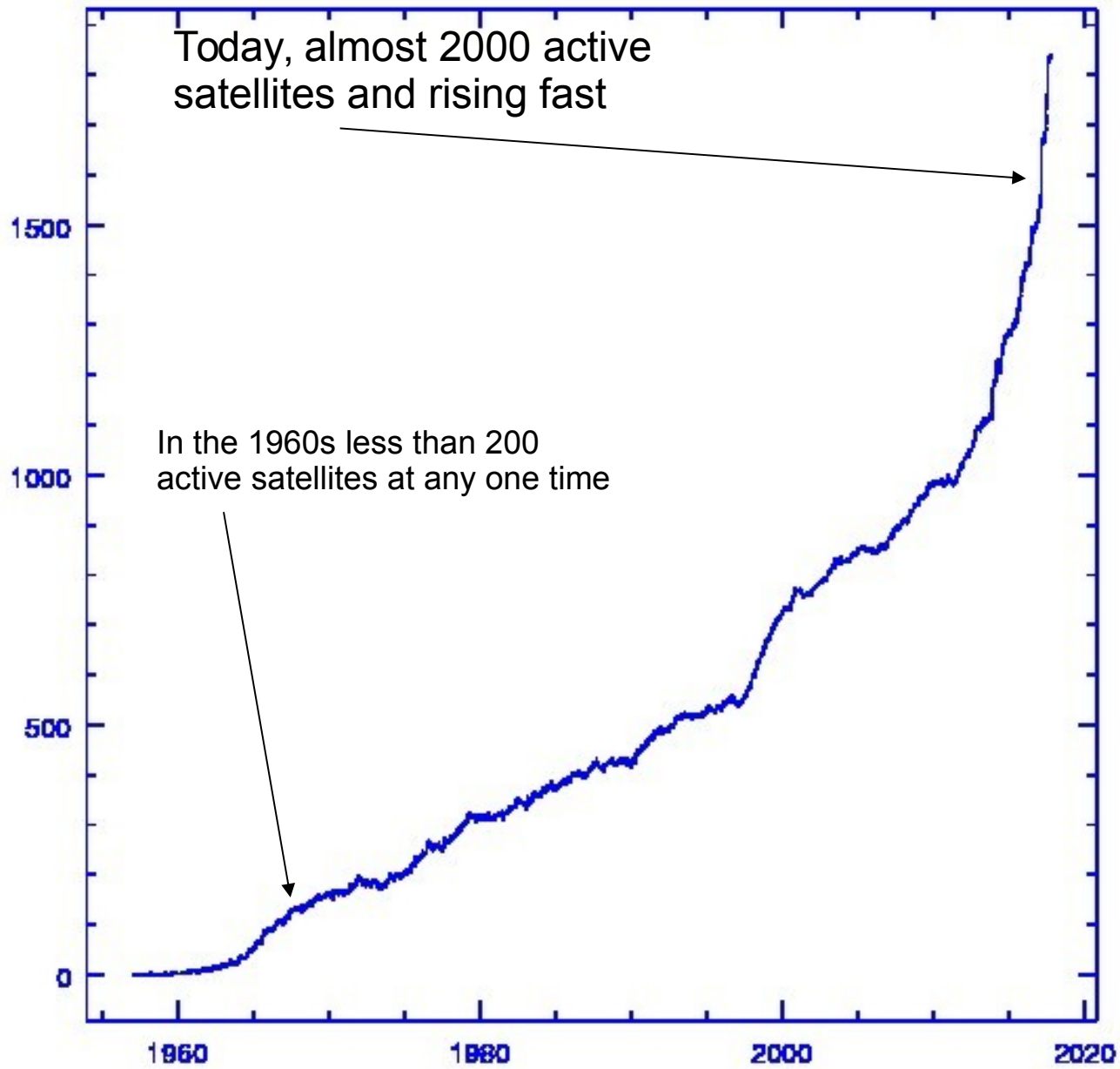
Large Uncontrolled Reentries 1957-2018



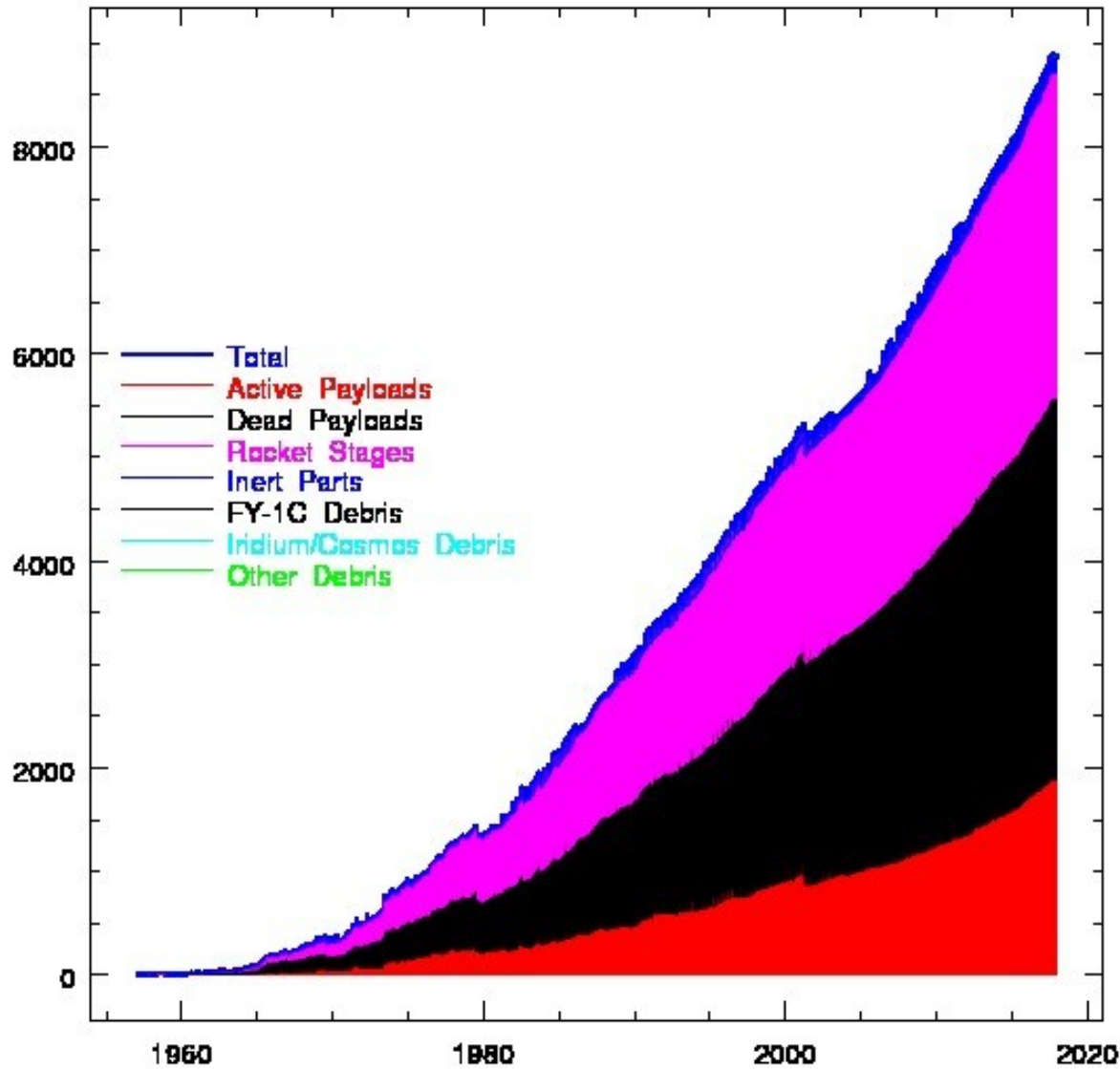
#	# Spacecraft	Reentry mass - tonnes	Date	Location
#	#-- The biggest uncontrolled reentries --			
#	# Note: STS-107 was controlled until its breakup but had similar consequences to an uncontrolled reentry.			
#				
1	OV-102 Columbia (STS-107)	106.4	2003 Feb 1	Texas/Louisiana
2	Skylab space station	75.7	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

HOW MUCH JUNK?

Active Satellites 1957-2017



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)

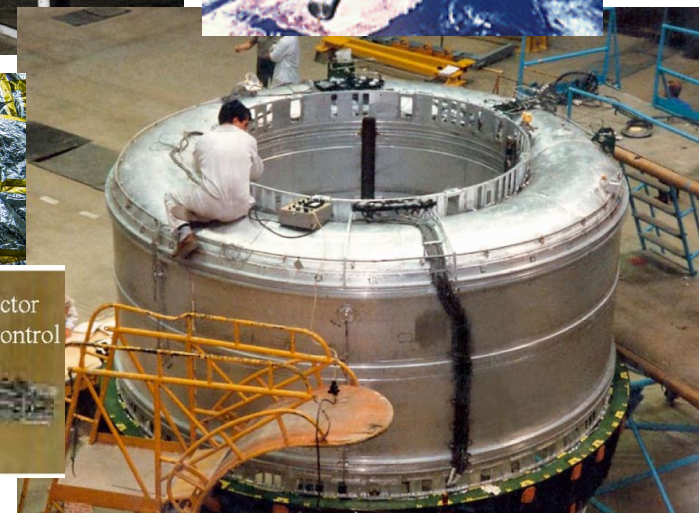
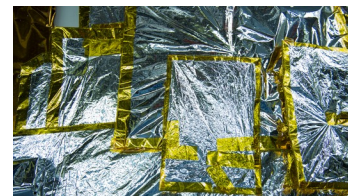
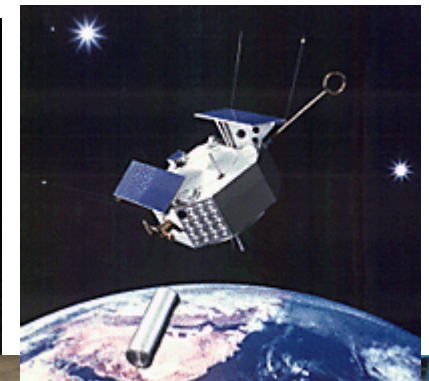
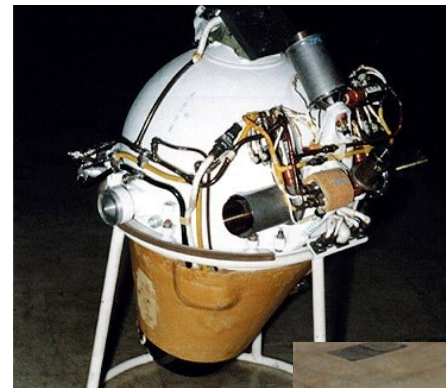
A Census of Space Debris

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) 10417
2007 Chinese ASAT debris	2855	
2009 collision	1443	
Other debris	6119	

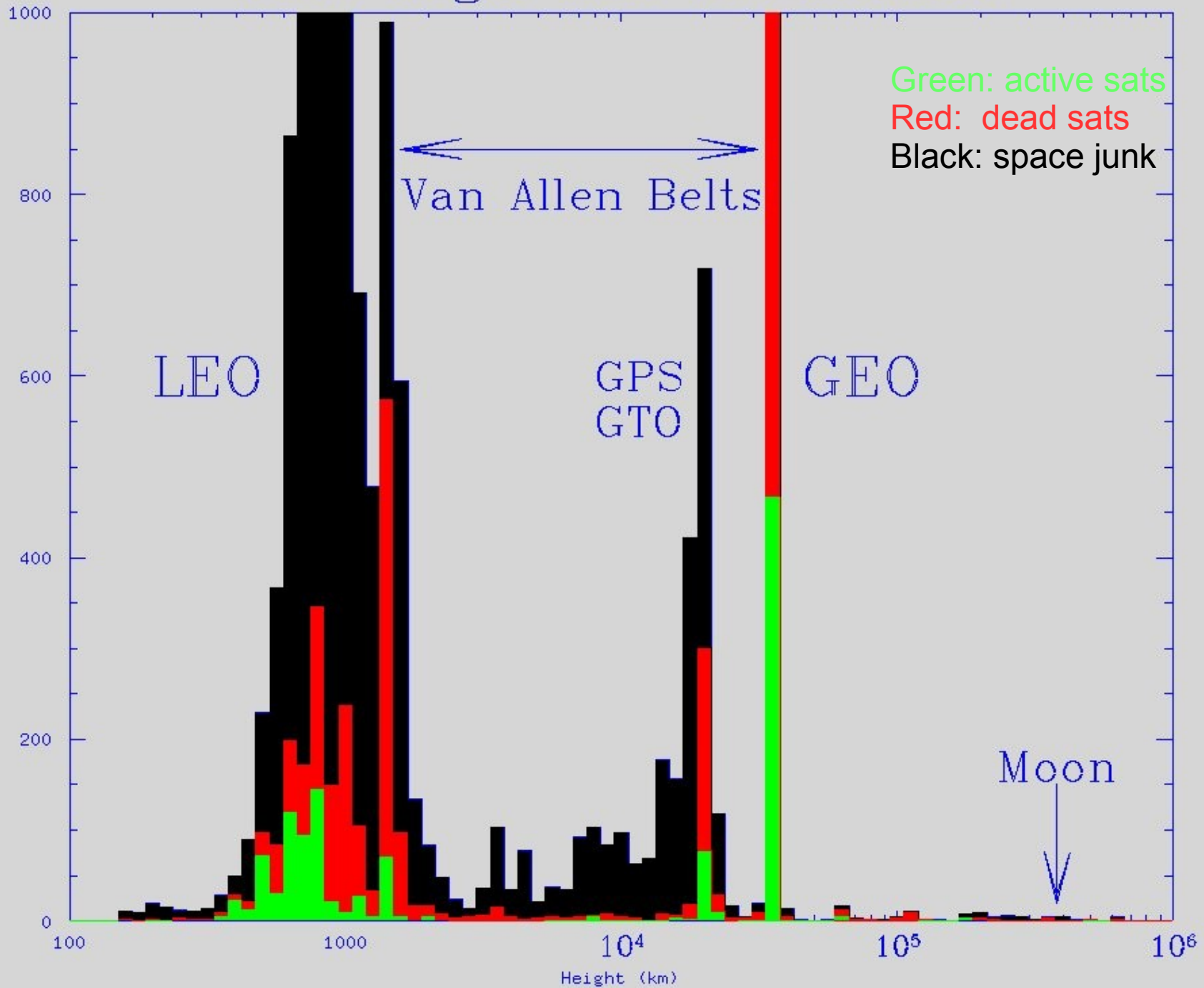
Covers, fairings	300
Jettisoned motors and tanks	170
Multi-payload adapters	141
Despin devices	131
Deployment canisters	38
Insulation blankets	36
Nuclear reactor cores	14
Misc	28
Unknown pieces	794

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

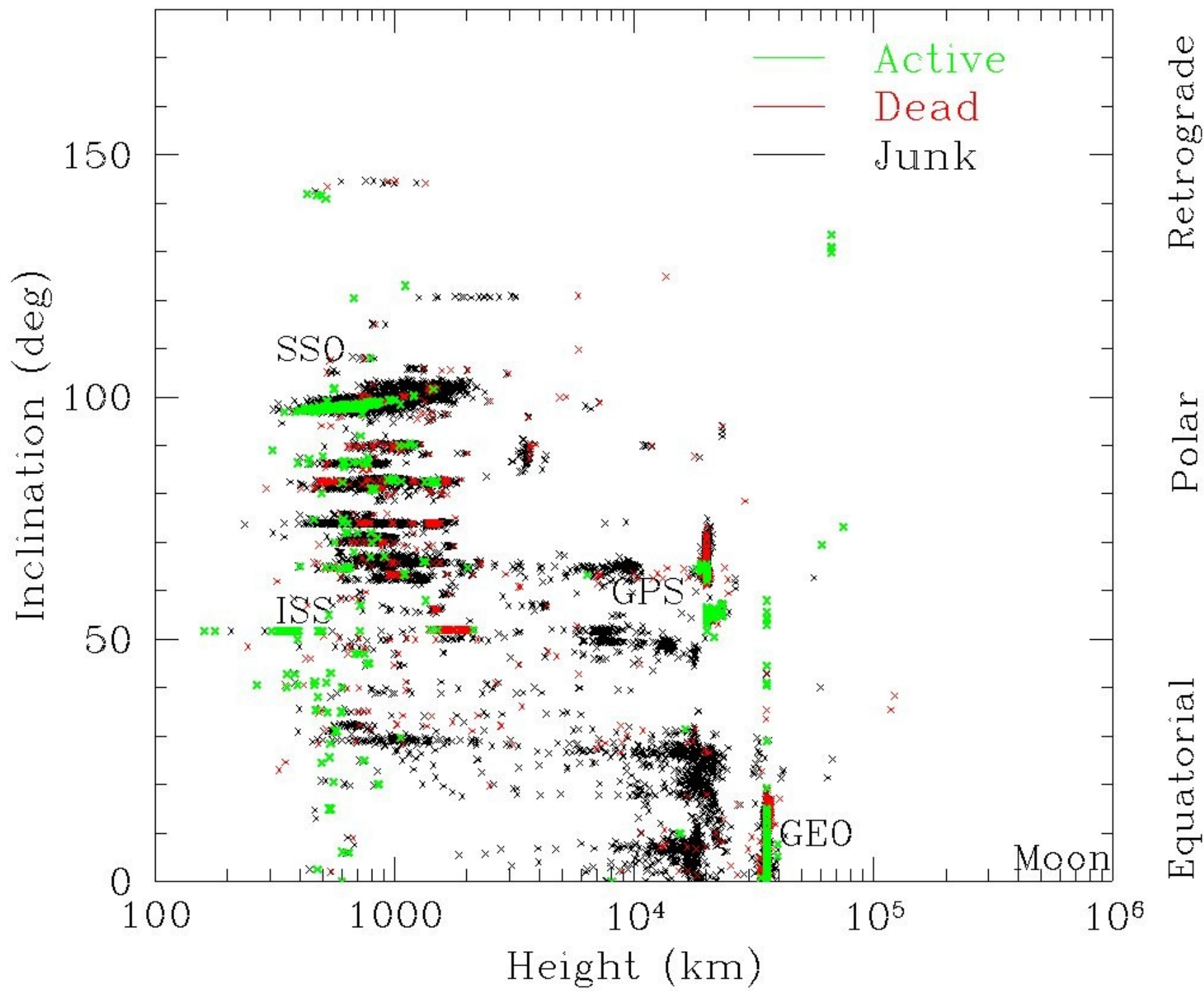


WHERE IS THE JUNK?

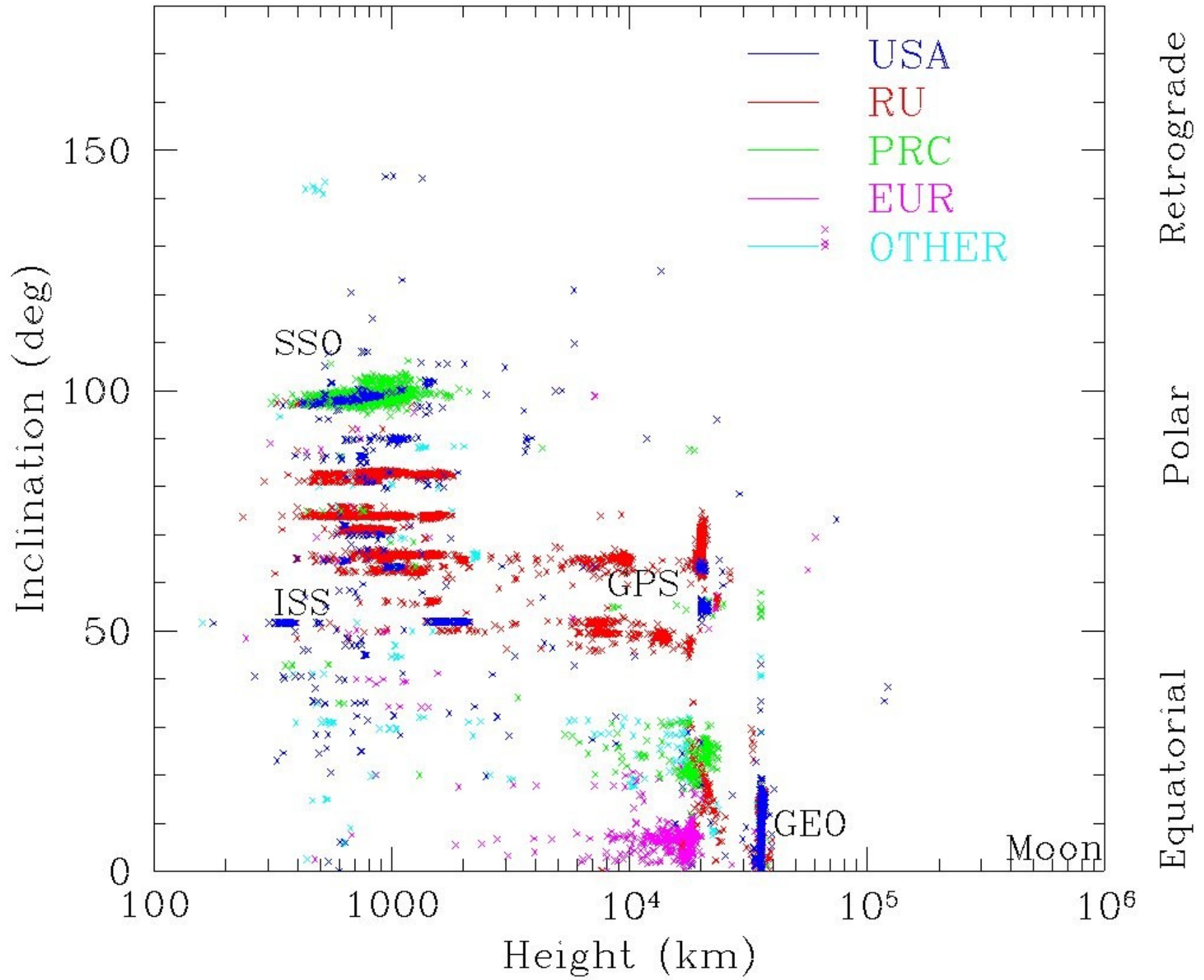
How high are satellites?



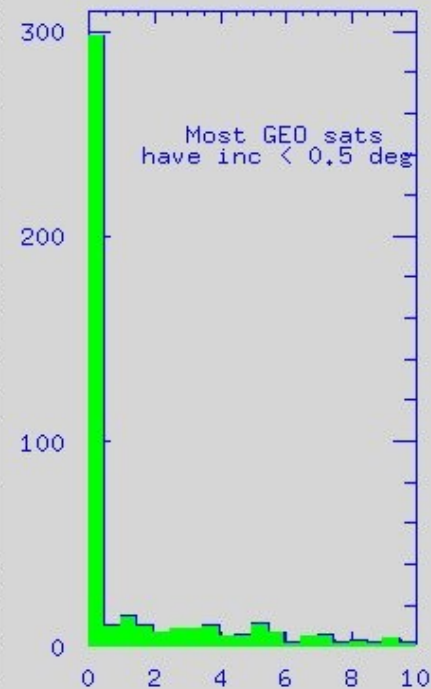
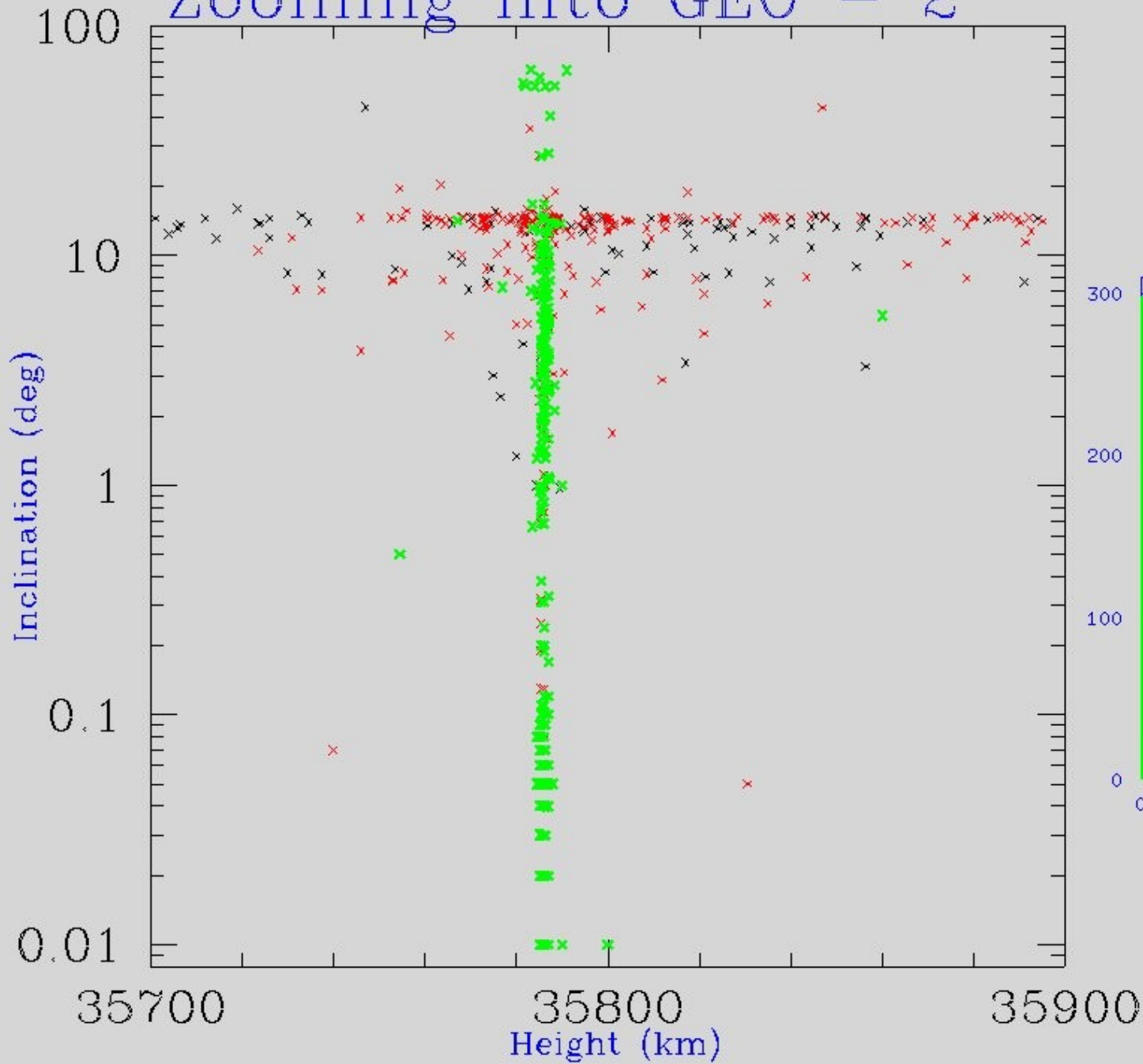
A Map of Earth Orbit



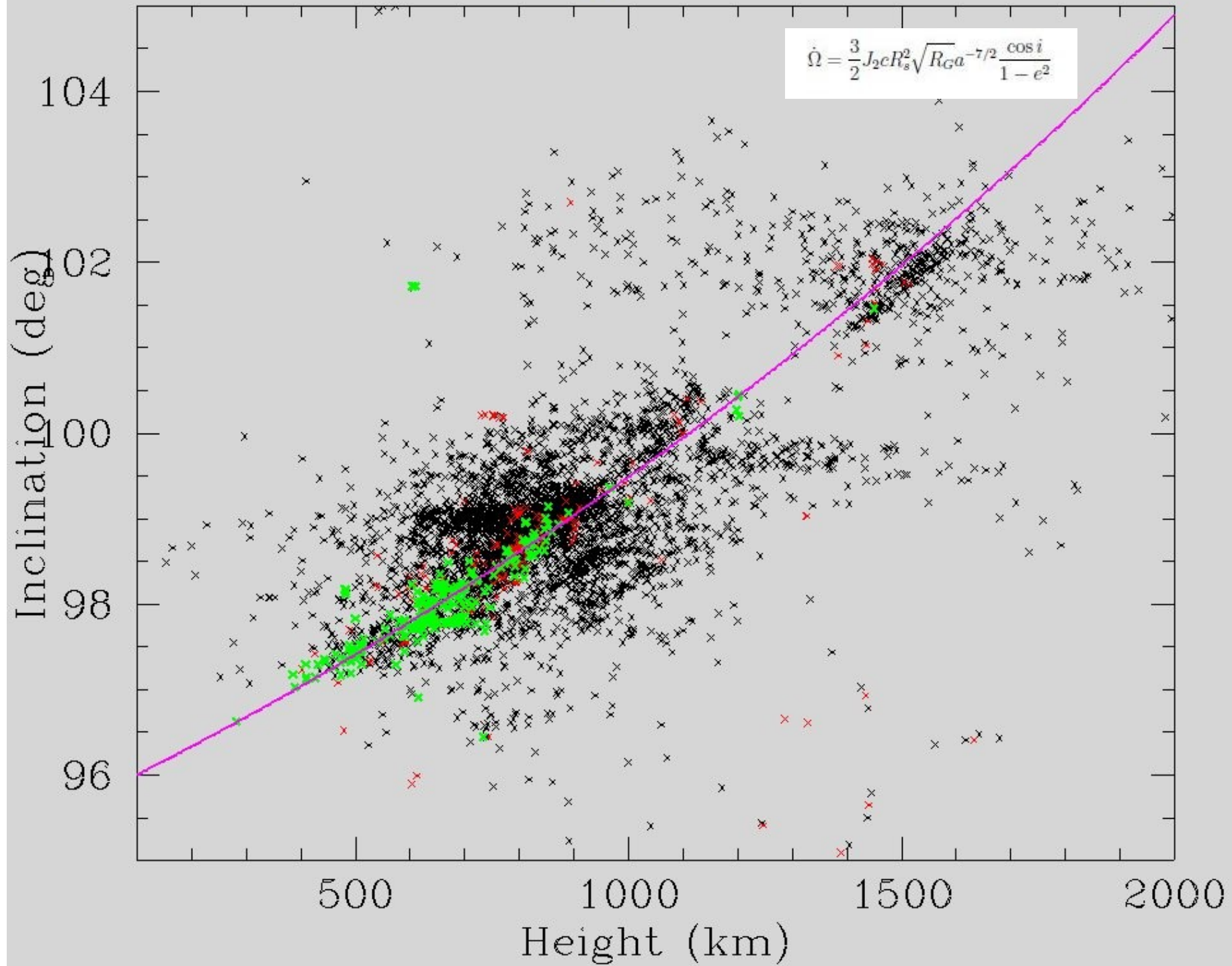
Whose Junk Is Where



Zooming into GEO - 2



Zooming into SSO

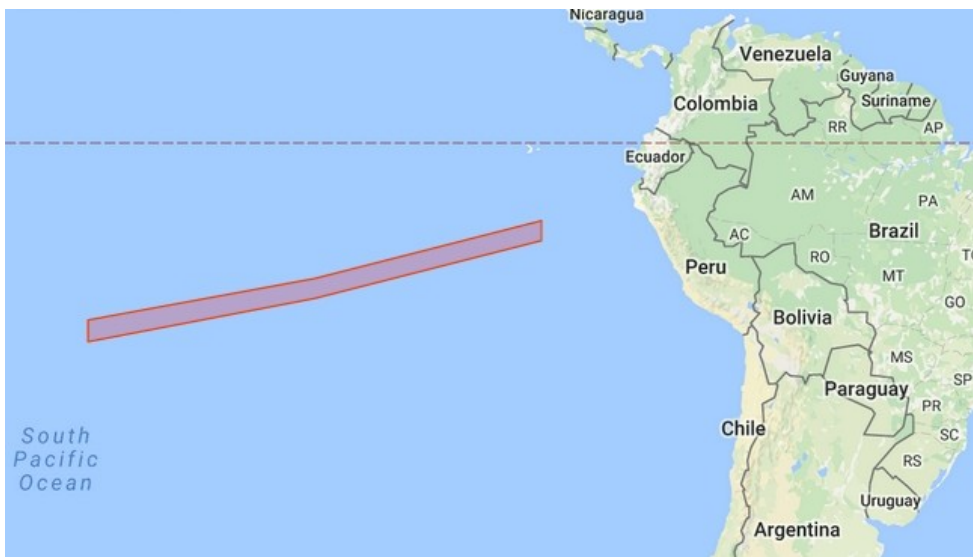


FIXING THE PROBLEM

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?



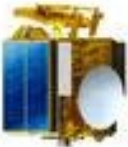
Dual satellite launch
(European Ariane 5)
4 objects end up in orbit -
two satellites, two pieces of junk



Top satellite



'Adapter': Container for lower satellite

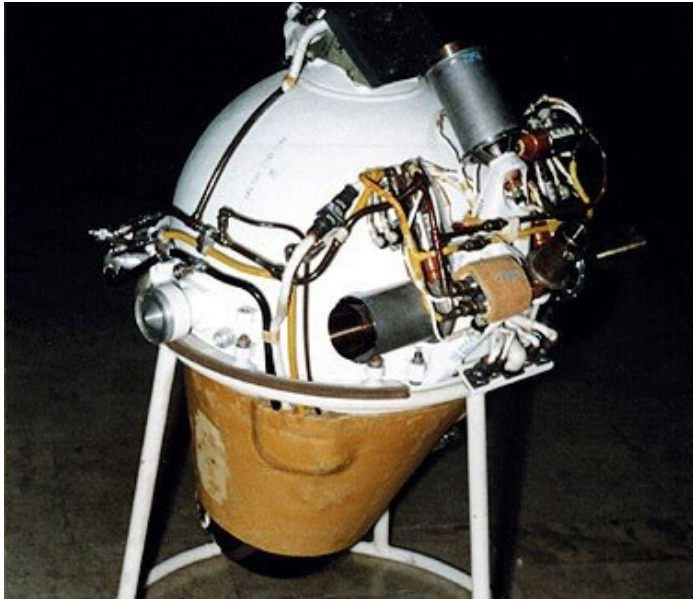


Lower satellite



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...

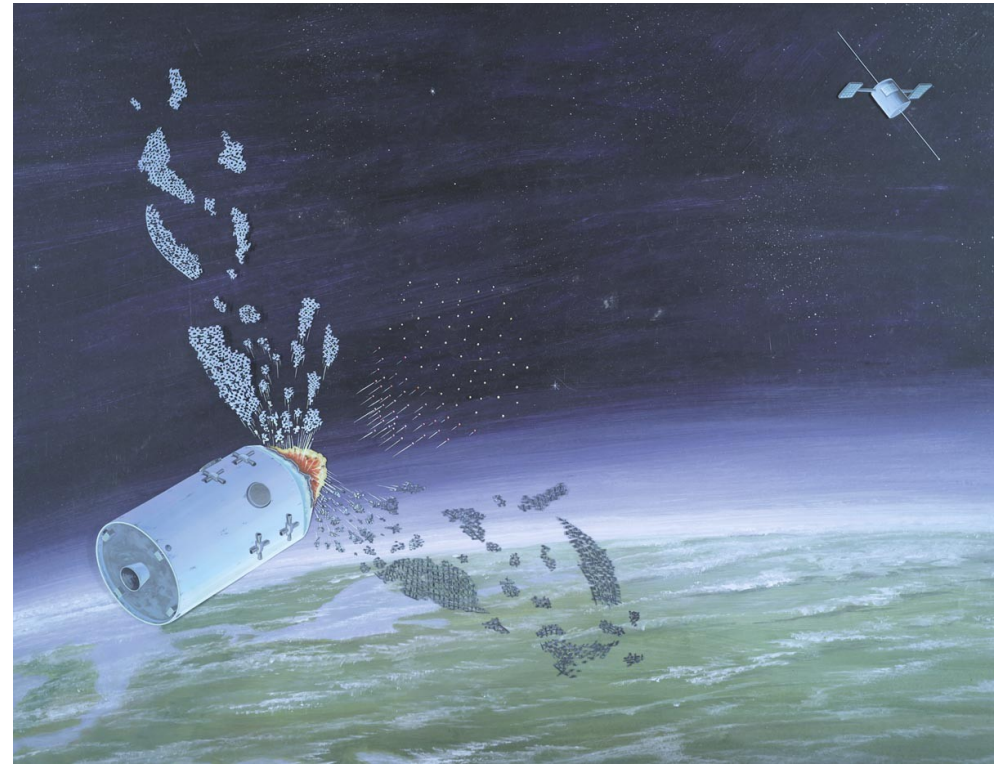


Configuration after activation
of APO self destruct device

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)

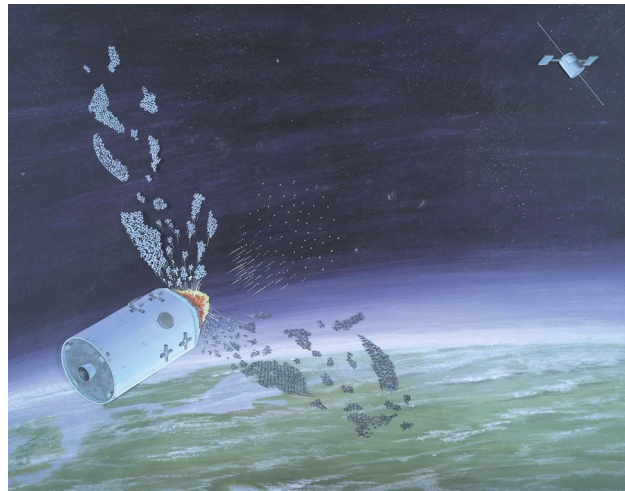
Don't do that

- Antisatellite weapons

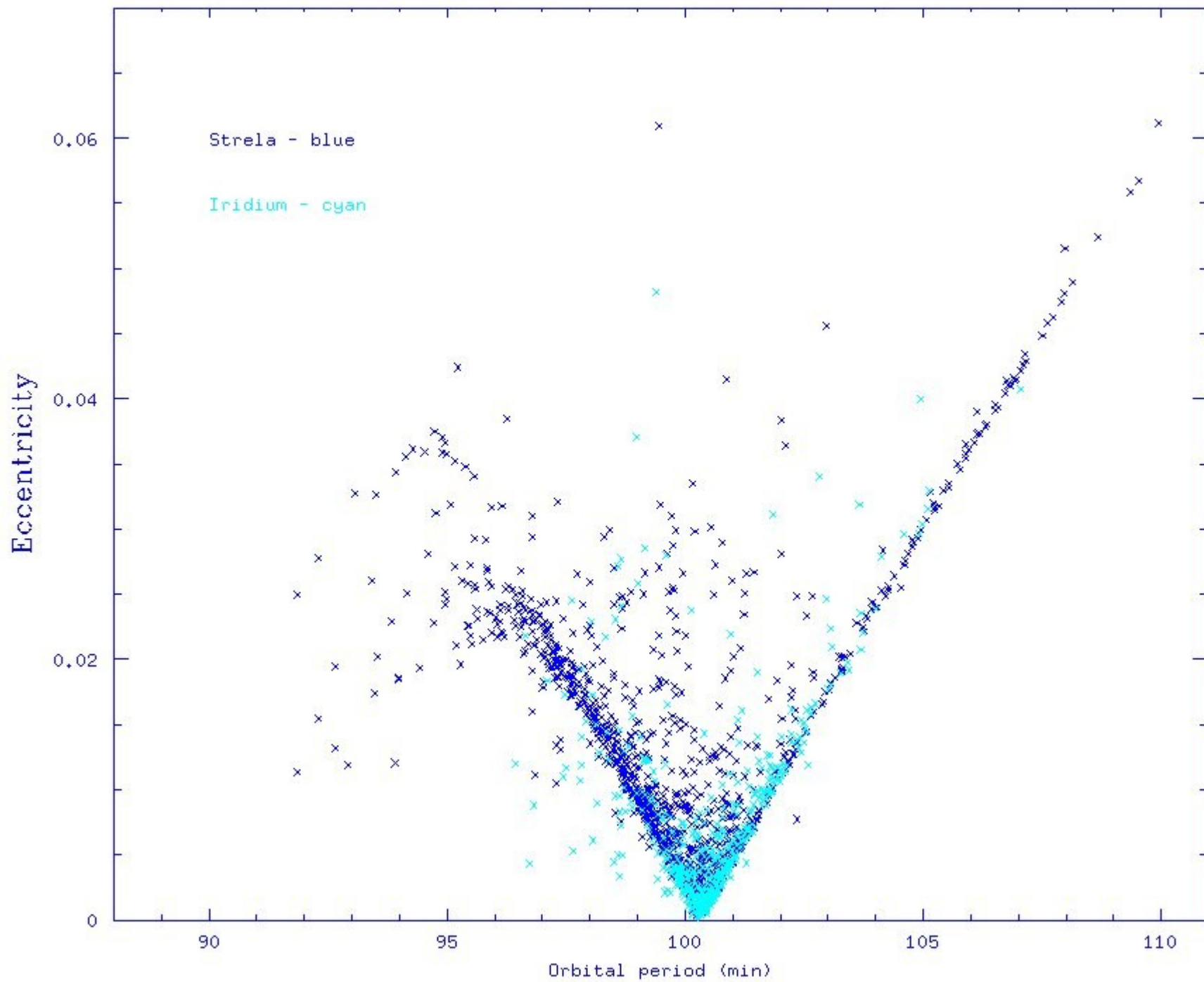
Really don't do that

- Collisions

Reduce total amount of debris

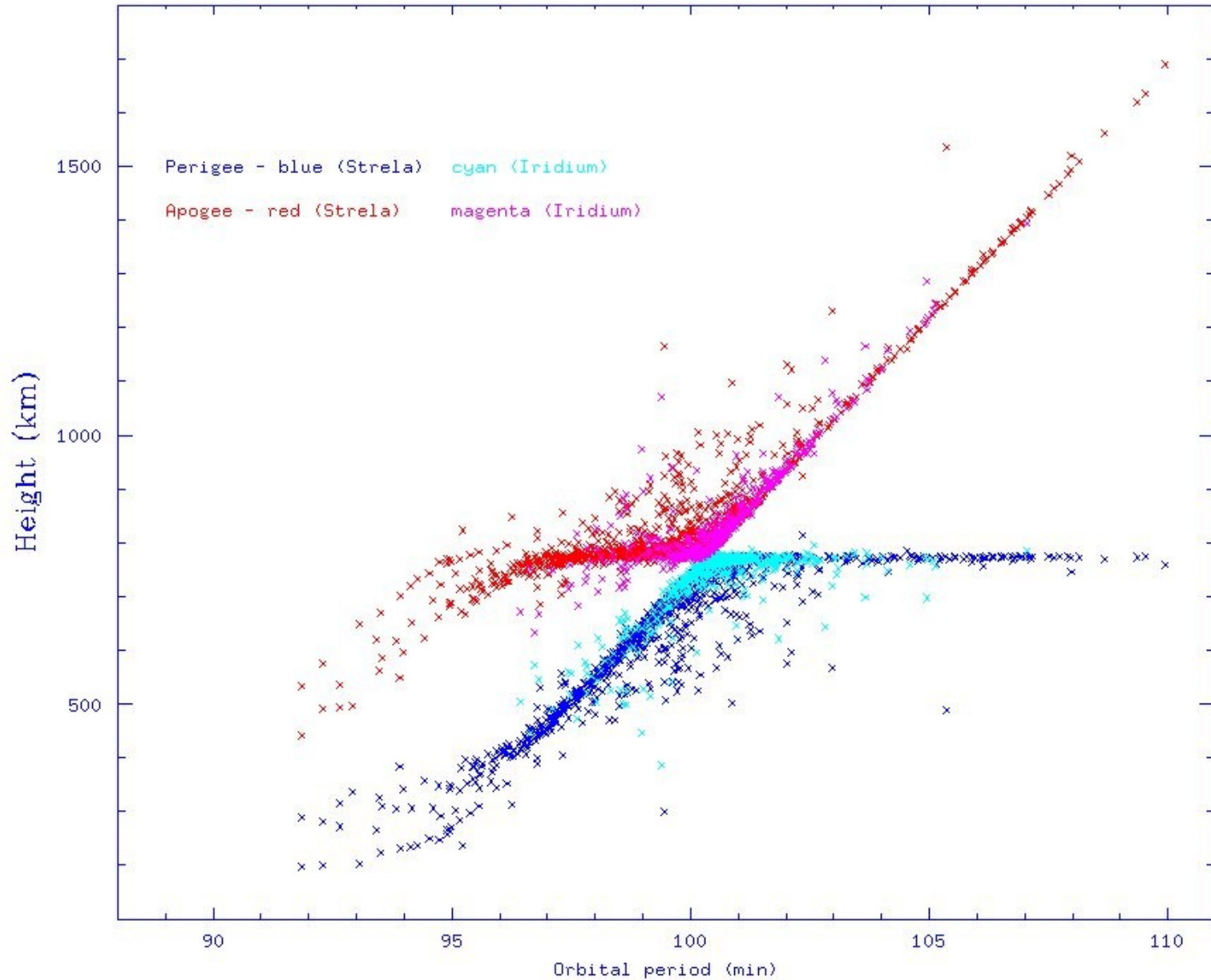


Eccentricity vs period, Iridium/Strela

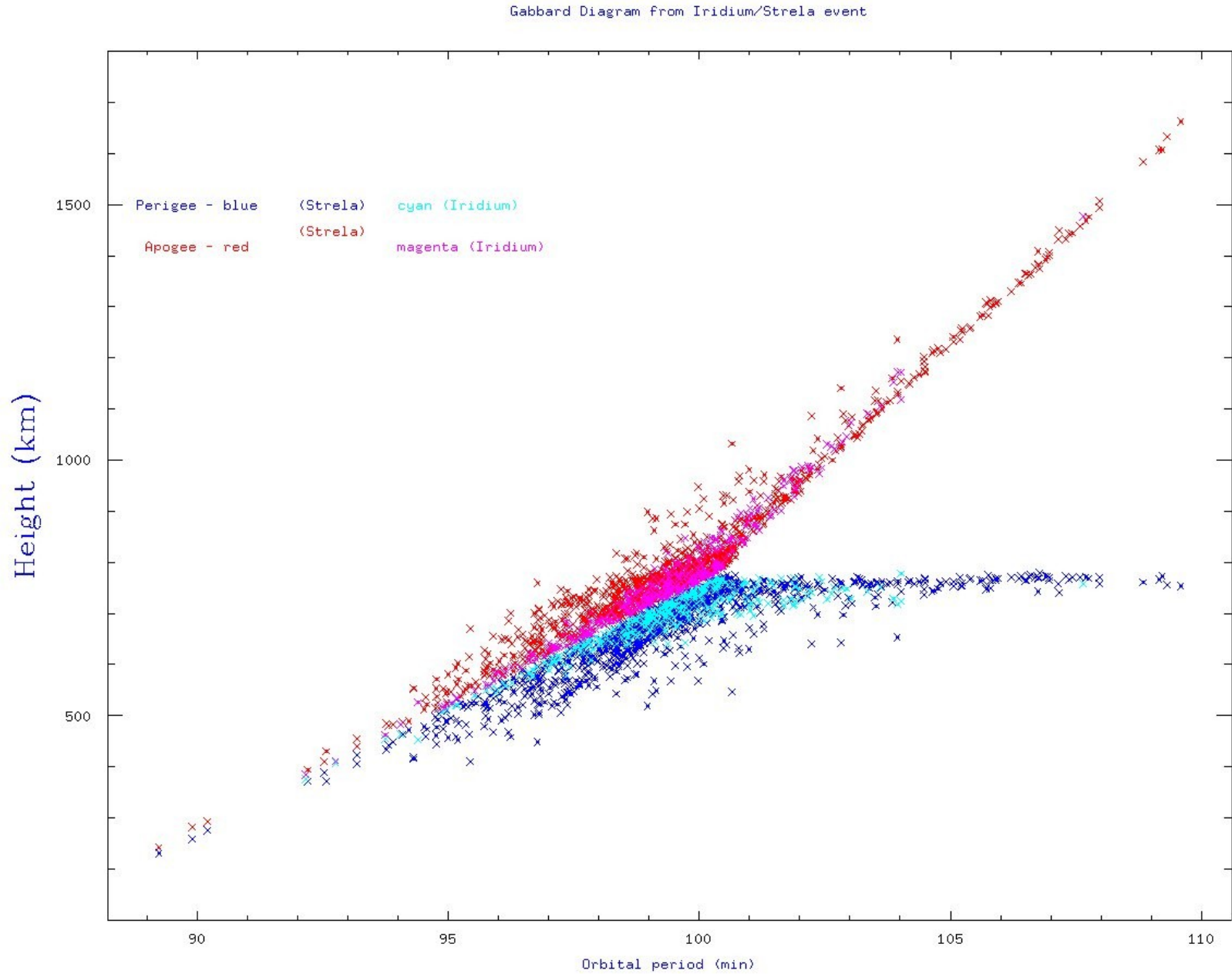


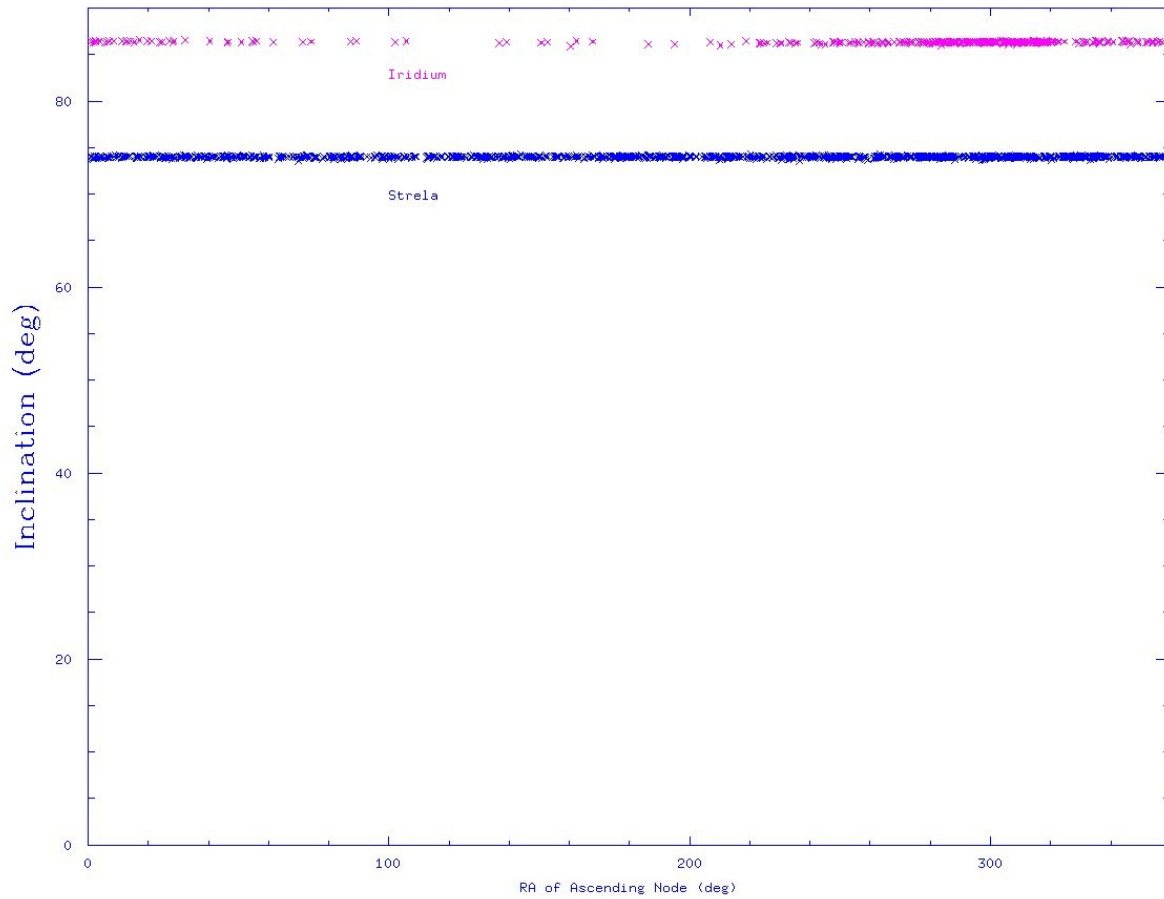
Gabbard Diagram (developed by NORAD's J. Gabbard in 1960s) shows perigee, apogee vs orbital period
Can see different ejection energies of debris objects

Gabbard Diagram for Iridium/Strela event - Feb 2010

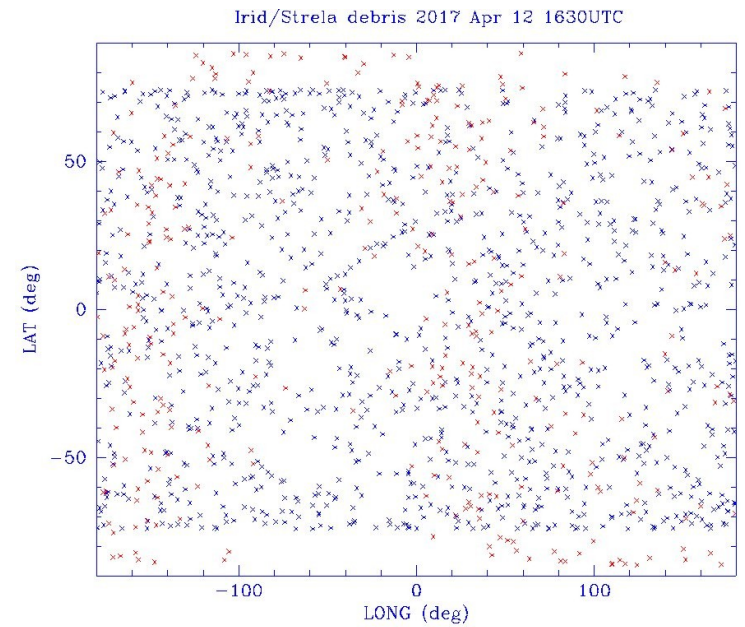
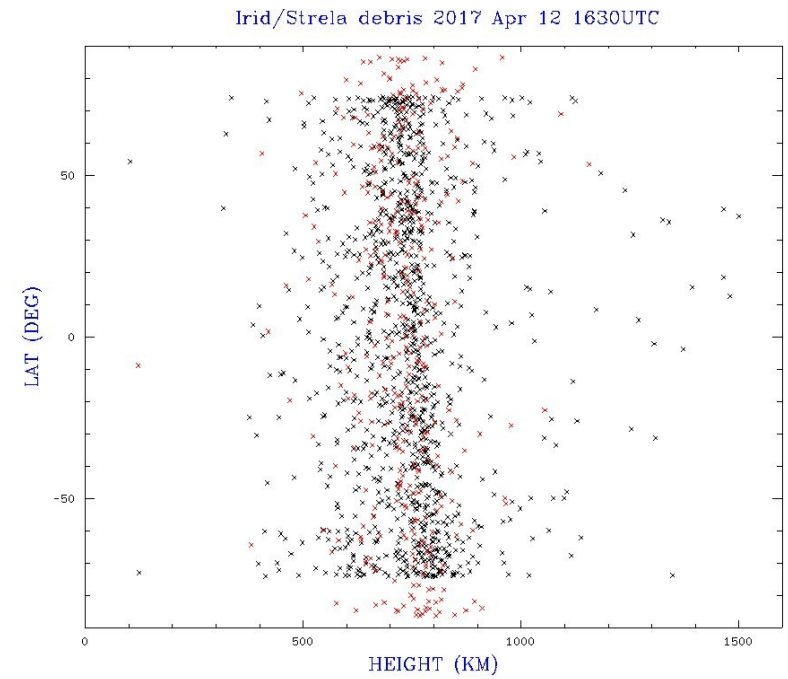


Gabbard Diagram for same event, updated to Apr 2017
Orbital decay has circularized low period objects





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)

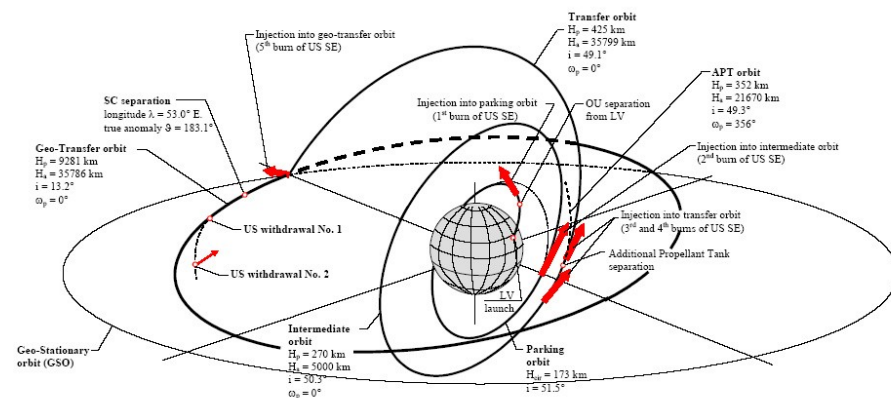
Catalog incompleteness for these is high; some data from optical telescopes, little from radars due to r^{**} -4 dependence

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

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



Proton launch profile for Turksat-4B (Credit: Khrunichev)

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 (J_2) 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

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

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

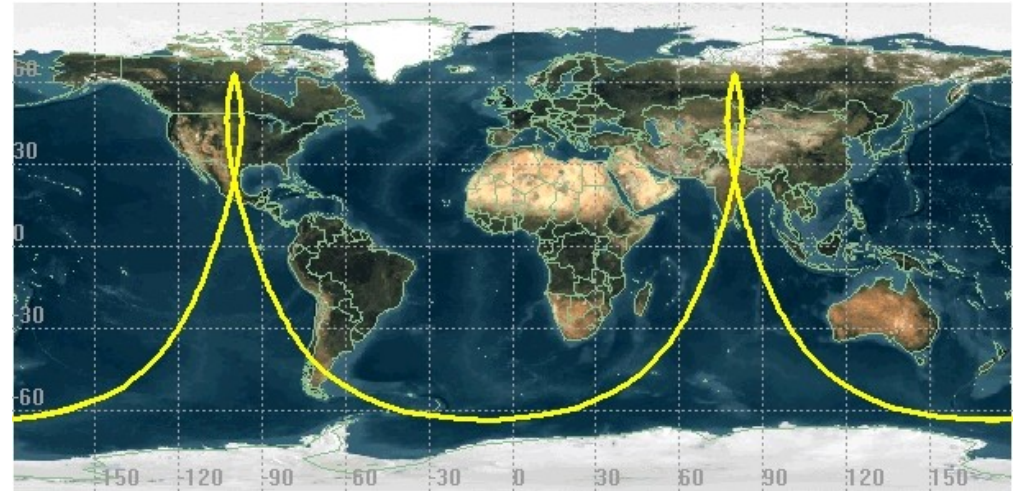
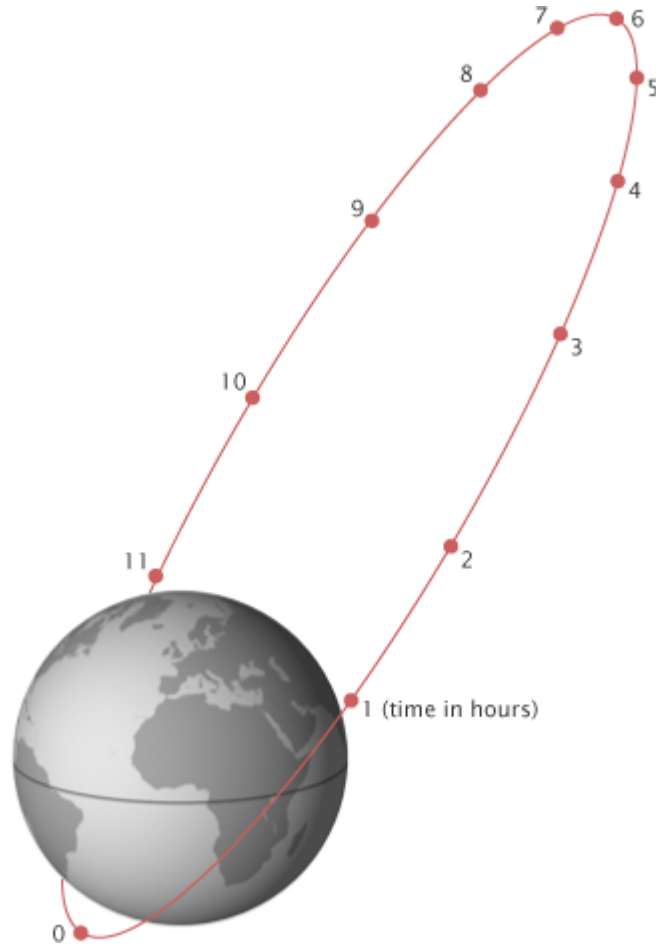
$$\dot{\omega} = f_p \left(2 - \frac{5}{2} \sin^2 i \right)$$

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

$$i = 63.43 \text{ degrees}$$

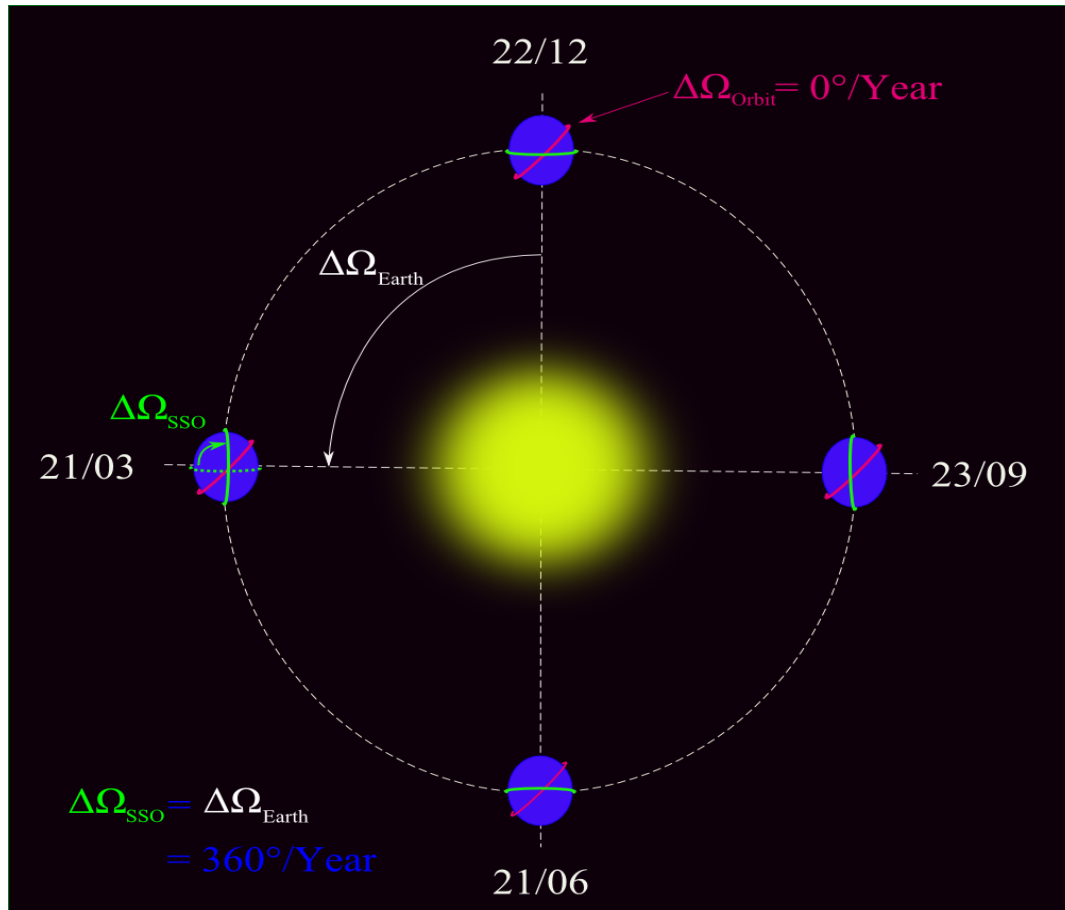
and lock in the latitude of apogee

the “Molniya orbit” (usually $T = 12 \text{ hr}$)

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.



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