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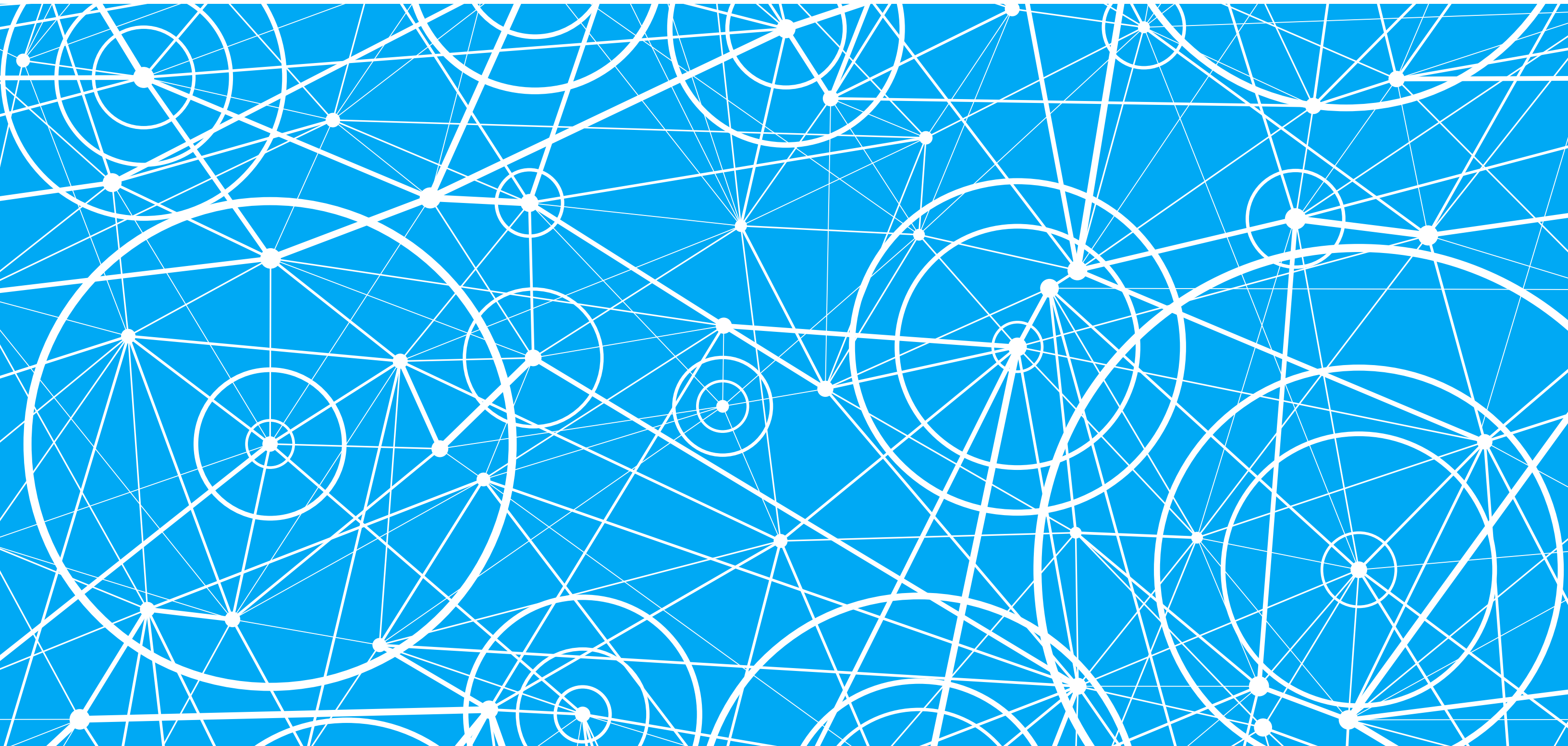
# Large LEO satellite constellations: Will it be different this time?

New satellite constellations are on the cusp of deployment, but their long-term success hinges on substantial cost reductions.

*by Chris Daehnick, Isabelle Klinghoffer, Ben Maritz, and Bill Wiseman*





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**More than 2,500 active satellites now orbit the Earth,** and amateur astronomers and other observers are seeing more every month.[1] Historically, satellite communication involved geosynchronous (GEO) spacecraft—large systems that have become increasingly capable over the years. But now nongeosynchronous-orbit (NGSO) communications constellations, including low-Earth-orbit (LEO) and medium-Earth-orbit (MEO) satellites, are taking to the skies, and their number could soon soar. If current satellite internet proposals become reality, about 50,000 active satellites will orbit overhead within ten years. Even if the most ambitious plans do not come to pass, the satellites will be manufactured and launched on an unprecedented scale.

The ambitions for the large LEO concepts may recall the 1990s, when several companies tried to provide global connectivity. Globalstar, Iridium, Odyssey, and Teledesic had impressive plans. In the end, however, all but Iridium scaled back or canceled their intended constellations because of high costs and limited demand. All suffered financial problems. After that experience, many industry analysts and investors remain skeptical about the viability of large LEO constellations. The recent failures of LeoSat and OneWeb reinforce that impression.

But much has changed over the past 20 years. Satellite technology has advanced; demand for bandwidth has soared, with no slowdown in sight; and companies have developed creative business models to generate profits from connectivity. Moreover, both tech companies and investors now have much larger stores of capital to invest, making it possible to fund large constellations—although this capital clearly does not have infinite patience.

These changes could well make satellite connectivity 2.0 a success. Our analysis, however, indicates that companies planning large LEO satellite internet constellations still need to reduce a range of costs significantly to ensure long-term viability. Lowering launch costs is one part of the equation, but it will be equally or more critical to reduce the cost of manufacturing spacecraft, ground equipment, and user equipment. If suppliers and constellation providers can achieve these cuts, they could unlock enough demand for large LEO constellations to transform both the B2C and B2B communications markets.[2]

The COVID-19 pandemic will also influence the satellite market's future, but as of the date of this article's publication it is hard to say how great the impact will be. In the near term, any company that tries to secure funding will face challenges because of economic uncertainty and immediate public-health concerns. These challenges will affect the progress of the remaining licensed concepts—Kuiper, Starlink, and Telesat—differently because their ownership and funding approaches vary.

While physical distancing and work-from-home measures remain in place, the development, manufacture, and launch of large LEO satellites will slow. But the crisis has also caused a spike in demand for internet connectivity and underscored its importance. Investment in any kind of new connectivity infrastructure will be expensive but will almost certainly be needed. Going forward, large LEO concepts could play an important role in meeting this increased demand.

## The new age of large LEO constellations

Traditional communications satellites with GEO orbits have proved their worth since the 1960s. Although costly, they are highly capable and have long service lives. Their altitude—more than 35,000 kilometers from Earth—provides them with a wide field of view, allowing operators to cover most of the planet's surface with three satellites spaced at appropriate intervals. Recent technological advances, including new high-throughput and reconfigurable designs, have improved both efficiency and performance.

[1] UCS Satellite Database, Union of Concerned Scientists, December 16, 2019, uscusa.org. We supplemented this information with data about launches through March 2020.
[2] The satellite market is evolving quickly, with companies frequently announcing new or additional launches. Our information on the number of satellites in orbit is current as of March 2020, but the numbers could soon change.

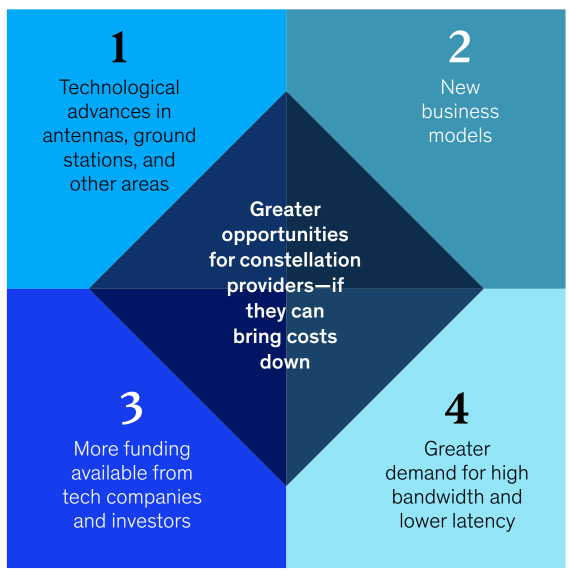
The new LEO-satellite concepts, which orbit 500 to 2,000 kilometers from Earth, offer faster communications (they have lower latency) and often provide higher bandwidth per user than GEO satellites do—even more than cable, copper, and pre-5G fixed wireless. Communication occurs through a constellation of LEO satellites; global coverage requires a large number of spacecraft.[3] These concepts will require major changes in satellite operations, including manufacturing and the supply chain, since they ask more of a satellite and shorten its average life span (estimated to be about five years with Starlink, the SpaceX constellation, for example).[4]

With the demise of OneWeb, SpaceX is well ahead in the race to deploy an operational system. For Starlink, 422 satellites were in orbit as of late April 2020, and the company claims that it can begin offering commercial service this year.[5] Telesat, with a proposed initial constellation of 117 spacecraft and the potential to deploy more than 500, appears to be moving forward with its plans.[6] Amazon, which has filed to launch 3,236 spacecraft in its Kuiper constellation, also appears to be proceeding and plans to move its growing team into new facilities this year.[7]

Why the renewed interest in satellite constellations? Our research suggests that it springs from a convergence of forces that make both the development and the market success of large LEO-communication systems more likely now than in the past: technological advances, the emergence of new business models, better funding, and higher demand for low-latency bandwidth (exhibit). Thanks to these developments, the current situation bears little resemblance to the 1990s, when large LEO concepts failed to gain traction.

Exhibit

## Converging forces could create new opportunities for low-Earth-orbit constellations.




[3] Low-Earth-orbit (LEO) satellites typically communicate through intersatellite links, but some may operate independently.
[4] Tariq Malik, "How to spot SpaceX's 60 new Starlink satellites in the night sky," *Space*, November 11, 2019, space.com.
[5] Sandra Erwin, "Starlink's busy launch schedule is workable, says 45th Space Wing," *SpaceNews*, January 7, 2020, spacenews.com.
[6] Caleb Henry, "Telesat says ideal LEO constellation is 292 satellites, but could be 512," *SpaceNews*, September 11, 2018, spacenews.com.
[7] Caleb Henry, "Amazon moving Project Kuiper team to new R&D headquarters," *SpaceNews*, December, 18, 2019, spacenews.com

## The operator of a large LEO constellation must monitor and manage the status and functions of thousands of satellites.

### Technological advances

The most relevant satellite-technology advances fall into four categories. Although these improvements benefit all types of satellite-communications systems, they may be particularly consequential for the new large LEO concepts.

**Spectrum usage**

The large LEO concepts are mainly planning to use Ka band. Some propose V band as well. These frequencies enable higher data rates, smaller antennas, narrower beams, and greater security. Higher frequencies are more vulnerable to weather and rain fade, which is the absorption of a radio-frequency signal by atmospheric rain, snow, or ice; frequencies higher than 11 gigahertz are more vulnerable than lower frequencies. Fortunately, expedients such as improved ground-station design, adaptive coding, and signal modulation can reduce this exposure. Improved spectral efficiency and spectrum-reuse rates can also increase the amount of data a system delivers.

**Satellite and constellation throughput**

In addition to better use of spectrum, advances in active antennas and processing have raised throughput per individual satellite, increasing constellation capacity. Consider a few changes:

— A satellite can now deploy more spot beams, and greater power can be delivered through each beam.

— Intersatellite links (ISLs) improve connectivity and confer particular benefits to large constellations, including improved throughput and management.

— Improved data-compression methods reduce bandwidth requirements without reducing the quality of communications.

**Ground equipment**

Traditionally, satellites have been accessed and tracked via parabolic-dish antennas. This equipment is poorly suited to LEO constellations, which will have numerous satellites all rapidly crossing a ground receiver's field of view at the same time. Antennas with electronically scanned apertures (ESAs), also called electronically steerable antennas, can shift beams (and track and access large numbers of satellites) without physical movement. ESAs can also be designed for modular assembly, which could allow manufacturers to produce large numbers of basic parts for use in both constellation ground stations and consumer equipment, thereby improving economies of scale. Other important advances in ground equipment include new predictive analytics and network-optimization techniques that use available ground-entry points more effectively.

**Management of large constellations**

The operator of a large LEO constellation must monitor and manage the status and functions of thousands of satellites. Recent advances in analytics, combined with improved computing power and artificial-intelligence algorithms, can assist with these functions while reducing response times and operating costs. Likewise, ISL advances that increase throughput also reduce backhaul costs and improve satellite control and network latency. Combining these elements would promote the autonomous and semiautonomous control and management of spacecraft, reducing staffing requirements.

## New business models

Just as technology has evolved, so have revenue sources from internet connectivity. In the 1990s, communications companies generally followed a business model in which revenues came from service fees for bandwidth and access; rates were often based on usage. With relatively low demand, this model was not viable for the satellite concepts of the 1990s. Today, it would also be risky to charge consumers for usage time, but for a different reason: there would probably be little uptake for such plans. The preference for unlimited access is clear from the mobile-phone industry, where per-text or per-minute billing has given way to unlimited plans.

Fortunately, companies have new options for generating revenue from connectivity:

— Some businesses—traditional connectivity players like AT&T and Time Warner, for example—have been using acquisitions to bring content development and distribution in-house. (They may still distribute some external content for a fee.) Companies that started as distributors, like Amazon and Netflix, increasingly look to original content as a source of revenue. In-house creation also allows them to provide bundled offerings and to obtain a revenue stream that is not dependent on access pricing.

— Online advertising now commands more spending than print or television ads do. By controlling an online distribution channel, companies can supplement their existing revenues by offering space for paid content or by charging advertisers for premium placement—options not available to companies in the late 1990s.

— Across industries, many companies now offer bundled services in which one or more elements are free (or offered below cost) to increase revenue elsewhere. Amazon Prime, with its free shipping, is the classic example. Some constellation providers may take a similar route by offering bundles that include free connectivity to increase revenues elsewhere: for instance, a social network that offered internet access free of charge or at a reduced price would almost certainly increase the time users spent on its site. This would drive direct revenue (such as ad spending) and potentially increase the number of people who use the platform's services.

Adding to the momentum, companies and investors may now be willing to wait longer for profits from large LEO constellations. Instead of expecting an immediate positive cash flow, many are focusing on business models that facilitate the acquisition of customers and the control of ecosystems, so they may initially set low prices for their offerings to attract business, even if that eliminates the possibility of profits. Their goal is to establish themselves as early leaders and to create a foundation for long-term success, following in the footsteps of many high-tech players over the past 20 years. These businesses first concentrated on creating scale and acquiring a critical mass of users and then shifted their focus to making money from the network.

## Growth in available funding

In the 1990s, many companies could not find enough investors to fund their satellite constellations. Teledesic, for instance, initially proposed spending more than $9 billion to launch 840 satellites but then reduced its plan to about 300.[8] Later, the company entirely suspended satellite production after burning through hundreds of millions of dollars in development costs.

[8] Rupert Goodwins, "Teledesic backs away from satellite push," ZDNet, October 3, 2002, zdnet.com; Graham Lea, "Teledesic raises more cash—but global broadband is still a dream," *Register*, November 3, 1999, theregister.co.uk.

# Despite echoes of the low investment that followed the bursting of the dot-com bubble, the funding picture is different from what it was 20 years ago.

Current satellite concepts will initially be as expensive as or more expensive than their predecessors. Although costs continue to evolve and many uncertainties remain, estimates for deploying an operational system generally range from $5 billion to $10 billion. Annual operating costs will be high: the cost of replacing satellites alone will total $1 billion to $2 billion for a large constellation if their life span is about five years. The ground segment, even if largely automated, will require a substantial number of sites and antennas, which entail significant capital and operating costs.[9] All this will require a substantial upfront investment and the ability to sustain expenses until revenue kicks in, especially if providers offer low prices to attract business. Cost levels, including the potential for decreasing them, are discussed in more detail later in this article.

A few companies have encountered financial issues as they sought to develop large LEO constellations. LeoSat recently ceased operations after being unable to secure additional investment, and OneWeb recently filed for Chapter 11 bankruptcy, again reportedly after running out of cash and failing to secure additional financing.[10] The COVID-19 crisis has injected further uncertainty into the investment market.

Despite echoes of the low investment that followed the bursting of the dot-com bubble, the funding picture is different from what it was 20 years ago. Some companies have enough cash available to build and deploy a constellation outright. Amazon, with $55.4 billion on hand, is the only large tech player with an announced constellation, but Facebook ($54.9 billion) has reportedly filed preliminary LEO-satellite plans through a proxy.[11] Other companies are said to be considering similar ventures, including Apple, which has $107.1 billion in reserves.[12] These companies and others may also finance such developments with cheap debt, since interest rates are at historical lows.

In another shift from the 1990s, companies that need outside investment to support their constellation plans have many opportunities. Venture capital has recently been bullish about space projects, investing more than $4 billion in the past two years alone. Funding from that source could diminish, however. The OneWeb example also shows that the capital needed to establish a system may be greater than the amount that venture investors are willing to provide to a single company. OneWeb raised $3.4 billion from a consortium of investors that included Airbus and Softbank, but this was not enough.[13]

Aside from pure self-funding, the remaining players do offer examples of other approaches:

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[9] Bruce G. Cameron, Edward F. Crawley, and Inigo del Portillo, *A technical comparison of three low earth orbit satellite constellation systems to provide global broadband*, 69th International Astronautical Congress 2018, October 1, 2018.
[10] Caleb Henry, "OneWeb files for Chapter 11 bankruptcy," *SpaceNews*, March 27, 2020, spacenews.com.
[11] "Amazon cash on hand, 2006–2019," *Macrotrends*, macrotrends.net; "Facebook cash on hand, 2009–2019," *Macrotrends*, macrotrends.net; Mark Harris, "Facebook may have secret plans to build a satellite-based internet," May 2, 2018, *IEEE Spectrum*, spectrum.ieee.org.
[12] Marc Gurman, "Apple has top secret team working on internet satellites to beam data to devices," Bloomberg, December 20, 2019, bloomberg.com; "Apple cash on hand, 2006–2019," *Macrotrends*, macrotrends.net.
[13] Caleb Henry, "OneWeb raises $1.25 billion from returning investors," *SpaceNews*, March 18, 2019, spacenews.com.

- SpaceX raised more than $1.3 billion in funding in 2019 alone; in February 2020, it hinted that it might pursue an IPO for Starlink, which could raise the remaining capital needed to deploy the system, although the company later downplayed the possibility.[14]

- SpaceX has reportedly persuaded the US Federal Communications Commission (FCC) to propose a rule change that would allow the company to compete for subsidies from the US government ($20.4 billion over ten years) to provide rural internet service.[15]

- Telesat has received investments and an upfront commitment from the government of Canada to buy its services.[16]

With the exception of Softbank, private investors have focused largely on space projects involving small launches and Earth observation. However, there is a large amount of dry powder on hand—investment firms had more than $2.3 trillion (and growing) to spend in late 2019—so funding for other space projects could soar if additional investors begin to see potential in the market.[17]

These shifts, combined with the new revenue opportunities, have created a very different investment landscape. In the late 1990s, the $5 billion to $10 billion required to deploy a constellation, and the $1 billion to $2 billion required for annual maintenance, were deal breakers for investors. That is no longer always the case.

## Strong demand for bandwidth and lower latency … at the right price

Bandwidth needs were modest back in the 1990s, given the nascent internet and low e-commerce and social-media activity. Most consumers were venturing online for the first time, usually on desktop computers with dial-up modems. Cellular-phone use was surging, but the need to connect globally—particularly outside normal terrestrial coverage—was relatively low.

Today, consumers not only routinely download high-definition movies but also play games and shop online, consuming vastly more bandwidth. In addition, entirely new demand segments, including in-flight airline connectivity, have emerged. Other markets, such as telecom backhaul, have greatly expanded with increased mobile usage.

In tandem with increased demand for connectivity, service expectations have risen. Both businesses and consumers seek high-bandwidth connections and, for many applications, low latency. Significantly, these expectations have spread beyond technologically sophisticated users to virtually all consumers in developed economies and many in emerging markets. Only people with limited connectivity options accept lower performance.

At present, the vast majority of consumers rely on terrestrial solutions, and the B2B use of satellites is limited to a few end markets where terrestrial solutions don't work—for example, in-flight internet, long-distance mobile backhaul, maritime internet, remote oil and gas extraction, and certain military applications. That's true largely because satellite-connectivity options are so expensive. But if constellation providers can offer competitive pricing, demand could soar (see sidebar "How could satellite demand evolve if costs drop?").

## The big obstacle: Satellite and ground-segment costs

How can large LEO-constellation providers unlock demand by making their prices competitive with terrestrial solutions? The answer is significantly reducing costs, from manufacturing to launch to

[14] Michael Sheetz, "SpaceX raising over $300 million as new Ontario Teachers' tech fund makes its first investment," CNBC, June 27, 2019, cnbc.com; Ashlee Vance and Dana Hull, "Musk's SpaceX plans a spinoff, IPO for Starlink business," Bloomberg, February 6, 2020, bloomberg.com; Shivdeep Dhaliwal, "No Starlink spin-off or IPO in the works, says Musk," March 10, 2020, Benzinga, benzinga.com.
[15] Ryan Tracy and Brody Mullins, "Musk's SpaceX looking to compete for $16 billion in federal broadband subsidies," *Wall Street Journal*, March 12, 2020, wsj.com.
[16] Caleb Henry, "Telesat outlines spending plan for Canadian government's LEO constellation investment," *SpaceNews*, August 7, 2019, spacenews.com.
[17] *A new decade for private markets: McKinsey Global Private Markets Review 2020*, February 2020, McKinsey.com.

## How could satellite demand evolve if costs drop?

How would demand rise for large low-Earth-orbit (LEO) constellations if the cost to users could match (or beat) the price of existing high-speed options? We conducted analyses on the B2B and consumer markets in the United States to make some projections.

### The B2B market

At the moment, the full impact of the COVID-19 pandemic on different businesses is impossible to determine with certainty. In the near term, airlines and cruise lines, among other sectors, have obviously been hit hard. Much will depend on the duration and depth of a downturn, and we did not attempt to forecast its impact on the B2B market. Precrisis trends at least provide a starting point for estimating future demand, however.

In the B2B market, user-equipment costs are less important than they are in the consumer market. We therefore first examined how demand for large LEO constellations would evolve if connectivity costs matched or beat current B2B options (Exhibit A). Even if costs remain high, this scenario could emerge over the next few years, since players might set artificially low prices to attract business. Over the long term, however, providers cannot forgo profits indefinitely and must therefore reduce costs.

In the markets that use satellites today—mobile backhaul, in-flight internet, maritime internet, oil and gas, and the military—we determined that demand for satellite connectivity would increase only slightly if the connectivity costs of large LEO constellations resembled those of existing offerings. In addition, the new constellations would face significant competition from existing satellite-communications providers, except where low latency is required—for instance, some military applications.

We then looked at a scenario that considered both connectivity and equipment costs. Our analysis showed that if providers of large LEO constellations reduce both equipment and connectivity prices significantly—to the levels needed for the consumer market to take off—a disruptive scenario would emerge in B2B: demand for satellite connectivity would grow by 65 percent annually through 2030. Large LEO systems would probably capture most of this demand.

### The consumer market

While providers of large LEO constellations could certainly pursue B2B applications, they will face competition from existing satellite options, which might be sufficient for most businesses.

The real prize and potential growth area is the consumer internet market. For our consumer-market analysis, we created a model based on two assumptions:

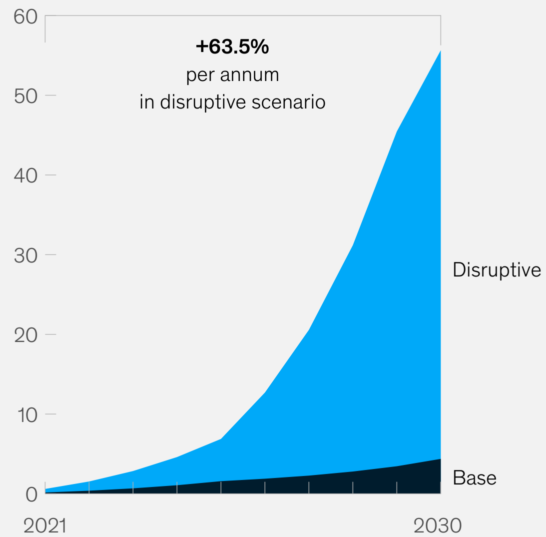
- Connectivity costs would match or beat current options (again, this may occur if providers initially set low prices to attract business).
- The potential customer base would include those who now have no internet, only have satellite, or rely on low-speed copper connectivity, including DSL; it does not assume that any cable customers will switch to satellite.

Our analysis also considered a second variable: the price of customer-premise equipment (CPE). To avoid the uncertainties of landing rights and other potential barriers to operating in different markets, we looked only at consumer demand in the United States (Exhibit B).

Exhibit A

**Less expensive user equipment and lower connectivity fees would generate strong demand in the B2B market.**

**B2B capacity demand that could be captured by NGSO[1] constellations,** terabytes per second

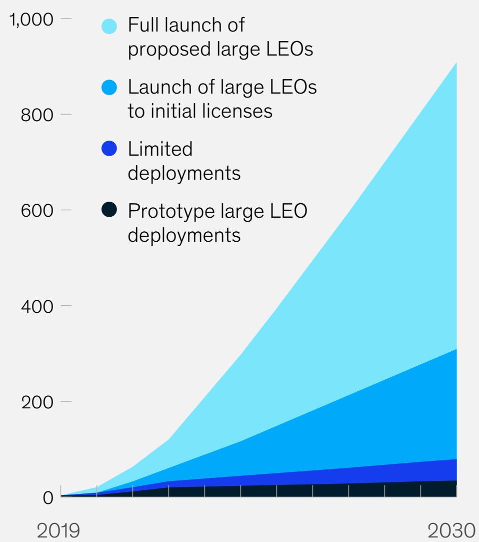



[1] Nongeosynchronous orbit.

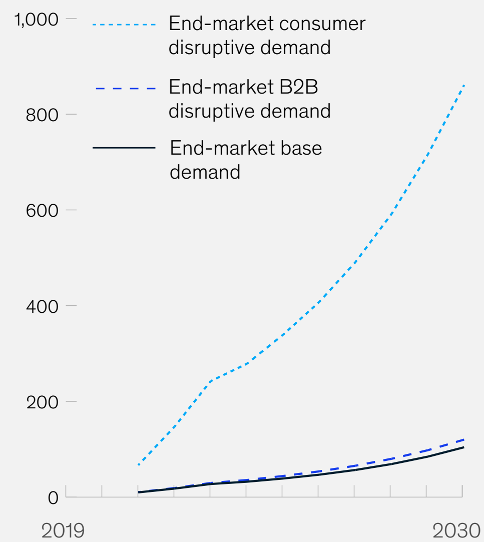
Exhibit B

## Demand for nongeosynchronous-orbit satellite connectivity will outstrip capacity if the disruptive scenario arises in the consumer sector.

**Capacity of NGSO[1] constellations,** terabytes per second




**Demand for NGSO satellite capacity generated by end market,** terabytes per second




[1] Nongeosynchronous orbit.

In one base-case scenario, the cost of CPE remains high when large LEO services are first introduced—$3,000 to $5,000 if they require current antennas with electronically scanned apertures (ESAs); otherwise, their cost is similar to that of other current satellite options. Under these circumstances, the baseline demand for large LEO connectivity would initially be very low and then rise by about 33 percent annually from 2021 through 2030, assuming that CPE costs decrease over time. In the disruptive scenario, which assumes CPE costs of about $300 to $500 when the services are introduced, base-line demand would be higher. The increase over time would be similar to that of the first scenario, at about 32 percent annually. In this disruptive scenario, we estimated that a small number of cable internet customers—conservatively, about 1 percent—would switch from their existing solutions to satellite.

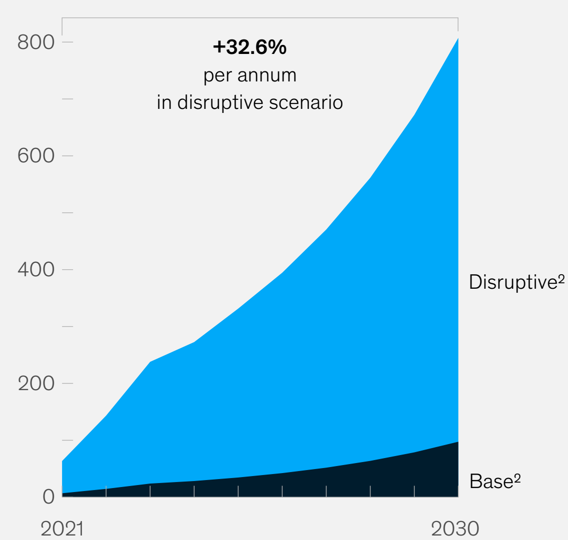
Comparing the potential bandwidth supplied by the large LEO satellites with estimated demand growth is illuminating. Given the assumptions above, even if all proposed LEO constellations are launched, connectivity demand will outstrip capacity if the disruptive scenario materializes in the consumer sector (Exhibit C).[1]

[1] Our estimate did not include the 30,000 additional satellites that Starlink submitted for licensing in January 2020.

Exhibit C

## If costs for on-premise equipment drop, consumer demand for satellite connectivity could soar.

**Consumer home-internet demand captured by NGSO[1] constellations,** terabytes per second




[1] Nongeosynchronous orbit.
[2] The base case assumes that on-premise equipment costs remain in the $3,000 to $5,000 range; the disruptive scenario assumes that these costs drop to $300 to $500 dollars.

user equipment—a difficult undertaking that will require close cooperation with suppliers. Of course, there are other obstacles (see sidebar “Other issues facing satellite providers”), but cost is the greatest challenge to profitability and long-term viability.

**Manufacturing**

Satellites have traditionally been more akin to handcrafted items than to mass-produced goods. That kind of customization, combined with long life-span requirements, explains why a typical large communications satellite costs from $50,000 to $60,000 per kilogram.[18] If costs remain at this level, large LEO constellations would be completely unaffordable. Although some recent GEO communications satellites reportedly are less expensive, this information has not yet been detailed publicly.[19] (We use cost per pound for satellites with similar functions and subsystems as a first-order approximation.) Further, other recent reports suggest that satellite costs will remain high.[20]

If large LEO constellations are to be financially viable, their manufacturing costs must fall by more than an order of magnitude from those of traditional satellites. That would probably be at least 75 percent lower than the costs any company has currently claimed it can achieve (for information on our methodology for estimates, see sidebar “Cost calculations for large LEO constellations”). To cut costs in this way, manufacturers must leverage every possible tool, from economies of scale to automation to reduced component costs across the value chain.

## Other issues facing satellite providers

Despite the high costs, we expect that companies with access to funding will remain committed to launching and extending their large low-Earth-orbit (LEO) constellations in the near future. After all, first movers get many advantages, including the chance to shape regulations in their favor and the ability to attract early customers. They could also lock in customers, such as airlines, that would have large switching costs. The path forward presents many obstacles besides costs, however. Constellation providers will also need to address the following issues to succeed:

— *Better constellation management.* Providers that launch hundreds or thousands of satellites need exceptional control and monitoring systems. Even if cost were not a factor, they would still need to develop highly automated solutions to manage this number of systems effectively.

— *Regulatory developments.* If companies wish to operate in multiple markets, they must address landing rights—the ability to operate in a specific country. The potential for electromagnetic interference (and the resulting liability) is also an area where rules are not yet clear. Once regulators and providers have more clarity, there could be more operating restrictions or additional costs.

— *Debris management.* Even if companies adhere to plans to remove satellites at the end of their life spans, the amount of space debris could increase because of early failures and loss of control. Companies should thus investigate solutions for removing satellites that fail unexpectedly.

— *Competition.* The market is unlikely to accept a new competitor passively. Existing satellite-communications providers, with large capital costs already invested, could try to lower prices. They will certainly work to lock in business customers, such as airlines, before the large LEOs can deploy. On the consumer side, cable and telecom internet service providers will no doubt not only offer lower prices and other incentives but also make an all-out marketing push to retain customers. The large LEO providers must therefore demonstrate that they can compete on service and reliability as well as price.

[18] For example, Intelsat 29e cost approximately $400 million and weighed 6,550 kilograms. Inmarsat 5 cost a reported $220 million to $250 million and weighed 4,000 kilograms.
[19] Inmarsat 7 is reportedly “substantially cheaper” than past satellites. See Caleb Henry, “Inmarsat details GX expansion, OneSat satellite orders,” *SpaceNews,* July 10, 2019, spacenews.com.
[20] The Eutelsat 5 West b geostationary satellite (3,000 kilograms) was insured for a reported $192 million. See Steve Evans, “Insurance market could face $192m+ Eutelsat 5 West B satellite loss,” *Reinsurance News*, October 28, 2019, reinsurancene.sw.

### Launch services

Many experts believe that launch costs should be the main target for cost reductions in large LEO constellations, and owners will certainly want to cut them. Launch providers will have to pull every cost-reduction lever available. In addition to reducing the cost of materials and manufacturing, they should lower their operating costs—for instance, by maximizing savings from reusability.

### Ground equipment

As mentioned in the technology section, large LEO constellations will require many ground stations, even with high-capacity ISLs. By one estimate, the 4,400-satellite version of Starlink will require 123 ground-station locations and about 3,500 gateway antennas to achieve maximum throughput.[21] The gateway antennas must be larger and will require significantly more power than user terminals do.

Current gateways for GEO satellite communications are quite expensive—typically from $1 million to $2 million each.[22] They are not directly comparable to LEO gateways, which have lower power requirements, but the numbers do suggest that gateway costs must be much lower than those of current approaches to make ground-segment costs manageable. Modular antenna designs could help, since they would enable

## Cost calculations for large LEO constellations

Estimating costs can be difficult for low-Earth-orbit (LEO) satellites, since there is little published information on them. We based our estimates for spacecraft and launch costs on recent announcements and then made some inferences. We used the cost per pound for geosynchronous (GEO) communications satellites as a proxy. Here is some of the information we considered:

### Spacecraft

Before bankruptcy, OneWeb set a target of $500,000 each for its 150-kilogram satellites—a cost of $3,333 per kilogram—although the cost reportedly did not improve below about twice that amount. Starlink's targets are probably even more aggressive; they have estimated the cost of their 12,000-satellite system at $10 billion.[1] This figure includes launch costs; if they were not included, each Starlink satellite would cost about $833,000, or roughly $3,700 per kilogram. If we assume that Starlink's $10 billion target for costs is split evenly between spacecraft production and launch, that implies a cost of $1,850 per kilogram.

### Launch

Again, consider Starlink. If all proposed satellites are launched as the initial batches were—on a Falcon 9, in groups of about 60 spacecraft weighing around 227 kilograms each—Starlink will need to make 200 launches to deploy all of the approximately 12,000 satellites that are part of its near-term target.

If Starlink had launch costs in the range of what it has offered to other customers (about $60 million per launch) the cost per kilogram in orbit would be $4,400. That would take total constellation costs to $12 billion—well above Starlink's estimate of $10 billion for both spacecraft and launch.

But let's assume that Starlink's proposed $10 billion budget is feasible, with half of that going to launch. If we divide $5 billion by 12,000 (the number of expected satellites) and assume that each satellite weighs 227 kilograms, the cost to orbit will be $1,835. This implies that Starlink is planning a significantly lower cost to orbit per kilogram than most rocket launches to date. Still, compared with the cost reductions needed for the spacecraft and ground equipment, this goal appears possible. Note: SpaceX would certainly launch its own satellites at cost rather than at commercial prices, and it might be planning to use the Falcon Heavy, its partially reusable super-heavy-lift rocket, which could reduce costs further.[2]

[1] Emre Kelly, "SpaceX's Shotwell: Starlink internet will cost about $10 billion and 'change the world,'" *Florida Today*, April 26, 2018, floridatoday.com.
[2] By one estimate, Falcon Heavy can already achieve this target. See Harry W Jones, *The recent large reduction in space launch cost*, 48th International Conference on Environmental Systems, July 8–12, 2018, tdl.org.

[21] Bruce G. Cameron, Edward F. Crawley, and Inigo del Portillo, *A technical comparison of three low earth orbit satellite constellation systems to provide global broadband*, 69th International Astronautical Congress 2018, October 1, 2018.
[22] Caleb Henry, "ViaSat plans massive ground network of smaller gateways for ViaSat-2 and ViaSat-3 satellites," *SpaceNews,* May 25, 2017, spacenews.com.

equally critical cost reductions in user-equipment antennas, but owners of large LEO constellations will also look for other efficiencies.

**User equipment**

To be most effective, user equipment for a large LEO internet network must incorporate advanced ESAs. These devices currently cost several thousand dollars, though manufacturing costs may be substantially lower; some analysts suggest that they are in the $300 to $500 range.[23] At current levels, ESA prices would be too high for residential customers—the largest source of potential growth—who now pay about $100 to $200 to purchase customer-premise equipment (CPE) or pay monthly rental fees of $10 to $20. Even if constellation providers made their satellite-access and bandwidth fees comparable to those of terrestrial solutions, the high cost of CPE would severely limit their success in the consumer market. If, alternatively, providers slashed CPE prices to compete, they would incur acquisition costs of several thousand dollars for each customer. Under this model, even a premium product would be unprofitable.

To unlock the consumer market—the one with the most potential—the cost of ESA antennas must drop by an order of magnitude or more. While some companies have recently claimed breakthrough reductions in manufacturing costs, none has yet brought a low-cost design to market, nor have any produced ESAs at scale.[24] Companies that do create less expensive ESA concepts will have to preserve their quality: for instance, ESAs will still need to provide high data rates, reliable beam steering, smooth satellite handoff, and other features that ensure a good customer experience.

## Implications for the supply chain

For satellite-component suppliers, the large LEO market has significant potential. Although many companies now working on large LEO constellations may produce satellites or even ground equipment in house, they will still require external components and service support. Suppliers could find huge opportunities by helping to reduce costs, and the eventual market could support a large amount of second- or third-party user equipment.

**Satellite components**

The growth of large LEO constellations will create an unprecedented demand for spacecraft—in particular, high-performance satellites at lower cost. This shift could open the door to specialty providers in a number of areas, including space-qualified solar arrays, power- and thermal-management systems, satellite guidance, navigation and control, on-board processing, and antennas (both to transmit and receive signals). Suppliers that can reduce component costs could be rewarded with contracts for thousands of spacecraft a year.[25]

**Consumer-premise equipment**

With the cost of ESAs now prohibitively high, constellation providers will struggle to capture the consumer market. At present, however, they remain undeterred. Starlink and OneWeb have filed blanket license requests with FCC for 1.0 million and 1.5 million user terminals, respectively—all in the United States. Amazon's filing proposes to connect "tens of millions" of users across the globe.[26] A supplier that can design a reliable but much less expensive unit could see a market for several million devices.

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[23] Caleb Henry, "Satellite operators view antennas as weak link in broadband business plans," *SpaceNews*, July 7, 2018, spacenews.com; Samantha Masunaga, "SpaceX faces daunting challenges if it's going to win the internet space race," *Los Angeles Times*, June 28, 2019, latimes.com.

[24] Caleb Henry, "Wyler claims breakthrough in low-cost antenna for OneWeb, other satellite systems," *SpaceNews,* January 25, 2019, spacenews.com.

[25] Starlink has said that its satellites were meant to have a five-year life span, which seems a likely target for most constellations. That will allow the company to avoid "gold plated" systems and will enable a reasonable technology refresh. With that life span, Starlink alone will need to launch about 2,400 satellites a year for its 12,000-satellite constellation so long as it is operational. Kuiper is a smaller constellation, and Amazon currently intends the satellites involved to have a seven-year life span. Even that will entail a refresh of about 500 spacecraft a year.

[26] Caleb Henry, "Amazon lays out constellation service goals, deployment and deorbit plans to FCC," *SpaceNews,* July 8, 2019, spacenews.com.

### Ground equipment

Large LEO constellations, even in their initial form, will require hundreds of ground stations and thousands of gateways to maximize throughput.[27] But the ground stations will not resemble current versions, which have teleports covering acres of ground with dozens of large dishes. Instead, they may be placed in multiple locations (somewhat like cell-phone towers today), with a large number in remote areas. This configuration will require highly automated management systems. The ground stations will also need antennas—almost certainly flat-panel ESAs that have the same design and technology used for consumer equipment, only in scaled-up or modular form.

### Launch and disposal services

A single large LEO constellation will require anywhere from three to 40 launches a year (depending on the size of the constellation and rocket type), both initially and during maintenance. For constellation operators—even those that build their own rockets—these launch costs will be significant. To ensure a viable business, launch providers will probably need to reduce the cost to orbit below $2,000 per kilogram.

Companies must have end-of-life plans for constellations. Many, however, lack strategies for addressing anticipated or unexpected on-orbit failures. Concerns about such issues could create demand for a completely new market to find satellites and take them out of orbit.

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For the stars to align so that large LEO constellations are deployable, one critical factor stands out: cost reductions across the value chain, from satellite manufacturing through launch and operations. Space operations have never previously occurred on this scale, and the manufacturers and suppliers of both space and ground equipment may find it challenging to meet ambitious cost-reduction and performance targets. If these companies succeed, however, they could serve a burgeoning market. The new constellations would add tens of billions of dollars of economic activity to satellite manufacturing, operations, launch, and consumer equipment. Simultaneously, more consumers will have access to internet connectivity. Together, these benefits should encourage providers of satellite components to persevere.

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[27] Bruce G. Cameron, Edward F. Crawley, and Inigo del Portillo, *A technical comparison of three low earth orbit satellite constellation systems to provide global broadband*, 69th International Astronautical Congress 2018, October 1, 2018.