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The Decade of Light: Innovations in Space Communications and Navigation Technologies

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INTRODUCTION

NASA's Space Communications and Navigation (SCaN) program office's vision of a fully interoperable network of space communications assets is known as the Decade of Light. Through relentless advancement of current technologies, NASA is progressing toward a future of seamless mission enabling space communications and navigation. This futuristic, interoperable system will include the development of optical communications, wideband Ka-band, hybrid optical and radio frequency (RF) antennas, user-initiated services (UIS), a cognitive network with disruption-tolerant networking (DTN) capabilities and autonomous navigation. This vision, although vastly complex, will introduce dramatic increases in performance and is already being worked at NASA Headquarters, NASA's Goddard Space Flight Center, NASA's Glenn Research Center, and Jet Propulsion Laboratory. Teams from around the country continue to investigate and strive for innovative solutions to the many complex challenges space communications and navigation faces.

CURRENT CAPABILITIES

For the past 50 years, NASA has primarily used RF to communicate mission data from satellites orbiting in our solar system to data users on Earth. Using the allocated segments of the electromagnetic spectrum, NASA can collect data from the International Space Station, Hubble Space Telescope, Mars Curiosity Rover, Saturn's Cassini, and many other significant agency missions. This data leads to discoveries about the universe, its formation, behavior, and the celestial planets that exist within it.

NASA's communications networks support more than a hundred missions, some of which are orbiting Earth, collecting vital weather and climate change data, while others are interplanetary missions venturing far out into the depths of our solar system and beyond. These missions use NASA's three communications networks, the Near Earth Network (NEN), the Space Network (SN), and the Deep Space Network (DSN).

The NEN is comprised of ground antennas systematically placed around the globe at 14 different ground stations to enable low-Earth orbiting (LEO) and geosynchronously orbiting (GEO) missions to communicate data down to the Earth. Using larger ground station antennas, the NEN is also capable of providing support to missions out to the L1 and L2 points, which are 1.6 million kilometers (km) away from Earth's surface.

Orbiting above the Earth at about 22,000 miles is a constellation of 10 Tracking and Data Relay Satellites (TDRS). TDRS provides continuous global communications coverage for NASA's near-Earth missions. Missions are able to send their data to a TDRS, which then transmits it down to the White Sands Complex in New Mexico or the Guam Remote Ground Terminal in Guam for processing. The first TDRS launched in 1983, and the network has been continuously evolving into today's architecture, the SN.

Spacecraft venturing out far into the solar system to investigate planets like Jupiter or Pluto must use the DSN. The DSN supports these planetary missions through expansive antennas set around the globe at three near-equidistant locations on the equator, approximately 120 degrees apart.

These networks, using RF technologies, enable NASA to collect scientific data, such as pictures and measurements, as well as information on astronaut and spacecraft health and location. While RF is a tried and true method of communicating, NASA is continuously looking for advancements. In recent years, NASA has been experimenting with optical communications, which uses lasers – light – to transmit data to and from satellites in orbit.

REALIZING THE VISION

Optical Communications

Advanced communications systems will enable NASA to support tremendous volumes of data at higher rates with quicker response times. NASA is developing and testing optical communications technologies to enhance communications and navigation activities and services for the user. Optical communications encode data into a beam of infrared light, which is then downlinked directly from a satellite or via a space relay to Earth-based ground system terminals.

Optical communications systems have significant performance advantages over RF technologies. By using optical communications, we achieve a lighter, more efficient and secure method to transmit mission data down to Earth. These advantages are being recognized by both NASA and commercial entities as we look for improvements for scientific data transmission and astronaut communication.

1. Optical communications systems have less mass, size and volume than the standard RF system, requiring less power to operate and reduced costs for a space mission. Additionally, optical ground stations are significantly smaller (less than 0.5-meter (m) aperture telescopes for near-Earth communications) and can be built around the globe at reduced costs. These infrastructure advantages are seen as highly desirable as we advance toward human spaceflight farther from the Earth.
2. The data rates that optical communications systems provide are also significantly higher than RF. This technology provides data rates that are 10 to 100 times better than RF systems. This will increase the amount of information that users on the ground can receive in regards to mission data and overall spacecraft health.
3. Optical communications technologies generate navigation observables four to five orders of magnitude more accurate than today's RF-based systems. Ultra precise navigation, time and frequency transfer will enable distributed spacecraft mission concepts and significantly enhance space-based geodesy and gravimetry.
4. Using optical communications is also significantly more secure, as the data is encoded into narrow beams of light. Data security is paramount in this recent era of cyber hacking. RF

technology uses a wider beamwidth signal to transmit spacecraft data, and is, therefore, more susceptible to infiltration.

NASA tested the use of optical communications on the Lunar Laser Communications Demonstration (LLCD) in 2013, when LLCD successfully transmitted data through the 400,000 kilometers from the Moon to Earth at a rate of 622 megabits per second (Mbps). Additionally, they successfully beamed data up to the satellite at 20 Mbps. These rates were significantly better than previous state-of-the-art RF communications systems at the Moon while the optical flight terminal was smaller, lighter and used less power.

To further demonstrate the tremendous capabilities of optical communications relay satellites, NASA has developed the Laser Communications Relay Demonstration (LCRD), which will display the operational longevity and reliability of an optical communications relay satellite. The LCRD mission will allow NASA to test optical communications technology in a variety of weather conditions and at various times of the day over an extended period of time. To communicate LCRD's data down to Earth, NASA has developed two optical ground stations at Table Mountain, California and in Haleakala, Hawaii. The demonstration will provide at least two years of continuous high-data-rate optical communications from GEO and will evaluate technologies for both LEO and deep-space applications. Additionally, NASA's TeraByte InfraRed Delivery (TBIRD) system will demonstrate a direct-to-Earth optical communication link from a CubeSat in LEO at burst rates up to 200 Gbps. This link is capable of delivering more than 50 Terabytes per day from a small spacecraft to an individual small ground terminal. [1]

Additionally, NASA has begun development of the Integrated Low-Earth Orbit Laser Communications Relay Demonstration User Modem and Amplifier Terminal (ILLUMA-T). ILLUMA-T will be the first fully operational user of the end-to-end optical relay services provided by LCRD. The terminal will leverage LCRD to send science data from the International Space Station (ISS) to mission control at Johnson Space Center (JSC) and then on to scientists around the world awaiting their mission data. This demonstration will prove that optical communications terminals onboard spacecraft are a reliable way to communicate mission data to laser communications satellites, which will then transmit the data to users on Earth. Typically, the ISS hosts six astronauts. Because they are living in a unique and challenging environment, communicating with them is a high priority. Maintaining communication and awareness about the station and its crew's health is imperative to keep the astronauts safe.

The Laser Optical Communications Near-Earth Satellite System (LOCNESS) is a next-generation relay concept that will be an operational optical relay. The optical communications technology will enable the relay to support user links and cross-links and at rates of tens to hundreds of gigabits per second.

In 2023, NASA is scheduled to launch the Orion Exploration Mission (EM)-2, which will be the first spacecraft in over 30 years to take astronauts beyond the Moon. EM-2 will observe the Moon and venture into deep space, gathering data about the unknown expanse. The Laser-Enhanced Mission Communications Navigation and Operational Services (LEMNOS) project will provide EM-2 with an optical communications system known as O2O. EM-2 will improve upon the communications capabilities of its predecessor EM-1, which will use RF technology by orders of magnitude. With the advancement of communications technologies, human spaceflight opportunities become a more feasible and less perilous journey for astronauts venturing into deep space. A future deep space optical communications demonstration is being developed. This robotic science mission will travel to the Psyche asteroid and will help mature communications technologies suitable for a human spaceflight mission to Mars as well as for increasingly complex robotic science and recognizance missions in deep space.

Optical communications ground system terminals need to be built in places with minimal cloud coverage to decrease the clouds' impact on data communication. Satellites utilizing RF systems can send data through clouds and do not have this disadvantage. Missions like LCRD, which utilize both RF and optical communications capabilities, can combat this issue by utilizing optical at the highest data rates when there is clear line of sight and using RF at lower data rates to send the highest priority data when cloud cover is present. If a satellite collects its data and is unable to transmit it to the ground stations due to cloud coverage, then the satellite must hold onto the data until communication is restored. If this halt in communication causes the onboard data storage to fill up, then the satellite will have to erase some data or will not be able to collect any new data, impacting its mission objective.

Expanded use of Ka-band

While optical communications systems have certain advantages, RF is still a reliable way to transmit data down to Earth. NASA is currently working to implement a wideband Ka-band network in space and across the globe. Ka-band is currently NASA's highest frequency used for communications, and wide bandwidth Ka-band systems span from 20 to 40 gigahertz (GHz), significantly surpassing the potential of X-band and S-band in terms of data rates. The long term goal of the Ka band effort is to enable a fully connected and interoperable network of ground and space relay assets. Missions could connect with either type of station, or both, based on the mission's communication requirements. With widespread Ka-band capabilities, satellites in orbit can be sure of constant and reliable wideband communication through these upgraded ground and space terminals.

Currently, six ground stations have Ka-band upgrades scheduled; these ground assets include both government and commercially provided capabilities. [2] A map of planned Ka-band upgrade is shown below in Figure 1.

These upgrades are taking place within the NEN and DSN. As the number of near-Earth and deep-space missions utilizing Ka band increase, our communications capabilities need to evolve to support future data downlinks. These missions are providing scientists, explorers and operations staff with both critical mission data and vital information on spacecraft health.

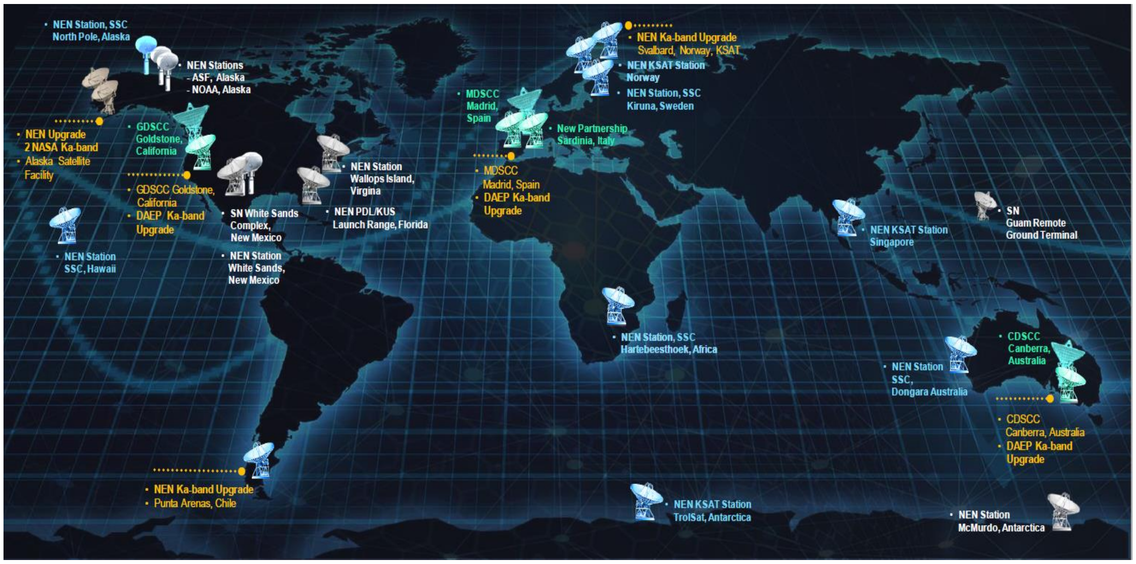

Figure 1. Map of Ground Station Assets and Planned Ground Ka-band Upgrades

Additionally, all second and third generation TDRS already have wideband Ka-band capability, supporting up to 1.2 Gbps rates in the near future. Future public private partnerships or commercial service providers will enhance these TDRS space relay capabilities. Flexible wideband user terminals will enable roaming in space between multiple commercial partners or other government providers.

RF/Optical Hybrid Antennas

As the NASA mission set evolves to include both RF and optical links, more ground apertures will be required. Ground apertures for deep space optical communications links will need to be optical telescopes in the 8m – 12m diameter range. To effectively meet this need, NASA came up with the hybrid communications systems idea. The hybrid antenna approach is a more economical way for NASA to get the large apertures required for deep space optical. Over the next century, the average data coming from deep space missions will significantly grow due to the increasing sophistication of science and reconnaissance instruments and eventual human presence in other planetary systems. This will radically increase required data rates. [3] To develop these hybrid antennas for deep space missions, NASA expects to integrate 8m optical apertures into a DSN 34m Beam Waveguide antenna by replacing the inner RF panels with primary spherical mirrors with appropriate correction optics and receiver packages behind the RF sub-reflector. [2] These hybrid antennas have been studied and are expected to have adequate stability and pointing capabilities with a small loss to the antennas' RF performance.

Operational Timeline for Optical Communications and Hybrid Antennas

These advancements are currently taking place through the efforts of many NASA centers. The timeline for these communications enhancements extends from 2018 through the next decade.

Many of the previously mentioned technology and system enhancements are already being worked on by NASA employees. NASA's NEN and DSN teams have already begun enhancing existing ground stations around the globe, adding Ka-band capabilities to support near-Earth and deep space missions. The LEMNOS, ILLUMA-T, LOCNESS and DSOC projects are in development and entering various stages of reviews and tests. Additionally, the LCRD payload is completed and ready for integration with the host spacecraft. The Decade of Light includes both the advancement of current technologies and the creation of new communications inventions that will enhance NASA's networks. The following sections discuss the interoperable services that would be available with these network enhancements.

See Figure 2 below for a detailed operational timeline.

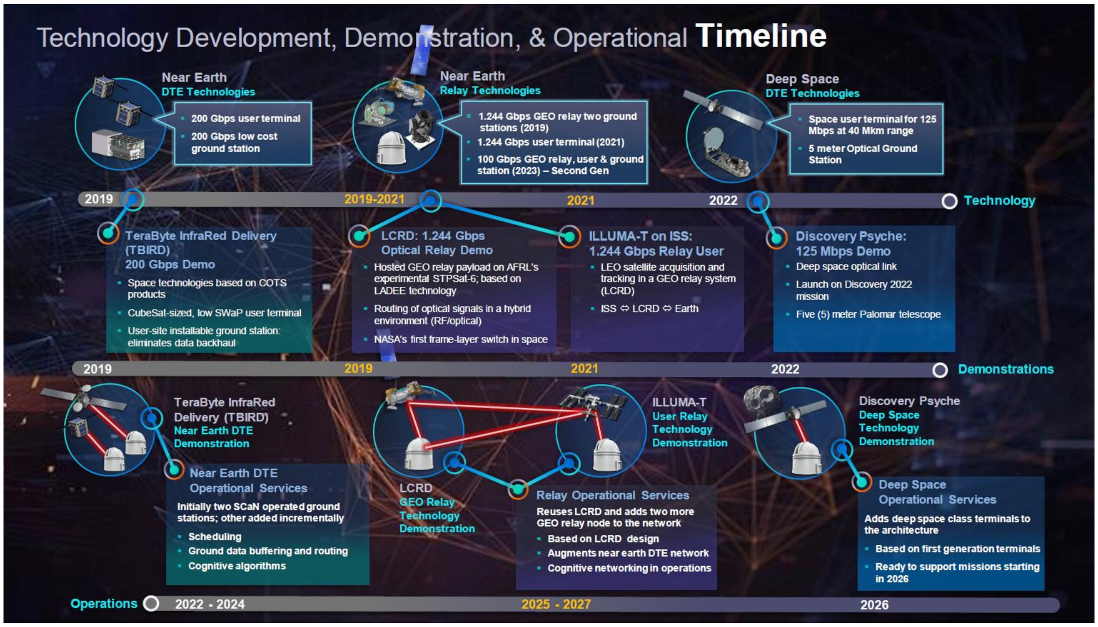

Figure 2: SCaN Development, Demonstration & Operational Timeline

THE SPACE MOBILE NETWORK

NASA is evolving its networks to provide functionality and mission user experiences to be more analogous to terrestrial mobile network users. This includes an emphasis on increased user interconnectivity and network availability all provided by services designed for interoperability with other international and commercial networks. This high-level architectural concept is referred to as the Space Mobile Network (SMN), it will allow for automated, efficient and easily accessible communications services, providing spacecraft with increased network performance that supports dynamic mission scenarios. [4]

Delay/Disruption Tolerant Networking

Delay/Disruption tolerant networking (DTN) will use standard interoperable protocols to provide networking functions such as routing, Quality of Service, and data security in ways that will operate in the challenging space communication mission scenarios. DTN protocols can ensure reliable data delivery despite intermittent link availability [2] and long delays due to the vast distances possible in space. The core DTN protocol is the Bundle Protocol (BP). BP uses a store-and-forward approach, allowing for data storage at nodes until the next link is available for connection. This enables spacecraft to send as much data as it can before a connection disruption, and then once the connection is restored, it can send the rest of the data. Data retransmissions and storage management can be done at the possibly smaller bundle level instead of the file level leading to some design and operational efficiencies.

The network-layer functionality enables ground stations to automatically send the mission data it receives to the proper users, without the ground station having prior knowledge. This includes automatic rate buffering to accommodate rate mismatches between space links and terrestrial data lines. Ground stations and relays then become the equivalent of network access points. The use of the interoperable network layer standards of DTN will allow the mission users and provider networks to evolve to be analogous to somebody connecting their laptop to a local Wi-Fi network.

As the number of users and data types increase in the larger network, prioritization of data flows will be required. Quality of Service (QoS) approaches will be used to allow missions to sign up and receive the desired level of service. This will be implemented by the use of prioritization of link scheduling and marking of the different user data streams.

Robust data security will always be a requirement and must be part of the system design from the beginning. Security may be implemented at each layer using different levels of encryption and other methods. A bundle security protocol will secure user data within each network data unit (bundle). This will not only provide protection over the space links but also as the bundles are stored in any intermediate locations.

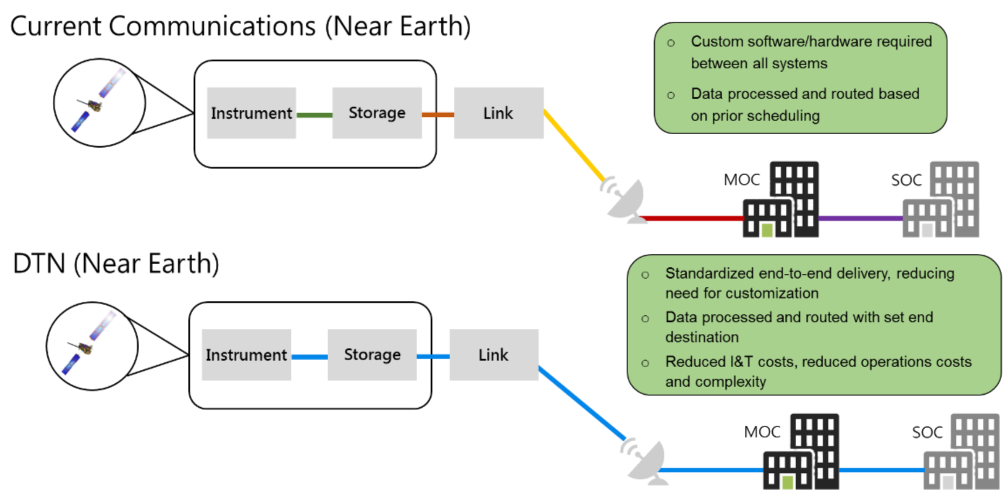

Figure 3. Current Communications Capabilities versus Disruption Tolerant Networking for Near-Earth Missions

User Initiated Services

User initiated services (UIS) is a service acquisition process that enables the data user to originate the service request. Typically, users have to schedule their services weeks in advance, and a sudden need for data or an unusual occurrence in space is difficult to capture with the usual scheduling method. UIS allows users to request data on a user platform; the platform then activates a request for end-to-end data delivery. This is done through a signaling channel containing possible links that are available to the user. Currently, the UIS technology is being explored and could possibly be integrated into the network capabilities. However, there are some restrictions to UIS implementation. Due to power constraints onboard, some spacecraft are unable to support a continuously-connected control channel. [4]

Cognitive Network

NASA is also experimenting with deep machine learning. This will enable the agency to program satellite systems to learn and think. In terms of space communications, the cognitive satellite system may track its repeated attempts to achieve communications, and learn which method works best for a particular situation or environment. This cognitive network of satellites will be able to sense the situation; it will know what job it needs to do and analyze the current environment and parameters. Through repeated attempts to communicate most effectively, the satellite system will learn. An example of this would be a satellite picking between direct to Earth versus space relay or RF technology versus optical communications systems to downlink data to Earth; Figure 4 is a visual depiction of this concept. The cognitive satellite system enables the spacecraft to make these decisions on its own, without needing humans to program the decisions.

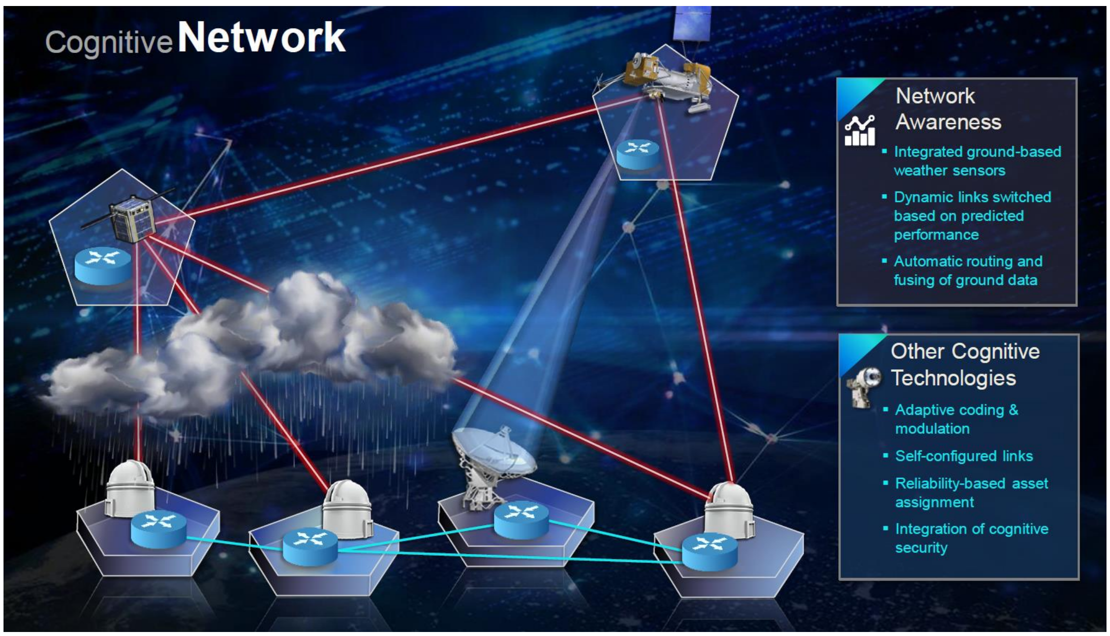

Figure 4. Space Communications and the Cognitive Network

Autonomous Navigation

Using the United States' Global Positioning System (GPS) and timing technologies, NASA can enable spacecraft to navigate autonomously. This will allow spacecraft to move from using current ground-based navigation systems, in which humans are in control, to real-time navigation onboard the spacecraft.

To enable the autonomous navigation, a forward link beacon signal has been designed. This will provide onboard navigation with enhanced radiometrics or optimetrics capabilities, while being able to also transmit critical mission data. Spacecraft navigation typically is controlled by ground-based orbit determination, but with autonomous navigation capabilities, the user state information can be determined to very high accuracy onboard the actual spacecraft. [4]

Government and Commercial Collaboration

The Decade of Light's plan to achieve space communications and navigation advancements cannot be completed unless government and commercial entities collaborate. The vision is to have a fully interoperable system in which both commercial and NASA satellites can achieve continuous communications support as the demand for critical, real-time mission data increases.

NASA's vision involves the interoperability of the industry-provided services alongside services provided by NASA, international partners, and other government agencies. NASA intends to develop shared RF and optical communications spacecraft and network capabilities. Commercial partners can provide operational services to NASA through shared investment, standards, risks, and benefits. Currently, the agency is exploring commercial opportunities to develop next generation space communications technology. [5]

By increasing government and private partnerships, the growth of the commercial satellite communications market continues and the development costs are shared. Through the development of the previously mentioned technologies, this interoperable system can be designed and implemented.

CONCLUSION

SCaN's Decade of Light will include the advancement of existing technologies alongside the development of never-before-seen space communications and navigation capabilities. With the next era of space communications arriving, NASA will support the increasing need for reliable data downlinks at all distances in space. This fully interoperable system will include the development of optical communications, wideband Ka-band, hybrid optical and RF antennas, UIS, a cognitive network with DTN capabilities and autonomous navigation, creating a Space Mobile Network. NASA is dedicated to finding optimal communications and navigation solutions to the challenging space environment.

ACROYNMS

BP	= Bundle Protocol
DSN	= Deep Space Network
DTN	= Disruption Tolerant Networking
EM	= Exploration Mission
GEO	= Geosynchronous Orbit
GHz	= Gigahertz
GPS	= Global Positioning System
ILLUMA-T	= Integrated Low-Earth Orbit Laser Communications Relay Demonstration User Modem and Amplifier Terminal
ISS	= International Space Station
JSC	= Johnson Space Center
LLCD	= Lunar Laser Communications Demonstration
LCRD	= Laser Communication Relay Demonstration
LEO	= Low Earth Orbit
LEMNOS	= Laser-Enhanced Mission Communications Navigation and Operational Services
LOCNESS	= Laser Optical Communications Near-Earth Satellite System
MBPS	= Megabits per Second
NEN	= Near Earth Network
O2O	= Optical Communications System for Orion
RF	= Radio Frequency
SCaN	= Space Communications and Navigation
SN	= Space Network
TBIRD	= TeraByte InfraRed Delivery
TDRS	= Tracking and Data Relay Satellite
UIS	= User-Initiated Services

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