Cellular to Satellite Communications Study

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Understanding the emerging technology of Cellular to Satellite Communications.

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Abstract

We are in an era where technology has been inserted in every part of our lives including the ways that we communicate with our friends and relatives who live in other countries, enabled by so many technologies (television, telephone, radio, internet, and military applications) that have been invented. For example, wireless networks have been used for this purpose, but they are not enough to contact people who live far away from us. Satellite communication system are emerging to provide coverage to wide areas where communications networks have heretofore not been able to reach. Satellites in Geocentric Orbit (LEO, MEO and HEO), Geostationary Satellites and others are used to cover as much as possible of area including rural and remote areas and mountains. This paper aims to provide a deep dive into satellite orbits (area coverage, working mechanism, advantages and disadvantages, comparison with the other types, applications, benefits brought by them over terrestrial wireless network and so on).

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1 Introduction

Cellular to Satellite Communications is not a matter of if, but when. With new phased array antennas and new satellite constellations out there, it is technically feasible and market forces are driving operators to consider partnerships to provide better services and retain customers.

1.1 Cellular and Satellite Communication[1]

Cellular Features

- Persistent network connectivity for uninterrupted, bi-directional communications
- Rugged design for use in extreme conditions and extreme mobility
- Compact form factor for easy installation
- Two-way communications enable messaging for monitoring and control operations

Satellite Features

- Easy to install with no satellite dishes to point
- Low message latency, in low earth orbit, allows for applications that require immediate communication to and from the asset. No long delays

Table 1 Cellular to Satellite Communications Complementary Advantages and Disadvantages

	Cellular	Satellite
Data Transmission	Via land-based cell towers	Via Earth-orbiting satellites
Coverage	More potential for gaps	Fewer gaps
Remote Location Use	Can be difficult, even impossible	Usually available in any location
Affordability	Less expensive than satellite	More expensive than cellular
Reliability	May experience interruptions as user moves through network	May experience delays due to long-distance data transfer or weather
Disaster risk	More vulnerable	Less vulnerable

1.2 Cellular vs Satellite Communications[2]

Cellular communications technologies send and receive data through land-based towers. Each tower forms a "cell" which is the area covered by its transmitters. A group of towers is referred to as a "cellular network." As your machine works, it sends data through the closest tower in the network.

Satellite communications technologies transmit data through satellites orbiting the Earth. Machine data flows directly to the orbiting satellite which sends a signal to the nearest land-based station which communicates to the receiving device.

Satellite systems offer broader coverage than cell networks. Each cell tower has a relatively short range, so it takes many towers to create a big network. But constructing many towers can be costly and difficult—

[1] Article "Cellular and Satellite Communications," website https://www.fedsig.com/product/cellular-and-satellite-communication, accessed 14 March 2023.

[2] Article "Cellular vs. Satellite Communications: What's The Difference?", website https://www.cat.com/en_US/articles/ci-articles/cellular-vs-satellite-communications.html, accessed 14 March 2023.

even impossible in remote areas. In contrast, satellite beams cover vast areas and no towers are required, so coverage extends to the hardest-to-reach locations.

The cost of renting or buying space on a satellite is higher than the cost of using a cellular network. Satellites are more expensive to build, place in orbit and maintain. Satellite costs are trending down though, making this option more affordable than it was in the past.

1.3 Cellular and Satellite Communications Overlap

In some circumstances, it is possible for a machine to communicate through both a cellular network and a satellite system. However, it must be equipped with what is known as a "dual-mode" tracking and monitoring technology, which, as the name implies, enables communication through both types of channels.

According to Verasat[3], satellite communications is "the process of communicating via signals that bounce off extraterrestrial satellites rather than cell towers." Most importantly "satphones and broadband satellite data terminals are among the most crucial applications of satellite communication. Cellular and terrestrial networks do not always extend to where your team needs to operate." One benefit of satellite communication is that it "allows your remote workers to stay in connection and work in any remote location.". Satellite communication allows for "exploration in remote areas possible, especially if your business requires you to stay connected for your job." Depending on the satellite operator used, it is possible to have connection across the globe even in locations where cellular connection is not an option.

There are four forms of broadband, DSL (digital subscriber line), Fiber-optic, Cable, and Satellite. "Broadband internet service is the most used form of internet access because of its high access speeds and being always on."[4]

"Latency or the amount of time between sending information and when the information is received, weather disruptions, more expensive than cable, minor obstructions can block the signals, potential for incompatibility with VPN's, some providers impose data caps." After identifying these benefits, what does the performance of satellite communications look like? Although not as fast as broadband, "satellite speeds for downloading are usually between 25 Mbps to 100 Mbps, with an average of 25 Mbps for uploading" (CenturyLink).

1.4 Acknowledgements

A special thanks to Danielle Beard and Odi Almashakba for their exceptional effort in researching this emerging field of cellular to satellite communications as part of their TCOM 750 studies.

[3] "Mobile Satellite Services," website https://www.verasatglobal.com/en/, accessed 25 April 2023.
[4] Website http://www.whatismyipaddress.com, accessed 02 May 2023.

2 Satellite Constellations

Satellite communications provide coverage to wide areas that terrestrial networks have not been able to cover (e.g., rural and mountainous area). The need to improve communications and ongoing monitoring of Earth phenomena ranging from weather and climate to disaster management are essential to progress. Large satellite constellations have the potential to offer global connectivity and complement low-cost high-speed broadband internet. A satellite constellation is a group of artificial satellites working together as a system; unlike a single satellite, a constellation can provide permanent global or near-global coverage, such that at any time everywhere on Earth at least one satellite is visible.

Advantages and disadvantages of satellite communications include:

- Advantages
    - Global Connectivity – The ability to provide Internet to people residing in every part of the world, satellite constellations are decreasing the digital divide. The reach of large satellite constellations will drive future technological and humankind advancements
    - The Global Internet – One of the most important commodities in the world, the Internet is enabling millions of opportunities around the world. As telecommunications companies prepare to launch their respective satellite constellations, they will increase global internet access.
    - Cheaper Components - Unlike single satellites, satellite constellations of smaller satellites in Low Earth Orbit are comparatively cheap. This cost advantage makes the process of installing such networks in space much easier and affordable.
- Disadvantages
    - The Space Junk Hazard – large satellite constellations will lead to a severe space junk hazard that will exert long term ecological impacts. Due to the nature of Low Earth Orbits, satellites expire after a certain amount of time and must be deorbited. Space junk has been a concern for several years and has required the International Space Station (ISS) to have to maneuver for astronaut safety numerous times. The establishment of large satellite constellations will only add to the burden.
    - Light Pollution - Another disadvantage of satellite constellations is light pollution from space that obstructs the natural dark sky. While the sun provides light during the day, nighttime witnesses no such light other than the luminous rays of the moon or light from distant planets or stars. When kept to a minimum, stars in the sky are visible to humans making the sky look beautiful and heavenly in the nights. Large satellite constellations have already obstructed this scenic beauty and interfered with earth-based telescopes.
    - Astronomical Endangerment - Astronomy is at risk if satellite constellations do not take precautions. Light pollution caused by large satellite networks will obstruct astronomical studies as the Earth's exosphere becomes congested due to satellites. As astronomists suggest, satellite constellations like Starlink impact on astronomy will altogether endanger astronomy and its related science in the coming few years.

Table 2 Currently Existing or Planned Satellite Constellations and their Characteristics lists the currently known and discussed satellite constellations.

Table 2 Currently Existing or Planned Satellite Constellations and their Characteristics

Satellite Constellation	# Vehicles	Altitude	Orbit	Capacity	Size	Launch Provider	Partners
Hughes Network Systems[5] Jupiter 3	1	22,236 miles Or 35,000 km	GEO	50-100 Mbps; upload +3-5Mbps. $65/ month with 15 GBytes data, $75 w/30 GBytes, $149 200 GBytes of data.	10-ton, 28-foot long, 100 ft solar array	SpaceX Falcon Heavy	Dish
Guowang[6]	12,992	500, 1,145 km at 30-85° inclination	LEO	TBD	TBD	Long March 5B[7]	Chinese Communist Party
OneWeb[8]	588, +6,372 phase 2	750 miles 1200km	LEO	100 ms latency, speeds 200+ Mbps	125 kg[9]	SpaceX Falcon 9, ISRO, Soyuz	14 companies in 35 countries?
SpaceX Starlink V1[10][11]	3,867/4,408	211-382 miles (340-614 km),	LEO	25-50 ms latency, speeds 20-250 Mbps	295 kg	SpaceX Falcon 9	

[5] Article "Hughes' Bus-Sized Satellite Promises Better Broadband in the Boonies", https://www.cnet.com/home/internet/hughes-bus-sized-satellite-promises-better-broadband-in-the-boonies/, accessed 02 April 2023.
[6] Article "If you hate Starlink, you're not going to like that China is working on its own mega constellation", https://spaceexplored.com/2023/04/01/if-you-hate-starlink-youre-not-going-to-like-that-china-is-working-on-its-own-mega-constellation/, accessed 02 April 2023.
[7] Long March 5B's have recently had several second stage rocket bodies have uncontrolled reentries.
[8] Article "OneWeb constellation nearly complete despite 36 satellites still stuck in Baikonur", https://spaceexplored.com/2023/03/22/oneweb-constellation-baikonur/, accessed 02 April 2023.
[9] Article "OneWeb 1, ..., 900", website https://space.skyrocket.de/doc_sdat/oneweb.htm, accessed 17 April 2023.
[10] Article "What's the Difference Between SpaceX's Starlink and OneWeb?", https://gizmodo.com/difference-between-starlink-oneweb-internet-satellites-1850283689, accessed 02 April 2023.
[11] Article "SpaceX unveils "V2 Mini" Starlink satellites with quadruple the capacity", website https://arstechnica.com/information-technology/2023/02/spacexs-2nd-generation-starlink-satellites-start-launching-as-soon-as-today/, accessed 17 April 2023.

Satellite Constellation	# Vehicles	Altitude	Orbit	Capacity	Size	Launch Provider	Partners
SpaceX Starlink V2	7,500 approved (22,488)	326-332 miles (525-535 Km)	LEO	110-120 satellites in a plane; +19,500 GBps	~7m long, antenna ~5m on a side or ~25 square meters.	SpaceX Starship	T-Mobile
Iridium	66	780 km/485 miles	LEO	TBD	TBD	TBD	TBD
Kuiper	3,236	TBD	TBD	100 Mbps	TBD	TBD	Verizon
AST Space Mobile[12][13][14]	243	725-740 km	TBD	30 MBps	64 square meter electronically steered antenna	SpaceX Falcon 9	Rakuten, Vodafone, AT&T
Lynk Global	3-9; 3 currently operating	550 km	LEO	Text	TBD	TBD	Vodafone Ghana, 25+
Astrocast[15][16]	100	504-533 km	LEO, sun synch, equatorial	1-2 Ghz	Nano satellites, 5 kg, 10cm	SpaceX Falcon8	Airbus, ESA, …
Sarteliot	256	310 miles	LEO	TBD	4x8x12 or 6U	SpaceX Falcon 9	Not named

[12] Article "5G race to space picks up (network) speed", https://www.lightreading.com/satellite/5g-race-to-space-picks-up-(network)-speed/d/d-id/784199, accessed 05 April 2023.
[13] Article "Absurdly Large Satellite Phones Home After Successful Launch", https://gizmodo.com/ast-spacemobile-contacts-internet-prototype-satellite-1849539901, accessed 04 April 2023.
[14] Article AST Space Mobile", website https://en.wikipedia.org/wiki/AST_SpaceMobile, accessed 17 April 2023.
[15] Astrocast website, https://www.astrocast.com/technology/, accessed 17 April 2023.
[16] Astrocast Wikipedia, https://en.wikipedia.org/wiki/Astrocast, accessed 17 April 2023.

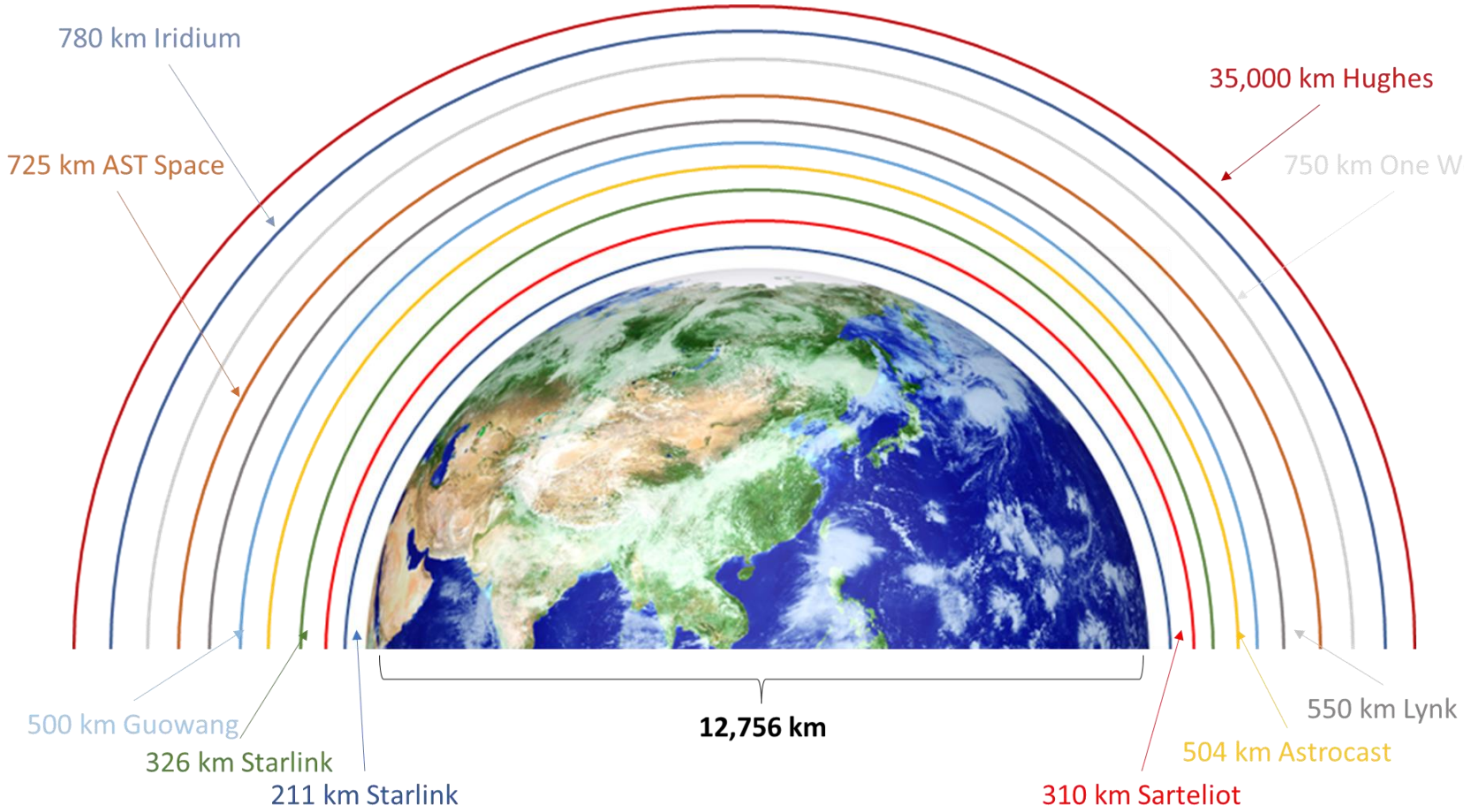

Figure 1 Relative Orbits of Current and Proposed Cellular to Satellite Providers

2.1 Starlink

The original Starlink satellites feature a single solar array wing, with each spacecraft measuring about 36 feet (11 meters) end-to-end once the solar panel is extended. In December 2022, the U.S. Federal Communications Commission gave Starlink approval to put up to 7500 of the new satellites.

The Starlink V2 Mini versions, which are smaller than Starlink V1's, have 4X the capacity to serve users speedy internet. This is due to a more efficient antenna array and the use of radio frequencies between 71 and 86 GHz – called the E band, according to SpaceX. The company has said the new satellites "represent a step forward in Starlink capability." The pros and cons of Starlink satellites are:

- Pros
    - Low Latency and High Bandwidth due to placement in LEO orbit
    - Real-World Performance - initial data transmission speeds of Starlink are 100Mbps downstream and 20Mbps upstream but SpaceX has a long-term goal of achieving and providing a data transmission speed of 1Gbps downstream. Real-world use has confirmed the capabilities and performance of Starlink.
    - Easy-To-Setup User Terminal or Kit - Starlink satellite Internet constellation communicates via a terminal the size of a 12-inch square box that can be mounted on any flat surface such as on the ground or the roof of a house. The terminal has phased array antennas that pinpoint and track the position of a particular LEO satellite and it is part of an entire kit that includes a 100-foot cable for connecting to the included Wi-Fi router. This known performance is a good indicator that the cellular-to-satellite service shall be viable.
    - Reachability in Remote Areas - satellite services do not depend on physical and conventional telecommunication infrastructures. There is no need for a nearby base station unlike wireless or cellular networks or long lines of cables running through underground or above-the-ground transmission lines.
- Cons
    - Intermittentness Due to Obstructions - Starlink service reliability depends on the terminal or cell phone positioned in an area with an unobstructed view of the sky. It cannot be placed near trees or tall structures and works best when placed on open ground or on a roof.
    - Expense - Starlink costs have increased due to high demand. It is unknown what the impact of the cellular-to-satellite service will encounter.

2.2 OneWeb

LEO constellation with expected high-speed, low-latency connectivity for governments, businesses and communities around the world. Each satellite can connect seamlessly to antennas (User Terminals) and the ground network, transmitting data in real-time and at high speed. Latency is approximately 100 ms or slightly higher than Starlink at 25-50 ms. OneWeb plans to have 648 satellites in LEO. Pros and cons are:

- Pros
    - LEO satellites are much closer to Earth than Medium Earth Orbit (MEO) satellites used by traditional Global Network Satellite Systems (GNSS). This means receivers/cell phones on Earth with stronger signals than those provided by MEO satellites for better potential indoor coverage and improved protection from jamming.

    - LEOs are easier to launch and replace due to their lower cost to achieve orbit.
    - LEOs move much more rapidly across the sky, which help to reduce the multipath interference.
    - OneWeb has access to launch capabilities, a schedule, satellite design and build capabilities, space-qualified hardware and a partially-deployed constellation.
- Cons
    - OneWeb system does not already include a signal for radio positioning, nor will the satellites be tracked with an accuracy good enough to provide GNSS.
    - OneWeb uses carrier frequencies higher than those used by GNSS.
    - Various components on the OneWeb platform and its ground infrastructure may need to be upgraded to provide high quality positioning signals and military-grade encryption.
    - Due to the much lower orbits, many more LEO satellites are required over MEOs for the same global coverage and a high number of satellites simultaneously in view.
    - LEOs need to be replaced more often than MEOs due to increased atmospheric drag; required station-keeping maneuvers burn through fuel at a much higher rate.
    - The issue of coverage and overlapping satellite footprints need to be resolved in an updated constellation plan.

2.3 Iridium

Iridium features 66 satellites in LEO. Iridium has been in use for over 20 years and have refreshed their constellation several times with more advanced features. Iridium satellites are closer to the Earth, in low Earth orbit, about 781 km (485 mi). Iridium builds their satellites in Gilbert, Arizona. Iridium satellites are electronically interconnected to provide continuous worldwide coverage. Communications are relayed via satellite and through terrestrial gateways, where billing information and user location data are stored. The big disadvantage Iridium has is signal may be temporarily lost if a satellite moves out of range, but it will quickly be regained once the next satellite is in view.

2.4 Globalstar

Globalstar is an American satellite communications company that operates a low Earth orbit (LEO) satellite constellation for satellite phone and low-speed data communications. The Globalstar constellation consists of 48 LEO satellites, with an additional four satellites in orbit as spares. Globalstar system software resides on the ground, not on the satellites, which enables fast and easy system maintenance and upgrades. It provides coverage from any point on the Earth's surface to any other point worldwide with multiple overlapping satellite beams for simplex and voice/duplex data, exclusive of both polar regions. Apple has agreed to reimburse Globalstar for 95% of the constellation; however, it previously required the satellite operator first to raise third-party financing to fund the manufacturing contract. Globalstar has stated that Apple is lending them $252 million to help cover upfront costs for replenishing its LEO constellation.

2.5 Inmarsat

Inmarsat’s constellation consists of 13 satellites in geosynchronous (GEO) orbit approximately 22,000 miles above the earth. There are three types of coverage for each Inmarsat satellite:

- Global beam coverage - Each satellite is equipped with a single global beam that covers up to one-third of the Earth's surface, apart from the poles. Overall, global beam coverage extends from latitudes of −82 to +82° regardless of longitude.
- Regional spot beam coverage - Each regional beam covers a fraction of the area covered by a global beam, but collectively all the regional beams offer virtually the same coverage as the global

beams. Use of regional beams allow user terminals (also called mobile earth stations) to operate with significantly smaller antennas. Regional beams were introduced with the I-3 satellites. Each I-3 satellite provides four to six spot beams; each I-4 satellite provides 19 regional beams.

- Narrow spot beam coverage - Narrow beams are offered by the three Inmarsat-4 satellites. Narrow beams vary in size and tend to be several hundred kilometers across. The narrow beams, while much smaller than the global or regional beams, are far more numerous and offer the same global coverage. Narrow spot beams allow smaller antennas and much higher data rates and form the backbone of Inmarsat's handheld (GSPS) and broadband service. This coverage was introduced with the I-4 satellites. Each I-4 satellite provides around 200 narrow spot beams.

Inmarsat constellations have excellent voice quality, broadband data (via BGAN) and affordable price. Some downsides are no coverage in the polar regions, longer network registration times, and best used in a stationary position (with the antenna pointed toward the equator).

3 Satellite Orbits

There are four major descriptions for satellite orbits; they are Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geostationary Orbit (GEO), and Highly Elliptical Orbit (HEO). There is a considerable gap between LEO, MEO and GEO orbits.

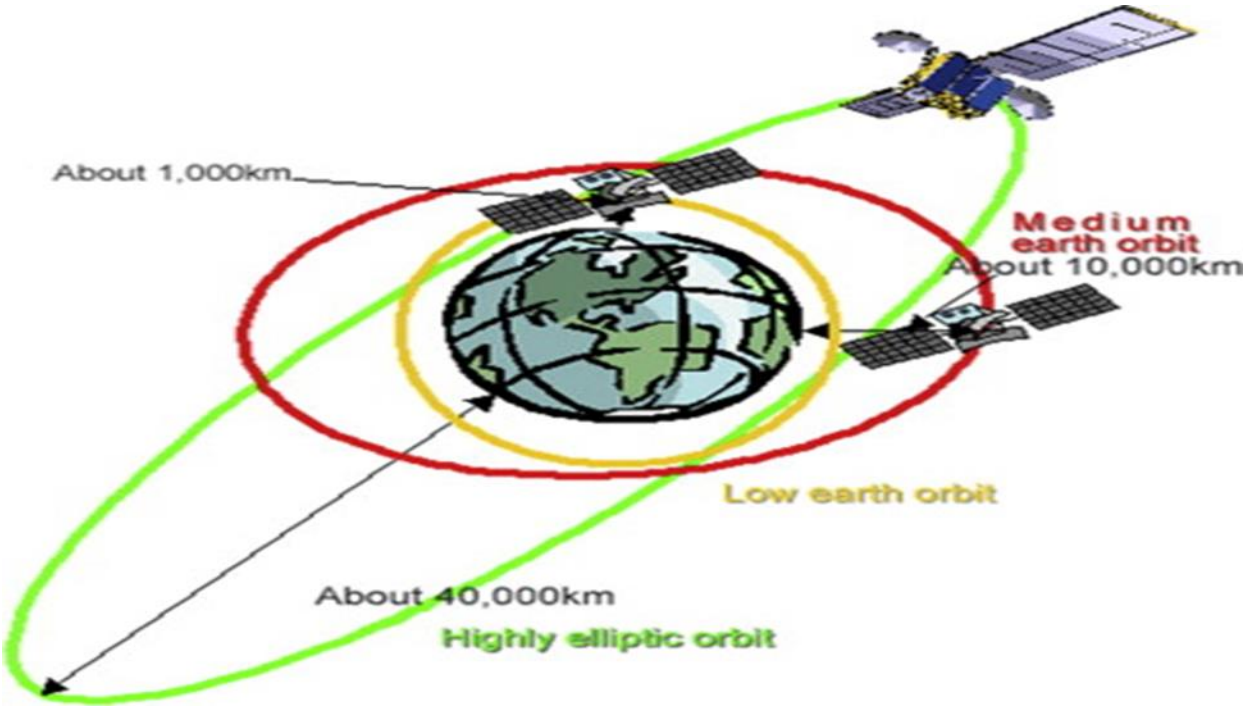

Figure 2 LEO, MEO and HEO Orbits

Satellites have been put in space for various purposes and their placement in space and orbiting shapes have been determined as per their specific requirements.

Four different types of satellites orbits have been identified. These are:

- LEO 500-1500km above the earth's surface.
- MEO or ICO (Intermediate Circular Orbit) 6000-20,000 km above the earth's surface.
- HEO (Highly Elliptical Orbit) varying height above the earth’s surface.
- GEO 36,000km above the earth's surface.

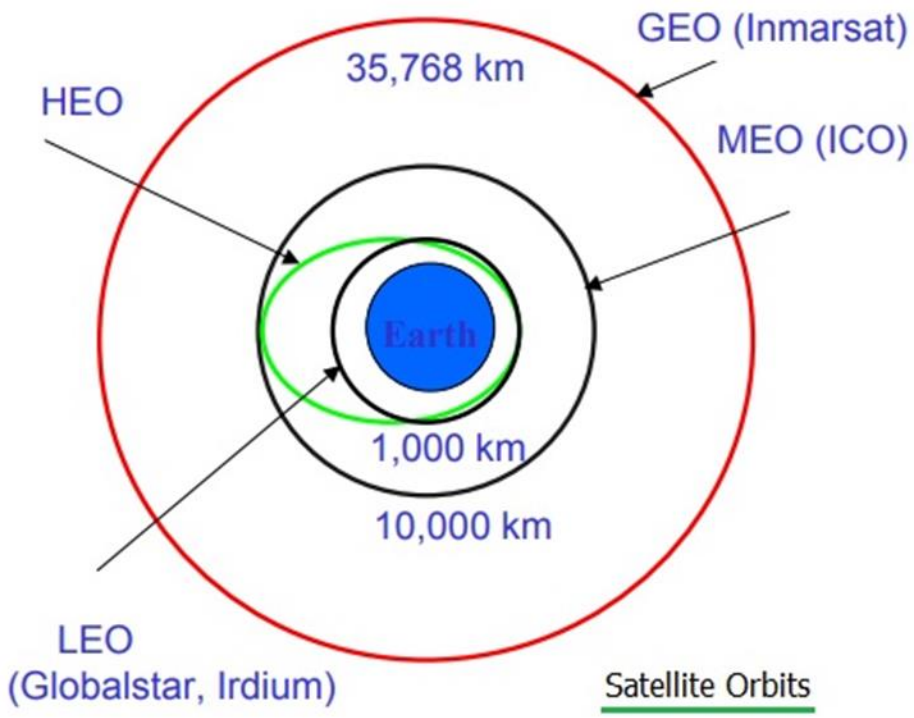

Figure 3 Comparison of Orbit Distances/Heights

3.1 LEO Satellites

LEO satellites have a circular (or elliptical) orbit at a height of 250–2000 km from the Earth as shown in **Figure 2 LEO, MEO and HEO Orbits**. The orbit period, or time it takes for the satellite to circle the earth, primarily depending on the altitude, and can vary from 90–120 minutes. As the altitude of LEO satellites is low, their velocity is very high (>25,000 km/h) and they make 12–16 Earth revolutions of Earth per day. This means a LEO satellite experiences at least 12 to 16 sunlight and night periods in 24 hours. Consequently, in LEO orbit, the maximum time during which a satellite is above the local horizon for an observer on the Earth is up to 20 min. This time is used to transfer data, images and photographs to selected ground stations positioned in strategic locations.

LEO satellites can have orbits inclined 0–90° vs. the equatorial plane, and inclination induces slight difference in the eclipse time. With an altitude of 650 km, the maximum eclipse time is close to 35 min. But with an inclination angle close to 90°, the satellite is then positioned in a polar orbit characterized by long periods with no eclipse at all like the solstice periods for GEO satellites.

Satellites in LEO are affected by atmospheric drag that makes the orbit gradually deteriorate and the typical lifetime of a LEO satellite is 7–10 years.

Most LEO satellites are used for Earth or space observation and science. The best examples of LEO satellites are the Hubble space telescope, the Spot family of satellites (Earth imaging and survey) and military observation satellites.

A specific orbit called “polar orbit” is inclined at ~90° to the equatorial plane and covers both (North and South) poles. The orbit is fixed in space, and the Earth rotates underneath. Therefore, a single satellite in a polar orbit provides in principle coverage to the entire globe, although there are long periods during which the satellite is out of view of a particular ground station. This may be acceptable for a store-and-

forward type of communication system. Accessibility can be improved by deploying more than one satellite in different orbital planes.

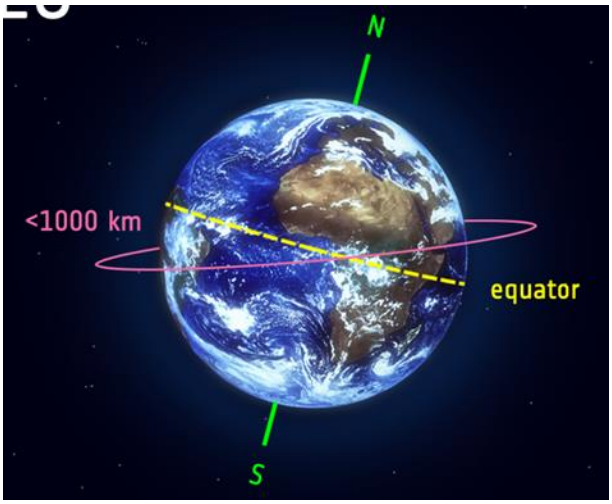

Figure 4 Depiction of a Low Earth Orbit

3.2 LEO Orbit Effect on Area Coverage?

Even though communication and networking technologies are developing rapidly we still far away from achieving the goal of connecting every user on the earth at any time. In previous world Internet development reports about 43.9% of the population had access to the internet[17]. This is because many people live in regional, rural and mountainous areas where there is no coverage of network. Terrestrial networks used to provide coverage feature high construction costs making it difficult to provide telecommunication services for everyone, especially regional, rural and mountainous areas.

Satellite communications are used because they feature large coverage areas, fast deployment and little interference from ground networks.

The different orbits (LEO, MEO, HEO, GEO) have advantages and disadvantages, but they provide the possibility to connect people around the world in any place. There were around 7,500 satellites in LEO as of September 2021, according to the United Nations' Outer Space Objects Index[18].

For LEO satellites with altitudes between 200 and 400 km, atmospheric resistance is noticeable and can be used to develop a restoring passive torque, while the center of pressure is shifted from the center of mass of the satellite[19]. To shift the center of pressure, a special aerostabilizer like a sphere fixed by a rod is connected to the satellite or “an aero skirt” again moved from the center of mass should be installed. The problem of damping can be solved using a grid of hysteresis rods (MAK-A, 1993; PAMS, 1996; SamSat QB50, 2019) or magnetorquers. However, the lifetime of a CubeSat with an aerodynamical attitude control system can be relatively short depending on the strength (time response) of the hysteresis rods and the eventual deorbiting due to atmospheric drag.

[17] “What Is Satellite Communication and Why Is It Important for Businesses?” Verasatglobal.com, 26 Oct. 2022, https://www.verasatglobal.com/en/what-is-satellite-communication-and-why-is-it-important-for-businesses/, 25 April 2023.

[18]

[19]

3.3 LEO Systems and Working Mechanism

LEO systems orbit at lower altitudes and move with respect to the earth. A typical LEO satellite orbits the earth in under two hours, which means the satellite is in view for only a few minutes. Because of this, users of LEO satellite services must be "handed off" from satellite to satellite as well as between "cells" within the footprint of a given satellite in order to maintain continuity of communication. The handoff between cells of a particular satellite is usually accomplished within the satellite itself; however, handoffs between satellites requires either the intervention of a ground terminal or communication between the satellites using crosslinks or some hybrid of these two approaches. Because of the relative velocity between a satellite and any point on earth, doppler (frequency shifting) is present on each communication link. In most cases, doppler is corrected for in the earth terminal equipment.

The choice of altitude for a LEO constellation is usually governed by regulatory authorities and the cost of placing satellites at the selected altitude. The higher the altitude, the fewer the number of satellites required to obtain full earth coverage, but the greater cost to launch the satellites. This is shown in **Figure 5 Number of Satellites Required to Obtain Full Earth Coverage as a Function of Altitude.**

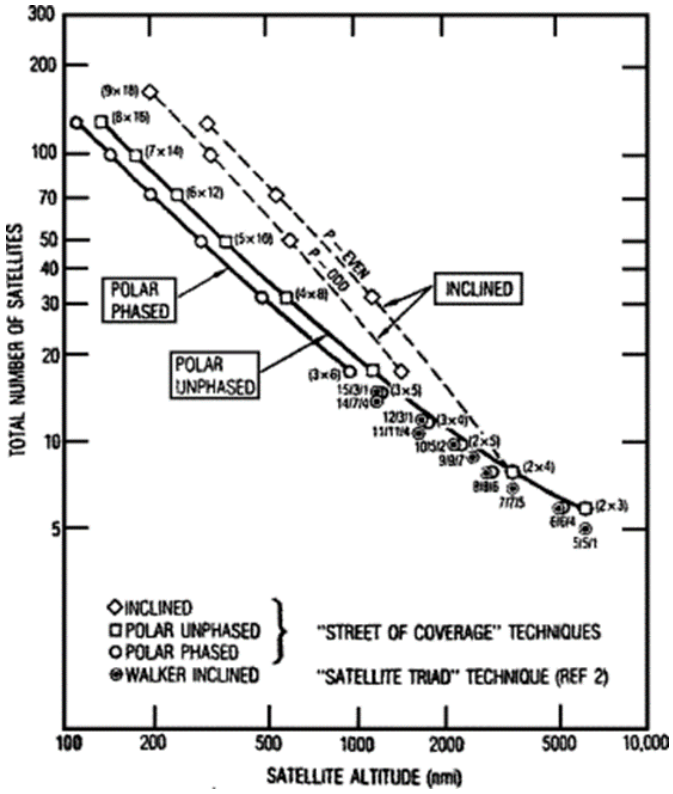

Figure 5 Number of Satellites Required to Obtain Full Earth Coverage as a Function of Altitude

Other factors that influence the choice of altitude are the radiation environment as a function of altitude and the amount of space debris at an altitude. The chosen altitude is generally a compromise between several conflicting factors, not the least of which is the intended market or mission.

3.4 Advantages and Disadvantages of LEO Satellites

Advantages:

1. LEO orbit provides better signal strength - because of their short distance from earth, power loss decreases due to the relationship between distance and power loss.

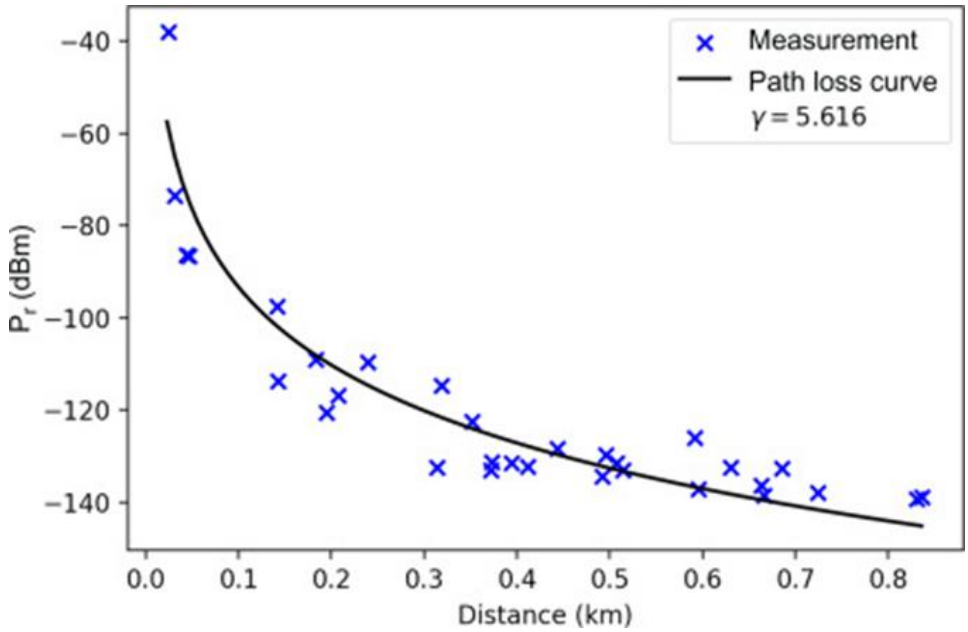

Figure 6 LEO Satellites Feature Lower Power Loss Due to Their Decreased Altitude

2. Least propagation delay (~10ms) compared to other orbits
3. No need for bulky receiver equipment due to higher C/N signal ratio.
4. Low price
5. Better frequency reuse
6. High elevation for polar regions and better global coverage

Disadvantages:

1. At a lesser distance above Earth, covers less area, therefore large number of satellites are needed to cover the entire the Earth at increased cost.
2. LEO satellites must constantly hand off service to the next satellite in the constellation. A succession of satellites is required to cover any region on Earth.
3. Atmospheric effects are greater and cause gradual orbit degradation requiring regular orbit maintenance or replacement.
4. A LEO satellite is only visible for 15-20 minutes from a particular spot-on Earth reducing time for testing and troubleshooting.
5. Ground station operations complex to handle frequent handoffs.

3.5 GEO (Geostationary Earth Orbit)

If a satellite should appear in fixed in the sky, it requires a period of 24 hours. Using the equation of distance earth and satellite, r = (g.r2 /2.r.f)2)1/3 and the period of 24 hours f = 1/24 h. the resulting distance is 35,786 km. the orbit must have an inclination of 0 degree.

Geostationary satellites orbit at 36,000 km to the earth. Use cases include almost all TV and radio broadcast satellites, weather satellites and satellites operating as backbones for the telephone network.

Objects in GEO moves around the earth at the same speed as the earth rotates. This means geostationary satellites remain in the same position relative to the surface of earth. Advantages of GEO satellite

1. Three Geostationary satellites provide complete coverage for any spot on the earth.
2. Receivers and senders can use fixed antenna positions; no adjusting needed.

3. GEOs are ideal for TV and radio broadcasting.
4. Lifetime expectations for GEOs are rather high, at about 15 years.
5. Geostationary satellites have a 24-hour view of a particular area.
6. GEOs typically do not need handover due to the large footprints.
7. GEOs do not exhibit any Doppler shift because the relative movement is zero.

Disadvantages of GEO satellite

1. Northern or southern regions of the earth have more problems receiving these satellites due to the low elevation above latitude of 60 degrees, i.e., larger antennas are needed.
2. Shading of signals in cities due to high buildings and low elevation further away from the equator limits transmission quality.
3. Transmit power needed is relatively high (about 10W) which causes problems for battery powered devices.
4. These satellites cannot be used for small mobile phones.
5. Biggest problem for voice and data communication is high latency of over 0.25s one way-retransmission schemes which are known from fixed networks fail.
6. Transferring a GEO into orbit is very expensive.

3.6 MEO (Medium Earth Orbit)

A MEO satellite situates in orbit somewhere between 6,000 km to 20,000 km above the earth's surface. MEO satellites are like LEO satellites in the context of functionality, but are visible for longer periods of time than LEO satellites; usually 2 to 8 hours and feature a larger coverage area than Low Earth Orbit satellites. MEOs can be positioned between LEOs and GEOs, in terms of their orbit and to their advantages and disadvantages.

Advantages of MEO

1. Using orbits around 10,000km, the system only requires a dozen satellites which is more than a GEO system, but much less than a LEO system.
2. These satellites move more slowly relative to the earth's rotation allowing a simpler system design (satellite periods are about six hours).
3. Depending on the inclination, a MEO can cover larger populations, so requiring fewer handovers.
4. A MEO satellite's longer duration of visibility and wider footprint means fewer satellites are needed in a MEO network than a LEO network.

Disadvantages of MEO

1. Due to the larger distance to the earth, delay increases to about 70-80 ms.
2. MEO satellites need higher transmit power and special antennas for smaller footprints.
3. MEO see a weaker signal than LEO satellites.

3.7 HEO (High Earth Orbit)

HEO is an oblong orbit around the earth, with one end nearer the Earth and the other end more distant. It is also called Molniya orbit. Following are the characteristics of HEO orbit.

- Altitude: 20,000-47,000 Km
- Orbital period longer than 24 Hours, satellites in this orbit appear to be retrograde
- Satellites in HEO are used for communications, satellite radio, remote sensing and other applications.
- HEO satellites are used to study magnetosphere of planet, astronomical observations etc.

- Satellites using HEO orbits include Ellipsoid, Molniya, Archimedes and Inmarsat satellites GX10A and GX10B.

Benefits or advantages of HEO orbit:

1. Satellite takes medium round-trip delay.
2. Satellite to Earth Path loss is smaller on one side and larger on the other.
3. Coverage area is smaller on one side of orbit and larger on the other side.
4. HEO satellites observe less exposure to atmospheric drag than LEO and MEO satellites.
5. It offers services to high altitude regions of the Earth unlike Geostationary orbits.
6. It offers longer dwell time at some point in the Sky.

Drawbacks or disadvantages of HEO orbit:

1. Satellite systems are complex compare to other orbit satellites.
2. Highest propagation delay on one side of the Earth.
3. Selected area coverage.
4. Satellites in HEO appear to be heading in opposite direction.
5. Cost of manufacturing and launching is higher.

3.8 Cislunar Space[20]

Cislunar space—the large region of space in the Earth-Moon system beyond geosynchronous (GEO) orbit, including the Moon. Cislunar space offers tremendous promise for advancing science, technology, and exploration. Humanity's activities on the Moon are uniquely inspiring for people around the world. Cislunar space provides opportunities for answering some of the highest priority questions in planetary science and exploring the history of our solar system and Sun. Cislunar space also contains radio-quiet environments that could help catalyze a new generation of radio astronomy, a valuable region for testing human exploration technologies and operations, and the potential to drive economic growth in space.

The decade ahead is critically important for exploration of Cislunar space, including the Lunar surface. NASA estimates that over the next ten years, human activity in Cislunar space will be equal to or exceed all that has occurred in this region since the Space Age began in 1957. Many more countries and other actors are planning to travel to this new sphere of human activity.

A key and related part of this paper is the plan to implement Cislunar communications and positioning, navigation, and timing capabilities with scalable and interoperable approaches**.** Communications and positioning, navigation, and timing (PNT) are the common information capabilities needed for all activities in Cislunar space, including in Lunar orbit and on the Lunar surface. This objective will promote early information capabilities that can enable a cooperative and sustainable ecosystem in Cislunar space, lower barriers to entry and foster new commercial space activities, and advance responsible and safe spaceflight practices.

Lockheed Martin and Nokia[21] are partnering to bring communications to Cislunar space. Lockheed Martin is planning to build a new satellite network around the Moon, and Nokia is planning to send the first functional 4G network to support the Artemis program.

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[20] "FACT SHEET: First National Cislunar Science & Technology Strategy", website https://www.whitehouse.gov/ostp/news-updates/2022/11/17/fact-sheet-first-national-cislunar-science-technology-strategy/, accessed 02 May 2023.

[21] "Lockheed Martin and Nokia are bringing Earth communication devices to the Moon", website https://www.techspot.com/news/98137-lockheed-martin-nokia-bringing-earth-communication-devices-moon.html, accessed 02 May 2023.

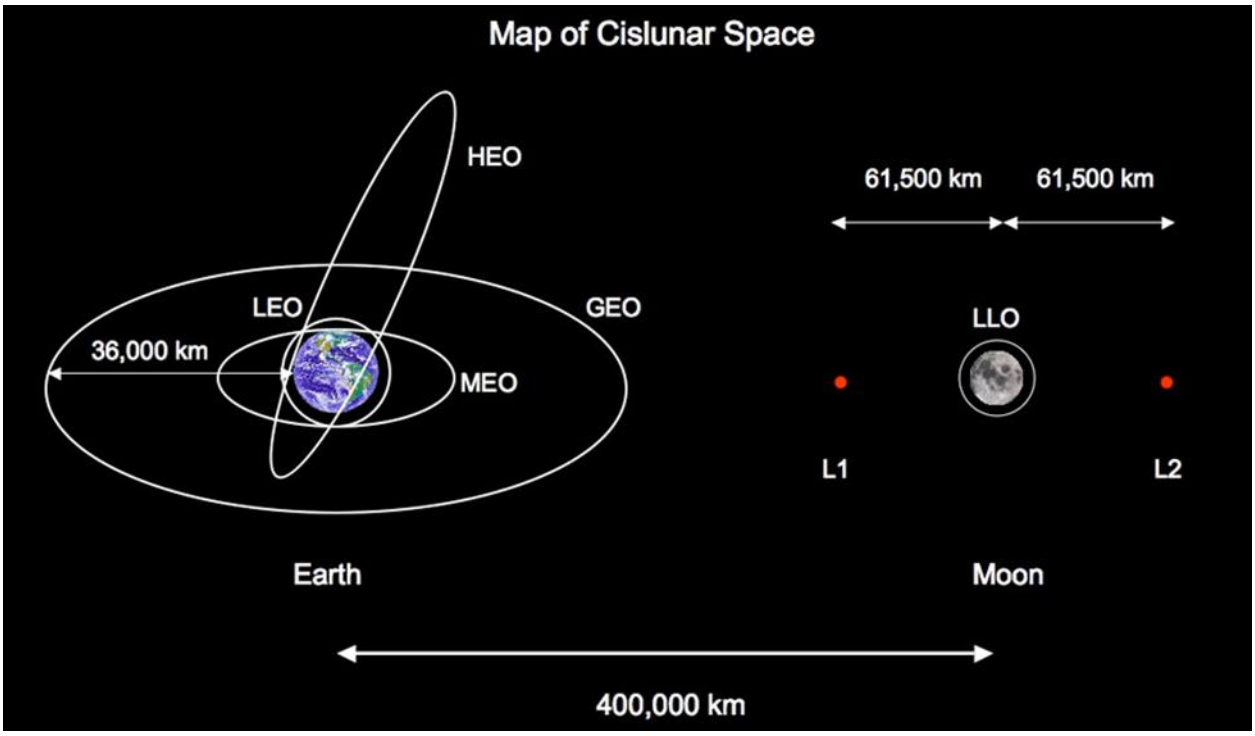

Figure 7 Map of Cislunar Space[22]

Lockheed Martin is planning to turn the Moon into a new revenue source, offering its services to NASA with Crescent Space, a newly-created subsidiary designed to establish "a permanent outpost on the Moon" with proper supporting communication.

Crescent Space is an "agile" company that provides "infrastructure-as-a-service for lunar missions." Its first official offering is a "novel cislunar communications network called Parsec." Parsec will employ a fleet of small satellites built by Lockheed Martin, which work in unison to provide a "seamless connection" between Earth, the astronauts, and the assets currently on the lunar surface.

The Parsec fleet should behave like a typical Earth-based GPS network, providing astronauts with their exact position and directions to return to their base station. The first nodes of the lunar fleet should start operations by 2025, with additional nodes coming over the following years.

NASA did recently select Finnish telecom Nokia to build the "first-ever cellular network on the Moon." As a "pioneer" of wireless communication and networking technologies, Nokia has begun the early planning stages of deploying an LTE/4G communications system on the lunar surface.

[22] Image from website http://d1jqu7g1y74ds1.cloudfront.net/wp-content/uploads/2011/10/Cislunar-space.jpg, accessed 01 May 2023.

4 LEO Examples

As we mentioned above Low Earth Orbit is close to earth surface (below 2000 km) so that many technologies use this orbit here I am going to describe them:

4.1 The International Space Station

This station is in a LEO about 400 km (250 mi) to 420 km (260 mi) above Earth's surface, and needs re-boosting a few times a year due to orbital decay.

The radiation environment of low-altitude LEO orbits, such as those utilized by the International Space Station (ISS) between 360 km and 440 km, includes electrons, protons, ions, and secondary neutrons. In addition, inside the ISS, the interaction of the external environment with the ISS walls produces a secondary radiation field, whose proprieties vary as a function of the position inside ISS, depending on the amount of shielding available. Peaks in radiation exposure will be registered when traversing the South Atlantic Anomaly (SAA).

4.2 Iridium telecom satellites orbit at about 780 km

An omnidirectional antenna was intended to be small enough to be mounted on the planned phone, but the low handset battery power was insufficient for contact with a satellite in geostationary orbit, 35,785 km (22,236 mi) above the Earth; the normal orbit of communications satellites, in which the satellite appears stationary in the sky. For a handheld phone to communicate with them, the Iridium satellites are closer to the Earth, in low Earth orbit, about 781 km (485 mi) above the surface.

4.3 Earth observation satellites

Also known as remote sensing satellites, including spy satellites and other Earth imaging satellites, use LEO as they can see the surface of the Earth more clearly by being closer to it. Most artificial satellites are placed in LEO. Satellites can also take advantage of consistent lighting of the surface below via Sun-synchronous LEO orbits at an altitude of about 800 km (500 mi) and near polar inclination.

4.4 Hubble Space Telescope orbits at about 540 km above Earth.

It is a space telescope that was launched into low Earth orbit in 1990 and remains in operation.

4.5 Chinese Tiangong space station

It is a space station being constructed by China in low Earth orbit between 340 and 450 km (210 and 280 mi) above the surface.

5 Existing Satellite Communications Services

5.1 Garmin InReach

Garmin InReach[23] - GPS Satellite mobile device that utilizes the Iridium Satellite network to send and receive custom text messages, or emails with a delivery confirmation" (Fly2Base Paragliding Shop). Service plans and costs are:

- InReach SAFETY plan $240 a year
- InReach Recreation Plan with unlimited tracking $480 per year
- InReach SAFETY FREEDOM Plan $25 AUD per month plus annual $37 Network Maintenance Fee $37 AUD; total cost per 6 months $187 AUD. Plan allows you to start and stop the service at any time so you can only use your satellite tracker during the months you are flying and stop service during the off season" (Fly2Base Paragliding Shop).

5.2 Orbcomm

ORBCOMM[24][25][26] advertises per type of earth orbit with two services on their website. LSAT Data Pro (GEO) is "Ideal for mission-critical applications requiring larger amounts of data, IDP delivers messages within seconds via, email, text, logs, e-forms and forms." ORBCOMM also advertises the OG2 (LEO) stated as "the world's first and only commercial satellite network 100% dedicated to IoT, providing two-way data communications in the most remote areas of the world. Continuously moving satellites provide network redundancy, minimal line of site issues and further signal propagation." Orbcomm's LEO hardware is the ST2100 that "can be installed on both mobile assets like light-and heavy-duty commercial vehicles, railcars, and heavy equipment as well as fixed assets like pipelines, pumps, generators and tanks used in industrial and utilities environments." It is also easy to integrate claiming "No scripting required. An intuitive AT command set enables quick integration with external PLCSs and general-purpose controllers. The ST 2100 can be installed with side or bottom cable access." ORBCOMM also advertises for the Satellite Modem[27], with the intention to set the industry standard. This device "simplifies the hardware decision-making process for OEMs and system integrators with its interchangeable OG2 and OGi satellite modems. Our versatile IoT satellite modems feature an identical footprint, connectors, power input, programming environment, communication interface and protocols." ORBCOMM advertises their devices to be plug and play, interchangeable for maximum versatility, and easy to integrate.

5.3 Motorola Defy

Motorola Defy[28] - Satellite phone developed in "collaboration with Bullitt, a company known for making rugged smartphones, the new smartphone will be sold as the Motorola Defy 2." This device comes with

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23 Garmin LTD. "INREACH® Satellite Communication." Garmin, https://discover.garmin.com/en-US/inreach/personal/, 25 April 2023.

24 http://www.Orbcomm.com

25 "Satellite IOT and M2M." ORBCOMM, https://www.orbcomm.com/en/partners/connectivity/satellite, 25 April 2023.

26 "Satellite Tracking Device." ORBCOMM, https://www.orbcomm.com/en/partners/iot-hardware/st-2100, 25 April 2023.

27 "Satellite Modems." ORBCOMM, https://www.orbcomm.com/en/partners/iot-hardware/satellite-modem, 25 April 2023.

28 "Motorola Unveils Defy 2, a Rugged Phone with Satellite Connectivity: Check Price, Specs and Other Details." The Indian Express, 26 Feb. 2023, https://indianexpress.com/article/technology/tech-news-technology/motorola-defy-2-rugged-phone-satellite-connectivity-price-specs-8467016/, 25 April 2023.

Table 3 Current Mobile Communications Satellite Offerings

Satellite Phone	Services Offered	Satellite Network	Global Coverage	Dimensions	Battery Life	Operating Temperatures	Durability	Ingress Protection
Iridium GO!	Satellite calls and SMS	Iridium	Global	114 x 82 x 32 mm	.5 hour talk time, 15.5-hour standby time	5	10 to 50 ℃	MIL-STD 810F IP65
SPOT X	SMS, automatic positioning, and SOS	GlobalStar	Global	166 × 38 × 24 mm 2	40 hours	-20 °C to 60 °C	MIL-STD-810G	IP67
Garmin inReach Mini 2	Two-way messaging, interactive SOS, and Trackback routing	Iridium	Global	2.04 x 3.9 x 1.03 inches	Up to 14 days in 10-minute tracking mode	N/A	N/A	IPX7
Thuraya XT-LITE	Satellite calls and SMS, GSM	Thuraya	Not in North/South America	128 × 53 × 27 mm	6-hour talk time, 80-hour standby time	N/A	N/A	N/A
Inmarsat IsatPhone 2.1	Voice calls, SMS, GPS tracking	Inmarsat	Near Global	16.9 x 7.65 x 2.9 cm	8-hour talk time, 160-hour standby time	N/A	IK04 shock resistance rating	IP65

"the world's first two-way satellite messaging app, Bullitt Satellite Messenger, which lets users directly communicate with each other. Built on standards set up by the 3rd Generation Partnership Project (3GPP), the Motorola Defy 2 uses a geostationary satellite to send text messages using the Bullitt Satellite Messenger." "Apart from sending texts, and 24X7 SOS assistance, users can also share their location and check-ins." Specifications include "The rugged smartphone can operate for up to 24 hours in temperatures ranging from negative 30 degrees Celsius to 75 degrees Celsius, survives drops on steel sheets from six feet, can withstand humid environments like salt mist, comes with an antimicrobial coating with silver ions and can be washed with soap and disinfectants as well." The device "In North America, Canada and Latin America, Motorola Defy 2 will be available sometime in the second quarter of 2023, will cost $599 and includes a 12-month subscription to Bullitt's Essential Plan."

5.4 Thuraya

Thuraya[29] advertises their satellite phone as "the world's most advanced satellite phone which is ruggedized and equipped with long battery life, ensuring connectivity no matter where you go." The Thuraya XT-PRO is "the first satellite phone with built-in GPS, Beidou and Glonass capability for highest flexibility in all regions. It has the biggest display on any satellite phone and comes with hardened Gorilla glass for harsh environments. The screen is designed for glare resistance which allows for optimal visibility in bright sunlight and it includes a brightness sensor to automatically adjust the backlight of the display." With the Thuraya XT-PRO "you can make phone calls and send messages in satellite mode and use a satellite data connection to send and receive emails or browse the web with a connected laptop or PC. For emergencies it has a dedicated SOS button with advanced navigation and tracking features." Finally, the specifications are, "supported by the most robust and powerful satellite network, Calls, SMS, and Internet connectivity in satellite mode, Compact and rugged design, Dedicated SOS button, Glare resistant Gorilla glass display, Longest talk-time on any satellite phone, and a Global Navigation Satellite System."

5.5 Spot X

SPOT and SPOT X[303132] - SPOT X is a newer version of the Spot Gen4. Beginning with SPOT Gen4, a 1-way communication device where you can only send information such as simple messages, location check-ins, and S.O.S in case of emergencies" (Huang, Author Samuel, et al, 2020). Spot X is a 2-way satellite messenger with Bluetooth wireless technology with the same capabilities as SPOT Gen4 with a backlit 2.7" display and backlit keyboard. Spot X allows for 2-way messaging with 14 predefined messages across the globe and advanced features like navigating with a compass and programmable waypoint (Huang, Author Samuel, et al, 2020). SPOT X costs on the GlobalStar website is $249.99. An SOS feature for emergencies, tracking locations in 5-, 10- or 30-minute intervals, check in feature to provide status updates. HELP/SPOT SOV (save our vehicle) send an alert to preprogrammed contacts when a vehicle is disabled or for roadside assistance" (GlobalStar.com). Spot X provides a built-in compass with programmable locations to guide

[29] "Thuraya XT-Pro: Satellite Phone: Thuraya Mobile Satellite Communications Company." Thuraya XT-PRO | Satellite Phone | Thuraya Mobile Satellite Communications Company, https://www.thuraya.com/en/products-list/land-voice/thuraya-xt-pro#:~:text=Thuraya's%20XT%2DPRO%20is%20the,stay%20connected%20wherever%20you%20are, 25 April 2023.

30 Huang, Author Samuel, et al. "Spot X and Spot gen4 are a Must-Have When Traveling off the Grid [Review]." G Style Magazine, 2 Dec. 2020, https://gstylemag.com/2020/12/02/spot-x-and-spot-gen4-review/#:~:text=The%20SPOT%20X%20has%20similar,just%20thicker%20and%20more%20ruggedized, 25 April 2023.

31 "Spot versus Garmin InReach Prices and Annual Plans." Fly2Base Paragliding Shop, https://fly2base.com/blogs/news/spot-versus-garmin-inreach-prices-and-annual-plans, 25 April 2023.

32 "Spot X®." SPOT X® Satellite Messenger | GlobalStar US, https://www.globalstar.com/en-us/products/spot-for-business/spotx, 25 April 2023.

the users when navigating. Plans cost $290 a year for the basic annual plan with the SPOT Flex Basic Monthly Plan, totaling $224 USD a year leaving the plan costing up to $514 a year.

5.6 Verizon

Verizon[33] provides two primary satellite communications devices, rental of Iridium Extreme 9575[34], and Inmarsat IsatPhone Pro 2[35]. Some important features of the Inmarsat IsatPhone Pro 2 Rental, include “free incoming calls, water, dust and shock resistant, up to 8 hours of talk time, Bluetooth for hands free use, extended battery capacity and includes international satellite phone number[36].” The device includes an “assistance button with GPS location data, tracking to send location information, incoming calls alerts and IP64 ingress protection against water, IK04 rating for durability.” Pricing is charged per minute, “to a landline $1.79 per minute, text messages $0.59 per message, cellular $1.79 per minute. Iridium Extreme 9575 includes “Global coverage, water, dust, shock and vibration resistant, SOS and text messaging capability, GPS-enabled location-based services, supports online tracking and Google Mapping services as well as, includes international satellite phone number, optional US number available at checkout.” Pricing includes “incoming calls and tests free, outgoing (landline and cellular) $1.79 per minute, satphone to satphone $12.00 per minute, Local Text Message $0.59 per minute.”

5.7 AT&T

AT&T Mobility[37] “launched the Genus smartphone from satellite service provider TerreStar” that provides “dual-mode satellite and cellular service, will be available to enterprise and government customers, and will provide users with a line of sight to TerreStar’s satellite.” It is available for the United States but also “provide ubiquitous voice and data roaming across the United States (including Alaska, Hawaii, Puerto Rico and the U.S. Virgin Islands and territorial waters). With these capabilities the “Genus will cost $799 without a contract but will require customers to sign up for AT&T’s voice and mobile data plans''. “Users will have to pay $25 per month extra for the ability to switch over the satellite service--users will have to pay $0.65 per minute for voice calls via satellite and $5 per MB of data.''

5.8 Apple and the iPhone and Globalstar

While not a communications provider, the iPhone is one of the most popular phones in the world. Apple has partnered with GlobalStar to provide Apple customers with Cellular to Satellite communications to retain a competitive advantage. The iPhone-Globalstar service is conceived as an emergency service. It is possible and likely that the iPhone will also be able to communicate with other providers given the service provided by the operators the iPhone is operating on.

33 “Verizon Satellite Products.” Verizon Satellite Phone Solutions - Home, https://www.vzwsatellite.com/#, 25 April 2023.

34 “Iridium Extreme® 9575 Rental.” Verizon Satellite Phone Solutions - Iridium Extreme® 9575 Rental, https://www.vzwsatellite.com/products/rental/iridium9575, 25 April 2023.

35 “Inmarsat IsatPhone Pro 2 Rental.” Verizon Satellite Phone Solutions - Inmarsat IsatPhone Pro 2 Rental, https://www.vzwsatellite.com/products/rental/isatphonepro, 25 April 2023.

36 Verizon Satellite Phone Solutions - Inmarsat IsatPhone Pro 2 Rental

37 “AT&T Launches TerreStar's Genus Cellular-Satellite Phone”, https://www.fiercewireless.com/wireless/at-t-launches-terrestar-s-genus-cellular-satellite-phone, 21 September 2010.

6 Cost as it Impacts Cellular to Satellite Communications[38][39][40][41][42]

SpaceX and Blue Origin are revolutionizing space by driving the cost of getting to space down dramatically. While we did not have figures for Blue Origin[43] on costs, we did find some insightful comments from Elon Musk about SpaceX and cost. Musk stated:

- "Payload reduction due to reusability of booster & fairing is <40% for F9 & recovery & refurb is <10%, so you're roughly even with 2 flights, definitely ahead with 3. "
- Boost stage, Musk stated, "costs around 60% of the total costs, with the upper stage 20%, the fairing 10%, and the final 10% associated with the launch itself."

It remains to be seen if Starship will work, but we believe it will and it will dramatically change access to space and further drive the cost of cellular to satellite communications down. SpaceX needs the Starship/Falcon Heavy combination to work as they need the large cargo bay to accommodate the new Starlink V2 satellites essential for their partnership with T-Mobile and others to work.

Starship is a 394-foot (190m) rocket sitting on the pad. It could radically redefine space travel, make orbital flight as cheap as airfare, and set the stage for opening the Solar System to humans. It could also leave SpaceX, and Musk, completely in control of a monopoly on the future.

SpaceX regularly lands and reuses the Falcon 9 bottom stage, and at least some boosters from Falcon Heavy at a cost much, much lower than their competitors with a reliability near 100%. The Falcon 90 has made over 80 successful flights with SpaceX offering flights at a reported cost to orbit of ~$2,600/kg. Falcon Heavy cuts that to ~$1,400/kg for those that need the capacity. If you have a satellite to put in orbit, particularly a large satellite, not using SpaceX takes a lot of explaining. This is shown in **Figure 8 Declining Costs for SpaceX for their Falcon 9, Falcon Heavy and Starship are well below their competitors**.

In 2016 it was reported that SpaceX could give customers a reported 30% discount on launch services and for 2022 it is reputed to be 40%. Reserving fuel in rockets' first stage and adding landing legs adds weight to vehicles that cannot be invested in task of placing payloads into orbit. Mass penalty, and not the cost of the fuel, that is key performance metric, and maximum performance numbers are for expendable launchers; subtract 30% to 40% for reusable booster payload.

Key features of the Starship are:

- Falcon rocket boosters are recovered but upper stage usually a one-off.
- Starship—larger, and much more powerful than Apollo-era Saturn V — is intended to be 100% reusable.

[38] Article "We're about to witness something that could vastly change the future, and absolutely no one is ready" https://www.dailykos.com/stories/2023/4/8/2162838/-We-re-about-to-witness-something-that-could-vastly-change-the-future-and-absolutely-no-one-is-ready, accessed 20 April 2023.

[39] "SpaceX's new price chart illustrates performance cost of reusability", https://spacenews.com/spacexs-new-price-chart-illustrates-performance-cost-of-reusability/, accessed 20 April 2023.

[40] SpaceX's reusable Falcon 9: What are the real cost savings for customers?, https://spacenews.com/spacexs-reusable-falcon-9-what-are-the-real-cost-savings-for-customers/, accessed 20 April 2023.

[41] Article "How Much Cheaper Are SpaceX Reusable Rockets? Now We Know", https://www.fool.com/investing/2020/10/05/how-much-cheaper-are-spacex-reusable-rockets-now-w/, accessed 20 April 2023.

[42] "SpaceX: Elon Musk breaks down the cost of reusable rockets", https://www.inverse.com/innovation/spacex-elon-musk-falcon-9-economics, accessed 20 April 2023.

[43] Blue Origin Website, https://www.blueorigin.com/, accessed 03 May 2023.

Vendor	Launch Cost per kilogram
Russia Soyuz	18,000.00
US Atlas II	18,000.00
European Arianne 44	18,000.00
China Long March 2E	10,000.00
US Delta IV	10,000.00
India PSLV	8,500.00
India LSV3	8,000.00
China Long March 3	4,500.00
SpaceX Falcon 9	2,600.00
SpaceX Falcon Heavy	1,400.00
Space X Starship	100.00

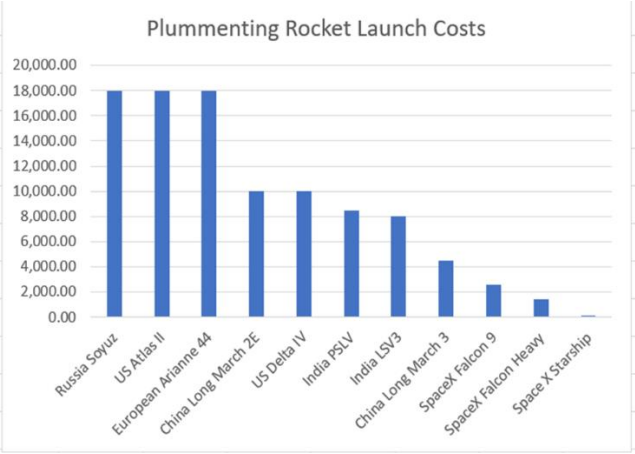

Figure 8 Declining Costs for SpaceX for their Falcon 9, Falcon Heavy and Starship are well below their competitors

- Musk has declared cost to orbit via Starship will be $10/kg, not $10,000/Kg. A better estimate is $100/kg.
- Cost of flying the rocket will no longer includes the cost of the rocket - just fuel, maintenance and launch services.
- 2022 a record year for rocket launches with 180 successful flights to orbit; 44 more than in 2021, also a record year.
- 61 of those 2022 launches were by SpaceX, and in those launches, it took more sheer tonnage to orbit than all other flights combined.
- With its Starlink constellation, SpaceX now owns most of all active satellites in orbit.
- SpaceX is the absolute dominant company in the launch industry. It is hard to find an example in any other field where a single company has such competitive advantage.
- Starship's huge size is in part to get past limitations that require rockets to be expensive precision machined devices made from the highest grades of aluminum and carbon fiber.
- Starship is made of stainless steel, welded together in hoops, like how water tanks are constructed and is cheap to build.
- Starship runs on methane and is cheaper to fuel.
- SpaceX wants to build 1,000 Starships - at the rate they are assembled it seems possible.
- 2nd plant to make Starships is under construction in Florida, and another launch tower.
- Starship individual boosters and ships are cheap enough that SpaceX has frequently built, then scrapped, whole ships as they have tested out ideas and moved through improvements in manufacturing.
- Starship on the pad right now is a couple of mini-generations behind ones currently resting in the "high bay" and "mega bay" up the street, waiting for their turn.

6.1 Starlink's Shrinking Satellite Costs[44]

A re-used Falcon 9, according to Musk costs about $15M to launch (15 tons to LEO.) Falcon 9 could carry 60 previous-generation Starlink satellites which is approximately $250,000[45] per satellite in launch costs. In a conference call in May of 2019, Musk stated the cost of launching a Starlink was more than the cost of building the satellite. That statement suggests Starlink's were being produced for about $250,000. SpaceX, has been building 120 satellites per month so clearly have economies of scale and associated cost savings. For later Starlink version 1 satellites they have introduced optical crosslinks that potentially added to the cost per unit. Speculation is that with growing economies of scale and efficiencies this likely cancels out the additional cost for optics keeping the price per unit at around $250,000.

The SpaceX Super Heavy Starship with a speculated fully reusable cost per launch of $5 million or less and the ability to launch 180+ could drive the cost to deploy 30,000 satellites, in the $3-5 billion range for a unit cost of $1 million per V2 Starlink without accounting for economies of scale. Additionally, the Starship program has a variant being built for NASA as a lunar lander which will help in economies of scale.[46]

[44] Cost to build Starlink satellites, website https://www.reddit.com/r/Starlink/comments/qurjn7/cost_to_build_starlink_satellites/, accessed 05 May 2023.

[45] SpaceX Starlink Satellites Could Cost $250,000 Each and Falcon 9 Costs Less than $30 Million, website https://www.nextbigfuture.com/2019/12/spacex-starlink-satellites-cost-well-below-500000-each-and-falcon-9-launches-less-than-30-million.html, accessed 05 May 2023.

[46] Musk Details Upcoming Starlink 2.0 Satellites, website https://www.extremetech.com/extreme/336495-musk-details-upcoming-starlink-2-0-satellites, accessed 05 May 2023.

7 Comparison between LEO satellites and terrestrial network

There is a lot of misunderstanding when it comes to satellite communications. Most people perceive satellite as an unreliable communications medium and that terrestrial services are superior in quality. Some people even think that a satellite can fall out of the sky. Others think that satellite cannot support TCP/IP or mission-critical applications or real-time applications like voice and video. None of these notions are correct. Many enterprises, when choosing a new IP infrastructure, choose satellite technology because of its lower cost, scalability, enterprise-wide consistency and ease and speed of deployment.

7.1 Ubiquitous Availability

Satellite is the only broadband wide area network technology that is available everywhere – in urban and rural areas around the world. All that is required for a location to receive connectivity from the satellite is a clear view of the sky unobstructed by trees, tall buildings or other objects. In contrast, terrestrial technologies are limited in their coverage area. In order to appropriately position satellite access against terrestrial alternatives, you need to be aware of the availability of terrestrial connection technologies. In fact, terrestrial connectivity is rarely available in remote locations, leaving no other alternative than satellite communications. But even if available, terrestrial connectivity still might not be the preferred option due to price competitiveness or SLA commitments that can be lower compared to satellite.

7.2 Network Reliability

Lines can be cut by construction projects; falling trees can take down utility poles; and equipment can fail at local telephone central offices – terrestrial networks have multiple potential points of failure where outages can occur. On the other hand, satellite has just three potential points of failure: the satellite, the hub and the satellite terminal, each of which has built-in redundancy in case of failure. Satellite outages are exceedingly rare but, should one occur, traffic to failed transponders is automatically rerouted to back-up transponders transparently to end users with no impact to the service. At the hub, online redundant equipment is used to provide immediate switching, again in a matter completely transparent to the end user, for uninterrupted service in the event of equipment failure. Finally, satellite equipment has the longest mean-time between-failure (MTBF) in the industry, and Orange provides its customers with extensive aftersales support via field engineers all over the globe.

7.3 Network Availability

Satellite communications are often said to suffer from rain fades and, therefore, presumably exhibit lower availability rates than terrestrial-based communications. This myth has been dispelled by properly engineering satellite links and provisioning enough margins so that rain fades have close to zero impact on link availability. This has allowed satellite links to feature availability ratios higher than 99.9% even in equatorial areas. More recently, new adaptive satellite waveforms (such as the DVB-S2 standard) have been able to exploit those power margins in order to provide higher throughputs while consuming the same satellite bandwidth.

DVB-S2 combined with ACM (automatic code modulation) is mitigating the issue of rain fade. Even under extreme rain conditions, the satellite link can still transmit and receive by lowering the bandwidth of the impacted site using the appropriate modulation scheme. And even while a site that is impacted by rain fade is transmitting at a lower bandwidth, this will not impact the other sites in the same network.

7.4 Single Service Provider

With satellite, the “long haul” and “last mile” are one and the same – a virtual circuit in the space between the hub, the satellite and the individual satellite terminal. Not only does this eliminate all possibility of failure – since construction crews digging up the street cannot sever a virtual circuit traveling over satellite

– it also means that satellite network users have a single end-to-end network provider that owns, operates and controls every portion of the network and can diagnose and fix problems immediately and unilaterally.

7.5 Uniform Service Levels

Orange satellite customers are assured of consistent, uniform service levels at every remote location: the same bandwidth, the same equipment, the same customer service and the same field support. Of course, consistency across all services, whether they be satellite or terrestrial, would be ideal. However, that is not always possible. For example, with DSL technology, the further the user is from the local telephone exchange, the less bandwidth he will have available. And in certain cases, the user might be out of reach and by consequence not eligible for DSL. These are just a couple of the factors that add complexity when managing the various service levels on a terrestrial network.

7.6 Economics

The economics of a satellite network are simple. The one-time charges for the antenna and associated net modem can be expensive; however, the hub and satellite space segment can be shared by many customer sites or even shared by different customers. This makes the ROI calculation attractive and, in certain cases, less expensive than terrestrial networks.

7.7 Timely Deployment and Installation

With a terrestrial network, deployment and installation of new locations typically involves multiple vendors. With a satellite network, installation and deployment are quick and simple. First, because satellite technology is completely free of terrestrial infrastructure, there is no need for coordination with the local exchange carrier or any other third party. An installation team can complete a site install in a matter of hours, no matter where the site is located. For this reason, satellite deployments are ideal in the case of emergency deployments. Satellite deployments are subject to authorized licensing and in country shipping regulations, which could, however, introduce deployment delays in some countries.

7.8 Multicast Content Distribution Capability

Satellite networks have a key strength in the distribution of bandwidth-intensive information to large numbers of remote locations. The advantage comes from satellite's inherent capability as a broadcast medium. Satellite can efficiently multicast content (at speeds up to 40 Mbps) in a single broadcast message to a virtually unlimited number of end-user locations. Through satellite technology, users are connected to the satellite through the same "virtual circuit" or space. By eliminating duplicate transmissions, satellite multicast technology maximizes the efficiency of existing servers and networks, freeing up valuable bandwidth and enabling more efficient use of current infrastructure. An added benefit is that content is delivered to all recipients simultaneously. The bottom line: satellite technology is a cost-effective choice for businesses that need to deliver large amounts of data, video or audio to many physically dispersed locations.

7.9 Site Relocation and Additions

One of the challenges of running a large multi-site network is the fact that remote sites tend to relocate over time and, if enough advance notice is not provided, it can be difficult and expensive to accommodate these moves. With a satellite network, the time frames required for moves are compressed. In fact, uninstall and reinstall can occur on the same day, in most cases, if the sites are close to one another. In addition, the monthly cost for providing service to a site does not change since, from a network perspective, the "virtual circuit" between the site and the satellite continues to serve the new location. When adding new sites, one of the major benefits of satellite technology is that, in most cases, additional

sites do not translate to additional monthly bandwidth costs. The bottom line: relocating and adding network sites is significantly less complicated and less expensive with a satellite network than with most terrestrial technologies.

7.10 Network Capacity Expansion

One of the biggest wide-area network challenges faced by many companies is the ever-expanding need for additional bandwidth to support new applications. With a satellite network, expansion is extremely easy and comparatively inexpensive. First, all bandwidth allocation is controlled at the hub, so increasing network capacity is as simple as increasing the amount of bandwidth allocated to the network. While it is possible that additional equipment may be required at the hub to support the increased capacity, this hardware can most often be installed in a matter of days. More importantly, no hardware changes or field technician visits are required at remote sites, since satellite equipment is designed out of the box to handle maximum bandwidth requirements. The bottom line: satellite technology provides a uniquely convenient environment for accommodating network and bandwidth expansion. emerging application support. As a broadcast medium, satellite is a perfect platform for the distribution of bandwidth-intensive content, such as video, software updates and large data files. Using satellite, you will add typically a 560 msec end-to-end delay, but that is not a significant drawback. A lot of improvement has been made by satellite manufacturers, and now satellite can easily support mission-critical applications like SAP and real-time applications like voice and video, providing a similar user experience as that of terrestrial networks. In addition, a satellite network can simultaneously transport a mix of very different applications for many different customers, while offering advanced quality-of-service mechanisms that enforce end-user SLAs. This ability to mix various streams on the same physical bearer enables large bandwidth gains using statistical multiplexing.

7.11 Conclusion

Satellite communications have emerged as an integral part of global IP networks. People and organizations need to stay connected to the network whenever they need it and wherever they are. However, terrestrial and wireless networks are inherently limited in their ability to provide this level of connectivity. Especially when companies are in remote places, satellite communications can be the only option. Even in low population density zones in Western countries, local PTTs can be disinclined to invest in communications infrastructure. Satellites can provide ubiquitous, instant coverage in these zones as well. Satellite communications can be used as a primary communications platform or as a back-up for a terrestrial infrastructure. Recognizing the growing demand, Orange Business Services offers satellite services on which IP applications can run reliably and efficiently. Orange provides organizations with immediate global reach – making critical communications possible in challenging and diverse environments. Orange is the only operator that can propose both alternatives – satellite and terrestrial infrastructure – and help customers decide which is the most appropriate to meet quality, availability and price-point requirements on a case-by-case basis. By integrating satellite technology within converged IP enterprise networks, we can serve sites in regions with poor or non-existent communication infrastructure either on land or at sea and in developed countries as an MPLS back-up.

Figure 9 A Rocket Launch from Earth as seen from the International Space Station (ISS)