**An Analysis of SpaceX's Starlink Megaconstellation Network**

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Andrianna Daniels

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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.

Signed: _____

Approved: _____ Date _____

Benjamin J. Laugelli, Assistant Professor, Department of Engineering and Society

## Introduction

In 2019, SpaceX began launching the first of their proposed thousands of satellites into Low Earth Orbit (LEO) for its megaconstellation Starlink. Starlink's goal is to provide reliable internet service globally, especially to areas with little-to-no current access to the internet. The idea was that, if SpaceX could remove the barrier of limited internet access from the world, it could keep people connected globally at rates never possible before due to limited satellite coverage. Though this is a grand and noble goal, scholars have raised some concerns regarding the success of this megaconstellation. Scholars currently agree that the Starlink satellites are posing issues with ground-based astronomical observations. They also argue that the number of satellites that are failing per-launch is too high for the proposed 12,000 satellite constellation.

A complication in the understanding of this case is that scholars are looking at these problems on a case-by-case basis and not as symptoms of a vulnerable network. By neglecting the connections between the various components in the system, the potential impact of the problems cannot be fully understood or assessed properly. If the current understanding of this problem is not updated to reflect the true scale of vulnerability that this network faces, then it cannot be properly fixed by SpaceX. The Starlink network, in fact, is largely vulnerable due to its network of satellites that are failing at unexpected and unsustainable rates and its failure to include astronomers as an important actor in the construction of this network, which has caused them to go rogue and work against the network due to the satellites interfering with their astronomical observations.

By examining the Starlink network through the lens of the Actor Network Theory (ANT), which analyzes the relationship between various actors in a given network as determined by the network builder, SpaceX, it will become clear that these separate instances of problems within

Starlink are actually connected and symptomatic of a vulnerable network. I will show why these problems reflect areas of weakness within the larger network and explain how the network is vulnerable and how these vulnerabilities could lead to total network failure in the future. To do this, I will use scholarly journal entries and web articles that provide insight into the Starlink network.

**Background**

There are some terms related to satellite operation and astronomical observations which should be defined before the analysis is completed. Low Earth Orbit (LEO) is defined as the region below an altitude of 2,000 kilometers in Earth's atmosphere (McDowell, 2020). This is a very populated region of the atmosphere and, as of December 2020, LEO hosted around 2,600 active satellites (In-depth details, 2021). In LEO, small amounts of atmospheric drag due to the low density of air can cause satellites to fall back to Earth if no thrust is available to boost them back into the right orbital altitude. If they fall back to Earth, small enough satellites fully burn up in the atmosphere.

**Literature Review**

There already exists a wide range of literature critiquing SpaceX's Starlink megaconstellation despite the fact that the first batch of 60 satellites was launched less than two years ago in May of 2019. Many of these sources focus on the fact that the satellites are causing issues for ground-based astronomy. These articles generally focus on problems that are occurring now that the satellites have already launched and are in space. They give some recommendations

for how to mitigate risks to scientific inquiry via telescopes and amateur astronomy on Earth, but they do not mention the likelihood that this network has been vulnerable from the beginning.

In Jonathan C. McDowell's article *The Low Earth Orbit Satellite Population and Impacts of the SpaceX Starlink Constellation*, he focused his criticism and analysis on the current and predicted problems within optical astronomy. McDowell claims that the Starlink constellation is causing the most observational issues during twilight observations (when the satellites are the brightest), in long-exposure observations with wide fields of view (where the probability of a satellite entering the field of view increases), and during local summertime (when sunlight is most direct). He explains that, while some measures can be taken to reduce the impact of these satellites crossing through fields of vision, they may require shooting more frames per observation to properly get rid of any streaks of light in an image (McDowell, 2020). Though this may work, it would require a company to have more money to photograph more frames in an observation, and it may not work properly if the streak covers any of the same pixels in more than one frame.

Daniels Clery comes to similar conclusions regarding the problems that this megaconstellation can cause in astronomy. Clery's argument focuses more on the impact on radio astronomy as opposed to McDowell's focus on optical astronomy. In his article *Satellite swarm threatens radio array*, Clery states that the Starlink satellites will reduce the frequency sensitivity of certain downlink bands due to the satellites' transmissions by around 70%. If the number of satellites continues to increase, this band may become entirely unusable to telescopes that are programmed to look for signals in these frequencies. These bands are important to radio-based astronomy because they can detect organic compounds and water in far away solar systems (Clery, 2020). Clery also mentions a possible solution that SpaceX could implement:

turning off/pointing away transmitters when flying over observatories. Like McDowell's article, the main focus is on effects of the satellites already in orbit and providing solutions to problems that were not solved before the implementation of the constellation.

While several scholars agree that the ever-increasing number of satellites in LEO will cause increasing problems for ground-based astronomers, they have not yet adequately considered that these problems are symptomatic of a vulnerable network. Instead of solving problems as they occur, the network that SpaceX has created should be analyzed to understand where it is the most vulnerable.

**Conceptual Framework**

My analysis of SpaceX's Starlink satellite constellation draws on Actor Network Theory which allows me to determine whether the network that SpaceX has created is failing or vulnerable. Actor Network Theory is a Science, Technology, and Society (STS) framework that allows the user to analyze the power dynamics between both human and non-human actors within the extended network in question. In ANT, a network-builder is defined as the person or persons that are the primary actors that construct the network itself. This theory also elevates non-human actors to positions of equal importance as human actors within the network (Cressman, 2009). By allowing objects to be seen on the same level as human actors, one can better understand why a network may succeed or fail. Associations and power dynamics between actors can be determined in order to fully evaluate the network. This is important because actors only have meaning in relation to other parts of the network; no actor intrinsically has power alone nor does it reside with any one actor (Cressman, 2009).

Actor Network Theory exists with the concept of 'translation.' Translation is the process of creating and maintaining a network of actors. The four main steps of translation are (1) problematization, (2) interessement, (3) enrollment, and (4) mobilization. Problematization represents the stage where the network builders select a problem or goal and then select the actors needed to solve or accomplish the task. Interessement is when the network builders actually recruit the various actors into the network. Enrollment is when the network builders assign the various roles that the actors will have in the network, and the actors themselves accept and fulfill their roles. Finally, mobilization is when the network builders become the spokesperson for the network and must accurately represent and speak for the other actors (Callon, 1986).

In the analysis that follows, I begin by applying this framework to the Starlink network to establish a network builder, heterogeneous actors within the network, and relationships between these actors. I will conclude by analyzing these relationships and state whether any actors or relationships leave the network open to vulnerability or total failure.

## Analysis

### *Network Formation*

In order to properly argue for the claim being made in this paper, the Starlink actor-network must be reconstructed to fully understand where exactly it is vulnerable. In this case, the network builder is SpaceX, the company behind and responsible for the Starlink constellation. Under the problematization step of ANT, SpaceX identified the problem that many regions in the United States and across the globe do not have reliable access to the internet. It set a goal to create a constellation of satellites around the Earth that would bring internet service to

these communities for a low price. SpaceX then had to establish a list of actors that were needed to accomplish this goal. Though an exhaustive list of actors would be beyond the scope of this paper, the most important actors include: SpaceX engineers, the Federal Communications Commission (FCC) (Sullivan, 2021), the National Aeronautics and Space Administration (NASA), SpaceX's CEO Elon Musk, the sun, the satellites themselves, and the rockets required to launch the satellites (Foust, 2021). During the stage of interessement, SpaceX then recruited these actors into its network. These various actors each accepted and performed their duties. SpaceX engineers were able to design and manufacture a constellation of satellites that would be able to deliver internet capabilities to areas with little or no access to the internet. The FCC and NASA approved of the designs and have allowed for launches to occur for the satellites to enter their orbits around the Earth. CEO Elon Musk has largely promoted and publicized the launches and successes of the constellation. Lastly, the satellites have been largely operational in connecting with each other and back to ground stations on Earth while being powered by the sun.

While designing this network, SpaceX left out an important consideration in one actor, the satellites, and also chose not to recruit a team of ground-based astronomers into this network. These actions have left the system even more vulnerable to failure.

*Satellite Failures*

One vulnerability in SpaceX's network is also one of the most fundamental actors involved: the satellites themselves. The satellites are vulnerable because they are failing at problematic rates, causing resources to be wasted and leaving SpaceX open for criticism and scrutiny. Without a working constellation of satellites, the Starlink constellation would have been scrapped long before the first launch as the satellites are the actor which provides the internet to low-access areas. A reason that they are currently vulnerable is because there are reports that

some of the current satellites in orbit around the Earth are failing. On May 23, 2019, SpaceX launched and deployed the first 60 Sarlink satellites into orbit around Earth using one of its Falcon 9 rockets (Grush, 2019). This was the first batch of 60 satellites out of an approved 12,000 to be launched in the coming years. Of the 60 satellites, SpaceX reported that three had lost contact with the ground and were thus no longer usable. This loss in communication meant that the satellite could not maneuver its ion propulsion system to achieve the proper altitude required for operation. These three satellites were left to naturally decay in their orbit until they burned up in the Earth's atmosphere (O'Callaghan, 2019). Having three out of 60 satellites fail may not seem like a huge deal, but if the 5% failure rate is scaled up to the planned 12,000 satellite constellation, then 600 satellites may be launched just to fail and deorbit back to Earth in five years (Cao, 2020).

The first 60 satellites were always intended to be prototypes for testing purposes. It was never expected for them to operate perfectly on this first attempt, and they were not planned to stay in orbit. As of October 7, 2020, the majority of these first satellites had been deorbited (Arevalo, 2020). A total of 775 satellites had been launched as of October 2020. According to more recent numbers, approximately 3% of these satellites have failed (Cao, 2020). Though a 3% failure rate is better than a 5% failure rate, it is still unacceptable when scaled up to the 12,000 satellite constellation, where 360 satellites may fail, as discussed below. These numbers also do not account for any additional satellite failures that may occur between the initial launches and the five-year projected lifetime.

This failure rate is alarming for a few reasons. From SpaceX's viewpoint, this level of failure of its satellites is not only a waste of space in LEO, but it is a huge waste of resources. If 360 satellites were to fail, it is a waste of not only the time and price to produce each satellite but

also the cost of launching them all into orbit (estimated to be six entire deployments of 60 satellites each). There is also a cost associated with the environmental and space pollution that occurs when each satellite deorbits and burns up in the atmosphere or collides with other 'space junk' and creates a plethora of uncontrollable debris. If the satellites cannot maneuver, then collisions are more likely to occur over five years. All of these costs could add up and become a burden to SpaceX both financially and in terms of publicity. If this failure rate is not lowered in the coming years, then SpaceX's network will continue to be vulnerable to waste, criticism, and failure.

*Failure to recruit astronomers*

In designing its network, SpaceX also forgot to recruit an important actor: ground-based astronomers. On a quick glance, it seems unnecessary to include a sector of scientists who focus on ground-based observations to be involved with the Starlink network whose goal is to put satellites into orbit (which are notably not on the ground). These astronomers have, however, become rogue actors within this network. They are acting against the network due to the problems that the satellites are causing for ground-based telescopes which are important tools for astronomical research.

Ground-based telescopes commonly use visible, infrared, and radio frequencies when observing distant objects from the ground. This is because these wavelengths are the easiest to observe through the atmosphere surrounding Earth (Observatories across, 2013). Humans can only observe light in the visible spectrum. For observing space based objects, humans can observe up to around a magnitude of +6 on the apparent magnitude scale (with higher magnitudes being fainter). The image below shows a visualization of this scale.

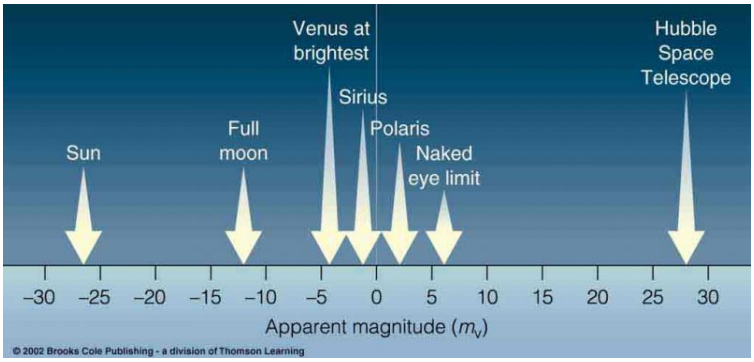


Figure 1: Line graph showing the apparent magnitude scale with various astronomical objects (McClure, 2017)

Upon the launch of the initial 60 prototype satellites back in 2019, SpaceX CEO Elon Musk took to twitter to reassure users that the "[satellites] will be in darkness when the stars are visible" when concerns of Starlink's visibility came to light (Musk, 2019). Though his comments were meant to reassure the public that Starlink would not be visible at night to the general public, they did not mention the impact on ground-based astronomy nor that the satellites would remain visible at most times throughout the day, around magnitude +5, and especially at twilight hours (McDowell, 2020).

Two main complaints that astronomers have are that: (1) with an increasingly crowded LEO, observations are being interrupted by satellites streaking by telescope's field of view at increasing rates and (2) that the satellites are operating at very similar radio frequencies that astronomers commonly use in observations (McDowell, 2020; Drake, 2019). The main issue in not recruiting astronomers into the Starlink network was that they were not able to properly voice concerns and work towards solutions with the SpaceX team before the Starlink satellites were launched. On this same topic, it is important to note that the sun, an actor recruited into the network, went rogue by illuminating the satellites instead of just powering them as they were recruited to do.

SpaceX only began compromising with the astronomical community after dozens of satellites had already been launched. One compromise has been to coat the Earth-facing side of the satellite with a dark coating to reduce their overall visibility. This also reduces the light-scattering effect the satellites can have when they are located near the field of vision of a telescope (McDowell, 2020). Though this is a start in the compromise process, it is not enough for some astronomers, as the satellites can still cross into a telescope's field of vision at any time and are still too bright for some astronomers (Zhang, 2020).

Starlink satellites operate in the range of radio frequencies from 10.7 to 12.7 gigahertz. This range contains an important frequency band that is commonly used to detect organic compounds and water in distant objects (Clery, 2020). Astronomers are not only asking for cooperation from SpaceX in protecting observatories from the effects of the satellites, but they are also seeking legal protections to prevent further satellite constellations from interfering with ground-based observations. There are also reports that the FCC unlawfully approved the Starlink megaconstellation and is open to being sued by environmental groups (O'Callaghan, 2020). The National Environmental Policy Act, enacted in 1970, states that it "obligates all federal agencies to consider the environmental impacts of any projects they approve" (O'Callaghan, 2020). The FCC excluded Starlink from this requirement by stating it would have minimal environmental impact despite evidence pointing to the disruption of astronomical observations. Should the FCC be sued, it could prevent future launches of Starlink satellites from being put into orbit. If the current constellation cannot be fully realized, then it may fail in its goal to provide globally reliable internet, and the network would fail. Had SpaceX included astronomers from various types of ground-based telescopes into its network, these problems may have been resolved long

before the first launch of satellites. By neglecting this actor's role in the network, SpaceX has left the network vulnerable to failure.

As I have argued, SpaceX has left its network for the Starlink megaconstellation vulnerable to failure from multiple angles. Some might argue that, under the original goal of the network, SpaceX has no obligation to protect the night sky or to work with astronomers to ensure that there is enough 'space in space' for everyone. According to SpaceX's mission statement page, its main values are making humanity interplanetary, making history, and reusability (of its rockets) (Mission, n.d.). Nowhere on this page does SpaceX indicate that it has a moral duty to preserve the integrity of LEO nor ensure that its projects do not interfere with astronomical observations. Ronald Drimmel, a concerned astronomer, stated in an opinion piece for the Scientific American that "no regulations exist governing how bright a satellite can be, let alone thousands of them together (Drimmel, 2020)." If no laws are holding SpaceX accountable for the preservation of the night sky, and it is not holding itself accountable, it raises the question as to whether it is obligated to compromise with astronomers at all.

This view fails to consider the moral obligations that all companies, networks, and people should undertake regarding the protection and preservation of the Earth (including the surrounding orbital environment). If SpaceX cannot have respect for other unrecruited actors outside of its established network, then what duty do these actors have to mutually respect SpaceX? The company has made some attempts to fix problems that are appearing within its network including lowering the satellite failure rate and attempting to remedy issues regarding the visibility of the constellation. This shows that SpaceX does have respect for actors outside of its network. It also shows that SpaceX is willing to admit that its network has vulnerabilities that need to be addressed and worked on to ensure its success.

## Conclusion

It is important to understand how the Starlink network connects the various actors involved in the success or failure of the project. This is a vulnerable network that requires some work to ensure the overall success of this endeavor. SpaceX has failed its own network by failing to recruit all required actors in the problematization step and by failing to properly analyze all of the relationships and effects the actors would have with each other. If the satellites continue to launch with a meaningful failure rate, it can leave SpaceX open for monetary losses and the creation of unwanted space debris which would harm its standing in the space community. Astronomers should also be recruited into the network as soon as possible to prevent them from working against the interest of the network as rogue actors.

This understanding is significant because SpaceX is just the beginning of a new space age of megacosntellations. Other countries and companies are working towards proposing and launching their own megaconstellations for use in the coming years and decades. This network will act as a precedent on how to proceed with the implementation of such constellations. In analyzing and repairing the network to ensure its success, it will allow future satellite arrays to succeed in the building of their own networks.

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