COMMERCIAL COMMUNICATION SERVICES FOR NASA SPACE MISSIONS: CAPABILITY ASSESSMENT, OPPORTUNITIES AND CHALLENGES

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Abstract

The concept of utilizing commercial satellite communication services has become increasingly more attractive to US government agencies. Agencies such as NASA and the Department of Defense (DoD) are looking to replace their government-operated networks and services to save cost and focus on expanding the breadth of their assistance to upcoming missions. When considering the use of commercial services in the aerospace domain, several opportunities and challenges exist. We provide an assessment of the landscape that both government and commercial satellite communication companies face in seeking to gain traction in this market.

To pursue this opportunity, NASA is initiating a new program in FY2020 which will allow future NASA missions to deploy flight qualified capabilities for near-Earth users and receive support from commercial providers. The goal of this new program is to provide NASA the capability to move away from government-owned, contractor operated communications services to purchasing commercial communications services and capabilities. This shift is expected to bolster American industry, significantly reduce the cost of communication services to NASA, assure access to latest technologies, and maximize interoperability between government and commercial service providers.

In this paper we firstly identify and summarize the NASA SCaN Space Network's service characteristics and mission use cases. Secondly, we identify and summarize the current and future commercial communication satellite networks and their potential capabilities to provide services to NASA space network missions. Lastly, we analyze the opportunities and challenges the commercial satellite communication industry faces in order to provide these services.

1. Introduction

Over the last 60 years, the commercial satellite communications industry has been working to create new communication applications to provide global terrestrial and aircraft Internet services to meet increasing demand for high-bandwidth connectivity for fixed and mobile users. Trends in the industry indicate that geostationary commercial satellite communication networks can provide communication services to space missions in low earth orbit (LEO). Recently LEO and Medium Earth Orbit (MEO) commercial communication satellite companies who plan to provide communication services using constellations of small satellites have also emerged. This emergence is driven by increasing demand for broadband Internet service, as well as the availability of low-cost launch services. It is suspected that the LEO and MEO commercial satellite communication companies have the potential to provide services to space missions [1]. Audacy in particular is developing the world's first commercial inter-satellite data relay network of MEO relay satellites and ground facilities to deliver real-time connectivity to both commercial and government users, from launchpad to lunar distance [2]. NASA, the department of defense (DoD), other government agencies, and emerging commercial LEO earth-observation services are expected to form the core of the potential market for services to space missions.

NASA is currently exploring how they can utilize commercial communication network services for their space missions [3]. NASA space missions require reliable communication links to exchange data between the mission and the data users from launch to final operation. Currently, the NASA Space Communication and Navigation (SCaN) Networks provides these communication links to meet mission requirements. The Current SCaN architecture is a government-owned, contractor-operated model. The Space Network (SN) provides both tracking and data relay satellites in Geosynchronous Earth Orbit (GEO) with ground stations that relay data from space missions requiring continuous global coverage. The Near-Earth Network provides globally distributed ground stations. The Deep Space Network provides ground stations for planetary missions. All three SCaN networks utilize the terrestrial wide-area communication services provided by the NASA Integrated Services Network (NISN) [4]. In this paper, we provide an assessment of NASA space missions which currently use the NASA SN Tracking and Data Relay Satellite System (TDRSS) and could potentially utilize commercial communication satellite networks.

The following section provides a status of NASA's current SCaN SN and service characteristics. Section three summarizes the capabilities of emerging commercial satellite communication companies and their capability to service space missions. Section four details the potential opportunities for commercial service providers to provision services to future NASA missions. Section five discusses the challenges facing commercial satellite communication service providers provisioning service to future NASA missions.

2. NASA SCaN Space Network and Its Service Characteristics

NASA's Space Network (SN) is a GEO-based relay system which provides tracking and data transfer services for NASA missions and other users. The SN provides forward and return data delivery as well as radiometric, science, and calibration services for a multitude of use cases [5]. These use cases include terrestrial (aerial balloon, UAV, and ground); launch and post-launch operation (ELV support, suborbital, LEOP); LEO science weather missions (mission commanding and telemetry, low, moderate, and high volume platforms, space weather operations); human space flight (LEO operations, LEO servicing, LEO operations cargo and crew); near earth science platform (GEO); and low latency (space weather and real time observation) [6].

The SN is supported by S-Band, Ku-band and Ka-Band frequencies. The SN supports various mission phases, including launch, early orbit, operations, and disposal. It uses the Tracking and Data Relay Satellite System (TDRSS) to provide global coverage, high data rates, and high-precision tracking and clock-correlation services. Multiple ground terminals and other support facilities form the SN Ground Segment [5]. Figure 1 below shows the overall SN architecture.

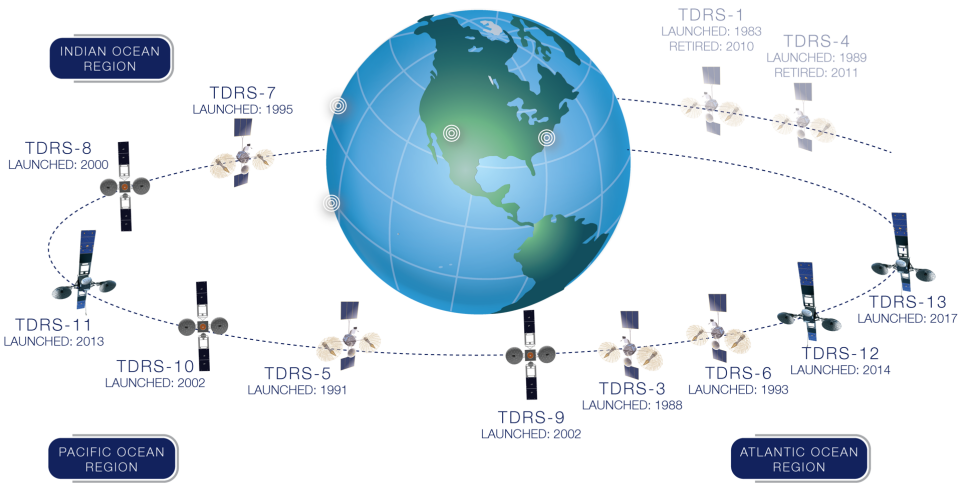

Figure 1. Space Network TDRSS and its Ground Stations

The TDRSS fleet is comprised of three generations of spacecraft. Thirteen tracking and data relay satellites (TDRS) have been developed, with seven spacecraft in operation and three spacecraft available for operations. A TDRS provides single and multiple access forward and return links to the user mission platform as well as providing radiometric tracking on each link and TT&C for the relay. The SN uses a demand access system to manage scheduling of extended durations and "near real-time" services. The SN can provide near-continuous communications services for 100 percent to platforms in LEO orbit about 73 km in altitude. For Medium Earth Orbit (MEO) and Highly Elliptical Orbit (HEO) SN can provide services when platforms are within the TDRS field of view [5] An example of TDRSS interfacing with multiple user mission platforms is shown in Figure 2 below.

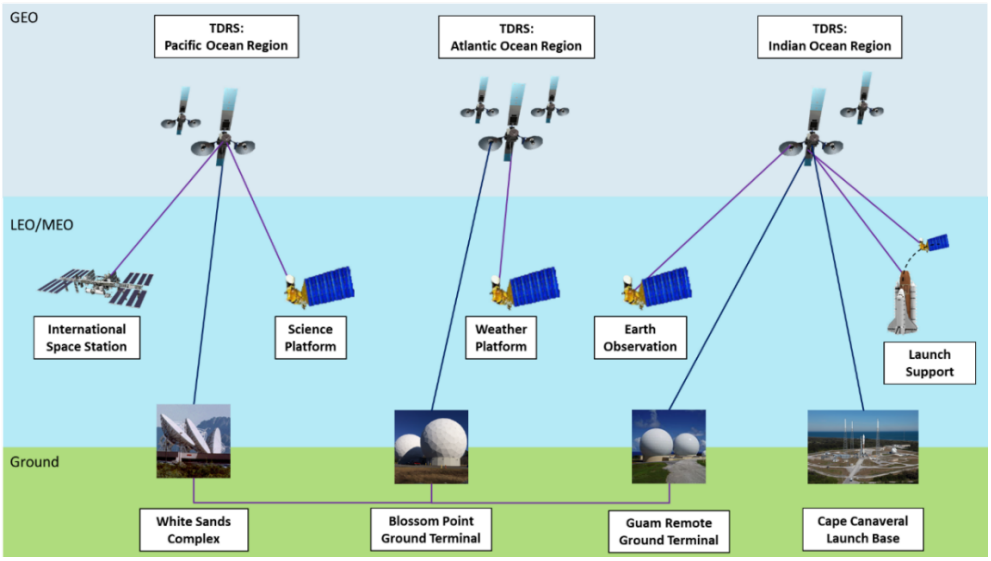

Figure 2. TDRS Support of Example User Mission

3. Commercial Satellite Communication Companies and Their Capability to Service Space Missions

Based on an understanding of SN services and NASA requirements, in this section we provide a summary of the companies most capable of providing commercial satellite communication services to NASA missions now and in the near future. This section is based on publicly available information. Table 1 lists the companies whose networks are currently available and Table 2 lists the emerging commercial satellite communication networks. At the end of this section, we outline the commercial satellite communication industry's overall capability to service space missions.

Table 1. Currently Available Commercial Satellite Communication Networks

Currently Available Commercial Satellite Communication Networks		
LEO	Frequency	Global
Iridium Communications (Iridium NEXT)	L-/Ka-Band	Yes
MEO	Frequency	Global
O3b	Ka-Band	No
GEO	Frequency	Global
ViaSat	Ka-Band	Currently- No Future - Planned
Inmarsat	L-/Ka-Band	Yes

Table 2. Emerging Commercial Satellite Communication Networks

Emerging Commercial Satellite Communication Networks		
LEO	Frequency	Global
OneWeb	Ku-Band	Planned for Global
SpaceX (Starlink)	Ka-/Ku-Band	Planned for Global
Telesat	Ka-Band	Planned for Global
MEO	Frequency	Global
Audacy	S-/K-/Ka-/V-Band	Planned for Global

3.1 Currently Available Services

3.1.1 Iridium Communications

Iridium Communications is an American company, headquartered in McLean, Virginia, which currently operates the Iridium NEXT satellite constellation, a system of 66 active Low Earth Orbit (LEO) satellites shown in Figure 3. Iridium Communication's original fleet has been officially decommissioned and the Iridium NEXT constellation is fully operational [7]. Iridium NEXT provides global coverage and can be used for voice and data communications. It provides services for a multitude of customers, including aviation, enterprise, government, land, IOT, maritime, and recreation.

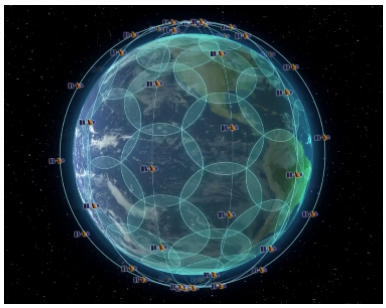

Figure 3. Iridium NEXT Constellation

Iridium NEXT has the strongest use case to support NASA balloon missions through the L-band frequency. Through the service platform Iridium Certus, the Iridium NEXT constellation can provide L-band downlink data speeds up to 128 kbps to mobile terminals and up to 1.5 Mbps to Iridium OpenPort class terminals. A 48-beam phased array provides global coverage via L-Band payload [8]. It uses Frequency Division Multiple Access (FDMA) combined with Tx/Rx Time Division Duplex (TDD) access and two hundred and forty 31.5 kHz bandwidth channels. It has a software-defined regenerative processing payload with a 176-element array, which is about 1m x 1m in size. The satellite has Ka-band cross links and Downlinks, an ADS-B payload, and an AIS payload.

Iridium Certus will deliver aviation services to aircraft cockpits and cabins for business, commercial, and rotorcraft aviation for an entire flight's duration from the runway to the flight ceiling. Iridium platforms are line-fit available on almost every original equipment manufacturer (OEM) platform and solutions for the cockpit, cabin, or a hybrid mix are available for all user profiles. It is expected that connectivity solutions are available from all current leading aviation industry manufacturers. Low-profile, small form factor antennas are compatible with several airframes, including turbo props and rotorcraft. [9] Table 3 below details the Thales Flytlink antenna options available to provide aircraft services by data rate [10].

Table 3. Iridium NEXT Aircraft L-Band Antenna Options by Data Rate

1.4 Mbps Download, 512 Kbps Upload	High-gain antenna variants to enable the fastest upload and download speeds to cover any cockpit communications need from safety services to an IP channel operational and business needs	Commercial Transport, Business Jets, Rotary, Military
708 Kbps Download, 352kbps Upload	Intermediate-gain antenna for broadband upload and download speeds and safety services	Commercial Transport, Business Jets, Rotary, Military
176 Kbps Data, and Voice	Active low-gain blade antenna for safety, voice and medium data rate services	Commercial Transport, Business Jets, Rotary, UAS, Military
2.4 Kbps Patch Antenna	Low-gain patch antenna for safety, voice and data services over Block 1 Iridium satellites	Commercial Transport, Business Jets

The company also states that Iridium NEXT will provide Ka-band downlink data speeds up to 8 Mbps to fixed terminals.

3.1.2 O3b.

O3b Networks Ltd. is a wholly owned subsidiary of SES, a Luxembourg based company headquartered in Betzdorf. The company is building and operating a Medium Earth Orbit (MEO) satellite constellation intended to provide voice and data communications to mobile operators and Internet Service Providers (ISPs). The network consists of 20 Ka-band satellites orbiting at an altitude of 8,000 km, completed with the final launch of satellites in April 2019 [11]. Now that the O3b constellation is complete, SES is planning to upgrade to O3b mPOWER, a seven-satellite constellation that will increase the network data rate from 1 Gbps to 10 Gbps. O3b mPOWER is expected to begin launch in late 2021 [12].

The core of O3b mPOWER will have 7 MEO satellites constructed by Boeing with 4,000 beams per satellite for a total of 30,000 fully shapeable and steerable beams capable of being shifted and switched in real time. The fleet of satellites will be designed to provide coverage to an area of 400 million square kilometers, about four fifths of Earth's surface, and deliver multiple terabits of throughput. It will provide coverage of +/-50 degrees latitude for nearly 400 million km^2. Table 6 below describes O3b mPOWER's customer markets and their offered services [13].

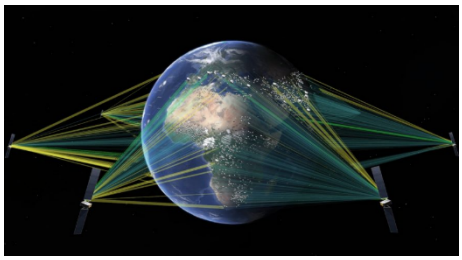

Figure 4. O3b mPOWER Constellation

Table 4 O3b mPOWER Customer markets and their expected services

Customer Market	Services Offered
Telco and Enterprise	Managed applications, intelligent traffic routing and more pervasive, high-performance connectivity designed for cloud-based applications
Mobile Network Operators	High-performance, rapidly deployed solutions for MNOs to expand footprint, connect more towers and migrate toward 5G
Maritime/Aero	Brings a premium, virtual fiber experience to more routes, smaller vessels, and commercial fleets, and brings the benefits of MEO-based service to the mass aero market
Governments	Secure, flexible and ubiquitous connectivity for today's high-tech military and its network-centric operations, as well as humanitarian operations

O3b mPOWER will include innovations in ground infrastructure, converging storage, computing, and routing resources with software intelligence and application-specific antennas. The network will also introduce the O3b mPOWER Customer Edge Terminal. The Customer Edge Terminals will deliver

advanced network capability in a small and easy to install device, making data services and advanced network functionality more accessible [14].

SES provides a hybrid approach to their network offerings, combining their GEO satellites with their MEO O3b satellites for increased reliability and optimum service. Through their hybrid combination, SES offers network communication services for customers in telecom, maritime, aero, energy, and government. From information publicly available, it appears SES networks does not provide solely MEO services from their O3b Constellation. However, from their website, it appears the new constellation O3b mPOWER is expected to offer solely MEO services [13].

SES Networks states O3b is the aeronautical industry's only hybrid GEO/MEO solution to provide broadband to airplane fleet owners and operators. They offer low round-trip data latency of fewer than 150 ms. Their services are capable of streaming, uploading and downloading large data files and communicating in real-time online. It is stated the service can provide low-latency, high throughput connectivity solutions up to 2 Gbps [13]. O3b markets several benefits of their own aviation services including:

- High-performance managed broadband internet service for global long-haul routes
- Regional solutions for short-haul flights
- Tailored MEO solutions with GEO diversity options
- Flexible future-proof satellite network solutions compatible with new antenna designs
- A dedicated team with a focus on enhancing the customer experience through new technologies
- 24/7 network operations center to monitor and ensure high quality of service
- Upcoming HTS capacity that will enable higher data throughput at a low cost per bit

3.1.3 Viasat

ViaSat is a global provider of satellite broadband and wireless services, infrastructure, and technology. They offer 3 types of primary services: Business, Government & Military, and Residential. On October 19th, 2011, ViaSat launched their first satellite, ViaSat-1, a single satellite offering 140 Gbps of throughput in Ka-Band. It is currently operational and providing residential internet services [15].

ViaSat-2 is also a single satellite and will offer 300 Gbps of throughput in Ka-Band. The satellite was launched on June 1, 2017 and has an expected lifetime of 15 or more years. The primary markets for the satellite's services are residential, aviation, and maritime. ViaSat plans to deploy over 40 gateways for the satellite to ensure that capacity capabilities are maximized. Users can connect to the ViaSat-2 network and then roam onto the KA-SAT network, a high-capacity Ka-band satellite system, part-owned by ViaSat through its European joint venture with Eutelsat, that delivers broadband communications across Europe and the Mediterranean basin. ViaSat-2 will offer download speeds of 100+ Mbps for residential customers.

ViaSat's current business aviation service plans offer peak download/upload speeds of 16/2 Mbps, with typical download/upload speeds of 10/1 Mbps and guaranteed download/upload speeds of 4/0.75 Mbps. The service plans vary in the amount of total monthly data allowance, ranging from 30 GB to 100 GB per month. ViaSat's current business aviation service plans range in cost from $6,995/month to $24,995/month, depending on the total monthly data allowance. ViaSat also has a currently active GSA schedule contract under Special Item Number 132-55 for Commercial Satellite Communications (ComSatCom) Subscription Services. The subscriptions services include pre-existing, pre-engineered Fixed Satellite Service and/or Mobile Satellite Service solutions, typically including shared satellite resources and contractor-specified equipment, in any commercially available COMSATCOM frequency band, including, but limited to, L-, S-, C-, X-, Ku-, extended Ku, Ka-, and UHF [15].

ViaSat-3, comprised of three satellites and ground network infrastructure, is expected to begin launch in 2021. Each satellite will offer 1 Tbps of throughput in Ka-Band. The satellites will be placed to provide global surface coverage, shown in Figure 4 on the right, as well as immediate connection to ground from satellites in LEO. The first two satellites will focus on the Americas and Europe, the Middle East, and Africa. The third satellite system is planned for

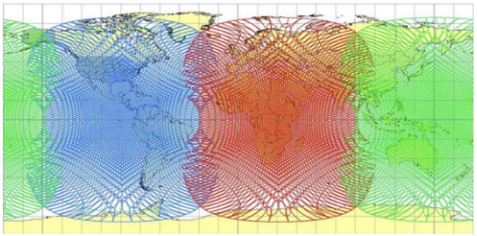

Figure 5. ViaSat-3 Fleet Coverage

the Asia-Pacific region. The first two satellites will deliver more than twice the total combined network capacity of the approximately 400 commercial communications satellites in space today. Communication using spot beams will provide constant connectivity through automatic service assignment and frequent, automatic handovers among spot beams. Ultimately, the ViaSat-3 network will provide 100s of Mbps residential internet service and up to 1 Gbps for use in maritime, oceanic, and other corporate enterprise applications [16].

ViaSat's network also provides government-certified data and network security. ViaSat high assurance filters are cross domain security products that permit data to pass between networks of different security classification levels. By enforcing rigid rules as defined by a "filter policy," these trusted filters ensure that only the desired data crosses the classification boundary, so that classified and non-classified data can be handled separately. ViaSat uses Inline Media Encryptors and Inline Network Encryptors certified by the NSA to provide data at rest and data in transit security for government communications. Additionally, ViaSat offers embeddable security systems certified by the NSA for Top Secret and below data and communications [15].

Viasat offers several mobile user terminal options for aircraft. Figure 5 at right shows ViaSat's global Aero Terminal 5530, a 2nd generation hybrid Ka- and Ku-band aviation satcom terminal that enables global broadband connectivity services for commercial and government users on global high-capacity satellite networks. The fuselage-mounted antenna and on-board modem can be configured for a variety of in-flight applications and missions [17].

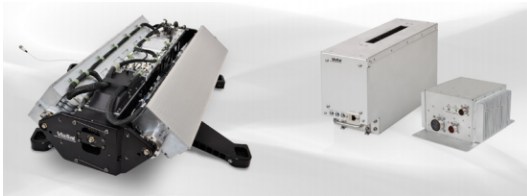

Figure 6. ViaSat Global Aero Terminal 5530

ViaSat-2 can accommodate most of the requirements of the defined Current and Future Use Cases of NASA space missions in terms of data rates. However, a LEO user mission is not compatible with ViaSat-2 as a relay satellite because only a very small portion of the globe is covered, and the connection time is minimal. If a LEO mission were to connect with ViaSat-2, the user can expect an EIRP of 63.43 dBW in the worst-case scenario. ViaSat-3 provides good coverage to low-inclination and low orbiting satellites, but coverage begins to reduce significantly at higher inclinations and higher orbits. ViaSat-3 can support the data rates of most of the defined use cases but the maximum data rate is heavily dependent on the supported modulation and coding schemes. A user mission can expect to require an EIRP between 61.45 and 70.25 dBW and a G/T of 16.76 – 22.76 dB/K to achieve the maximum data rates in worst-case scenarios.

3.1.4 Inmarsat

Inmarsat is a British satellite telecommunications company offering global telephone and data services. The company provides these services via portable or mobile terminals which communicate with ground stations through geostationary telecommunications satellites. Inmarsat has grown to a fleet of 13 geostationary satellites, providing services to the maritime, enterprise, aviation, and government markets and has become the world's leading provider of global mobile satellite connectivity. Inmarsat's current operational satellites include both the Inmarsat-4 (I-4) and more recent Inmarsat-5 (I-5) constellations. Figure 6 below is a graphical representation of Inmarsat's I-3 (now out of service), I-4, and I-5 networks. Inmarsat's future constellation is Inmarsat-6 (I-6), projected for launch in 2020 [18].

I-4 was the world's first global '3G network' via Inmarsat's BGAN network and has a projected lifespan into the late 2020s or longer. Each satellite has 19 wide beams, 200 narrow spot beams, and dimensions of 7m x 2.8m x 2.3m [18].

The I-5 constellation currently consists of 4 satellites to support Inmarsat's Global Xpress service, a global commercial wideband Ka-band satellite system. The constellation utilizes either solely Ka-band or a hybrid of L-band and Ka-

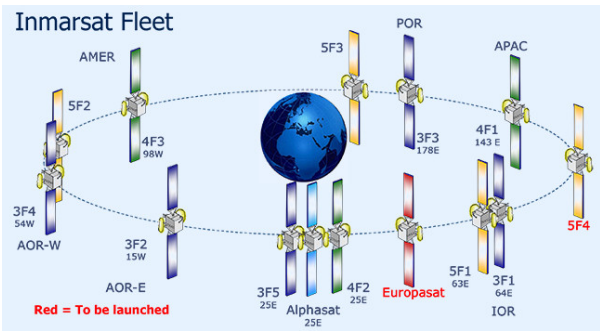

Figure 7. Inmarsat Fleet representing I3, I4, and I5 by color

band to provide increased network reliability. Each I-5 satellite has 89 spot beams, 6 steerable spot beams, and an overall throughput of 330 Mbps. The I-5 constellation has a projected lifespan of 15 or more years and will most likely function into the early 2030s [18].

The next generation of Inmarsat satellites is projected to augment both L-band and Ka-band Global Xpress services. It is yet unknown how many satellites will ultimately be in the Inmarsat-6 (I-6) constellation, but the first two mobile communication satellites have been contracted to Airbus Defense and Space, with the first satellite scheduled for launch in 2020. I-6 has a projected lifespan of 15 years and will function until the late 2030s. The design of the initial satellites will take advantage of lower mass electronic propulsion technology to enable a dual payload mission, including an above average next generation digitally processed payload. The satellites will have over 200 spot beams, a 9-meter aperture L-band antenna, and nine multibeam Ka-band antennas [18]. Figure 2 below demonstrates how an Inmarsat satellite can provide services to LEO spacecraft.

To provide services for LEO satellites, Inmarsat uses the Addvalue Inter-Satellite Data Relay System (IDRS) and its transceiver as shown in Figure 7 on the right. This user terminal is intended to provide consistent real-time, on-demand LEO communication links for applications which require longer connectivity than can be provided by connections to ground stations alone. IDRS connects to a LEO satellite bus via Ethernet to act as an on-board, full-duplex IP modem/router. It was developed based upon the existing Inmarsat constellation and tested in space through a dedicated LEO mission interacting with the Inmarsat network. IDRS weighs 1 kg and has a data rate up to 200 kbps. It has several antenna options, including a fixed directional antenna that requires satellite pointing, a fixed hemispherical antenna with no pointing required and 100% coverage above 20 degrees elevation, and a fixed switched antenna with no pointing required and 100% coverage above 5 degrees elevation. The system's power consumption for Rx and Tx is typically 9-10 Watts, dependent on traffic and antenna configuration.

Figure 8. IDRS Transceiver

For the I-4 constellation, the allocated bandwidth per channel is only 200 kHz. This bandwidth only allows a maximum data rate of about 450 kbps, far too low for any science or human space flight use cases. The only case that can be used with the I-4 constellation is TT&C. I-5 allows much larger data rates than I-4, which can be very useful for the science use cases. While it can also do TT&C, the user requirements are significantly worse than those of I-4, which is due mainly to the use of different frequency bands (L-band for I-4 and Ka-band for I-5).

3.2 Emerging Commercial Communication Companies in LEO and MEO Orbit

The most notable companies preparing to provide LEO-based services include Telesat, OneWeb, and SpaceX. Audacy and O3B are preparing to provide MEO based services. In sections 3.2.1 and 3.2.2 we focus on Telesat and Audacy, as these are the emerging networks that have made recent progress, and give brief overviews of OneWeb and SpaceX.

3.2.1 Telesat

Telesat is a Canadian telecommunications company that has been in business for over 50 years. Until the announcement of their new LEO constellation, Telesat operated solely as a fixed satellite service provider, successfully operating a fleet of GEO Ka-band satellites and holding the title as the fourth largest fixed satellite provider in the world. Telesat successfully launched a test satellite in January 2018 and have performed multiple tests and demonstrations [19]. Their proposed satellite constellation is shown in Figure 8 at right.

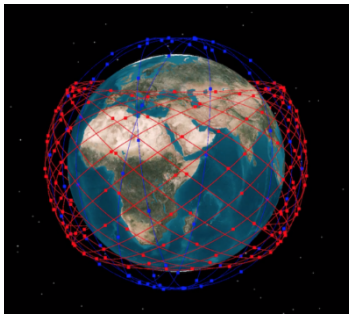

Figure 9. Telesat LEO Proposed Satellite Constellation

Telesat LEO plans to provide universal, cost-effective, high-performing, fiber-like global connectivity for business, government, and individual users. Telesat states it will provide full speed voice, video, encrypted and non-encrypted web services. Telesat LEO plans to have a high capacity with a total system output of multiple Terabits per second and reduce latency from 0.6-0.7 seconds of the current GEO satellites to 0.03-0.05 seconds. Telesat plans to use mechanically and electrically steered antennas to track and control the satellites movements. The

Telesat LEO constellation will provide high capacity optical cross links among satellites to function as a global mesh network. With advanced payload technology, the system will allow satellites to concentrate significantly more capacity over areas of high demand. The patent-pending design of the constellation contains 291 small satellites in two different orbits: Polar (91) and inclined (200) [19].

ThinKom Solutions has announced the completion of the first live test of a commercially available phased-array antenna with Telesat's Phase 1 LEO satellite. The test was performed using a production model of ThinKom's Ka2517 aeronautical satcom antenna, designed for business aviation, commercial air transport and military airborne applications. ThinKom's Ka2517 antenna successfully acquired, tracked, and maintained seamless end-to-end connectivity with the Telesat LEO satellite. [ThinCom] Once Phase I testing is completed, Telesat will initiate Phase 2, currently set to begin in 2020, to deploy the rest of their satellites. Telesat plans to begin providing commercial services with their LEO constellation by 2021 [20].

3.2.2 Audacy

Audacy, founded in March 2015 by a team of Stanford graduates, NASA award winners, and SpaceX veterans, is planning to launch a MEO space-based relay system consisting of three relay satellites to offer global communications services by 2021. Their proposed constellation is shown in Figure 9 below. Audacy's network architecture consists of four primary elements: the relay satellite constellation, a network of ground stations, user communication terminals, and Audacy's Quindar software platform. Together, these four segments will enable a seamless solution for space users ranging from CubeSats to space stations. Audacy plans to roll out its network in stages, beginning with services to a network of ground stations. Signals from users of Audacy's space-based network will be relayed to only three Gateways worldwide. Accordingly, data for all Network Users is routed through only one discrete U.S. location [21]. In December 2018, Audacy launched its first satellite, a CubeSat technology demonstrator called Audacy Zero which was also the world's first entirely Ka-band CubeSat. To date, the CubeSat has not been located after deployment and no communication has been established [2].

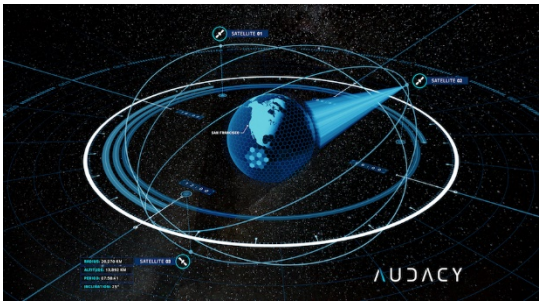

Figure 10. Audacy Proposed Satellite Constellation

Audacy provides several user terminal options to link to their network: integrating the Audacy client terminal on the user spacecraft, designing the user spacecraft's communications system to comply with the Audacy Interface Control Document, or reprogramming a deployed spacecraft on orbit to achieve Audacy compatibility. Once operators have integrated a Network-compatible User terminal onto their spacecraft, they will be able to uplink and downlink to and from their spacecraft anytime through any Internet-enabled device upon obtaining appropriate regulatory approvals. Figure 10 below displays the structure of Audacy's user terminal, which is a CubeSat form factor radio and antenna combination. Audacy supports a range of frequencies from S- to V-band with worst-case data rates ranging from 35 kbps to 22 Mbps for small satellite users.

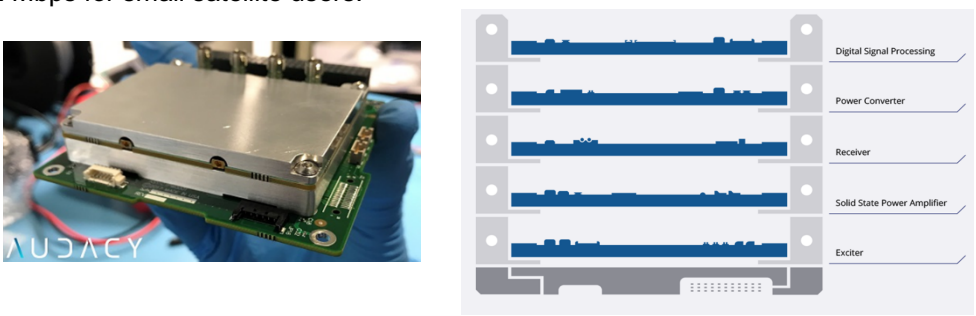

Figure 11. Audacy User Terminal Exterior and Interior Views

Audacy's business model is primarily geared towards providing relay services to LEO satellites. The basic user coverage provides service for LEO satellites while advanced users can receive coverage up

to an altitude of 10,000 km using steerable spot beams. Along with advertised rates for advanced users up to several gigabits per second, Audacy can potentially satisfy all the desired use cases.

3.2.3 OneWeb

OneWeb's overarching goal is to bridge the digital divide by 2027, making Internet access available and affordable to everyone on Earth. The company's satellite constellation will initially consist of 648 satellites operating in Low Earth Orbit (LEO) and communicate through the Ku-band frequency. OneWeb has also acquired priority rights to an additional 1,927 satellites. In March 2017, OneWeb filed plans for an additional constellation of 2,000 v-band satellites in non-geosynchronous orbit for communication services. This constellation would include 720 LEO satellites and another 1,280 satellites in MEO [22]. The company's proposed satellite constellation is shown in Figure 11 at right. Near the end of 2017, OneWeb announced a $190 million contract with Echostar subsidiary Hughes Network Systems to provide the terrestrial infrastructure necessary to distribute the company's internet services [23].

Figure 12. OneWeb Proposed Satellite Constellation

On July 22nd, 2019, OneWeb Satellites formally opened its facility to support the mass production of satellites. The company states they will be able to produce 2 satellites per day for a cost of under $1 million per satellite. Currently OneWeb is its only customer, with plans to start launching around 34 satellites per month beginning in December 2019. OneWeb plans to complete its launch cadence within two years, with the completion of the company's first constellation around 2022. OneWeb has already launched its first six test satellites in February 2019 and has stated that they are fully operational. The test satellites demonstrated the ability to provide broadband access at 400 Mbps and a latency of around 30 milliseconds [24] As OneWeb continues to plan launch tactics, the company is simultaneously building terrestrial gateways across the globe to ensure global broadband access [25].

OneWeb states that its constellation will be fully compatible with existing connectivity technology solutions, including Wi-Fi, 3G, and 4G and will offer 200 Mbps download and 50Mbps upload speeds. Latency is expected to be less than 50ms. Broadband service through ethernet is expected to offer rates of 2, 10, 24, and 48 Mbps. OneWeb provides several use cases for its constellation, including assured global communications for emergency response, in-flight connectivity, vehicle cell network for first responders, direct to home, schools, or health centers, and rural coverage for mobile operators. OneWeb plans to provide aviation services including weather, navigation, and aircraft health monitoring to business jets, commercial airlines, and military aircraft [26].

In May 2019, OneWeb announced a user terminal partnership with Intellian to enable high-speed, low latency service for remote enterprise and cellular backhaul connectivity expansion. These terminals will be used for a range of use cases, including connecting businesses in rural areas, schools, hospitals, farms, and community centers [27]. No information has been found or publicized on hardware for aviation services.

3.2.4 Space Exploration Technologies Corp.

Space Exploration Technologies Corp., commonly known as SpaceX, is a private American aerospace manufacturer and space transport services company headquartered in Hawthorne, California. SpaceX was founded in 2002 by entrepreneur Elon Musk with the goal of reducing space transportation costs and enabling the colonization of Mars. In addition to its many space ventures, SpaceX plans to deploy its own LEO satellite constellation, Starlink [28]. SpaceX ultimately plans for Starlink to include 12,000 satellites but will begin with 4,425 satellites as demonstrated in Figure 13 at right. The constellation will use the Ka- and Ku- band spectrum to provide a wide range of broadband and communications services for residential, commercial, institutional, governmental, and professional users worldwide [29]. In May of 2019, SpaceX launched its first 60 satellites into orbit. 45 of those satellites have officially

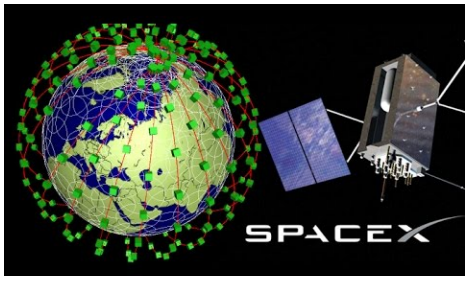

Figure 13. SpaceX Proposed Satellite Constellation

reached their intended orbit, 10 are in the process of reaching their final orbit, 2 are being tested for deorbiting, and 3 have lost communication and will eventually deorbit into Earth's atmosphere [30]. It is currently unclear when the next launch of Starlink satellites will occur. Musk has stated that the company will continue to launch batches of 60 satellites at a time with the goal of getting between 1,000 to 2,000 spacecraft into orbit each year. The company estimates it should take 24 launches to reach global internet coverage [31]. No terminal hardware has been made publicly available at this time.

3.3 Commercial Satellite Communication Services Capability Assessment

The NASA Space Communication and Navigation (SCaN) program is in the process of conducting multiple studies to assess the commercial satellite communication industry's capabilities and business interests in providing services to NASA space missions. The preliminary overall conclusion based on information provided during these studies and through analysing public information is that the commercial satellite communication industry cannot currently address all NASA space mission use cases.

There is moderate interest for established GEO-based commercial satellite communication providers such as Viasat and Inmarsat to provide services to NASA and other aerospace entities, but it does not appear that industry is developing a communication payload or terminal to enable NASA missions. If NASA wishes to use commercial satellite communication services, the administration will need to adapt itself to industry technologies and standards. This can be challenging, as many industry technologies are not standardized. Furthermore, industry estimated service costs do not include the upfront cost necessary to develop the compatible user terminals or other system adaptations necessary in order for NASA missions to use these systems without modification on the commercial entity side.

MEO-based commercial satellite communication providers like O3b and Audacy plan to provide high data rate, low latency services to aircraft and a variety of other platforms. Adaptability for these companies to provide services to NASA's future user missions is feasible. O3b already has an operating Ka-band MEO constellation with a planned upgrade in the near future. Audacy is less feasible to provide services, due to the fact the company has not launched any satellites and is only in the planning stages. It is unclear if and when Audacy will begin offering services.

LEO-based commercial satellite communication providers like Iridium Next plan to provide services to aerospace platforms such as airplanes and unmanned aerial vehicles. These companies will be able to address communication services to NASA aerospace platforms as well. The emerging LEO providers such as Telesat and One Web are developing small object applications for aircraft as well.

The NASA SCaN program is primarily interested in industry's ability to provide Ka-band link services. From our analyses, it appears industry will have comparable or lower performance for NASA missions when compared to TDRSS links. Current commercial satellite communication networks do not have additional links available to provide tracking services. Inmarsat, for example, only currently supports global coverage for terminals with omni-directional antennas. The NASA SN network will need to be kept in service for tracking purposes until industry can adopt the technology.

4. Potential Opportunities for Commercial Service Providers to Provision Services

In an effort to accelerate industry capabilities to suit government agency needs, the U.S. government and commercial aerospace industry are aligning their interests to create commercial satellite communication service applications. As discussed in the introduction, the main impetus for these efforts is the recent developments by commercial satellite communication companies to provide global broadband internet. The ability to successfully take advantage of these opportunities is highly dependent on how the U.S. government and commercial aerospace industry come together to reduce risks quickly and enable the desired services for their respective aerospace assets. This section therefore discusses NASA's initiative to partner with and provide opportunities for the commercial sector, identifies the existing market opportunities, and outlines the challenges for commercial service providers in provisioning services.

4.1 NASA's initiative in creating opportunities for the commercial sector

NASA recently set a goal to foster public private partnerships with commercial entities to reduce NASA development and operations costs and increase commercial engagement in providing services to space missions. Partnerships of this kind will foster new U.S. space commercial markets and expertise and enable an affordable, sustainable, flexible, and secure next generation open architecture for space communications and navigation. NASA has already successfully partnered with commercial industry to support cargo missions to the International Space Station and will soon do the same with crew missions as well. The flexibility of the future system will help NASA meet dynamically changing mission needs, access commercial services and capabilities, and lower development and operations cost. NASA's investment with commercial entities seeks to accelerate the availability of new services and capabilities and advance US commerce in space. It will also enable advanced US commercial communication relay capabilities [1].

4.2 Market opportunities

Market opportunities to provide communication services to current NASA missions are driven by the compatibility of the current TDRS system. Except missions which can accommodate commercial communication payloads like the ISS, balloons, or aero platforms, currently deployed science missions will not be able to utilize commercial services. If a commercial service provider has a low rate system that will operate in the government S-band, there may be some backward compatibility.

Certain use cases for future NASA missions will be candidates for utilizing commercial communication services. The emergence of smallsat missions offers the opportunity to use relay services not only for future NASA missions, but for future DoD and commercial LEO missions as well. If the spacecraft communication payload SWaP for smallsats can be reduced, made autonomous, and/or if services are set up as pay as you go, the commercial service providers can increase their market share. For high data rate missions, a pairing of optical communication services with Ka-band services will be optimal. Currently many of these missions are downlinking to Earth stations which do not provide real-time and global services, and relay can fill these gaps. Table 4 below outlines the opportunities

How quickly the opportunities can be realized by the private sector depends on what type of technology and operational expertise NASA is willing to share. It also depends on NASA missions' willingness to enable and participate in the development of communication payload, testing, and acceptance. In addition, it also depends on industry's willingness to work with NASA and tailor some capabilities/services to their mission needs.

Table 5. Market Opportunities for Current and Emerging Networks by Sector and Use Case

Use Case	NASA	DoD	Commercial Space Missions
Launch			X
LEOPs	X		X
SmallSat (Low Data Rate)	X	X	X
Medium Sat (Medium Data Rate)			
Large Sat (High Data Rate)		X	
UAV		X	
Airplane		X	
Lunar	X		X

5. Challenges for Commercial Service Providers in Provisioning Services

Several challenges exist for both NASA and the commercial aerospace sector in provisioning services to NASA Space missions. One challenge is the availability of commercial services and communication terminals to assist NASA user platforms. The current pattern is for commercial industry to release optimistic forward-looking statements about their services and availability but lack detailed actions for a realistic timeline. NASA will require more information to understand the availability and coverage data in order to determine which types of services can serve various categories of NASA missions. Once these requirements are satisfied, the development of communication terminals for a variety of NASA user mission platforms will remain a challenge due to cost, testing, and interoperability. Even though NASA simply plans to obtain commercial services, without significant cooperation between NASA and industry the rate of using the commercial services will be slow. Other changes NASA faces include reliability of commercial communication networks and services, security, spectrum allocation, frequency band sharing, regulatory considerations, sustainability of the services, and the ability for NASA to adapt to the commercial services.

6. Summary

NASA initially formed TDRSS to serve human exploration missions. Several decades later, the novel system has grown to provide a large variety of relay applications for science, LEOP, UAVs, and balloon platforms. TDRSS operates using a diverse set of technologies, including multiple frequency bands and single access/multiple access links and is now working to demonstrate optical communications. Significant growth in commercial satellite communication networks and the advancement of new technologies is attracting NASA to seek alternative solutions for its relay services to space missions. NASA is currently taking action to enable commercial satellite communication services, but there are many factors involved in allowing NASA to take advantage of commercial capabilities. NASA's overall desired outcome is to reduce in-house communication operations by allowing multiple commercial satellite communication networks to provide low cost services to NASA mission platforms in a reliable, secure, and sustainable manner. How NASA and the commercial sector work together moving forward will determine the outcome in the coming years.

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