WasteX

ENVIRONMENTAL HARMS OF SATELLITE INTERNET MEGA-CONSTELLATIONS

U.S. PIRG Education Fund

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Executive summary

The number of satellites in low earth orbit has increased by 127 times in five years, led by SpaceX. The new space race is ramping up quickly: some estimate an additional 58,000 satellites launched by 2030. Another 500,000 have been proposed in order to create new mega-constellations that power satellite internet. At peak, 29 tons of satellites will re-enter our atmosphere per day, nearly equivalent to a Jeep Cherokee entering our skies every hour. The rocket launches to maintain these mega-constellations will release soot in the atmosphere equivalent to 7 million diesel dump trucks circling the globe, each year.

The environmental harms of launching and burning up so many satellites aren't clear. That's because the federal government hasn't conducted an environmental review to understand the impacts. What we do know is that more satellites and more launches lead to more damaging gasses and metals in our atmosphere. We shouldn't rush forward with launching satellites at this scale without making sure the benefits justify the potential consequences of mega-constellations. This is a new frontier, and we could save ourselves a lot of trouble by making sure we move forward in a way that doesn't cause major problems in the future.

For the history of the space industry, environmental harms haven't been a serious concern because of the small number of operators, mostly governments and researchers, with few satellites and launches. These non-commercial players were never held to strict government regulations because the low frequency of launches was assumed to have minimal impact at a global scale.

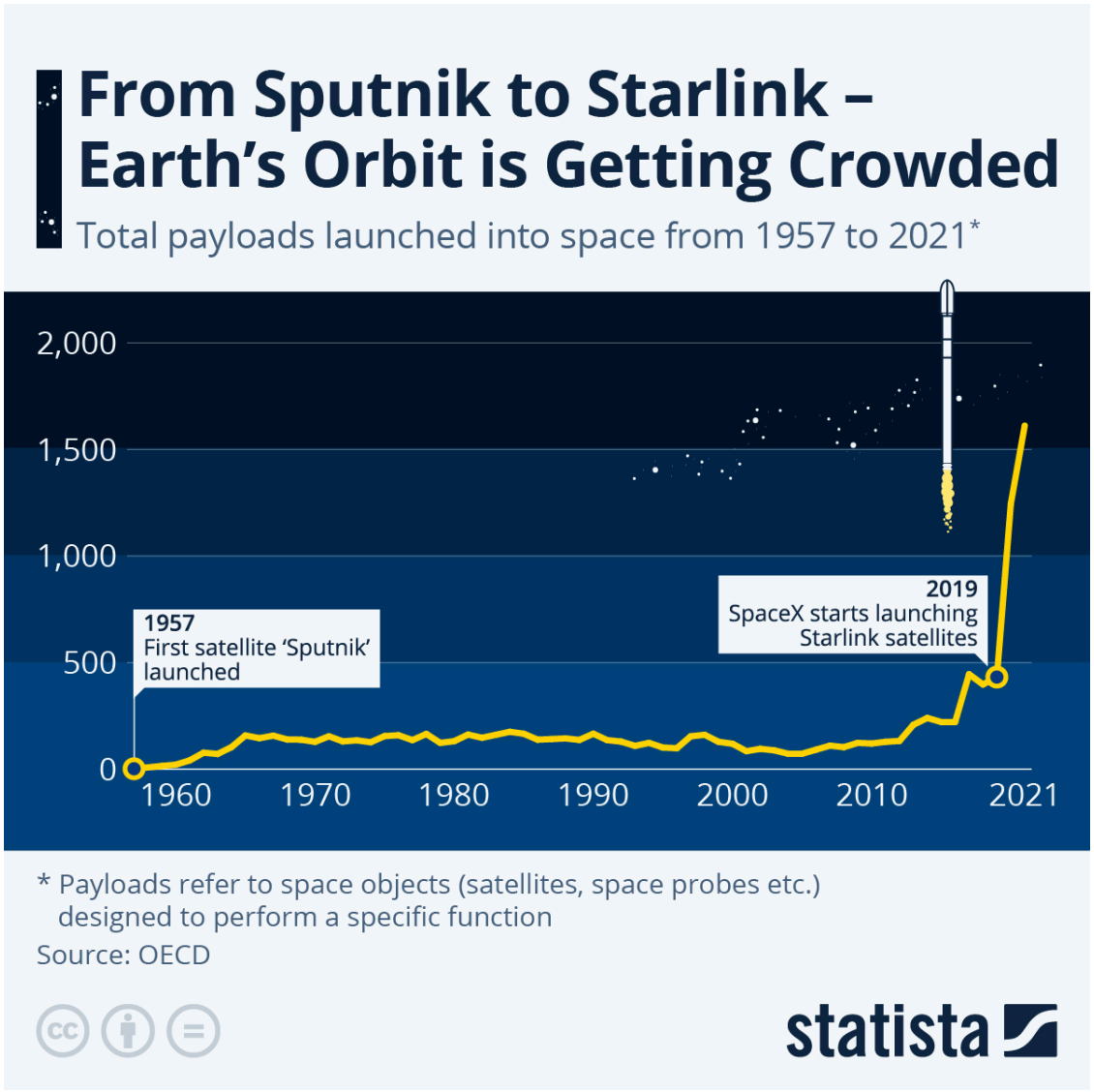

Figure 1. Total payloads launched in space from 2057 to 2021. Credit: Statista.

With the new space race in full swing, these assumptions no longer hold. There's much ambiguity regarding the extent of environmental effects from rocket emissions, space junk, and satellite reentry on our atmosphere, Earth, and climate. With the scale of proposed satellite mega-constellations, and their disposability that requires constant replenishment, we can't look away from the environmental harms of the space industry because we assume they're science fiction. The science-reality of environmental harms is coming fast.

Our policies should come from a comprehensive plan that prioritizes using this technology safely and sustainably. We need to look before leaping, with an environmental review and an upper limit of how many satellites can be deployed to ensure safety and opportunity for everyone. Our use of space should be measured against its benefit to the public interest rather than rewarding companies for being the first to launch.

500,000 satellite mega-constellations

Low Earth orbit (LEO) satellite mega-constellations, such as SpaceX's Starlink, promise a faster technology for delivering satellite internet connection.[1] This technology uses satellites much closer to the surface of the earth than the geostationary satellites that power technology like GPS or slower satellite internet connections. The closer distance to the Earth's surface also means many more devices are required to provide consistent and fast connections.[2] One estimate puts the number of additional satellites launched at 58,000 by 2030.[3] Starlink's proposed mega-constellation ranges from 30,000 to 40,000 satellites with constant replenishment as older satellites expire.[4] Researchers have tracked international proposals for over 500,000 satellites in multiple competing constellations from Amazon's Project Kuiper, OneWeb and others.[5] The U.S. licenses for this exponential increase in satellite launches are granted from the Federal Communications Commission and are exempt from federal environmental reviews.[6]

Regulators require LEO satellites to deorbit within five years after the end of their mission to prevent space junk from building up, making them far more disposable than other kinds of satellites.[7] Regulators want to control the lifespan of objects in orbit to prevent collisions, which in turn would start a chain-reaction resulting in a cloud of dangerous space junk.

Mega-constellations will also affect how we can appreciate the night sky. The International Astronomical Union has raised urgent concerns on the impact of light pollution from tens of thousands of additional satellites.[8] At peak deployment, one in 15 stars we see would be a satellite, moving throughout the night sky.[9] Worse, a spike in collisions could leave the sky looking like a shaken-up snowglobe.[10]

If collisions increase rapidly, the resulting cloud of orbiting junk could make it dangerous to launch new space missions, effectively trapping us on the planet's surface in a state known as Kessler Syndrome. Preventing this shroud of space shrapnel is why regulations require older satellites to be deorbited. Manufacturers design satellites to burn up (or "demise") in the atmosphere once they've expired.[11]

When a satellite "burns up," the materials it was made from are distributed in the upper atmosphere.[12] Due to the large number of short-lived satellites, at its peak deployment, Starlink's mega-constellation will require 29 tons of satellites to enter the upper atmosphere every day.[13] That's nearly equivalent to a Jeep Cherokee entering our skies every hour.[14] The composition of satellites is different from the metals found in natural sources, such as meteorites, and the effects are understudied.[15] The metals from satellites as well as black carbon emissions from increased rocket launches, could affect our climate and ozone.[16]

Global internet connectivity is a political, not a technical, challenge

Starlink claims we need these mega-constellations to provide broadband to the world, especially the one-third of the global population who remain unconnected from the internet.[17] Connecting

these people is a laudable goal, and part of the UN sustainable development goals, however satellite internet is unlikely to be the solution.[18] According to the UN, 95% of the world's population is already covered by mobile broadband.[19] In other words, the barrier to global connectivity is not "coverage," it's other factors such as affordability and skills training.[20] Starlink internet subscriptions, which cost $120 per month, don't address these barriers.[21]

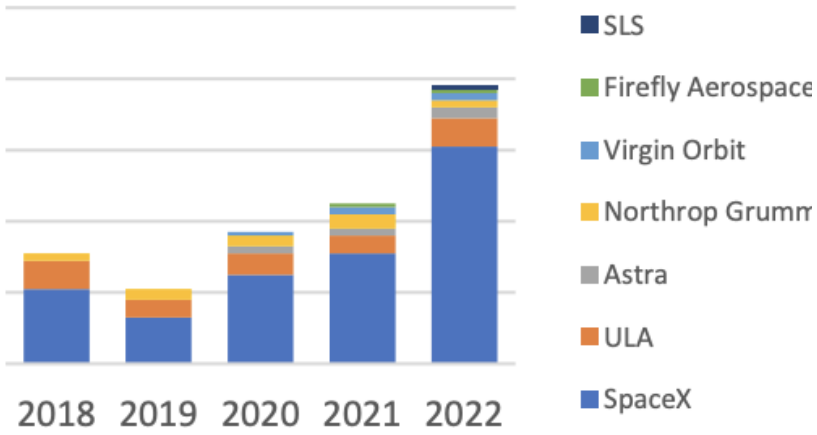

Figure 2. U.S. commercial space launches by company. Credit: USITC.[25]

Think before you leap

Large scale technological change to a new ecosystem requires precaution and oversight. Instead, the FCC has granted Starlink more than 30,000 satellite licenses, which are exempt from federal environmental impact studies.[22]

More than 4,600 additional satellites were active in 2022 than in 2019, more than tripling the total orbiting our planet.[23] In 2023, 73% of all satellite launches were for Starlink.[24] We need a precautionary agency that can regulate the commons of our final frontier, as has been recommended by the Government Accountability Office (GAO). The FCC should follow the GAO's recommendations and conduct environmental reviews for large constellations of satellites.[25] Regulators should also ask if we really need multiple disposable constellations competing for the same limited space.[26] We can have affordable internet for everyone without surrounding our globe with tens or hundreds of thousands of disposable satellites that could harm our environment.

Findings

Starlink is licensed to launch over 30,000 satellites. More than 500,000 mega-constellation satellites are proposed overall.
Starlink has been granted licenses from the FCC to launch 39,396 satellites in various levels of non-geostationary orbit.[27] The scale of these mega-constellations are unprecedented and pose serious technical and regulatory challenges to the environments in space and on earth. Although Starlink is the most ambitious and prominent mega-constellation proposed, it's hardly the only one. A new space race has been kicked off with Starlink in the lead. Astronomer and astrophysicist Jonathan McDowell at the Harvard–Smithsonian Center for Astrophysics has tracked proposals for over 500,000 satellites from constellations including Amazon's Project Kuiper, OneWeb, and Globalstar.[28] The scale of all these combined proposals need to be taken into consideration by government agencies and the United Nations International Telecommunication Union. Given the novel technology and unknown harms, they can't be granted licenses on a one-at-a-time and first-come-first-served basis.

Figure 3. Distribution of space debris around Earth. Credit: European Space Agency. ©ESA.

The number of satellites in Low Earth Orbit has increased by 127 times in five years.
It's been 67 years since Sputnik inaugurated the space age as the first human-made satellite launched into orbit.[29] We're now in a full-blown second space race. When Starlink launched its first satellite in May 2019 there were about 50 similarly-sized LEO satellites in orbit.[30] Starlink has now launched more than 6,000 satellites as of May 2024, an increase in LEO satellites of 127 times.[31] In those five years, Starlink's constellation now contains more than 60% of all satellites orbiting our planet.[32]

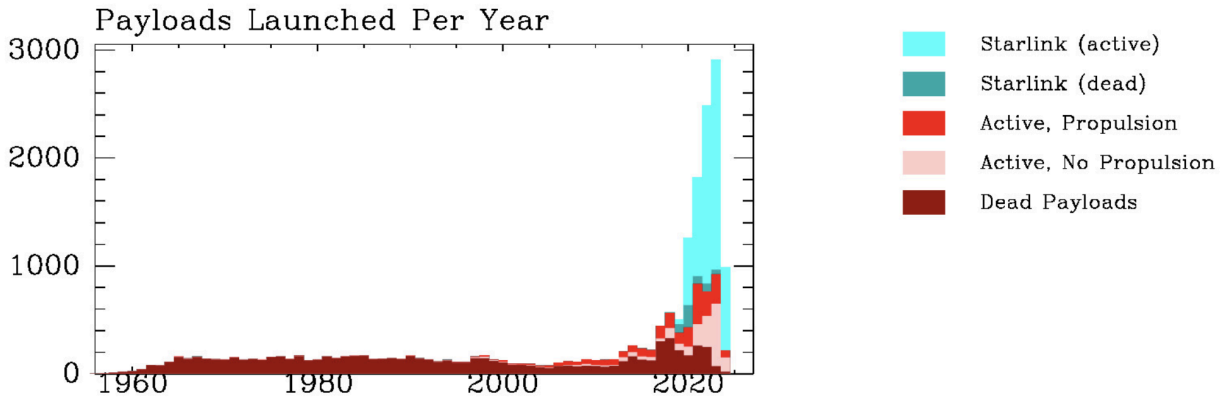

Figure 4. Payloads launched per year. Credit: Jonathan's Space Report.

Starlink satellites are designed to last only five years before they expire.

LEO mega-constellations promise that their closer distance to the surface provides faster internet connections than previous generations of satellites. Inherent to this technology is the need for constant replenishment and managing their disposal.[33] Their low altitude means they're moving extremely quickly, circling the globe 12 to 16 times per day at a speed over 15,000 miles per hour.[34] We can't manually clean up these speeding space objects so they need to be designed to safely leave orbit on schedule. In 2022, the FCC started formally requiring satellites to deorbit no later than five years after the end of their use.[35] Formalizing these requirements is intended to prevent space junk from building up. More objects in space means a higher possibility of collisions, which can create a chain reaction of more space junk. We could even reach a state known as Kessler Syndrome in which the huge amount of space junk in orbit traps us on the surface of the planet at the risk of further collisions. LEO satellites are affected by particles in the upper atmosphere which cause their orbit to deteriorate and can typically only last seven to 10 years.[36] Concern of further space collisions is well founded, but the FCC's requirements do not necessitate mega-constellations to be composed of tens of thousands of short-lived disposable satellites.

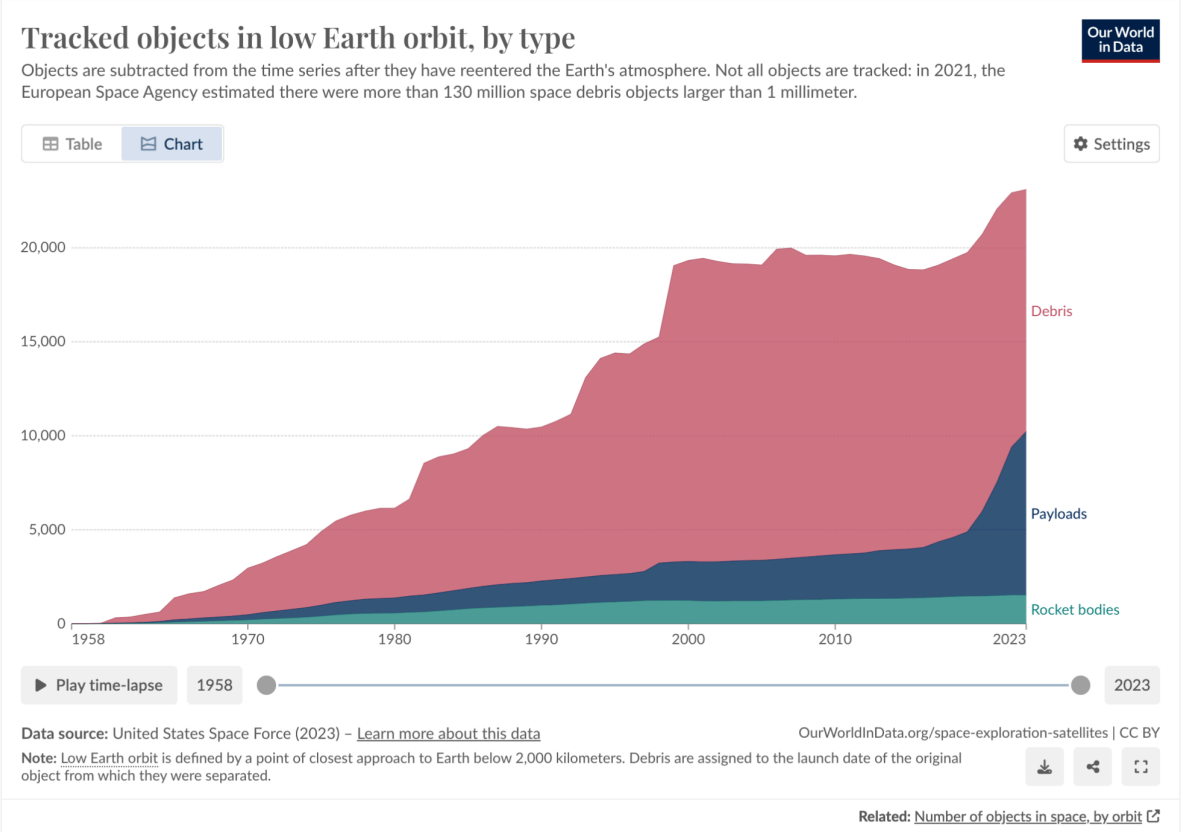

Figure 5. Tracked objects in low Earth orbit, by type. Credit: Our World in Data.[36]

Technology has become increasingly disposable, with phones, laptops, and even cars that aren't designed to last. Why does every new advancement in electronics seem to reinforce the disposability treadmill that pushes us into a cycle of manufacturing, tossing, and replacing? We can't afford to continue our culture of unsustainability with more disposable technology at this scale.

At its peak, 29 tons of satellites will re-enter our atmosphere per day.

This constant rate of replacement also means a corresponding constant rate of waste entering our atmosphere. Assuming a Starlink satellite is fully operational after five years, it will use propulsion to reenter the atmosphere and "demise."[37] However, mass doesn't disappear when it burns up on reentry, it's just distributed throughout the upper atmosphere.[38] The effects on our atmosphere and climate from this huge addition of metals are unknown. At its peak, 23 satellites from Starlink's constellation will be deorbiting each day.[39] That's about 29 tons of metals from satellites each day entering our atmosphere—nearly equivalent to a Jeep Cherokee each hour. Satellites are made of different materials than the natural metals that typically enter our atmosphere and their effects are understudied.[40]

Tens of thousands of satellites require an increase in rocket launches. Researchers found that the black carbon produced by these launches "increases stratospheric temperatures and changes the global circulation, both of which cause a reduction in the total ozone column."[41] This team found that the increase in rocket launches could cause a global depletion in ozone by up to 4% in the North Pole. Other researchers have noted the huge increases in rocket launches needed to create mega-constellations would result in atmospheric warming comparable to the aviation industry.[42]

The Government Accountability Office's study found, "Emissions from rocket launches and satellite reentries could change the temperature of the stratosphere and deplete the ozone layer, which could increase the amount of harmful ultraviolet solar radiation reaching Earth. However, more information is needed to determine how significant these effects may be, particularly with the potential for almost 3 times the current number of rocket launches projected for the future."[43]

Concerns have been raised about effects to the magnetic field that protects our planet from solar radiation. A researcher found that "mass of the conductive particles left behind from worldwide distribution of re-entry satellites is already billions of times greater than the mass of the Van Allen Belts,"[44] the radiation belts that surround our planet. The waste created by mega-constellations could create holes in the magnetic shell which protects us from harmful cosmic rays. Also, when satellites burn up, they create aluminum oxides which are known to deplete the ozone layer.[45]

Permanently changing the night sky: one in 15 stars will be a satellite.
The U.S. Government Accountability Office's September 2022 report found that satellite constellations can harm astronomic research and communications.[46] Satellites are already disrupting research with streaks of light corrupting images taken by research telescopes and noise affecting sensitive radio antennas.[47] The International Astronomical Union is, "concerned about these satellite constellations," because they "can pose a significant or debilitating threat to important existing and future astronomical infrastructures."[48]

Researchers have noted that if mega-constellations reach their peak, one out of every 15 points in the sky will be a satellite, not a star.[49] We don't know what effects this change could have on wildlife, but we do know it will change the night sky humans have always observed.

We don't need to choose between global internet connectivity and our environment. 95% of the global population is already covered by other internet technologies.
Connecting the global population to the culture, opportunities, knowledge, and joy of the internet is a laudable goal. The UN's Sustainable Development Goal 9 includes universal connectivity, but also notes that 95% of the world is already covered by mobile broadband access.[50] Operators of satellite mega-constellations claim that their technology is necessary for global connectivity but researchers don't agree. The main barriers to achieving global internet connectivity concern affordability, not technology.[51]

Given the high costs to consumers compared to already existing internet infrastructure such as mobile broadband, fixed wireless, and fiber optics, researchers have concluded that "satellite constellations will not on the whole provide Internet to those who need it most."[52] They warn, "the rush to launch tens of thousands of satellites should be fundamentally reconsidered."[53] Starlink offers a service plan for boats marketed as, "High-speed internet on the water. Starting at $150/mo with a hardware cost of $599,"[54] but this is far from affordable for the 31% of the population in Oceania outside Australia and New Zealand without internet coverage.[55] Another team found, "the current cost of satellite technology (~$200 per Mbps/month) are affordable for less than 1% of the uncovered and under-served population in the countries of interest."[56] Satellite internet mega-constellations can provide internet services to yachts but do nothing about the political challenges of investing in infrastructure for affordable global connectivity.

There might be a place for satellite internet in efforts for rural broadband access, however planned mega-constellations could be a fraction of their proposed size to achieve this goal. Analysts found that mega-constellations of disposable LEO satellites are inefficient and have diminishing returns as more satellites join orbit.[57] Researchers recommend a mix of highly capable satellites at different altitudes as the most affordable way to connect uncovered regions. They concede that LEO constellations can be competitive if they contain 200-450 individual satellites—but not 30,000.[58] Operators like Starlink and Project Kupiter should have to justify the scale of their proposed mega-constellations measuring the benefit to the public interest against the environmental harms.

Satellite internet and risks to human life

The FCC's licensing system requires operators to demonstrate a less than 1:10,000 risk of a reentering satellite to cause death.[59] That means that one person would be expected to be injured or die per 10,000 satellite reentries. That level of risk likely seemed overly cautious before proposals for hundreds of thousands of concurrent satellites in mega-constellations—now it seems reckless. FCC policy doesn't need to take into account the cumulative risks of constellations, just each individual satellite on its own.[60] The GAO reported, "debris from a 7,518-satellite constellation with 1,253 reentries per year could approach a 1:10 human casualty risk for the general population by 2030.[61] The study also predicted that having a total of 15,968 satellites in LEO by 2030 with 2,413 reentries per year could result in approximately a 1:4 human casualty risk."[62] Already debris from satellite reentry and launches are falling to Earth, although no casualties have yet been reported. In March 2022, a couple in Brazil, found a 1,300 pound piece of space debris 160 feet from their home. Two Australian sheep farmers stumbled on space junk in a field. A farmer in Canada found a 6 foot-wide, 80 pound piece of space junk in his field.[63] A smaller piece of junk has been found by two residents of North Carolina.[64] The frequency of discovered debrief is increasing and it's no wonder given the huge increase in launches and satellites reentering our atmosphere. What's the cost we're willing to pay for satellite internet and how long before someone is injured or killed from falling debris?

Recommendations

1. Pause new satellite internet low earth orbit satellite launches until the Federal Communications Commission conducts environmental reviews for mega-constellations.
We shouldn't rush into deploying an untested and under-researched technology into new environments without comprehensive review. Over just five years Starlink has launched more than 6,000 units and now make up more than 60% of all satellites. The new space race took off faster than governments were able to act. Regulatory agencies review individual licenses and lack the policies in place to assess the total effects of all proposed mega-constellations. Until national and international environmental reviews can be completed we should stop launching further low earth orbit satellites part of constellations that provide consumer internet connectivity.

The FCC is granting licenses on a first-come, first-served basis but both orbital space and the broadcast spectrum are not infinite.[65] National and international regulators need to develop an unprecedented system of cooperation to share the commons of our final frontier. Until extensive coordination is in place, we shouldn't let the commercial interests "first to launch" determine the rules.

2. FCC should end the environmental categorical exclusion of satellites.
In November 2022, GAO released their report, "Satellite Licensing: FCC Should Reexamine Its Environmental Review Process for Large Constellations of Satellites."[66] The report found the FCC sidesteps the National Environmental Policy Act's required environmental review of satellite mega-constellation by claiming a "categorical exclusion." Excluding all 24 applications for mega-constellations is absurd given the unprecedented pace at which the FCC is granting licenses.[67] The GAO recommends that "the Federal Communications Commission should review whether licensing large constellations of satellites normally does not have significant effects on the human environment." As of May 2024 the FCC has not reexamined their rules and still exclude satellite constellations from environmental review.

That launching 30,000 to 500,000 satellites into low earth orbit doesn't even warrant an environmental review offends common sense. The GAO found that the FCC doesn't have a documented reason for deciding mega-constellations are categorically excluded from environmental review.[68] The FCC should immediately begin a comprehensive review process working with experts from academia, the Environmental Protection Agency, NASA, and other federal agencies. This review must consider the total effects of proposed mega-constellations in the context of other internationally proposed constellations—not on a one-by-one basis. The effects on the space environment such as orbital debris, and on the atmosphere, astronomy, climate, aviation, and surface all need to be considered. This review needs to be coordinated with international agencies such as the International Telecommunication Union, and researchers.

In response to the huge increase in commercial satellite license proposals, the FCC launched a Space Bureau in April 2023.[69] However, the agency's avoidance of responsibilities under the

National Environmental Policy Act means it might not have the capacity or expertise to oversee the new space race. Federal leaders should consider if another agency might be better suited to oversee the exponential growth in the commercial satellite industry and ensure regulators have the resources and oversight necessary for the job.

Conclusions

New large scale technologies require oversight and study. The long term effects of this massive change to our environment aren't clear. What is clear is that we can bring the world online without the unknown environmental harms of satellite mega-constellations. The FCC should coordinate closely with the EPA, NASA, and other national and international regulators to require extensive environmental reviews for the new space age. We're in a short window of time when we can prevent making a mess of space and our atmosphere rather than spend decades cleaning it up.

The new space race doesn't need to create massive space waste.

Methodology

A diesel dump truck would need to drive around the world 1,125 times to emit the particulate matter equal to the soot from one rocket launch. 2023 set a new record of 223 orbital launch attempts. The GAO predicts that the number of launches could increase nearly 3-fold given the growth in the industry.[70] These launches would pollute our atmosphere with soot equivalent to 7 million diesel dump trucks driving around the world, each year.

- 1,000,000 kg[71] of soot from 150 rocket launches = 6,667 kg of soot per rocket launch.
- Heavy-duty diesel trucks emit 0.238 g of PM2.5 per mile driven.[72] Given the literature, I equate soot, black carbon, and particulate matter (PM2.5).[73] Black carbon (soot) is the largest component of PM2.5, but PM2.5 also contains other particles. "A large proportion of diesel particulate matter (DPM) is composed of BC."[74] In other words, diesel trucks release less soot than 0.238 g per mile, but this assumption treats them as more polluting per mile. This undercounts the extent of rocket launch pollution.
- 6,667 kg of soot per launch / 0.238 g soot per heavy-duty diesel truck mile = 28 million miles driven by one heavy-duty truck is equal to the same amount of soot emission from 1 rocket.
- 24,901 miles to circle the globe.[75]
- 28 million miles driven / 24,901 miles around the earth = 1,125 times driven around the earth.
- 6,667 kg soot per launch * 223 launches per year * 3-fold increase = 4.46 x 10e6 kg of soot from projected launches each year.
- 4.46x10e6 kg soot from annual projected launches / 0.238 g soot per heavy-duty truck mile = 1.874x10e11 miles driven by a truck to produce soot equal to annual rocket launches
- 1.874x10e11 miles driven by trucks / 24,901 miles to circle the globe = 7,525,802 trucks circling the globe to make the soot equivalent from annual rocket launches.

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