Perspectives on LEO Satellites

Using Low Earth Orbit Satellites for Internet Access

November 2022

Internet Society

Executive Summary

There's a space race happening right now to connect the world to the Internet. Companies such as SpaceX, OneWeb, Amazon, and Telesat, are racing to launch large constellations of low Earth orbit (LEO) satellites to provide Internet access. They could help bridge the digital divide, particularly in rural regions, but they could also introduce new security and privacy concerns. Will these LEO satellite systems help us connect the unconnected and build an open, globally connected, secure, and trustworthy Internet for everyone?

At the Internet Society, we see considerable potential in the use of low Earth orbit (LEO) satellites for Internet access for unserved or under-served communities, especially where other ways of delivering Internet access are not viable. We also see potential for Internet access to communities affected by natural or human disaster, and to increase the overall resilience of Internet connectivity. But as of late 2022, most LEO constellations are in early stages of deployment and there are still many unknowns.

As the LEO-based industry matures over the next few years, there is an opportunity to guide the discussion and shape the future of this new form of Internet access.

This document identifies some of the opportunities and the issues that need to be addressed and is intended to start conversations that lead to sensible decisions that advance Internet access for everyone, whether ground-based or space-based or both.

The document begins with some background about satellite Internet access in general, and some of the terminology and components of satellite Internet systems. It then explores the many opportunities for individuals, communities, organizations, and governments.

Next, we outline some issues to be considered, such as the affordability, spectrum allocations, space debris, interoperability, security, privacy, and the use of open standards. We follow that with some of the questions we just cannot know, yet we think need to be thought about, including the overall market, sustainability of business models, and environmental concerns.

Finally, we provide some recommendations we see as necessary so that LEO-based systems can help achieve our vision to bring the Internet to everyone, everywhere.

Low Earth Orbit (LEO) Satellites and Internet Access

For many years, Internet access has been available from geostationary[1] (GEO or GSO) satellites operated by companies such as Eutelsat, Hughes, Inmarsat, Intelsat, Viasat, and many others. These systems are an option for Internet access to regions that lack other connectivity. GEO satellites are typically the size of a bus and are expensive to build and launch but have the advantage that global coverage can be provided with a few satellites. Configuring ground antennas is also very simple because geostationary satellites move in the same direction as the Earth rotates and always appear in the same location in the sky.

However, GEO systems have a significant challenge. It takes a long time for signals to travel 36,000 kilometers (km) from Earth to a geosynchronous orbit—and then 36,000 km back. In networking terminology, these connections have a high amount of "latency." This delay, or "lag," is typically over 600 milliseconds (ms) and does not work well for many modern services, including real-time and video communications, gaming, e-sports, live streaming, financial trading, and emerging virtual and augmented reality ("metaverse") communication systems. It is difficult to make a Zoom call or be active in a virtual world with the latency present in GEO systems.

In contrast, LEO systems can provide low-latency, high-speed Internet connections[2] because the satellites orbit the Earth at a much closer distance, between 160 and 2000 km. But with such close orbits, LEO satellites move too fast to stay above a single location and are only visible from the ground for a short time during each orbit (typically less than 2 hours). Because of this, a "constellation" of hundreds or thousands of LEO satellites is needed, as well as ground antennas that can track satellites as they pass overhead.

Earlier attempts in the 1990s to establish a LEO satellite Internet access industry (by companies such as Teledesic) largely failed, but since then, the development of commercial launch systems and other advances in satellite technology have substantially reduced the cost to deploy LEO satellite constellations[3]. Many well-resourced companies, as well as several governments, are now seeking to provide Internet access via LEO satellite constellations.

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[1] For information regarding GEOs, see https://www.esa.int/Education/3._The_geostationary_orbit and https://www.sciencedirect.com/topics/earth-and-planetary-sciences/geostationary-satellite. For the difference between a geostationary and a geosynchronous orbit, see https://www.scienceabc.com/nature/universe/what-is-a-geosynchronous-satellite-and-how-is-it-different-from-a-geostationary-satellite.html.

[2] Ookla analyzed the performance of Starlink connections in Q2 2022 across 26 countries and compared the performance to fixed broadband and geostationary satellites: https://www.ookla.com/articles/starlink-hughesnet-viasat-performance-q2-2022.

[3] See, for example, Figure 1 in *The Recent Large Reduction in Space Launch Cost*, Harry W. Jones, NASA Ames Research Center, Moffett Field, CA, 94035-0001 for the 48th International Conference on Environmental Systems, available at https://ttu-ir.tdl.org/bitstream/handle/2346/74082/ICES_2018_81.pdf.

However, the LEO satellite Internet access industry is still in its infancy. At this time, there is only one LEO provider supplying Internet access at a relatively large scale—SpaceX's Starlink with over 3,000 satellites in orbit—but direct competitors are on the horizon. OneWeb has launched over 400 satellites and is offering some commercial services. Others such as Telesat and Amazon's Project Kuiper have tests under way or will be launching their LEO satellite constellations over the next two years. Available information indicates that, by 2024, there should be several providers, with some offering services within the same countries or geographical regions.

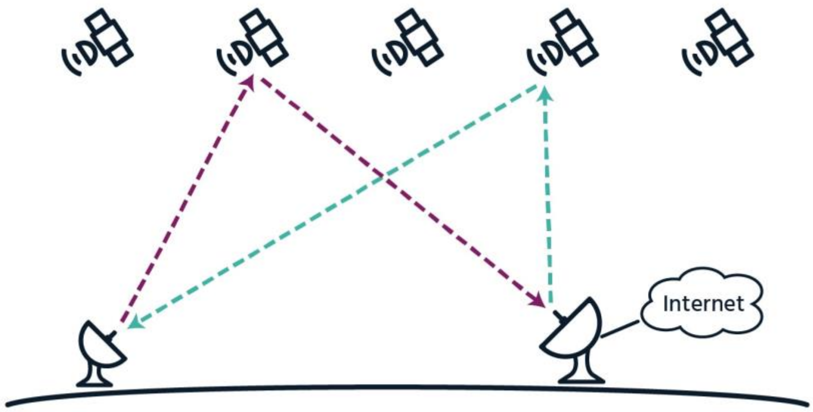
LEO Satellite System Components

To understand the technology and policy aspects of LEO satellite systems, it is helpful to understand the components that are needed for successful operation:

- **Satellite constellation**: the hundreds or thousands of satellites that are launched into orbit and typically arranged into different "shells" at different altitudes.
- **User terminal**: also sometimes called a ground terminal or simply an antenna or dish, this is how the users receive data from and transmit data to the satellites. LEO companies selling direct to consumers may also package additional equipment with the terminal such as a Wi-Fi router.
- **Ground stations**: also sometimes called gateways, these are the large antennas and facilities that connect the satellites to the rest of the Internet.

As an example, to view a web page using a LEO system, a web browser on a computer will send the request to the local user terminal using standard protocols such as DNS, HTTPS, TCP, and IP. The user terminal connects to a LEO satellite and sends the request. The LEO satellite then sends the request to a ground station, which will send the request out on the Internet. When the response comes back to the ground station, the process will go in reverse with the ground station sending to a satellite, and the satellite sending back to the user terminal which will send the info to the user's computer.

Because the LEO satellites are moving so quickly, the ground station may send the response back via a different satellite than the one used for the initial request. LEO ground terminals must be able to track and work with multiple LEO satellites within the LEO constellation.



Similarly, LEO satellites usually need to be within range of a ground station to send or receive data. This can limit the availability of a LEO system in a region if no ground station is available.

However, new technologies are emerging that involve the use of laser beams to exchange data between satellites in orbit. Often called inter-satellite links (ISLs), inter-satellite laser links (ISLLs), or optical inter-satellite links, these links would allow a data connection to hop from satellite to satellite until it reaches a satellite within range of a ground station. This allows a user who is in a region without a local ground station to still be able to connect to the Internet via the LEO system.

These "space laser" connections could potentially also offer the ability to provide services within the satellite constellation such as caching, content distribution networks (CDNs), or edge computing, potentially speeding up access to information for users and increasing communication efficiency. However, these capabilities are still in development or testing.

Note that satellites, user terminals, and ground stations all communicate using spectrum frequencies allocated through regulatory licensing processes. Before a LEO system can operate within a country, these spectrum licenses must be approved by the country's regulator. Additionally, user terminals and ground stations may require additional licensing before they can be used in a country.

Terminology Tip: In regulatory and policy documents, satellites are often referred to as either GSO for geostationary satellites at approximately 36,000 km from Earth, or NGSO (or non-GSO) for non-geostationary satellites in either low Earth orbit (LEO) up to 2000 km or middle Earth orbit (MEO) between 2,000 km and 36,000 km.

The Opportunities

LEO Internet access systems offer potential benefits to connect the unconnected, provide competitive options for connectivity in underserved communities, or add resilience to existing access. Internet access from LEO systems can dramatically improve, or even change lives:

- **Individual consumers:** individuals in rural or remote locations have reported that they finally have reliable and fast Internet connectivity. Online forums contain many testimonials[4] as to how LEO systems have improved individuals' connectivity.
- **Roving users**: people who travel in recreational vehicles (RVs) are finding that LEO systems allow them to have Internet access wherever they stop, whether in a campground, parking

[4] One example of many: https://www.reddit.com/r/Starlink/comments/xkrft1/just_a_reminder_starlink_does_have_good/.

lot, or a remote wilderness.[5] With recent advances allowing use on vehicles in motion[6], connectivity is available to any vehicles within a region with coverage.

- **Community centers:** libraries in Indigenous or rural regions have shared how LEO Internet access has improved their communities, helped students, and made their lives better. Pilot programs with schools have also highlighted how the improved Internet access greatly helps students.
- **Community networks:** pilot programs with community networks have found LEO systems to be useful for backhaul connections to the rest of the Internet.
- **Ships and airplanes:** recent approvals have allowed use of LEO systems in motion in marine or airborne environments. Multiple cruise lines are now using LEO systems to bring low-latency connections to their passengers. Similarly, multiple airlines are evaluating LEO systems for inflight connectivity (IFC).
- **Disaster response:** the ability to rapidly deploy LEO access has been seen as a "game changer"[7] by organizations that respond to natural disasters such as earthquakes, hurricanes, and wildfires. Groups have been able to move into a region and set up low-latency, high-speed connections back to command posts, allowing for faster response.
- **High availability and network resilience:** large interruptions, such as the disconnection of Tonga due to a subsea cable break or the destruction of Internet infrastructure in Ukraine, highlight the role that satellite communication can play in providing additional capacity and resilience when LEO systems can be quickly deployed. LEO systems can add additional or alternate capacity and the ability to provide even more resilience.

Other potential use cases include Internet access for remote monitoring (sensors for earthquakes, bush fires, and floods), Internet of Things (IoT) devices, agricultural machinery, and medical centers in remote locations.

Considerations

While there are many potential benefits, there are some aspects of the emerging LEO satellite Internet access industry that require closer consideration.

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[5] In July 2022, SpaceX was authorized for RVs: https://seekingalpha.com/news/3853510-spacexs-starlink-internet-authorized-for-boats-planes-and-rvs.

[6] In October 2022, SpaceX announced a new antenna, allowing vehicles in motion to connect to the Starlink network: https://twitter.com/SpaceX/status/1585041428711104514.

[7] One example from IT Disaster Resource Center: https://www.linkedin.com/pulse/frequency-daily-pulse-florida-itdrc-hurricaneian-rollinson-/.

Business Models and Operations

Affordability and availability – The market remains too immature to understand how affordable these systems may be, especially for users in unserved or underserved communities.[8]

In the direct-to-consumer business model, providers typically charge an initial fee for the ground terminal, then a monthly fee for the Internet service. The only direct-to-consumer service currently widely available, Starlink, presently charges a one-time fee of US$600 for the ground terminal and a monthly fee of around US$100 in many countries[9]. Many individual users, especially those in low-income countries, may not be able to afford this service if the price remains this high.

There are some government programs emerging to help provide user access to LEO Internet systems.[10] Some subsidize the initial equipment and the subscription for a period of time. However, more subsidies, grants, service fees, or other financial support may still be needed to ensure access is affordable for all users who need it.

It remains to be seen how pricing will be affected as competitors come online, or ground-based Internet services move to fill the gap. It is also not clear what other business models may emerge, or what demand and price points will be needed for LEO system operators to sustain viable business models.

Competition with existing operators – As LEO systems are providing new options for Internet access, not surprisingly, existing GEO satellite Internet providers, fiber, broadband and mobile network operators, are challenging LEO providers' access to spectrum, licenses and government funding, as well as raising environmental and other concerns. Is this simply competition in action or are incumbents trying to create barriers to entry and deter new competition based on different technology?

Consolidation – The LEO-based Internet access industry is not immune to the concerns about market power and economic consolidation that are prevalent across all sectors of technology. As multiple LEO systems are deployed over the next few years, there is the potential that operators could be acquired

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[8] Unpublished analysis performed in 2022 by A4AI (Alliance for Affordable Internet) and USAID (United States Agency for International Development) shows preliminary data demonstrating that in certain remote and hard-to-reach areas in Kenya, community anchor institutions see significant cost savings with LEO-based Internet access services over alternative access providers. But, there is insufficient data to predict future affordability at this time.

[9] Note that SpaceX has responded to feedback and has begun offering different pricing models including a lower monthly fee and "best effort" connectivity. In many countries the initial fee and monthly fees are now substantially lower than the US price.

[10] For example, some school systems in the USA are providing Starlink access to students: https://www.nbcnews.com/tech/internet/elon-musks-satellite-internet-flies-radar-public-schools-nationwide-rcna44318. As another example, the government of Quebec allocated CAD $50 million to connect 10,000 homes to Starlink: https://montrealgazette.com/pmn/news-pmn/canada-news-pmn/remote-quebec-homes-getting-high-speed-internet-access-with-elon-musks-starlink/.

by other operators leaving the LEO-based Internet access market dominated by one or two companies. The LEO operators could then be potential control choke points.

Policy and Regulation

Orbits and objects in outer space – The United Nations Office of Outer Space Affairs (UNOOSA) maintains a Register of Objects Launched into Outer Space . It has become a means of identifying which states' bear international responsibility and liability for which space objects, including satellite debris. However, there are some concerns that the register is incomplete and there is no agreed standard as to how objects are reported.[11]

No international entity currently assigns or regulates orbital slots for LEO satellites and other non-geosynchronous orbit (NGSO) satellites.[12] LEO system operators apply for spectrum allocations from the national regulator in the country or countries in which they wish to operate and specify their intended orbits in that application.[13]

As low Earth orbits are essentially first come, first-served, there is no fee for occupying an orbit. Optimal orbits are a finite resource, so there is a very strong incentive for early entrants to quickly take over as many orbital slots as possible, leaving later entrants with less optimal choices, or none. However, to avoid orbit squatting, some regulators are establishing build-out requirements, where LEO operators must meet certain deployment timelines to keep their spectrum allocations.

Spectrum allocation – The UN Committee on the Peaceful Uses of Outer Space (COPUOS) non-binding *Guidelines for the Long-term Sustainability of Space Activities* re-iterate the principles in Article 44 and 45 of the International Telecommunication Union (ITU) Constitution and emphasize the need to promote the long-term sustainability of outer space activities. Specifically, "so that countries or groups of countries may have equitable access to those orbits and frequencies, taking into account the special needs of developing countries and the geographical situation of particular countries". At the World Radio Congress 2019, ITU Members agreed to require LEO satellite constellations to have 10 percent of their constellation in orbit within the first two years after the start of deployment, 50 percent in five

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[11] See, for example, the paper at https://www.sciencedirect.com/science/article/abs/pii/S2468896721000409#! and https://www.esa.int/ESA_Multimedia/Images/2021/03/We_re_launching_more_than_ever.

[12] At the ITU's Plenipotentiary 22 in October 2022, member states adopted a new resolution on "Sustainability of the radio-frequency spectrum and associated satellite orbit resources used by space services" instructing the ITU Radiocommunication Sector (ITU-R) to undertake studies around spectrum and orbit usage by NGSO systems and further encouraged member states to develop the appropriate regulatory frameworks for NGSO systems. The ITU-R Director was asked to report back on this at the World Radio Conference (WRC) 2023.

[13] See the sovereign right of each state to regulate its Telecommunication: Page 3, Guidance on the regulatory framework for national spectrum management Report ITU-R SM.2093-4 (06/2021) (https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-SM.2093-4-2021-PDF-E.pdf), and the international recognition of these rights by recording the frequency assignments and (if applies) orbital positions used or intended to be used in the Master International Frequency Register.

years and 100 percent in seven years.[14] This decision is intended to prevent unrealized or failed projects from occupying limited and valuable frequency spectrums for extended periods of time, having benefited from the "first-come, first-served" principle. In other words, "use it or lose it."

Space debris – With multiple potential shells of thousands or even tens of thousands of satellites[15] adding to the already abundant objects in low Earth orbit, there is a potential for a large amount of satellite debris, both planned (i.e., end of life cycles) and unplanned (i.e., collisions). This debris could physically damage other Internet access systems in low Earth orbit space, cause interference, or present a danger, in space and on the ground. However, at least now in the US, the Federal Communications Commission (FCC) requires LEO satellite operators to de-orbit their satellites within 5 years of ending operation. There is also guidance in the UN Committee on the Peaceful Uses of Outer Space (COPUOS) *Space Debris Mitigation Guidelines*, the International Inter-Agency Space Debris Coordination Committee (IADC) *Debris Mitigation Guidelines*, and IADC *Statement on Large Constellations of Satellites in Low Earth Orbit*, as well as the ISO standard ISO-24114 Space systems – Space debris mitigation requirements.

Critical infrastructure and national security – As civilian, government, and military use of LEO systems expands, there are likely to be increasing calls[16] to declare LEO systems critical infrastructure, so that they would be covered by relevant national policies and international norms. LEO systems also become an attractive target for organized crime and nation state attacks (e.g., Viasat in 2022), especially if they are used or could be used for military purposes. Even purely civilian-use LEO systems might be perceived as a nuisance to national space assets (e.g., space stations) or a potential future national security threat.

Technology

Capacity – With around 800,000 users in one system (Starlink), LEO systems capacity limits are not yet well understood. Network analysis firm Ookla reported reduced speeds for Starlink connections in Q2 2022 in some markets, while SpaceX has introduced new service levels of prioritized versus deprioritized traffic in France, Canada, and the USA[17] and anecdotal complaints cropped up in online

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[14] ITU News, 'Managing radio frequency spectrum amid a new space race', 12 November 2021 at https://www.itu.int/hub/2021/11/managing-radio-frequency-spectrum-amid-a-new-space-race/

[15] Initial constellation estimates: Project Kuiper (3,236 satellites); Starlink (4,408 satellites (1st generation)); OneWeb (648 satellites); SatNet (~ 13,000 satellites); Telesat (188 satellites) - (https://www.cnbc.com/2022/05/01/amazon-takes-on-spacex-in-the-satellite-internet-with-project-kuiper.html; https://spaceflightnow.com/2022/05/13/spacex-passes-2500-satellites-launched-for-companys-starlink-network/; https://oneweb.net/resources/oneweb-secures-investment-softbank-and-hughes-network-systems; https://spacenews.com/chinese-satellite-propulsion-startup-secures-funding-as-countrys-constellation-projects-grow/; https://www.satellitetoday.com/business/2022/05/06/telesat-downsizes-lightspeed-constellation-plans/.

[16] For example, https://www.scientificamerican.com/article/the-biden-administration-must-designate-civilian-satellites-critical-infrastructure/.

[17] See https://techcrunch.com/2022/11/04/starlink-adds-a-1tb-monthly-soft-cap-for-residential-users/ and the official policy at https://www.starlink.com/legal/documents/DOC-1134-82708-70.

forums[18]. But it is not clear if these are simply growing pains while SpaceX continues to build out its full constellation. Independent research and capacity simulations are beginning to emerge[19], but more research is needed. As deployment increases, it is important to have access to open data so that independent research organizations can measure the capacity of LEO systems in terms of number of users supported, latency, throughput, and reliability.

Interoperability – Related to open, interoperable standards, the industry appears to be in the process of creating multiple separate and mutually incompatible constellations of LEO satellites. Given the limited number of appropriate orbits and the high cost of operation, it would be ideal if LEO systems could operate as a network of networks in space as well as on the ground.

Open Standards – Ideally, the Internet access you receive from a LEO system should provide the equivalent type of connection you would receive over a ground-based broadband or mobile connection. In the ground or terrestrial segment, it should use the open standards published by the Internet Engineering Task Force (IETF), 3GPP, and other standardization bodies. Starlink, the system we were able to test, supports most current protocols, although users report inconsistent availability of IPv6[20], a protocol we view as extremely important for the Internet's future capacity. Internet open standards ensure interoperability and provide a common user experience with the rest of the global Internet. In the space segment, where it is more challenging to use conventional routing protocols, such as Border Gateway Protocol (BGP), constellation operators implement proprietary routing and bandwidth allocation protocols. Several standards development organizations (SDOs) are actively involved in space-related standards, including the ITU's Radiocommunication Sector (ITU-R), as well as the Consultative Committee for Space Data Systems (CCSDS).

Privacy – Users of a LEO system for Internet access should have at least the same level of support for private communication that they have on regular broadband or wireless Internet connections to prevent eavesdropping, tampering, and unauthorized re-direction of Internet traffic. Technologies such as Transport Layer Security (TLS) should be supported in a way that ensures end-to-end encryption. Overlay networks such as virtual private networks (VPNs), private relay, and other similar privacy services should work without interference or comparable degradation of service. Virtual private networks (VPNs) should work. All LEO systems should provide this support.

Peering and Interconnection – Space network operators would need to connect to the terrestrial networks to have access to content, cloud services, and other Internet applications. One way to get access to these networks and services at lower cost is to connect to an Internet exchange point (IXP).

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[18] See Ookla's research at https://www.ookla.com/articles/starlink-hughesnet-viasat-performance-q2-2022. SpaceX's introduction of data caps and "fair use" policy is at https://www.pcmag.com/news/spacexs-starlink-quietly-mentions-high-speed-data-caps-are-coming-for-us User complaints could be seen in Reddit's r/starlink and in various social media.

[19] Examples: https://mikepuchol.com/modeling-starlink-capacity-843b2387f501 and https://starlink.sx/.

[20] A search on IPv6 in https://www.reddit.com/r/Starlink/ shows discussion threads about this issue.

IXPs help network operators to interconnect and exchange traffic locally and deliver content to end users at lower latencies. IXPs usually act as hubs for content providers and Content Delivery Networks (CDNs), allowing these operators to cache their content closer to their end users. Users of satellite-based services would benefit greatly, in terms of cost and performance, if LEOs take advantage of the global network of Internet exchanges.

Security – LEO systems add new layers of complexity to the already complex Internet infrastructure. Like traditional GEO systems, they involve ground stations linking the satellites to the Internet—and ground terminals used by customers to connect to the satellites. As outlined in a recent document from the US government, there are many areas of satellite infrastructure that need to be secured. LEO systems bring the additional challenges that there are so many more satellites, and in the future many of the satellites will be communicating between each other in orbit.

Questions

In such an emerging market there are more things we don't know compared to what we do, such as:

Overall market – Many factors are driving the market for LEO-based Internet access, including advances in satellite and Internet technologies, miniaturization, and rapidly decreasing launch costs, coupled with government funding or subsidies, largely open access orbits, and demand for Internet access in the air (airlines) and on the water (maritime).

What is the overall available market for LEO-based Internet systems? Will LEO-based Internet access only be useful for remote or underserved regions with few other options? Will LEO-based Internet access be viable for the polar regions, given the current limited coverage by constellation orbits?

Sustainable business models – In the rush to provide LEO-based Internet access, there has been massive investment in many different LEO constellations targeting different customers. Some focus on direct subscriptions by individual users. Some focus on backhaul to enterprise or terrestrial ISPs. Others aim to supply Wi-Fi to airlines or shipping vessels. At least one is targeting embedded devices, a.k.a. the Internet of Things (IoT).

Are the different business models all sustainable? If they are not sustainable, will governments subsidize their operations, and what criteria would they use to decide which operations to fund? Would that divert funds away from terrestrial-based Internet access? Is a pure consumer LEO-based Internet service viable absent government grants, subsidies or military spending? What will happen to users when some LEO systems are no longer financially viable?

Space weather – At this time it is not clear if threats from space weather, such as solar storms, are well-understood for LEO constellations and how they could affect Internet access. However, in February 2022. SpaceX reported the loss of over 40 satellites to a solar storm.

If we get a solar storm that is 10X or 100X larger, how would it affect the satellites in LEO constellations? How resilient will LEO systems be to these type of threats?

Externalities, subsidies, and the true cost of service – The true cost of providing LEO Internet access may be difficult to assess, not only because of external costs, subsidies, grants, tax breaks, and military investment, but also because the total operating costs may be obscured by integration with other businesses (e.g., space launches) and commercial confidentiality. External costs of providing LEO Internet access include orbital debris (such as increased collision avoidance, tracking, and clean up), and environmental costs associated with manufacturing, launching, decommissioning, and uncontrolled re-entries. Those external costs are borne by society, and potentially by countries that do not supply or do not use LEO-based Internet access.

Will they be as economically efficient in the long-term as other Internet access technologies? What is the most efficient, economic, and sustainable use of public funds to support Internet access in unserved or underserved communities?

Environmental cost – While not directly related to Internet access, there are serious questions that need to be addressed as a society about the environmental impact of LEO systems. We may soon surround our planet with many separate shells of tens of thousands of satellites. Beyond the space debris concern, there are questions about the environmental impact of manufacturing the satellites and the very large number of rocket launches needed to create all these constellations, and also about the impact to our atmosphere as so many decommissioned satellites burn up during re-entry.

What is the environmental impact of LEO satellite Internet access?[21]

Astronomy – Satellites have been a part of astronomy studies since the launch of the first satellite in the late 1950s, but large LEOs constellations pose concerns on optical astronomy activities—in particular, the trails left by satellites reflecting sunlight while in orbit. Efforts are underway to minimize the impact of satellites on observations, both in satellite constructions and through the use of image processing to remove satellite presence from images. However, the full impact on astronomy studies when all the planned LEO systems are launched in the near future is not yet known. There is particular concern among astronomers that study Earth-crossing ("Apollo") asteroids. Their ability to detect potential Earth impactors depends on the kinds of observations most affected by satellite constellations.

Will LEO satellite Internet access hamper astronomical research?

[21] In November 2022, the US General Accounting Office (GAO) issued a report stating that the FCC should re-examine its environmental review process for large satellite constellations: https://www.gao.gov/assets/gao-23-105005.pdf The FCC appears to agree, and this could both provide more information and also impact the launch plans and timelines for US-based companies. More info: https://www.pcmag.com/news/large-satellite-systems-may-need-environmental-reviews-gao-says.

Summary and Recommendations

We are at a pivotal time in connecting those not yet connected to the Internet and achieving universal connectivity. The combination of less expensive launch systems, smaller and mass-produced satellites, better and smaller ground antennas, and improved technology has created a situation where large-scale deployment of LEO satellite systems for Internet access is now possible. There is considerable potential to bridge the digital divide and connect many more people to the Internet using a combination of land-based and space-based Internet access solution. However, to be a useful solution to connect the unconnected, Internet access via LEO systems needs to be sustainable, as well as affordable and reliable, for the people who need it most.

LEO-based Internet access is an emerging industry using a relatively new resource (low Earth orbits) that is owned by no one, shared by everyone, but only within reach right now for a small number of entities. Without careful collaboration and thought as to how to develop this new form of Internet access to extend the Internet's global reach as a resource to enrich people's lives, there is a risk that a tragedy of the commons will ensue. One possible outcome: the environment will be irreversibly damaged.

A starting point has to be that no matter the method of delivery—wires, wireless, mobile, or satellite—the networks must incorporate the critical properties of the Internet and its enablers (see Appendix). This means:

- Supporting the latest open Internet standards and common, interoperable protocols that enable the open Internet
- Implementing industry best current practice for Internet security and resilience, such as those behind the Mutually Agreed Norms for Routing Security (MANRS)
- Ensuring that the information transmitted through their systems is kept private, confidential, and is not altered in transit (supporting end-to-end encryption wherever possible)
- Promoting the use of localized Internet infrastructures, such as IXPs, to connect ground stations and allow end users to have access to other networks at lower cost and latency (and exploring other options for shared infrastructure)
- Implementing the latest practices for physical and network security and ensuring systems are secure by design and practice defense in depth
- Ensuring satellites' software can be securely upgraded remotely, and encouraging security researchers to investigate and report vulnerabilities
- Advocating for fair use of spectrum, allocated clearly and shared fairly across all technologies and operators (avoiding frequency interference)
- Being transparent about the capacity, latency, and reliability of services (and benchmarking against other forms of Internet access)

It is crucial that new entrants and new technologies be able to enter and exit the industry on a fair footing, with access to spectrum and orbits that enable them to compete effectively.

In the rush to connect the world through space, we need to limit the environmental impact of LEO based systems, including debris. Given the almost impossible task of removing space debris once it is there, LEO system providers should take whatever steps are necessary to minimize the number, volume, and type of debris their systems create before or in early stages of deployment.

Further, this is a clear case where global cooperation is needed: to address issues such as interoperability, orbital planning, interference, debris, and other environmental concerns.

If we want to bring the Internet to everyone, and if we want people to join an Internet that is open, globally connected, secure, and trustworthy, it is critical that all of us address the concerns outlined in this document. We must pursue these recommendations—and ensure that LEO satellite-based systems will deliver the Internet experience we all need to thrive.

Acknowledgments

In developing this document, we interviewed representatives of SpaceX, Amazon's Project Kuiper, OneWeb, Telesat, and ViaSat. We spoke with academic researchers including Larry Press, Joanna Kulesza, Berna Akcali Gur, and Rose Croshier. Don Means and other participants in the Gigabit Libraries Network provided useful insights. We also spoke with users of LEO systems and ran tests on some deployed networks. Over 120 members of our Internet Society community provided feedback on a draft version of this document, as part of our policy development process. We thank them all for their time and interest in this topic.

Appendix: Internet Way of Networking Analysis

The Internet Society has identified five critical properties that are responsible for the success and adaptability of the Internet. The properties have enabled the economic and technical development the Internet has brought around the world. As we look at LEO-based systems for Internet systems, the question is, will these LEO systems support these five critical properties that make the Internet work? The challenge remains that, at the moment, we only have limited data for one LEO system. However, preliminary analysis suggests the answer is yes (with a few caveats).

Critical Properties of IWN	Impact
1: **An Accessible Infrastructure with a Common Protocol** that is open and has low barriers to entry	Positive with some uncertainty. Current LEO systems seem to provide unrestricted access and support common protocols. The uncertainty is around global affordability and the full support of all modern protocols (e.g., IPv6).
2: **Open Architecture of Interoperable and Reusable Building Blocks** based on open standards development processes voluntarily adopted by a user community	Positive with some uncertainty. Current LEO systems support the Internet's open architecture and open standards at the user/application level and in the ground-based systems. The one area of uncertainty is the use of open standards within the space segment.
3: **Decentralized Management and a Single Distributed Routing System** which is scalable and agile	Positive with some uncertainty. So far, IP routing is working across LEO networks as it does across any other Internet access network. The only uncertainty is around the routing within the space segment of LEO networks.
4: **Common Global Identifiers** which are unambiguous and universal	Positive. IP addresses and the domain name system (DNS) operate across current LEO providers as they do across other networks.
5: **A Technology Neutral, General-Purpose Network** which is simple and adaptable	Positive. Current LEO networks act similarly to ground-based networks in terms of providing a general purpose network.

Additionally, our mission states our goals for the Internet to be open, globally connected, secure, and trustworthy. We have identified seven enablers that advance those goals. Will LEO-based systems support these characteristics that enable to Internet to grow and thrive? Or will they potentially decrease these characteristics and reduce the future growth of the Internet?

Enablers of an open, globally connected, secure, and trustworthy Internet	Impact
Easy and unrestricted access	Positive, but with a concern. LEO systems have so far proven to be very easy to deploy and offer unrestricted access. However, capital expenditure and affordability are concerns.
Unrestricted use and deployment of Internet technologies	Positive. LEO systems are currently working with existing Internet technologies.
Collaborative development, management, and governance	Uncertain. So far, all LEO systems are being built by commercial companies using proprietary systems. We hope to see a similar level of transparency into the development and operation of their systems as we do with ground-based network operators.
Unrestricted reachability	Positive with some uncertainty. In the existing countries of deployment, users have had no restrictions on reachability. It is not yet clear if LEO systems operators will implement the ability to block content or resources. They may *be required* to do so in order to operate within some countries.
Available capacity	Positive. The growth and deployment of LEO systems should increase the overall capacity of the Internet and enable more connections by more people. This is provided they do not cause significantly reduced investment in ground-based services and capacity.
Data confidentiality of information, devices, and applications	Positive. Systems and services that use end-to-end encryption are working fine over current LEO systems.
Integrity of information, applications, and services	Positive. Existing technologies that support integrity, including end-to-end encryption, currently work over LEO systems.
Reliability, resilience, and availability	Positive with some uncertainty. LEO systems are already demonstrating their ability to increase the overall resilience and reliability of the Internet. They are being deployed in regions of disasters and wars, and being used

	as additional connectivity options for networks. The uncertainty is only that more time is needed to understand the full range of reliability.
Accountability	Uncertain. LEO systems are currently being deployed by commercial companies with limited requirements for accountability or transparency. We would like to see the same level of accountability for LEO operators as for terrestrial network operators.
Privacy	Positive with some uncertainty. Current LEO systems support end-to-end encryption and allow users to interact with existing systems and services with the expected level of privacy. However, within LEO systems, the level of privacy of user information is uncertain.