# Examining Social and Scientific Aspects of the Satellite Constellation Controversy

A Research Paper submitted to the Department of Engineering and Society

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science, School of Engineering

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Spring 2021

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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## Introduction

Satellite constellations are used to provide global coverage for navigation, communications, or Earth observation. Satellites have been launched into orbit continuously since the beginning of the Space Age, and recent advancements in technology and consumer demand have led to the creation of several ambitious satellite constellation plans. The number of satellites in orbit is expected to skyrocket as these massive networks become more common. At the forefront of this new era is SpaceX with its satellite internet project known as *Starlink.*

While this endeavor will provide internet access to users anywhere on the entire planet, several opponent groups have expressed their concerns about the light pollution effects of satellites, which are detrimental to astronomical observations, and the dangers of rapidly accumulating space debris. The evolution of this technology will be analyzed through co-production, an STS framework that relates the inseparable influences of science, technology, and society. This paper will examine the satellite constellation controversy, and particularly Starlink, within the context of co-production and seek to answer the research question: How are opponents and advocates of satellite constellations advancing their respective agendas?

## STS Framework: Co-Production Theory

Co-production is an STS framework that describes the interactions between science and society. In short, co-production states that “the ways in which we know and represent the world (both nature and society) are inseparable from the ways in which we choose to live in it” (Jasanoff, 2004). According to Jasanoff, advancements are formed from a combination of scientific, technical, and social contributions. In essence, this means that science, technology, and society are continuously shaping each other.

Groundbreaking inventions lead to changes in the social or physical environments we live in; these changes then lead to the creation of new ways of living in these environments. For example, the invention of controlled fire by early humans led to drastic social changes: humans could remain active after dark, migrate to colder climates, create better tools, and develop healthier diets (Nerlich, 2015). Additionally, advancements in scientific knowledge or technology are inextricably bound to various social aspects which may include internal biases, political influences, and flawed logic (Michael, 2011).

There are four main tenets that are used to examine phenomena through the co-production framework: the emergence and stabilization of new technology, the resolution of scientific or technical conflicts, the processes by which the technology become standardized, and the adjustment of scientific and cultural practices in response (Jasanoff, 2004). This paper will focus primarily on relating the first two tenets of co-production to the emerging sociotechnical system of satellite constellations, with some consideration given to the latter two.

## Background

Artificial satellites (distinguished from natural satellites, like Earth's Moon) are an integral part of humanity's modern, technology-focused existence. They are vital for telecommunications and GPS data which support air, ground, and marine transport. Over 95% of the data that the NOAA's National Weather Service (NWS) uses for forecasting is provided by the Geostationary Operational Environmental Satellite (GOES) network (Hertzfeld & Williamson, 2002). This information is crucial for predicting weather disasters like hurricanes, which cause billions of dollars' worth of property damage and claim many lives annually. Satellites are also used to improve agricultural efficiency, monitor climate change, protect ecosystems and conservation efforts, improve access to public health, and assist in search and rescue operations. Even an everyday activity like making a purchase with a credit card will sometimes use satellites, which establish a direct link between the cardholder's bank and the business' card reader (Canadian Space Agency, 2020). According to a report by Highfill et al. (2020) from the Bureau of Economic Analysis (BEA), the overall US space economy generates an estimated $200 billion in total economic activity every year.

On its own, a single artificial satellite offers fairly limited coverage and may only be useful if it serves as a space station or space telescope like the International Space Station or the Hubble Space Telescope (HST). Satellite constellations are groups of satellites that work together as a system to provide global or near-global coverage for navigation, communications, or Earth observation. Some examples of constellations are GPS, GOES, Sirius XM, Dish TV, Iridium, Intelsat, and PlanetLabs. Until the late 2010s, all satellite constellations consisted of less than 100 satellites, with an average number between 20 and 30. Between 1957 (Sputnik 1, the first satellite) and 2019, about 8,900 satellites were sent into orbit; only about 2,300 were still active (Mazareanu, 2021). However, low Earth orbit (LEO) is now cluttered with space debris from old satellites, complicating future space missions. Reflected sunlight from satellites is an additional form of light pollution, which obscures astronomical observations and may even prevent the detection and timely preparation for an impending asteroid or comet impact.

In the 1990s, several companies set out to build satellite constellations to provide global internet access. However, none of these projects were successful. The $5 billion Iridium constellation, consisting of 66 satellites and funded by Motorola, became the world's largest and most ambitious satellite constellation when it was launched in the 1990s (Mellow, 2004). But since the concept was designed in the 1980s, it was largely obsolete once it was finally deployed. The offer of global communication using a “brick-size, $3,000 phone at charges from $6 to $30 a minute” failed to repay even a fraction of the debt from building the constellation, and in 1999, Iridium filed for what became one of the top 20 largest bankruptcies in US history at the time (Glasner, 1999; Mellow, 2004). Another large, revolutionary communications satellite company, Globalstar, filed for bankruptcy shortly after. Teledesic, funded by Microsoft, shut down its daring $9 billion constellation project in 2002 (Dilley, 2019). Thus, the first wave of global satellite internet ground to a halt.

Companies such as HughesNet and Viasat have offered regional internet service using small networks of high-altitude satellites since the mid-2000s. Renewed interest in global satellite internet, building upon the lessons learned from the first wave, began in the 2010s. This second wave is the result of a drastic decrease in launch costs and an increase in demand and competition for high-speed internet (Dilley, 2019). The new satellites are also different in two ways: (1) they will use much lower orbital altitudes to significantly improve latency; and (2) they are much smaller, lighter, and cheaper than previous telecom satellites. Starlink, the pioneering project, is SpaceX’s plan to assemble a constellation of satellites in LEO to provide internet access to any location on Earth. However, this ambitious design is drastically different from any other constellation in history. The Federal Communications Commission (FCC), which regulates communications by radio, television, wire, satellite, and cable in the US, has approved SpaceX for 12,000 Starlink satellites, and paperwork is well underway for an additional 30,000 (Henry, 2019). With a collective 42,000 planned satellites, SpaceX alone might soon operate nearly 20 times the number of satellites that were in orbit in 2019. This signals the beginning of a new era of constellations with thousands of satellites each, dubbed *mega-constellations.*

As of March 2021, over 1,600 Starlink satellites have been launched into orbit (Foust, 2021a). Several other companies are following SpaceX's lead and planning their own mega-constellations. Resulting from a joint venture between OneWeb and Airbus, the OneWeb constellation may even surpass Starlink with its planned size of 48,000 satellites (Cao, 2020). Project Kuiper has an initial plan for 3,200 satellites, and may soon become a formidable competitor fed by the vast resources from its parent company, Amazon. The European Union is also in the process of creating a $7.3 billion mega-constellation, to be built by a consortium of aerospace and telecom companies including Arianespace and Airbus. Other upcoming satellite internet projects include Hongyan, Telesat, LeoSat, O3b mPOWER, and Viasat. If these mega-constellations continue as planned, the number of active satellites in orbit will soon exceed 100,000. This is an unprecedented increase over the total of about 8,900 satellites launched since the beginning of the Space Age, as mentioned previously.

## Emergence of the Technology

At the conceptual level, mega-constellations are primarily designed to provide global internet access to remote and underserved areas. Traditional telecom satellites are in geostationary orbit (GSO), and they remain stationary above fixed points along the Earth's equator. The new satellites in mega-constellations will be placed at a lower altitude, in low Earth orbit (LEO), allowing the network to provide coverage for the entire globe. The difference between these two is especially apparent when considering polar regions, where establishing connections with GSO satellites over the equator is impossible. The new LEO satellites will provide internet to extreme northern and southern latitudes for the first time (Cooke, 2021).

GSO satellites are about 36,000 km (22,000 miles) above the surface. This great distance is why the average latency for traditional satellite internet is between 500 and 600 ms (McNally, 2021). Data speed is also limited by outdated technology, with current providers offering 12 to 25 Mbps download speeds. In comparison, Starlink is the first internet constellation placed in LEO, orbiting at altitudes between 340 and 1,300 km (210 and 810 miles); as a result, the initial latency is predicted to be 20 ms (McNally, 2021).

SpaceX originally launched a beta testing program that was limited to the continental US but later expanded it to include Canada and the United Kingdom (Foust, 2021a). Over 10,000 people enrolled in the beta testing, and users confirmed the predicted low latency of 20 ms while reporting average download speeds of 100 Mbps (Carter, J., & Hector, H., 2021). Starlink already outperforms all traditional satellite internet networks, even though these tests were conducted with only about 1,000 out of the 42,000 planned satellites. Thus, the first principle of co-production (emergence and stabilization of the technology) is in progress for satellite mega-constellations. The stabilization aspect of this tenet depends heavily on the second tenet, which is the resolution of scientific or technical conflicts. These two tenets will be attained concurrently as the Starlink network advances and other companies follow suit.

## Resolution of Technical Challenges

In the future, Starlink may offer speeds up to 10 Gbps. The company plans to accomplish this using laser crosslinks, which will allow satellites to transfer massive amounts of information between each other and find the fastest path between any two ground stations on Earth (Maloney, 2020). Since the speed of light in a vacuum is about double that of in glass, these connections may even surpass the fastest fiber optic connections on the ground. Constructing this system is extremely complex and it requires an extraordinary amount of precision. Nonetheless, a batch of 10 Starlink satellites equipped with laser crosslinks was launched in early 2021 (Foust, 2021b). Preliminary tests show that the lasers are able to transmit hundreds of gigabytes of data, although they have yet to be used extensively in a complete network.

Previous telecom constellations like Iridium allowed users to connect directly with satellite phones. Starlink, on the other hand, requires its users to purchase *user terminals*, which are usually described as “pizza box sized” (Maloney, 2020). User terminals act as ground stations which link to the phased-array antennas on the Starlink satellites to establish an internet connection. They are also capable of tracking satellites across the sky for reliable access. However, the cost of funding the constellation, working out technical issues, and manufacturing the user terminals leads to a moderately high price for each user. Elon Musk says “lowering terminal equipment cost… is actually our most difficult technical challenge” (Cooke, 2021).

Mega-constellations are significantly more expensive than standard constellations or standalone satellites. Funding is a limiting factor for the majority of projects. The total cost of building Starlink is estimated at $10 billion (Sheetz, 2020). This enormous cost is a major risk, especially considering the fate of previous companies during the first wave of global satellite internet. Nonetheless, the company estimates that its mega-constellation will earn $30 billion annually by 2025, which would be an exceptional return on investment. SpaceX has stated that the revenue generated by Starlink is crucial for funding its missions to Mars. Overall, the satellite internet business is targeting a $1 trillion potential market (Sheetz, 2020a).

## Social and Technical Considerations

The development of mega-constellations is driven by both social and technical aspects. An estimated 3.7 billion people, about 50% of the worldwide population, still do not have access to the internet, while hundreds of millions more are stuck with connectivity that is “too slow, too costly, and too unreliable to have made a meaningful difference to their lives” (Bogdan-Martin, 2020). According to the United Nations, having access to internet “helps reduce poverty, improves economic opportunity, and increases access to healthcare in the least developed countries” (Cooke, 2021). However, underdeveloped countries suffer from the lowest quality internet, and the wealth gap is expected to widen as wealthier countries make technological advancements. The main problem that hinders internet access in rural or remote areas is the significant cost of infrastructure. This includes “the cost of digging trenches, laying cable or fiber, and even dealing with property rights disputes” (McNally, 2021).

Starlink seeks to bridge the internet gap by offering high-speed access to the entire world, including those living in rural or remote locations. However, it is uncertain if the project can actually do so. Starlink would be immensely beneficial to “low-income, underserved, and rural parts of the world, but cost is a big deterrent for those who need it most” (Cooke, 2021). The ongoing beta testing costs $99 per month, in addition to the initial sign-up fee of $499 which covers the cost of a user terminal. In December 2021, the FCC awarded SpaceX with $885.5 million in federal subsidies over 10 years as part of the Rural Digital Opportunities Fund (Sheetz, 2020b). The subsidies are meant to incentivize bringing service to underserved and hard to reach areas of the US. Thus, SpaceX is required to deliver service to 643,000 new locations over the next 10 years. Despite the FCC funding, Starlink will lose money on a per-user basis unless SpaceX can reduce the cost of building each user terminal (Mohney, 2020).

The ongoing resolution of these challenges indicates that mega-constellation technology is still progressing through the first and second themes of co-production. These barriers are preventing the technology from becoming standardized and achieving the third and fourth tenets of the framework. If the problems are resolved, the standardization and adjustment of cultural practices may bear similarities to the way that GPS technology progressed. As the technology transitioned from exclusively military use into widespread civilian use during the 80s and 90s, the cost of a GPS receiver dropped from $3000 to $1.50 (The Aerospace Corporation, 2021). GPS now plays an important role in everyday life for many. According to a 2019 study, location-based services like navigation apps helped Americans save 52 billion gallons of fuel between 2007 and 2017 (The Aerospace Corporation, 2021).

## Negative Impacts on Astronomy

Mega-constellations like Starlink have drawn criticism from opponents because of their contribution to light pollution. Since GPS constellations are in medium Earth orbit (MEO) and thus appear dimmer in the night sky, they do not cause notable light pollution. Smaller networks in GSO are even farther away and are confined to a fixed orbit directly above the equator, rendering them invisible to most astronomical observations. The now defunct Iridium constellation produced bright flares of reflected sunlight that were even visible in daylight because of its satellites' high albedo. But because Iridium had fewer than 100 satellites and these flares were very rare occurrences, it was much less controversial.

The American Astronomical Society (AAS), National Radio Astronomy Observatory (NRAO), and International Astronomical Union (IAU) have released statements expressing concern about large satellite constellations (Gough, 2020; IAU, 2020). According to Gallizzi et al. (2020), satellite trails ruin astronomers' long-exposure photographs and the irradiation of satellite communications interferes with observations in other wavelengths such as radio waves. The drastic increase in radio-emitting objects, including satellites and grounds stations, could make radio astronomy impossible from Earth. For optical astronomy, satellites are especially detrimental to the ongoing search for near-Earth objects (NEOs). If a NEO larger than 140 m (460 ft) has an orbit that crosses Earth's, it is classified as potentially hazardous (National Aeronautics and Space Administration [NASA], 2019a). NASA estimates that only about 30% of all NEOs larger than 140 m have been discovered.

In 2013, an undetected NEO entered Earth's atmosphere over Chelyabinsk, Russia at 64,000 km/h (40,000 mph) and exploded several miles above the surface; the energy released from the blast was 30 to 40 times greater than that of the Hiroshima atomic bomb and was detected as far away as Antarctica (Howell, 2019). The Chelyabinsk meteor caused over 1,500 injuries and inflicted $30 million in damage. Scientists determined that the object was only 17 m (56 ft) in size. A similar explosion occurred over a remote region of Siberia in 1908. The meteor, estimated at 100 m (330 ft) in size, created an air blast roughly 20 to 50 times more powerful than that of the Chelyabinsk meteor and leveled over 2,000 $km^2$ (800 $mi^2$) of forest near the Tunguska River (NASA, 2019b). Another event like the Tunguska meteor can easily destroy a populated metropolitan area. If an incoming NEO is detected with sufficient notice, planetary defense experts can predict the severity of an impact event and determine ways to mitigate the effects (NASA, 2019a). Mitigation efforts may include launching an impact avoidance mission to change the object's orbit and evacuating the impact zone to protect lives and property.

Ground-based telescopes play an important role in detecting NEOs and will continue to do so (Howell, 2019). While space-based telescopes like the HST have been immensely beneficial for scientific research, some scientists believe the future of astronomy will rely more on ground-based telescopes (Foust, 2019). Telescopes with larger mirrors can discover fainter, smaller, and farther objects. Because ground-based telescopes are much cheaper to build and operate, several upcoming telescopes have mirrors up to 17 times larger than that of the HST. With the advent of adaptive optics, which eliminate the effects of atmospheric turbulence, some ground-based telescopes can now produce higher resolution imagery than the HST (Lee, 2013). Thus, astronomers argue that mega-constellations will not only pose a risk to future astronomy, but also to humanity by reducing the detection rate of NEOs and decreasing the chances of predicting a future impact (Gallizzi et al., 2020).

## Criticism from Other Social Groups

Satellite operators warn that growing constellations may make collisions inevitable and render certain orbits unusable (Lehoucq, 2020). As the risk of collisions increases, the cost of space insurance will rise. Some companies are simply leaving the LEO launch market. The managing director of Assure Space, a space insurance underwriter, believes space insurers will eventually stop insuring LEO satellites: “there is too much risk and too little being done about mitigating space debris or managing space traffic globally” (Johnson, 2020). Others expect that insurance premiums will rise dramatically as collisions become more frequent. Launch service providers (LSPs), including United Launch Alliance (ULA) and Northrop Grumman, will face rising launch costs for space insurance and collision avoidance systems (Ailor, 2010). The increase in orbiting objects may eventually lead to the Kessler syndrome, a theoretical disaster in which one collision leads to an endless chain reaction of further collisions until LEO is uninhabitable. However, some argue that constellation operators have a vested interest in keeping their orbits clean for the safety of their own satellites (Werner, 2018). Starlink satellites are low enough for their orbits to naturally decay from atmospheric drag within 5 years.

The FCC's decision to award SpaceX with nearly $900 million in subsidies has also drawn criticism. Jim Matheson, CEO of the National Rural Electric Cooperative Association, argues that Starlink is "a completely unproven technology" and the FCC is essentially funding a science experiment (Shields, 2021). Others assert that SpaceX should not have been considered for funding since they would have served customers with or without the subsidy. Local broadband providers, struggling because of competition with monopolies, could have used the funding to deploy traditional fiber connections that are much more affordable. Some critics even argue that the entire FCC program is flawed after determining that many "hard-to-reach rural areas" in the agreement were found to include luxury resorts, golf courses, airport terminals, and a parking lot outside the Pentagon (Turner, 2020).

Proponents of mega-constellations tend to focus on the humanitarian benefits. In response to critics, Elon Musk has said "potentially helping billions of economically disadvantaged people is the greater good" (O'Callaghan, 2019). Many advocates believe that projects such as Starlink are noble causes, and their detrimental effects to astronomy and space can be overlooked. While helping underserved communities may be the end goal of mega-constellations, critics argue that the only social groups that can currently benefit from this technology belong to the middle and upper classes. Even after earning FCC funding, the cost of Starlink is not expected to decrease from $99 per month. Most people in developing countries will not be able to afford it, although some communities might avoid this issue by sharing connections among community buildings, businesses, and residences (Press, 2021). Other similar projects heeded the advice from critics; after setting out to provide free internet for Africa, Facebook plans to provide internet "the oldfashioned way" by building undersea cables (Iyanda, 2021). It is unclear how SpaceX plans to provide internet to underserved communities, particularly those in developing countries.

## Conclusion

In this paper, the rapidly evolving sociotechnical system of satellite constellation technology was analyzed within the contexts of co-production. The emergence of the technology, which builds upon earlier satellite internet attempts of the late 1990s, is the result of a decrease in launch costs and an increase in demand for high-speed internet. Starlink, at the forefront of this new wave of constellations, is working to resolve challenges related to both the performance of the technology as well as the criticisms from various social groups. As these problems are addressed, the first two tenets of the co-production framework will be fulfilled and the technology may later advance to the third and fourth tenets. Companies planning future mega-constellations like Starlink must find ways to reduce the cost of their internet services while also taking note of the impacts on astronomy and space debris. If new satellite projects can pursue their ambitious goals conscientiously with sound ethical reasoning, the stars are the limit.

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