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Strategic challenges of large satellite constellations

Jonathan McDowell

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Part 1: What are the effects of constellations on activities in outer space?

1. Satellite constellations
2. Evolution of the satellite population
3. Space traffic and traffic management
4. Space situational awareness

Part 2: What are their effects on astronomy from the ground?

5. The threat to astronomy and the night sky

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1. Satellite constellations

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Image: SpaceX

A new era in space utilization has arrived: the `megaconstellations'.

As of Oct 23, 2022
3505 SpaceX Starlink satellites and 428 OneWeb satellites have been launched.
FCC and ITU filings include requests for over 400,000 satellites

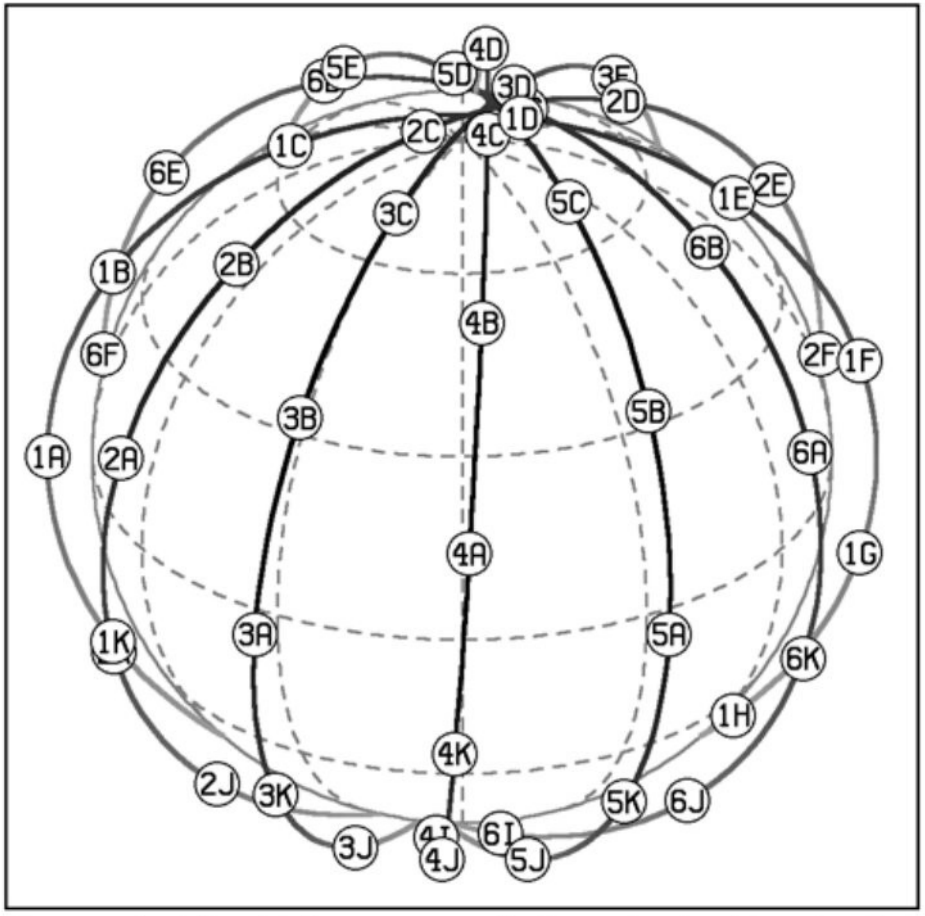
Constellation Shells:

Circular orbit at given height and inclination

Multiple orbital planes spaced in longitude around the Earth

Multiple satellites spaced around the orbit

Repeat for different heights and inclinations!



Iridium constellation, from Kidder and Vonder Haar 1995

Existing large, but not “mega”, LEO constellations (50-500 sats):

Strela-1M	360 in orbit, 0 working
Strela-3/Gonets	185 in orbit, 51 working
Parus	143 in orbit, 3? working
Orbcomm	58 in orbit, 31 working
Iridium	108 in orbit, 75 still working
Globalstar	85 in orbit, 31 still working
Planet Doves	311 in orbit, 179 still working
Spire Lemur	116 in orbit, 48? still working

Constellations we expected based on mid-2022 FCC and ITU filings:

Starlink Generation 2: 30,000 satellites at 328 to 614 km
OneWeb Phase 2: 47,844 satellites at 1200 km
Amazon Kuiper: 3,236 satellites at 590-630 km
Guangwang 13000 satellites at 590-1145 km
Astra V-band 13600 satellites at 380-700 km
E-Space (US/Rwanda) 337,323 satellites at 530-630 km !!
and others totalling over 430,000 satellites planned
"Megaconstellations" (well, really only myriaconstellations... nevertheless unprecedented)

OneWeb sats are smaller and higher than Starlink – V ~ 8 -- 9 or so: too faint to see with naked eye but glaringly bright by astronomical detector standards.

Following bankruptcy and reorganization last year, OneWeb has reduced its proposal to only 6372 satellites (factor 7.5 reduction)

Example constellation definitions

MODEL III-B: Starlink Constellation, Modified Gen 2 Config 1 (Aug 2021 Filing, 30000 satellites)

Layer	Element	Altitude (km)	Inclination (deg)	No of planes	Sats per plane	Total sats
A	1	340	53.0	48	110	5280
A	2	345	46.0	48	110	5280
A	3	350	38.0	48	110	5280
A	4	360	96.9	30	120	3600
B	5	525	53.0	28	120	3360
B	6	530	43.0	28	120	3360
B	7	535	33.0	28	120	3360
C	8	604	148.0	12	12	144
C	9	614	115.7	18	18	324

MODEL V: (KP1) Kuiper Constellation (2019 filing, 3236 satellites)

Layer	Element	Altitude (km)	Inclination (deg)	No of planes	Sats per plane	Total sats
A	1	630	51.9	34	34	1156
B	2	610	42.0	36	36	1296
C	3	590	33.0	28	28	784

MODEL VI: (OW2R) OneWeb Constellation (2021 revision, 6372 satellites)

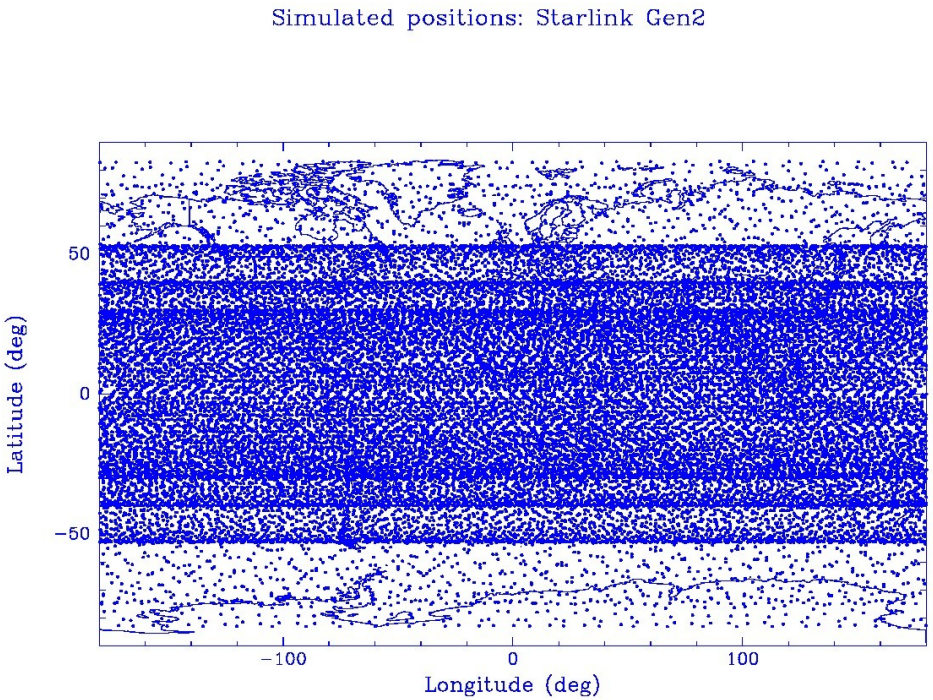
Layer	Element	Altitude (km)	Inclination (deg)	No of planes	Sats per plane	Total sats
A	1	1200	87.9	36	49	1764
B	2	1200	40.0	32	72	2304
C	3	1200	55.0	32	72	2304

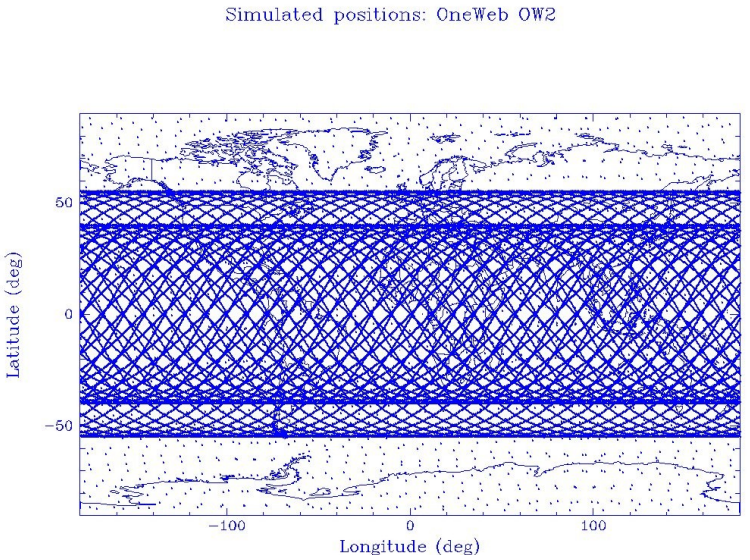
MODEL VII: (GW) Chinese Guangwang Constellation (2021 revision, 12992 satellites)

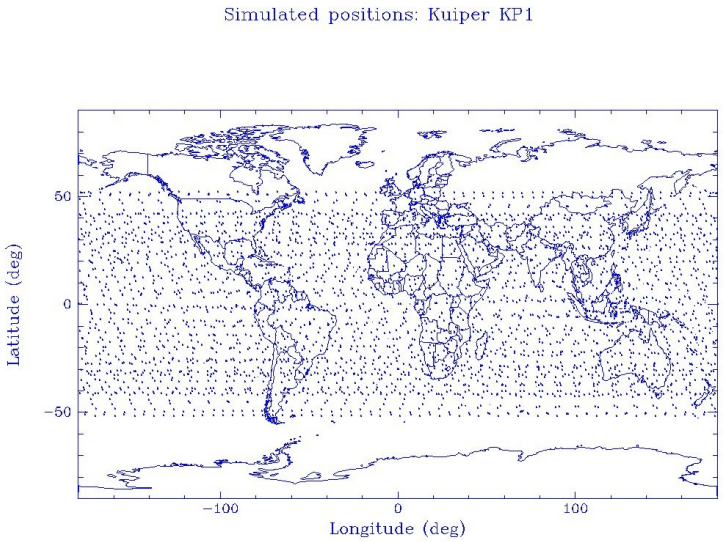
Layer	Element	Altitude (km)	Inclination (deg)	No of planes	Sats per plane	Total sats
A	1	590	85.0	16	30	480
A	2	600	50.0	40	50	2000
A	3	508	55.0	60	60	3600
B	4	1145	30.0	48	36	1728
B	5	1145	40.0	48	36	1728
B	6	1145	50.0	48	36	1728
B	7	1145	60.0	48	36	1728

Realization of constellations showing latitude/longitude distributions.

Limited polar coverage







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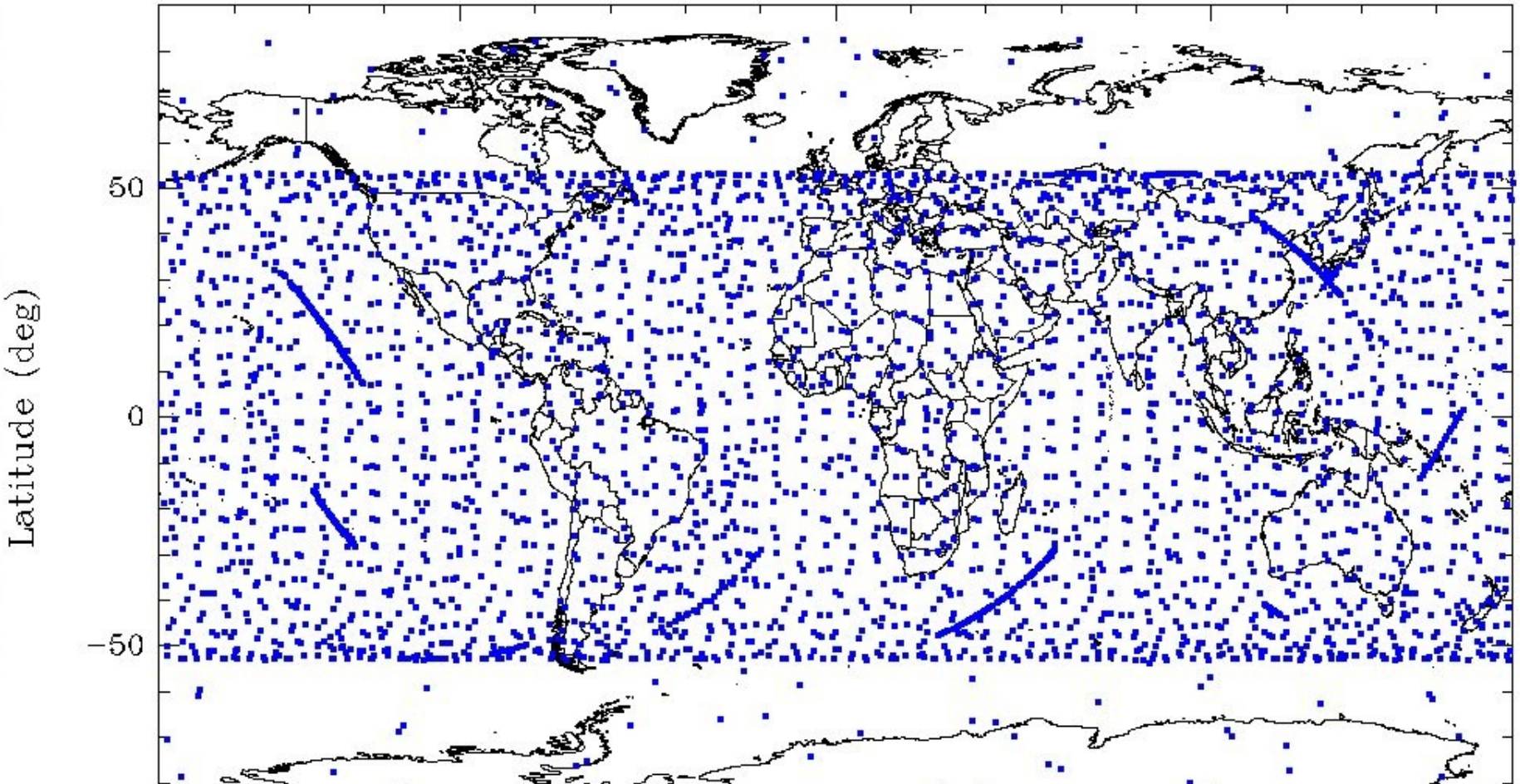
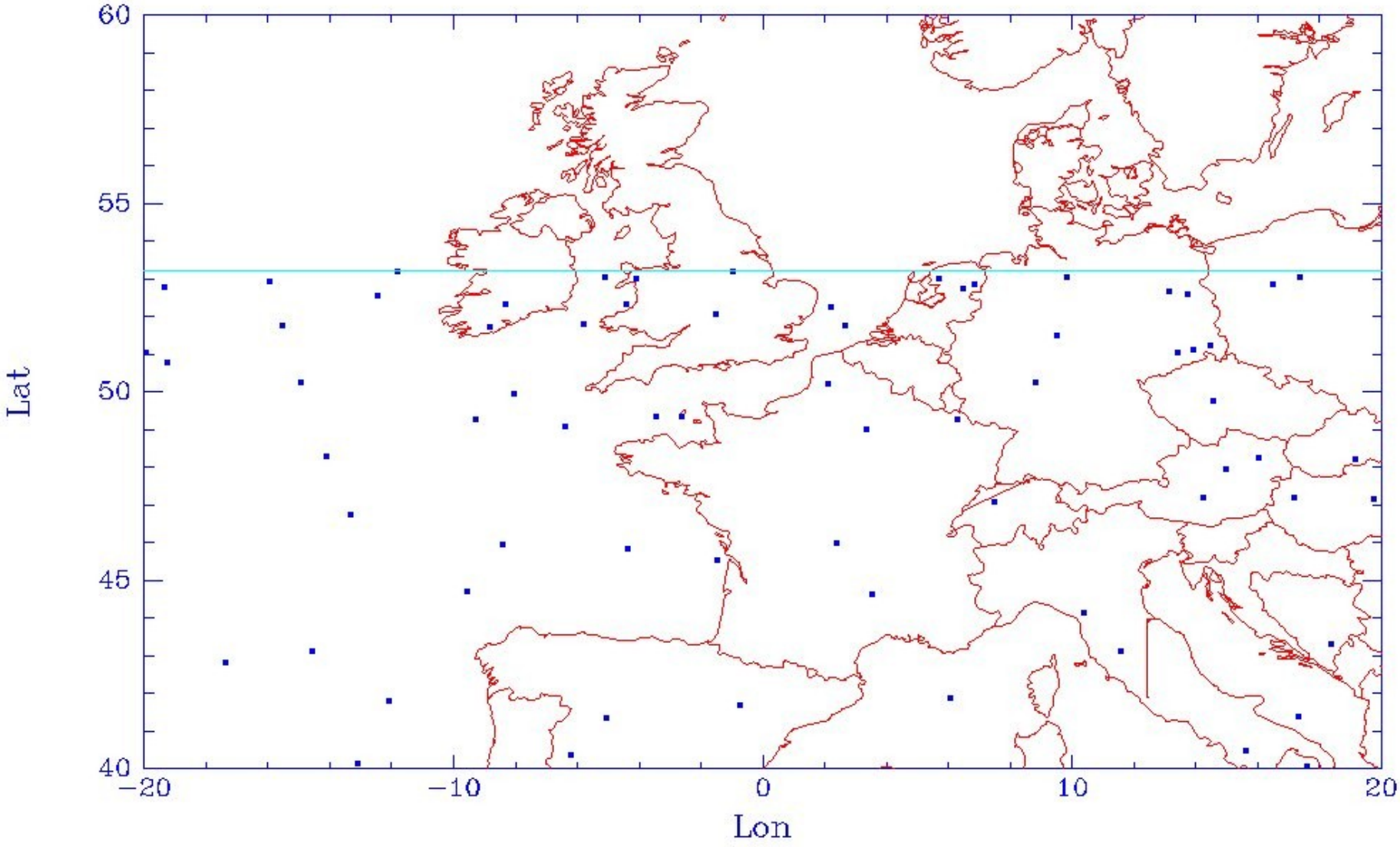
Starlinks on 2022 Oct 23 at 0h GMT:
3229 in orbit
(see https://planet4589.org/space/stats/star/stats.html)



Note sharp cutoff at
53 deg North



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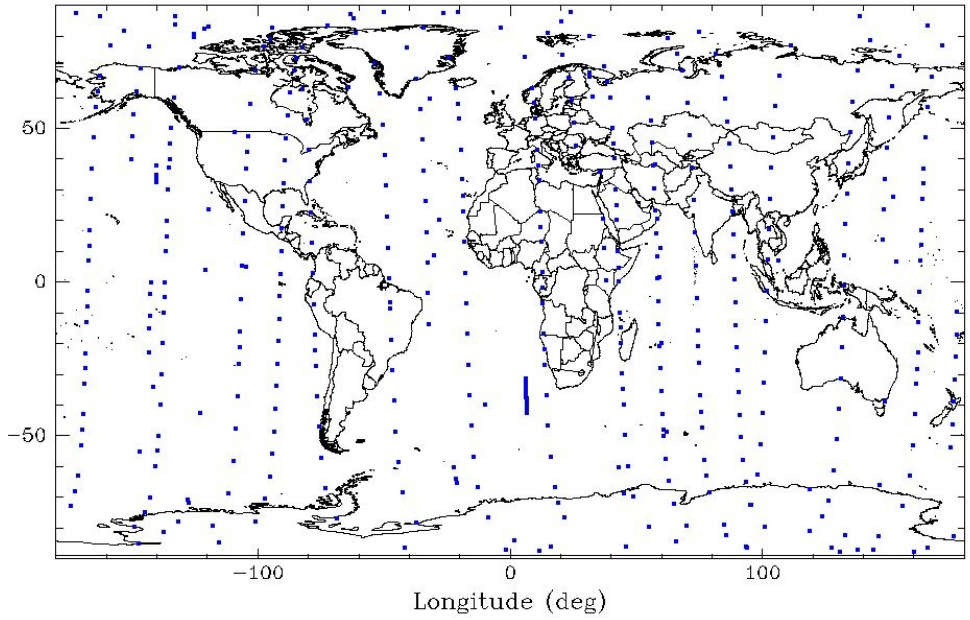
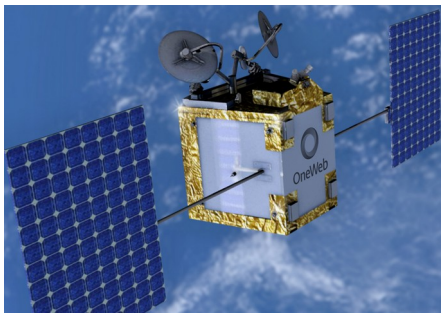
OneWeb
2022 Oct 24 at 0h GMT
426 in orbit



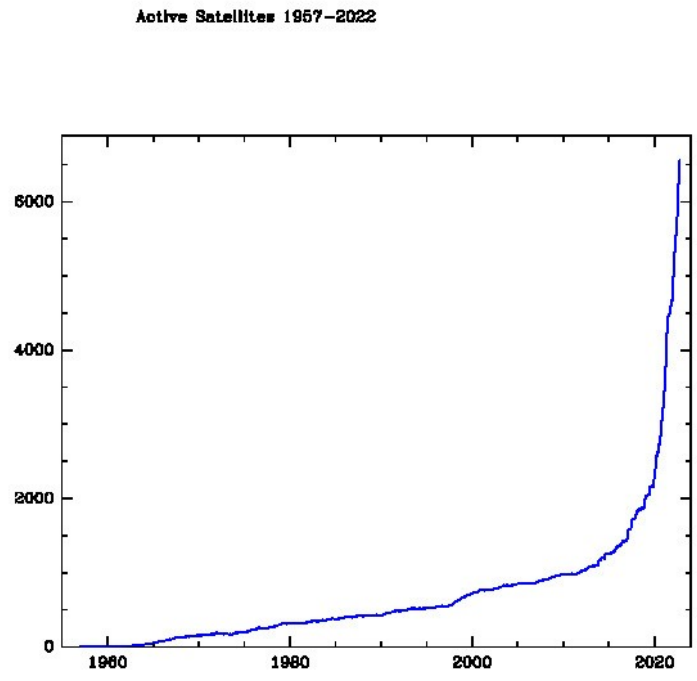


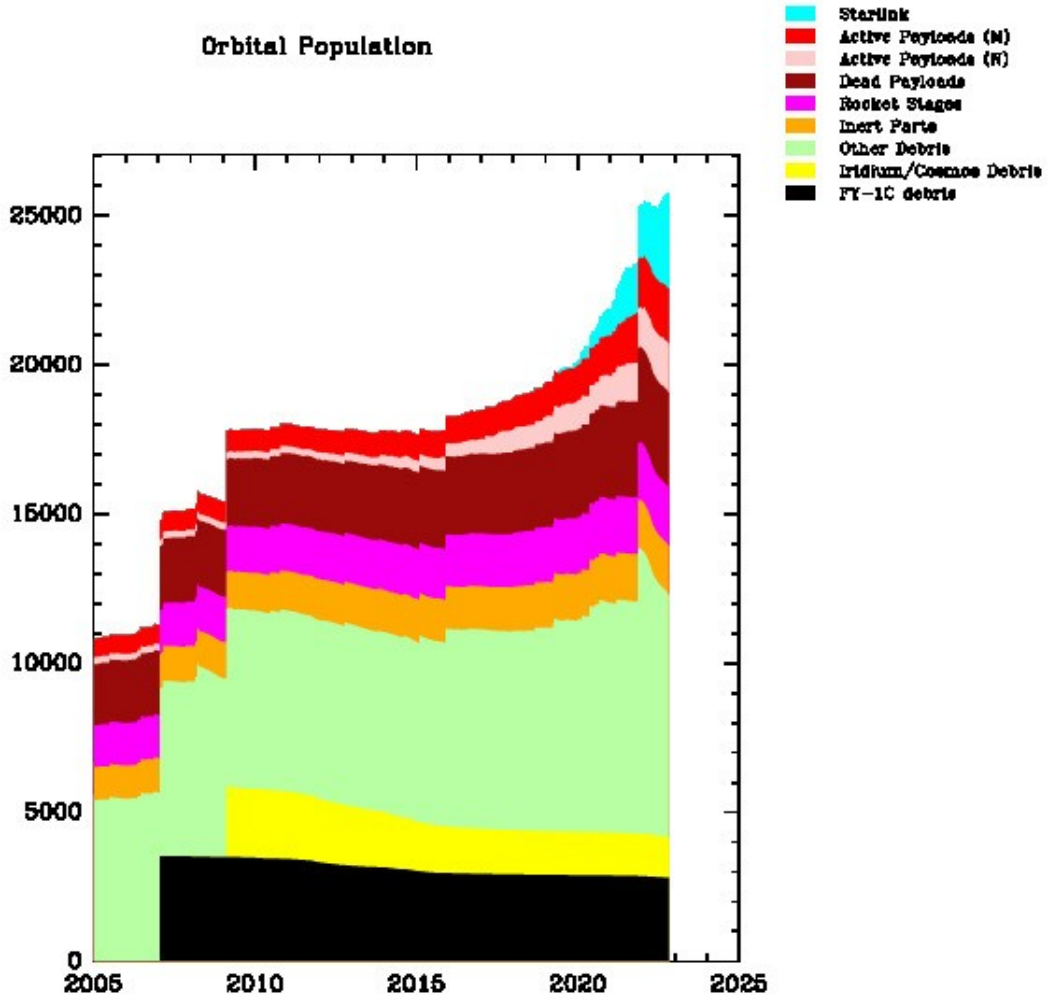
The new entrants:

Yinhe Hangtian – Six Yinhe-2 test sats launched Mar 2022
E-Space - Three test sats launched May 2022
Boeing - Sherpa LTC2/Varuna, test sat launched Sep 2022
AST Space Mobile - BlueWalker-3, test sat launched Sep 2022
ISS Reshetnev - Skif-D, test sat launched Oct 2022

BlueWalker-3

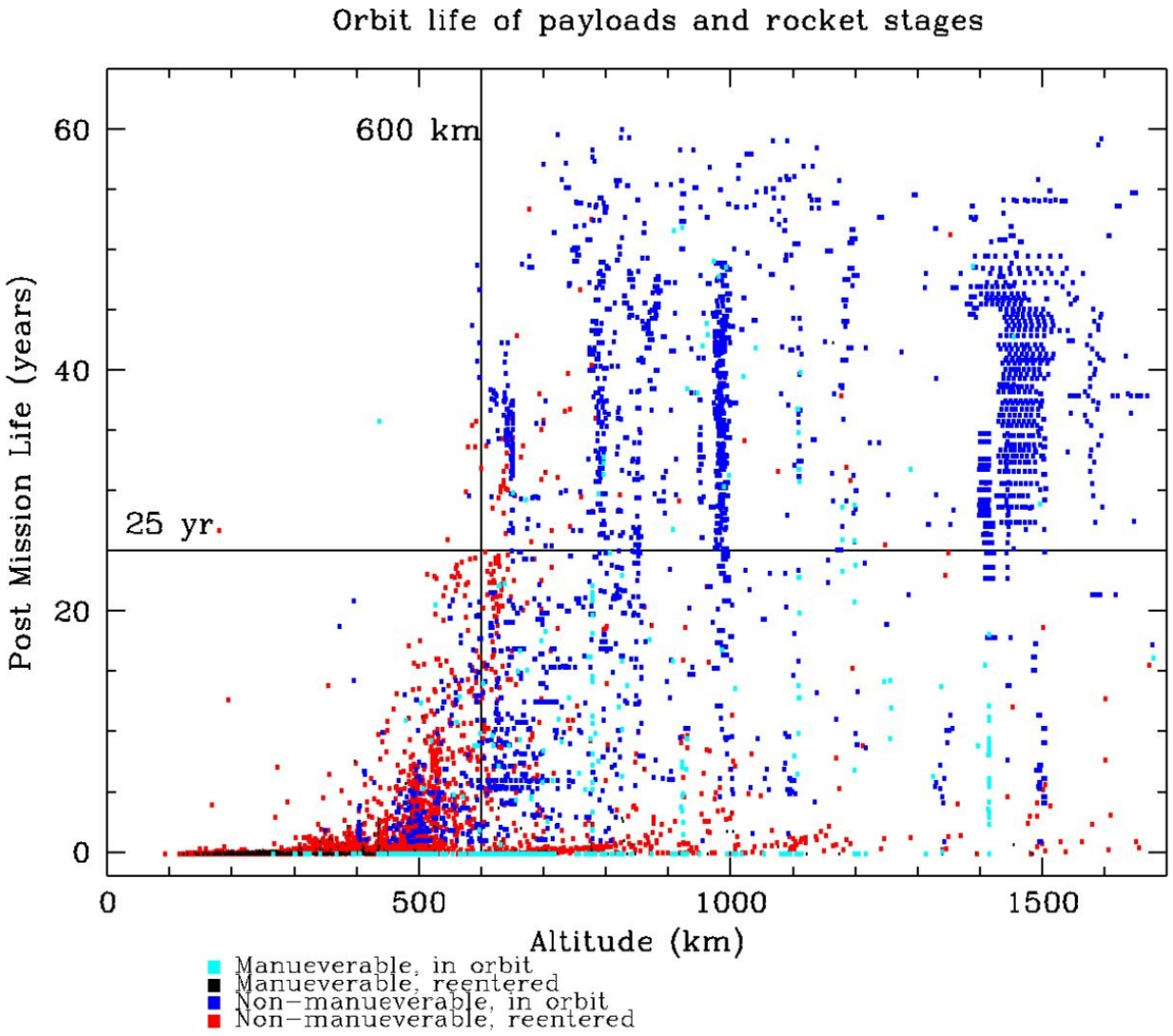
2. The tracked space object population and its evolution





Unprecedented rise in number of active satellites in past few years

Tracked orbital debris population stable since 2010
~25000 objects tracked (> 10cm)
1 million estimated: 1- 10 cm
0.1-1 billion above 1 mm?

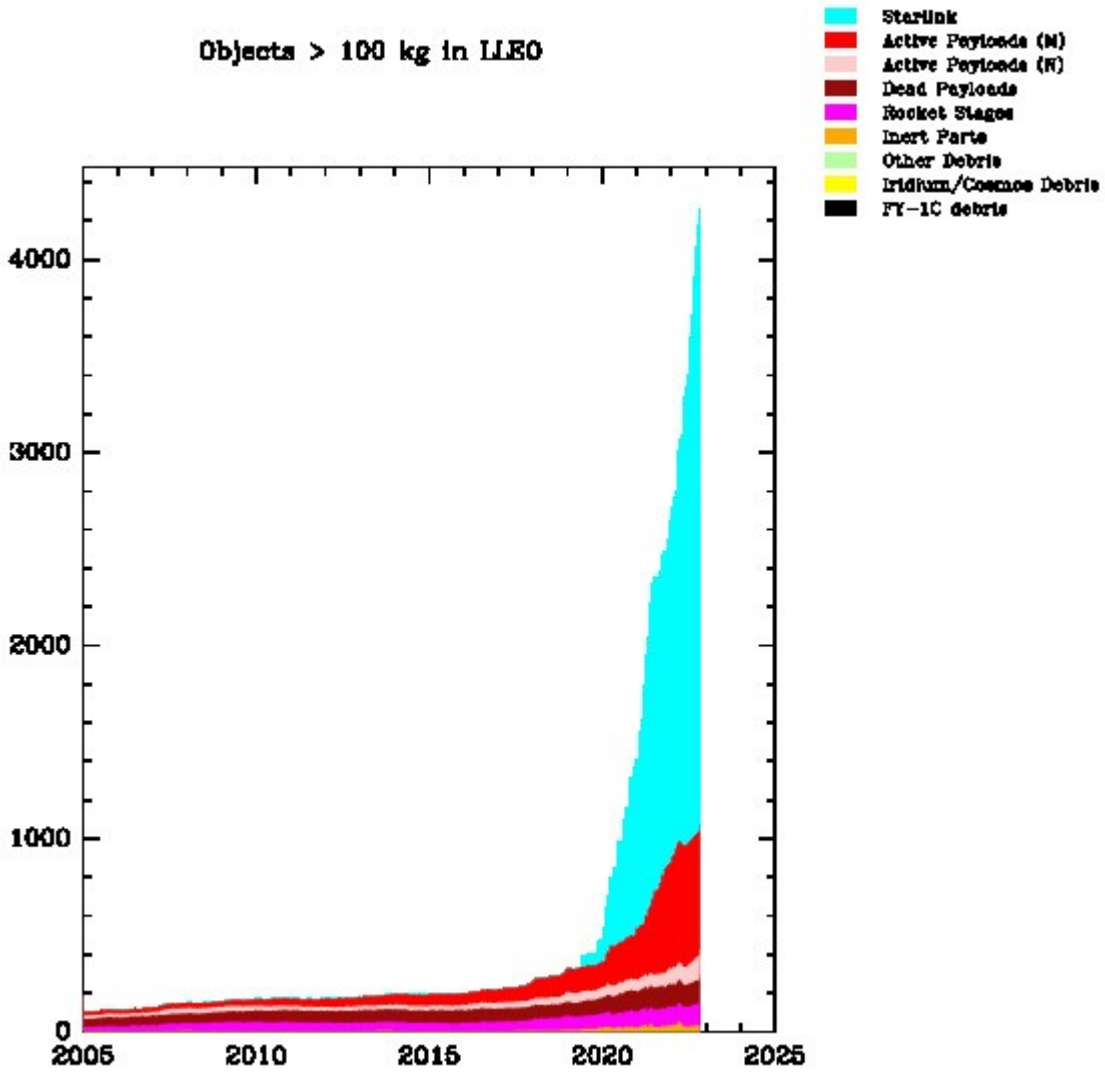


The density of the atmosphere drops off really quickly with altitude.

As a result, orbital lifetime (against natural decay) changes rapidly with height.

This is especially true in the 500-600 km region where lifetimes rise from ~years to centuries.

I pick 600 km as a working boundary between lower and upper LEO.

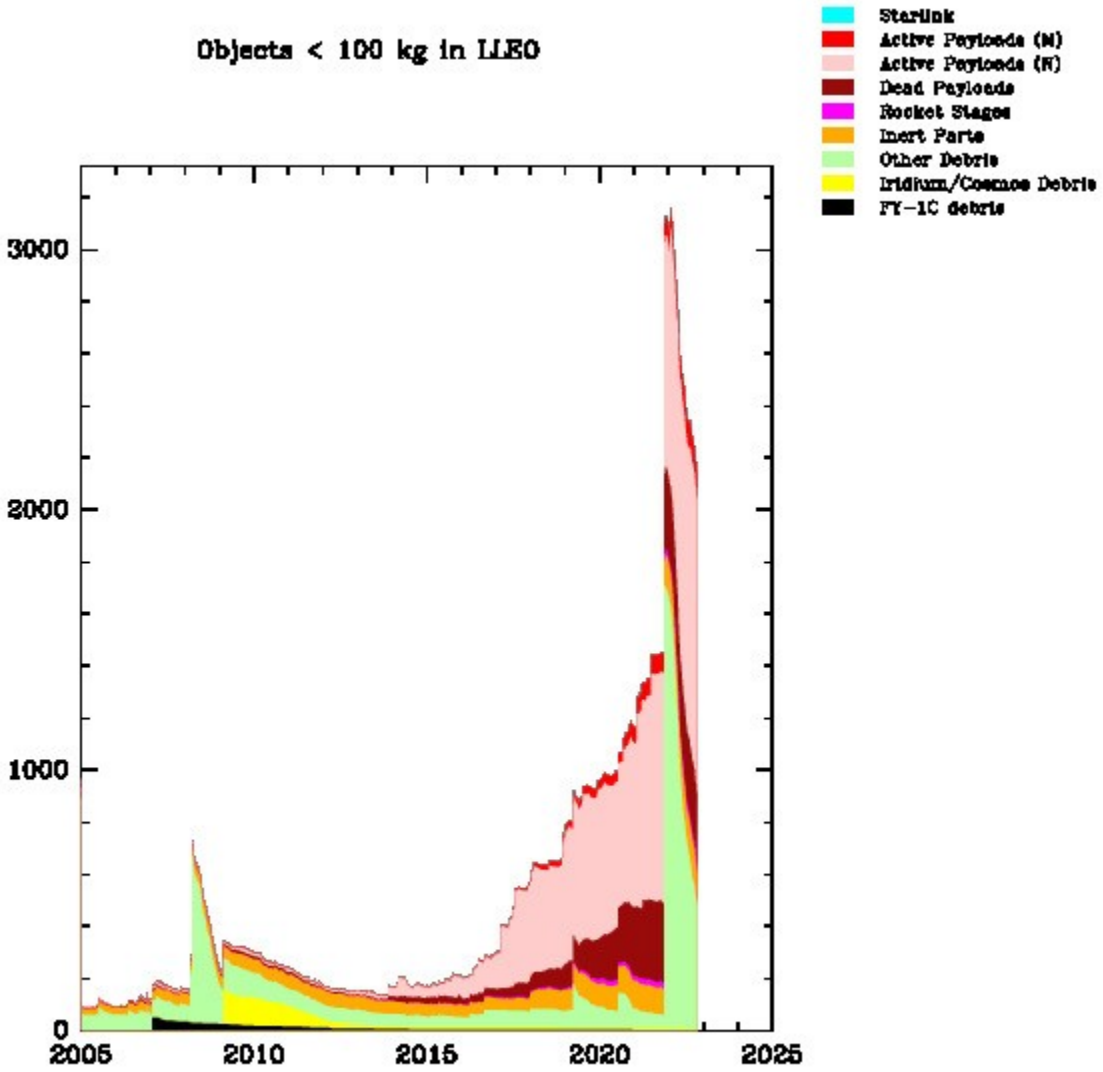


Musk: there are thousands of sats up already

BUT: mostly small debris or in high orbits

Not so many BIG and LOW: Starlink already dominates this subclass in 2022

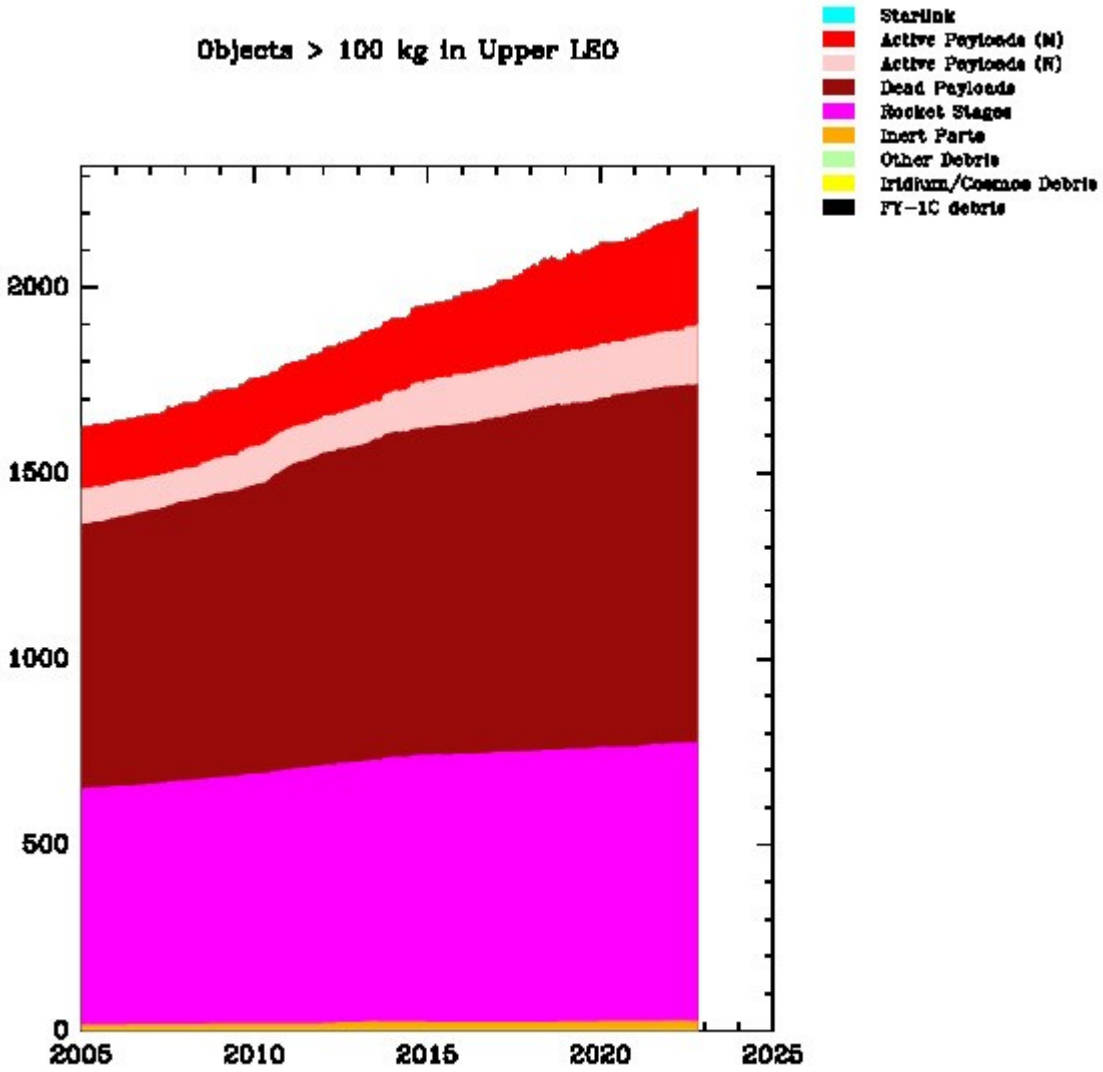
Plot shows tracked objects below 600 km and more massive than 100 kg as of Oct 23 (Starlink in cyan)



Population of tracked SMALL, LOW objects (<100 kg, < 600 km) has also changed in past 5 years: the cubesat revolution

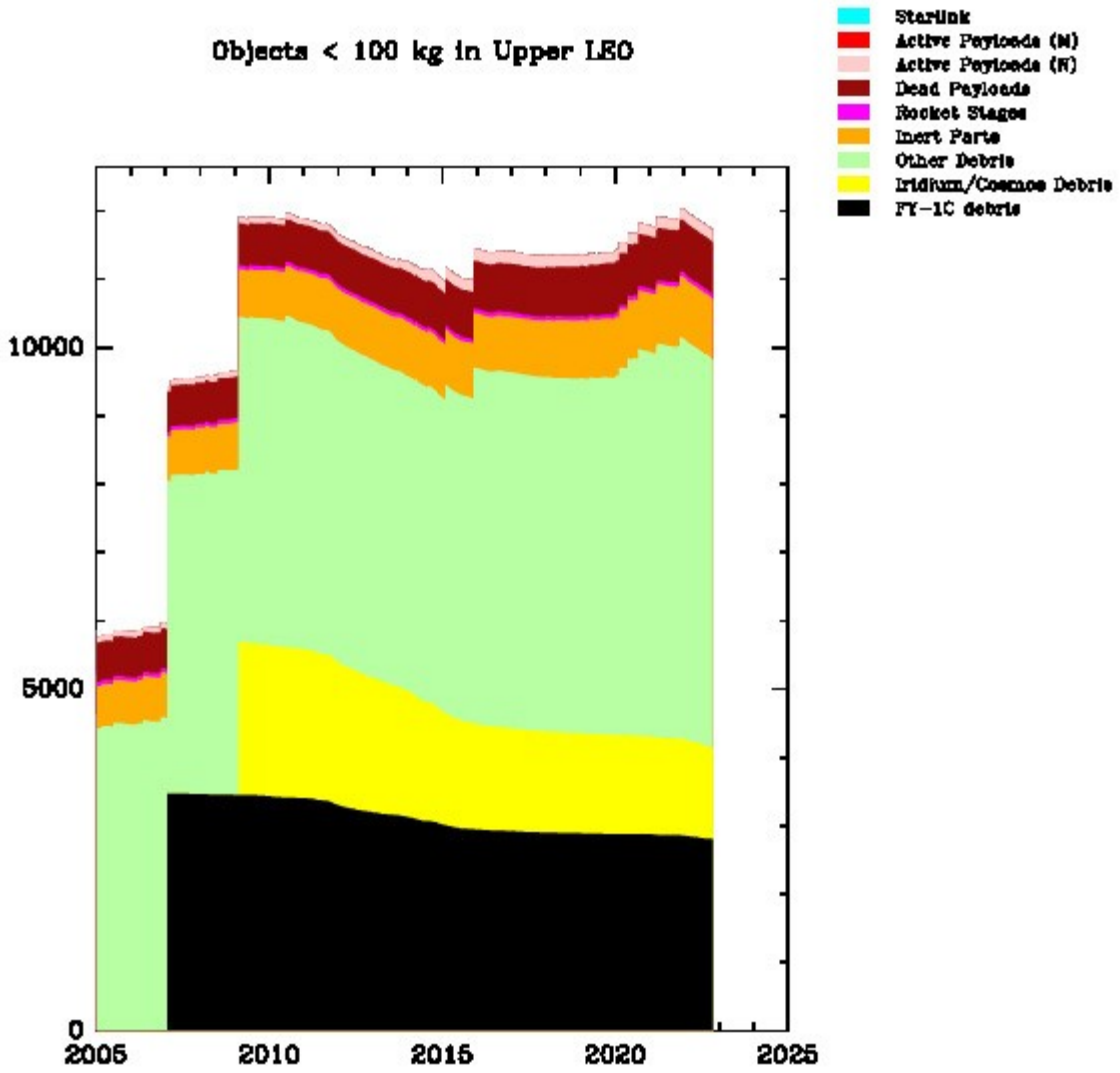
Tracked population was debris-dominated: now dominated by active (but not manueverable) payloads.

The green spike in 2021-2022 is debris from the Russian ASAT, already many of these debris have reentered



In contrast to the situation in lower (<600 km) LEO, the population is evolving only slowly in upper (>600 km) LEO. (This will change if OneWeb is deployed).

Current population of large objects: about 2000, mostly dead payloads and discarded rocket stages. **Not** currently dominated by active satellites.



Following the large 2007 and 2009 debris events, the (tracked) small debris population in upper LEO is almost steady state over the past 10 years.

Dominated by debris from satellite collisions, ASAT tests and by rocket stage breakups caused by ignition of residual propellants (often years after launch).

Note the much higher normalization here.

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Summary of satellite population trends:

- Upper LEO dominated by debris, slow change
- Lower LEO now dominated by payloads, rapid increase
- Commercial satellites are now dominant over govt ones
- Chinese commercial space (sats and launchers) starting to take off (pun intended)

What are the challenges to space governance and space law as a result?

2. Space traffic and traffic management

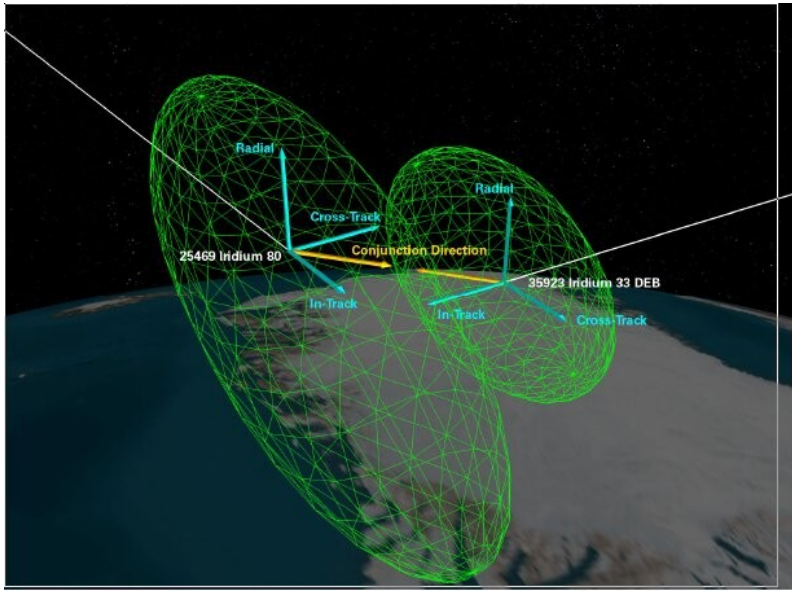
Biggest worry: “conjunctions”

A conjunction is when two satellites are predicted to pass closer to each other than the uncertainty in their positions

Most of these are ‘false alarms’:
uncertainty is ~ tens of metres to ~ 1 km
Size of spacecraft is 1-10 metres usually

So probability that a conjunction will be a collision is usually 1% to 0.01%

But you may still want to alter your orbit just in case



Hall et al (AMOS conference)

The white lines are the best guess satellite tracks
But actually at a given moment they could be anywhere in the green ellipsoid

How often do you get a conjunction?

It's proportional to the SQUARE of the number of satellites

In lower LEO (ISS regime) we are increasing the total number of cataloged objects from ~1000 to ~100000

100 times as many objects? A FACTOR 10,000 MORE CONJUNCTIONS
Can overwhelm operators

And – in the absence of successful avoidance manuevers – 10,000 times as many ACTUAL COLLISIONS

In upper LEO the total number is changing less, but it's still an issue.

How can we safely operate in LEO with many, many more satellites?

Current strategy:

- US licensing requires debris mitigation plan
- Careful constellation design to avoid mutual collisions of operating satellites in the same constellation
- Apparently informal strategy of using different orbital heights for different companies?
- Satellites which fail partially but still have propulsion are lowered to reentry
- But if you have a significant percentage of totally failed sats, you could run into problems.

NO INTERNATIONAL COORDINATION (Unlike GEO)

No guarantee Chinese Guanwang constellation won't interfere with Starlink

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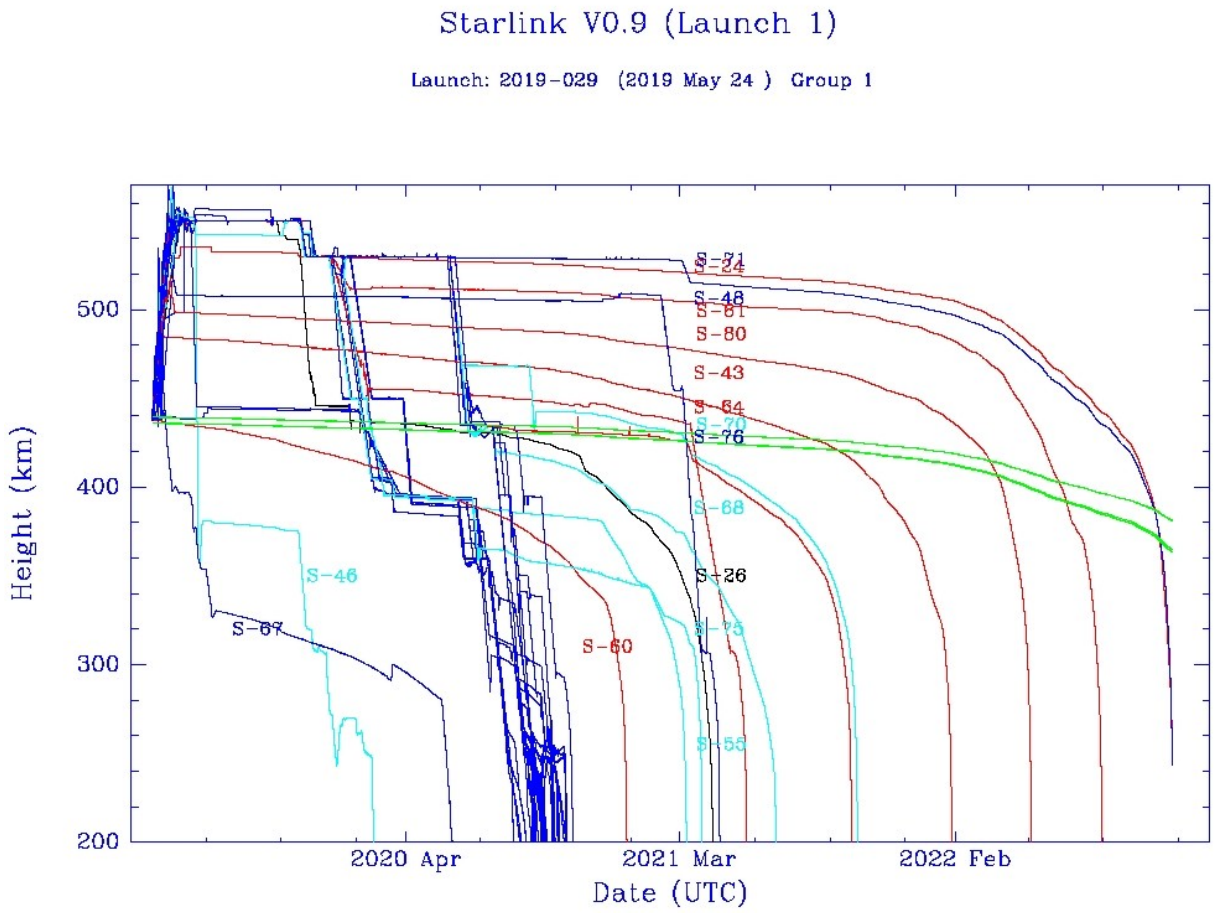
Starlink prototypes (launched May 2019)
16% failure rate (10 sats) 'dead in the water',
Most have now reentered, the last two will be down soon
Remaining 50 sats actively removed from orbit by early 2021



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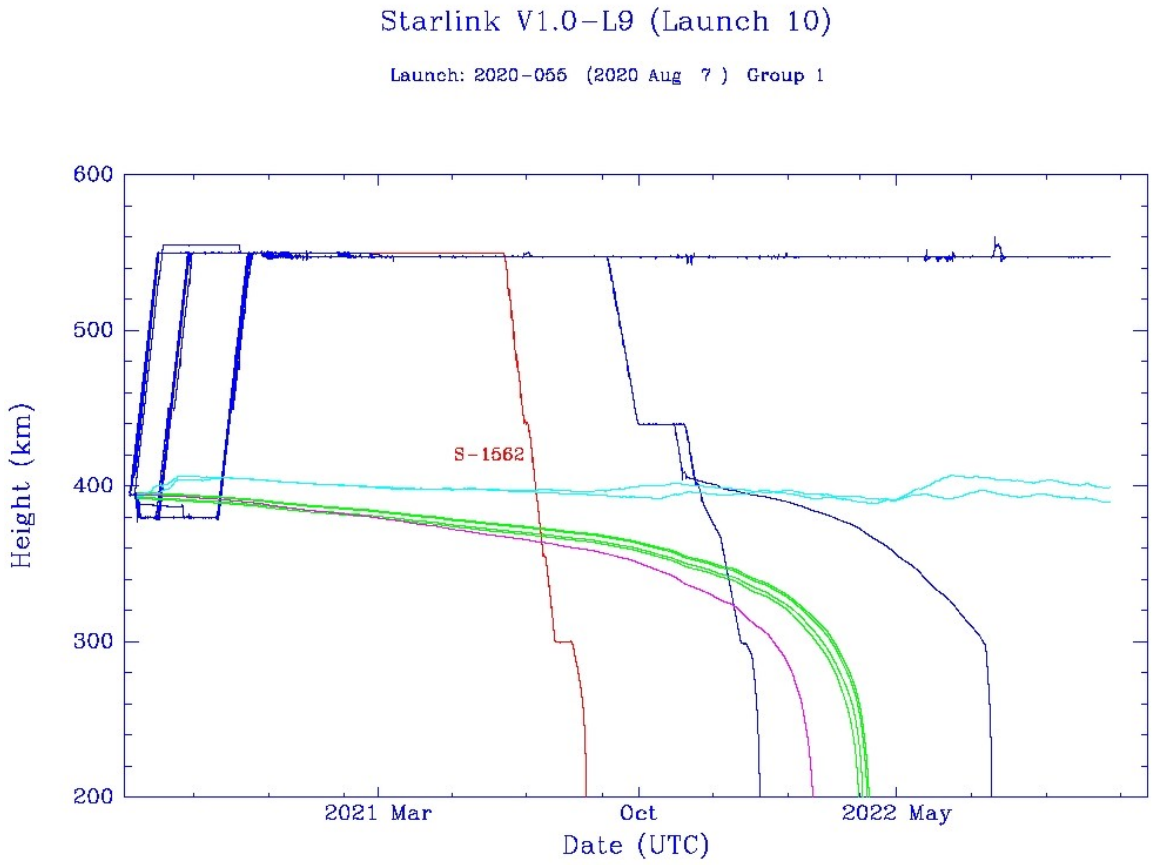
Starlink V1.0 launch L9 - mid-2020
57 sats: 3 deorbited, 54 still in operational orbit
None are undergoing uncontrolled decay
Two rideshare sats (cyan) with adapter (magenta)
Four deployment rods (green), all reentered



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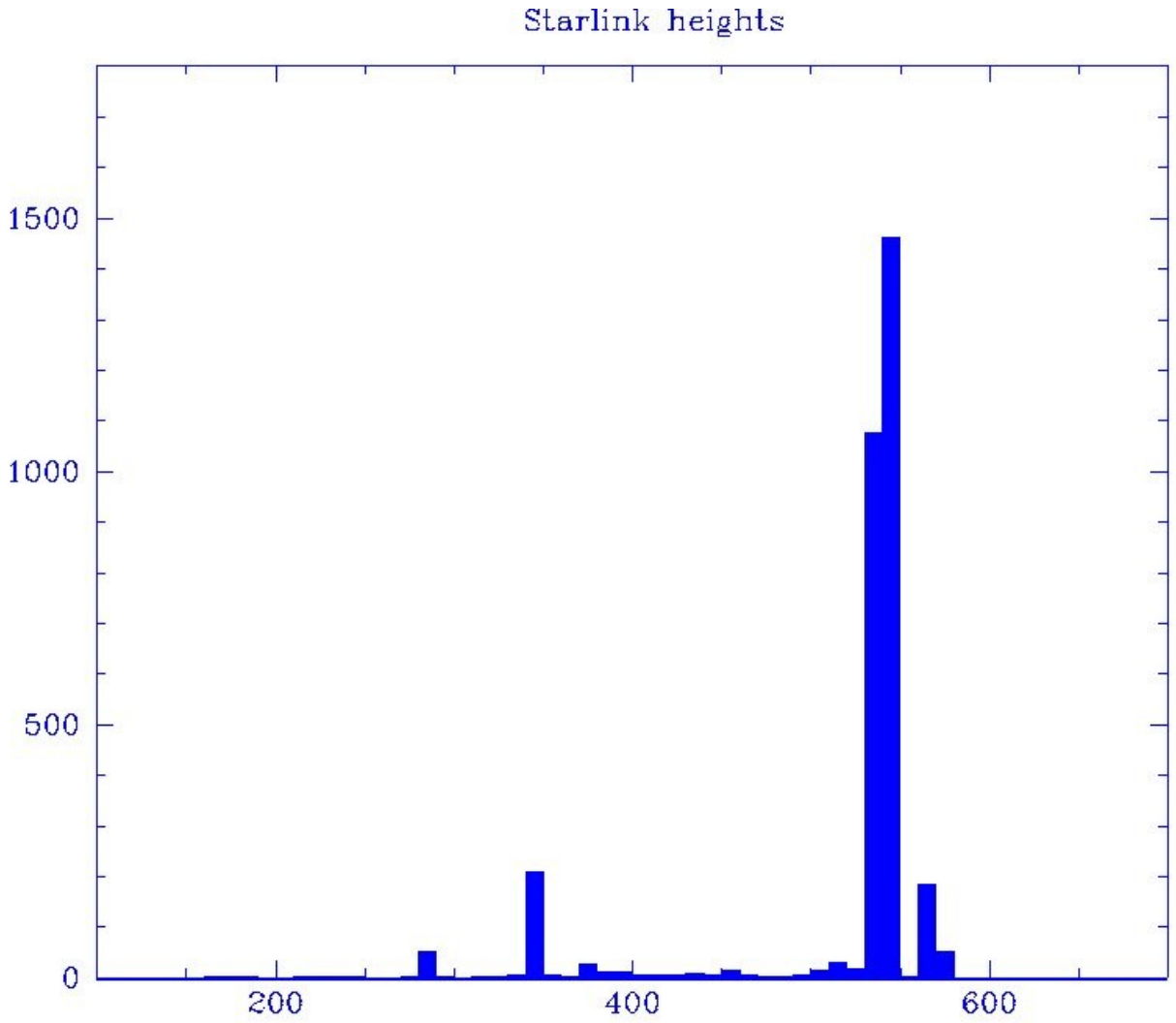

3229 in orbit

400 (12%)
below 500 km

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Reentering satellites

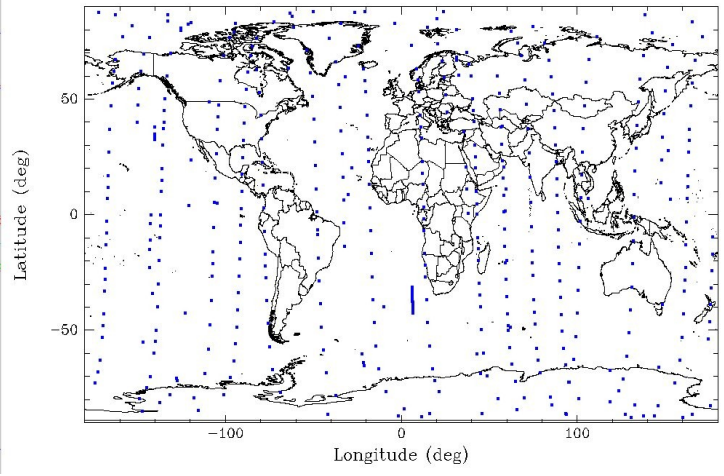
With 30,000 Starlinks proposed
Typical 5 year lifetime to replace
Launch to operational orbit takes 1 to 3 months
Operational orbit to reentry similar

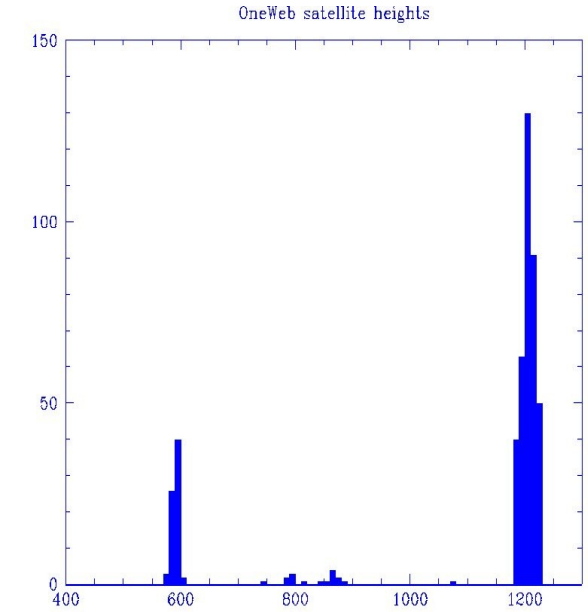
So, at any one time 5 to 10% of sats
are on their way up or down – collision concerns

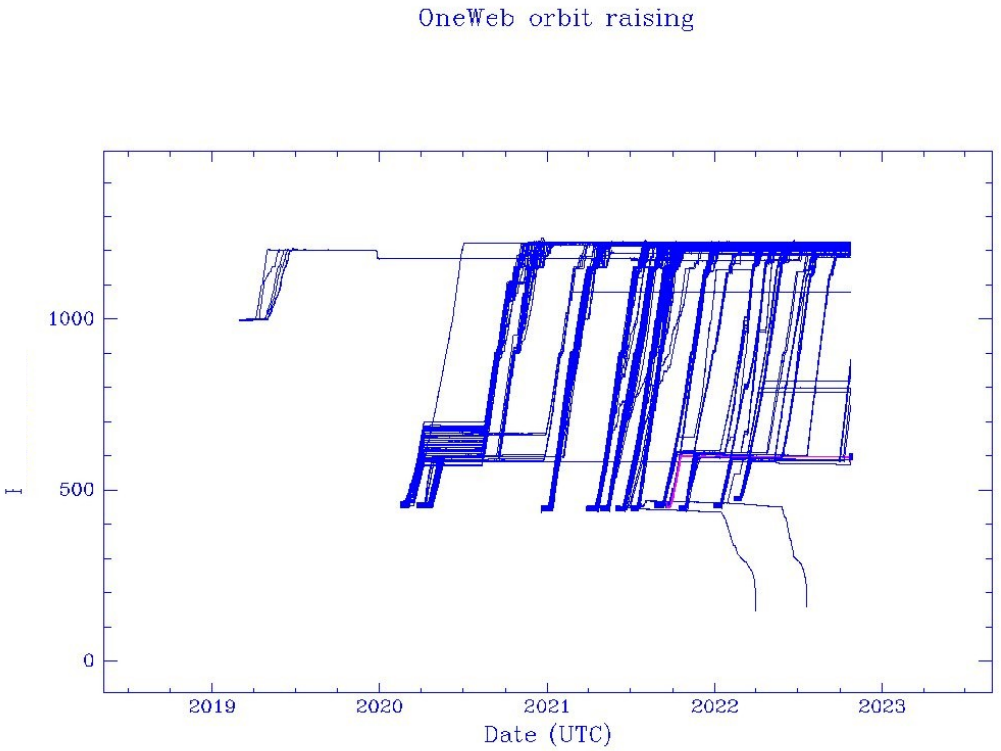
15 satellites launched a day on average
15 satellites reentering a day on average
Break up and melt around 40-60 km altitude,

- Space Force reentry monitoring not currently scoped for that reentry rate
- Emerging concerns about metallic contamination of upper atmosphere, potential unknown environmental consequences

OneWeb:







Only 2 total failures to date, plus 2 actively deorbited
High orbit -> critical that orbits are lowered at retirement

Future options:

- International coordination
- Assignment of circular orbits in 5 km (?) shells
- Prohibition on elliptical orbits in LEO?
- Active debris removal in upper LEO
- Reduction of 25 year decay limit
- Mandatory propulsion for large sats
- Mandatory drag chutes or other deorbit measures for cubesats

- Improved space weather models to reduce number of ‘false positive’ conjunction alerts

Still, there is some limit on the number of sats you can fit in LEO

3. Space situational awareness

Another issue: catalog maintenance

Launch 80 similar-looking satellites on 1 rocket
30 different owners
Which satellite is which?

Current system not scoped to handle this

5 sats of the 80 fail --> even the owners don't know which one is theirs.
Who's liable if it hits someone?

Contributing factor: Registration convention

- Compliance and processing delays improved in past few years
- Still inadequate: 2 year delay in registration, no reason it can't be 2 minutes.
- Data also inadequate to distinguish which sat is which.

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4. Constellations as a threat to astronomy and the night sky

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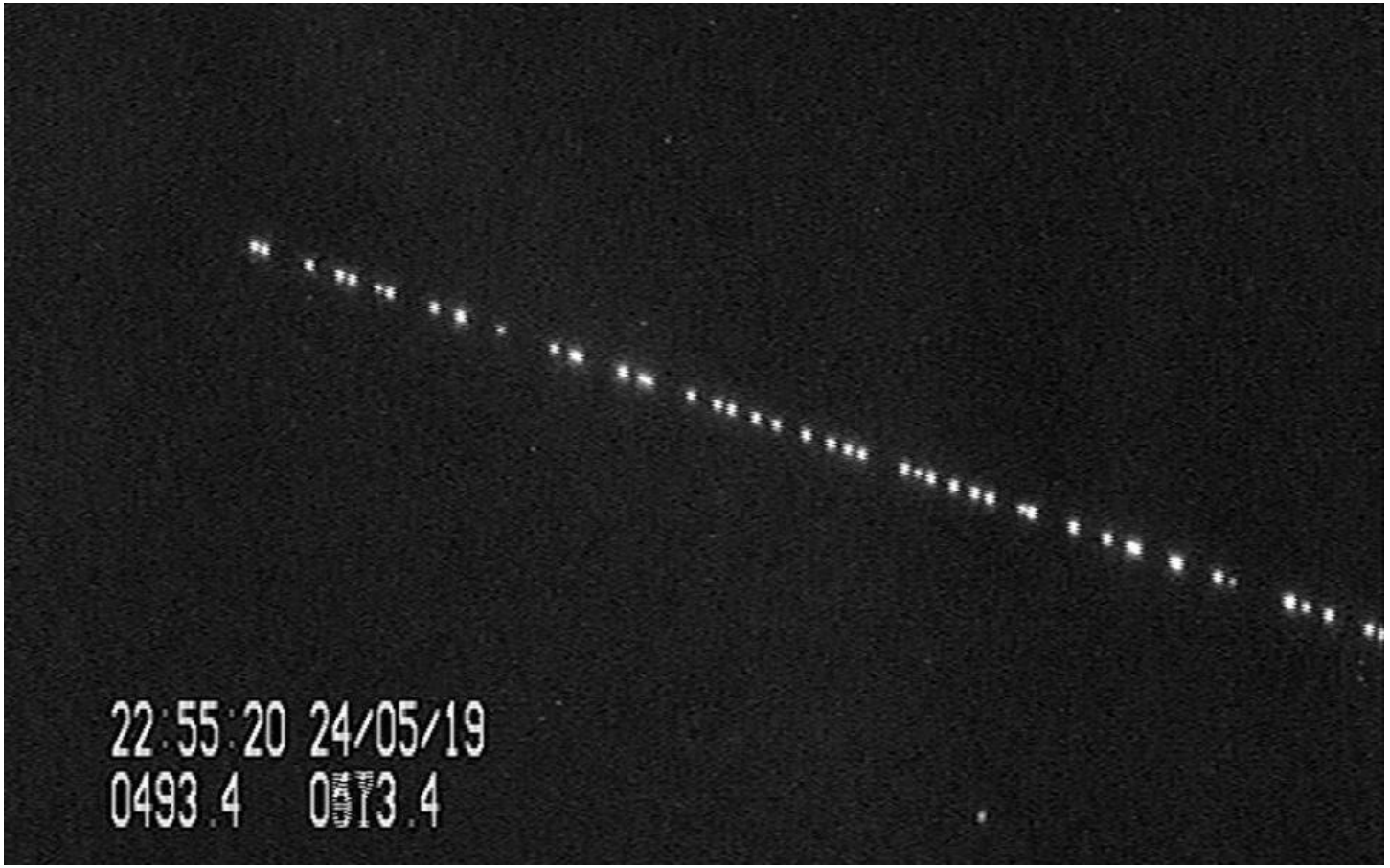
May 2019, first Starlink launch:
Astronomers see a train of satellites across the sky as bright as the familiar constellations.
What happens when there are 100,000 of these?



- Satellites became fainter once they switched to operational orientation
- Fainter still once orbit was raised to 550 km operational altitude
- Current Starlinks even fainter once visors were added
- Still naked-eye in dark skies for part of the time

BUT
- This very first observation made it clear that it is TECHNICALLY POSSIBLE to launch a bright naked eye constellation that would outnumber the visible stars

- Change the night sky for everyone? Everyone in the world, including non-spacefaring nations that may not have paid attention but have cultural connections to the night sky....

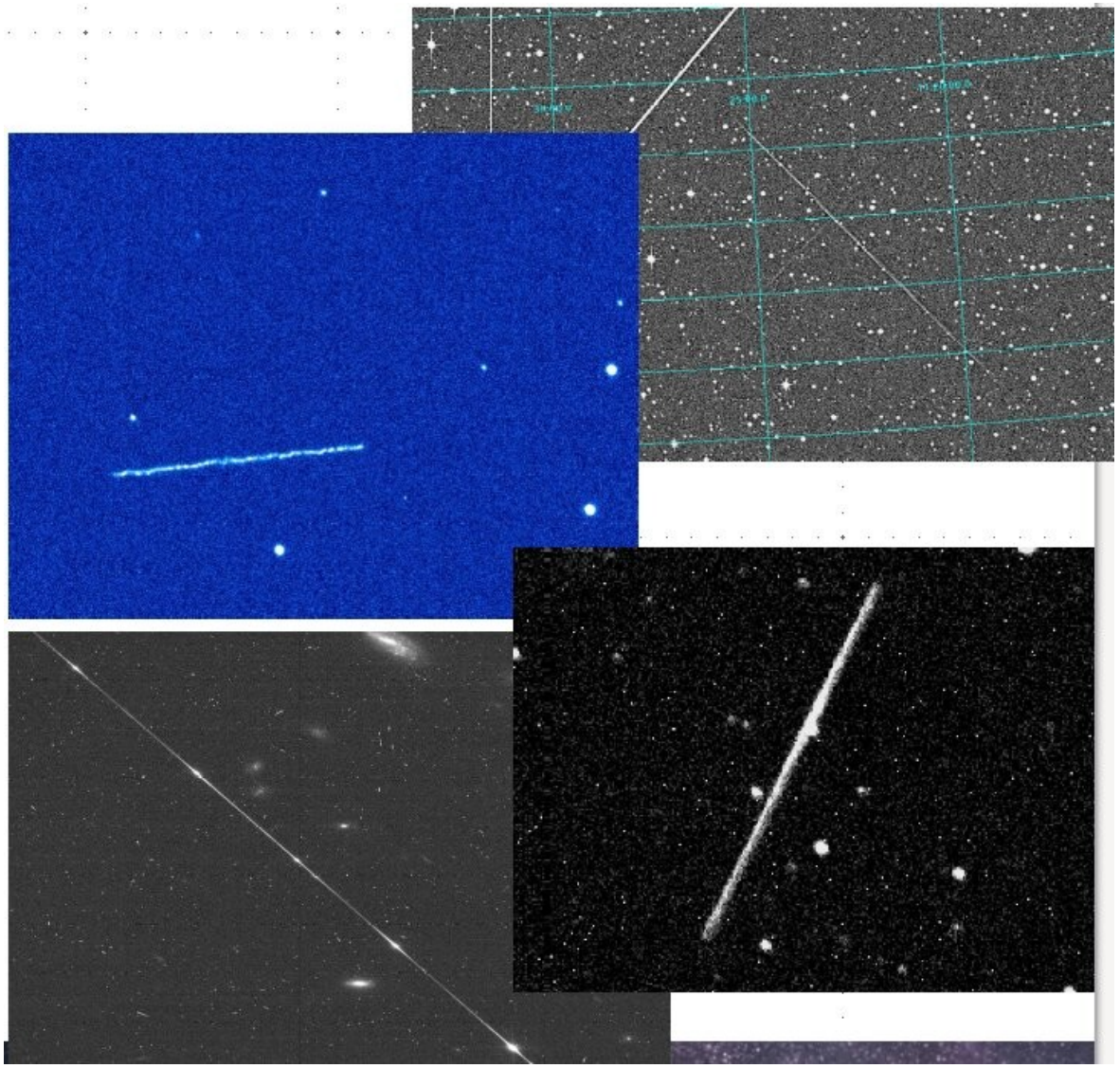
- Next generation Starlinks will be in a lower operational orbit and will not have the visors (which interfere with intersatellite laser links). Not clear yet how bright they will be.

- Nothing to stop some other country licensing a very bright LEO megaconstellation

More and more frequently our astronomical images are marred by satellite streaks

Astronomers aren't just taking pretty pictures – we do things like measure star brightness to 1% accuracy

So just cosmetically fixing the obvious streak isn't enough. The data are compromised.



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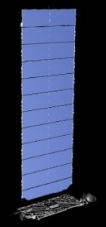
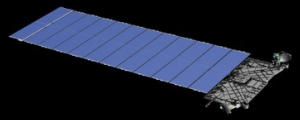
On station, brightness is driven by antennas since the satellite is in the "shark-fin" configuration during sunset and sunrise.



SHARK-FIN

During orbit raise, brightness is driven by the "open book" configuration for thrusting and drag and sunlight reflects off both the antenna and array.



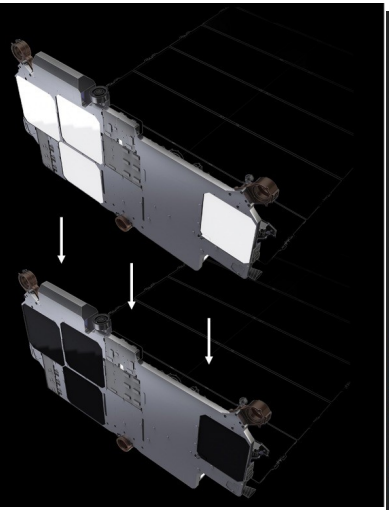
OPEN BOOK

Starlinks are:
LARGE (260 kg, ~10m)
and LOW (300-550 km)
and REFLECTIVE.
- Bright (naked-eye) objects)
- Mitigations have reduced brightness by about 1 mag

Images: SpaceX

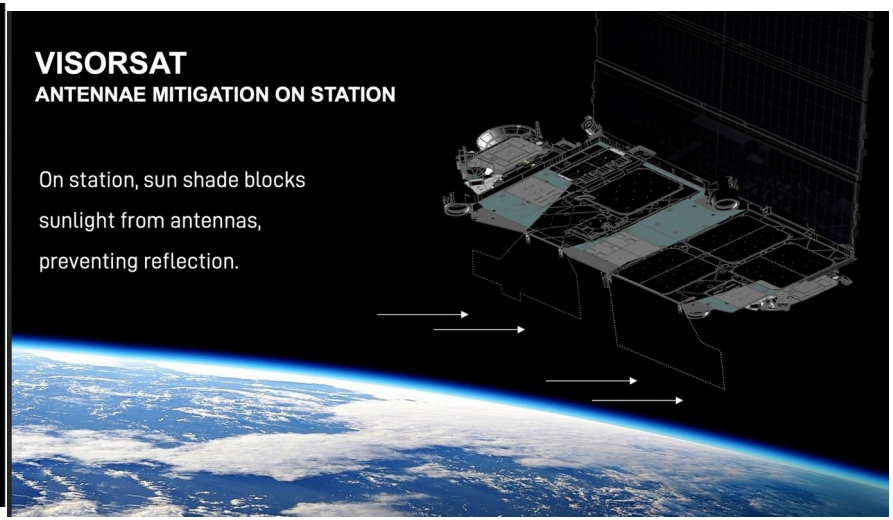
DARKSAT
ANTENNAE MITIGATION ON STATION

Ground-based observations of our initial test experiment proved we can significantly reduce brightness. Subsequently, we developed a higher-performance option.

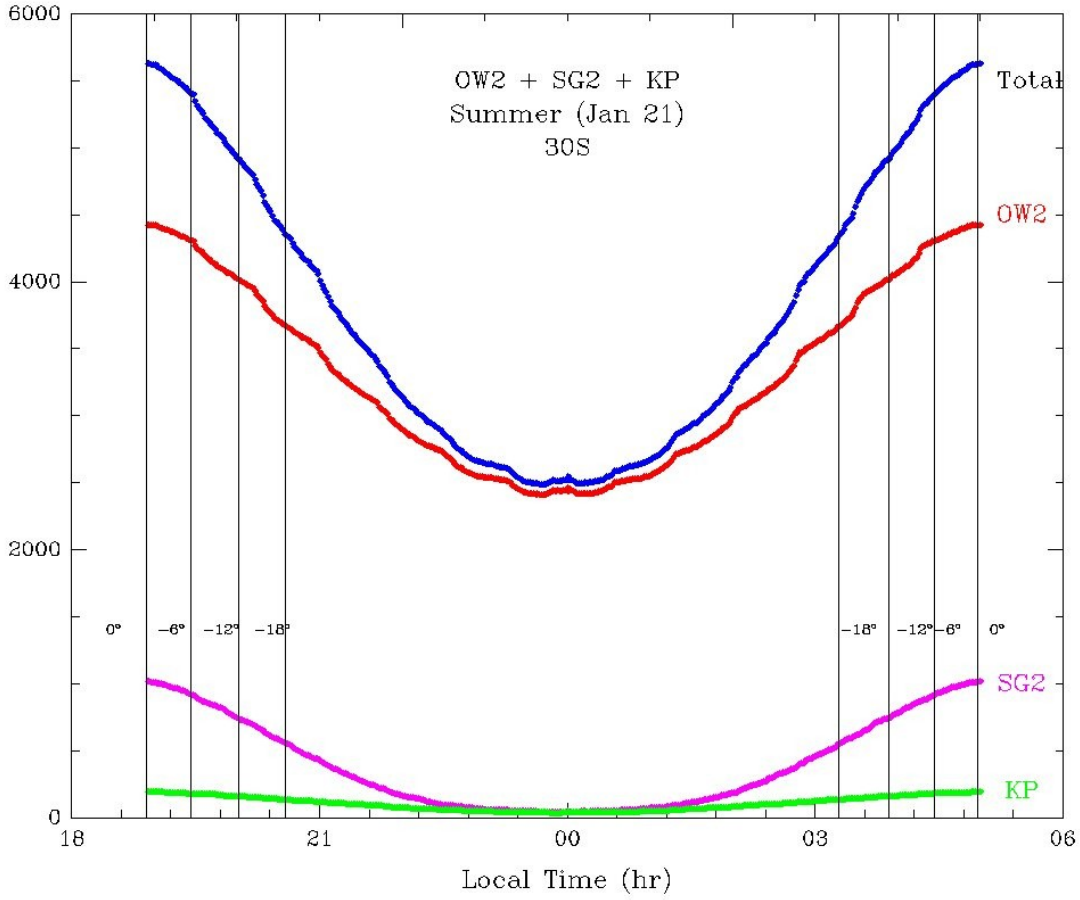


VISORSAT
ANTENNAE MITIGATION ON STATION

On station, sun shade blocks sunlight from antennas, preventing reflection.



Number illuminated with elevation > 0°



Worst case: observing near horizon during twilight.

Over 5500 satellites illuminated (30S, summer)

Even without the OneWeb contrib, 500-1000 during twilight hours from Starlink Gen2

Implications:

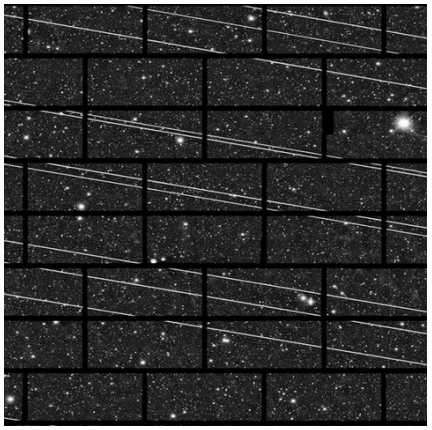
n = 500 satellites above 30 deg elevation corresponds to 0.2 sats per square degree

They are mostly OneWebs at 1200 km, angular velocity at zenith is ω = 0.35 deg/s (scales roughly as 1/height)

The expected number of satellite streaks on an astronomical image with field-of-view width D and exposure time T is

$$N = 3.7\ (n/500)\ (\omega / 0.35\ \text{deg/s})\ (T / 60\text{s})\ (D / 1\ \text{deg})$$

So for LONG EXPOSURES with a WIDE FIELD OF VIEW all images will have multiple streaks, very hard to mitigate.



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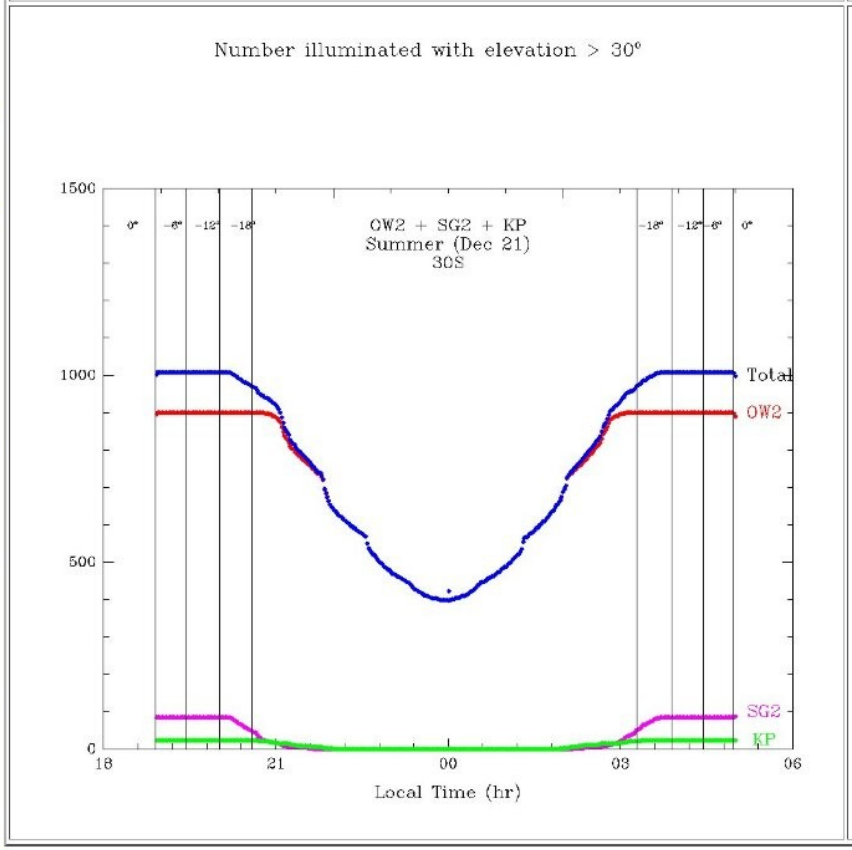
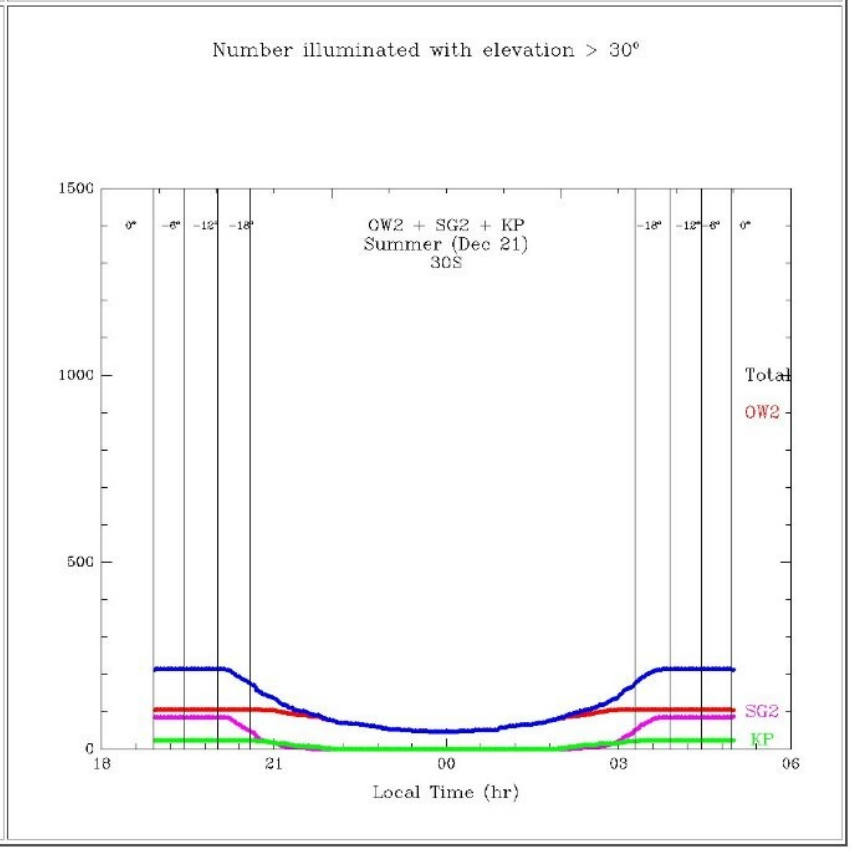
Reduction of proposed OneWeb constellation in 2021

In Jan 2021 OneWeb announced a major reduction in the number of planned satellites in their constellation. Here I show the combined OneWeb/Starlink Gen 2/Kuiper visibility plots at 30 deg South in summer, for both the old and the new plans.

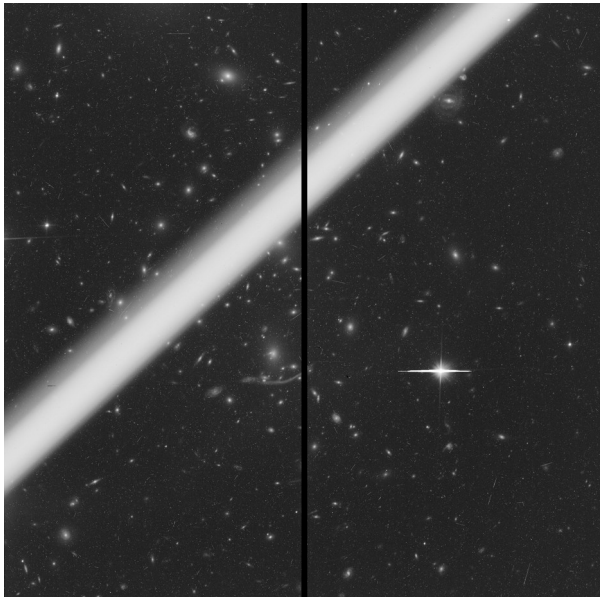
Old plan	New Plan
	

What about LEO space telescopes?
OneWeb at 1200 km is above them

Hubble Space Telescope, currently at 540 km, has narrow field of view (3') but long exposures (20 min to 1 hr?). Starlinks are 10 km above it.
Orbit geometry changes angular velocity factor (but only by O(1)-O(10) or so)
BUT HST pixels are small, streak surface brightness reduced

Conclusion: Problem exists for HST but less severe
Any wide-field telescope in LEO would be in very big trouble.

Image courtesy Judy Schmidt: Chinese rocket stage passes 35 km above HST in Feb 2020, right in direction telescope was looking.



CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

Astronomical community response:

SATCON working group at AAS

NoirLab/AAS SATCON1 conference, July 2020: Report to AAS
NoirLab/AAS SATCON2 conference, Jul 2021: Report to be released soon

IAU/UN Dark and Quiet Skies conference,Oct 2020: report presented to UN COPUOS Apr 2021
DQS 2 – Oct 2021, report in prep for UN COPUOS

Going forward

- Work with satellite companies on mitigation
- Continue public pressure
- Work with UN COPUOS on protecting the sky?

The night sky as part of humanity's heritage and environment

Conclusion on astronomy impacts:

The megaconstellations will be a significant change to the LEO environment and to the night sky

Impact on astronomy depends sensitively on constellation architecture

Lower (500 km and less) orbit satellites may be naked eye objects but this can perhaps be mitigated with changes to satellite design. They are illuminated near horizon so are a threat to some (NEO search?) but not most astronomical observations

Higher (~1000 km) constellation shells will be illuminated all night long in summer and will be visible over a wider area – and so, although not naked-eye, will be a threat to professional astronomy.

Policy and legal issues:

Is the night sky part of “the environment”, subject to environmental regulations?

Is astronomy a “space activity” under the Outer Space Treaty and does the “due regard” clause apply?

Can we get the UN to say that the night sky is part of humanity’s heritage and should be protected?

Current US licensing requires companies to do a debris assessment. Can we require them to do a brightness assessment as well?

Living with big constellations: can we regulate along the lines of ‘no more than X satellites above brightness Y’ ?