NATIONAL TELECOMMUNICATIONS AND INFORMATION ADMINISTRATION

OFFICE OF SPECTRUM MANAGEMENT

The Spectrum Needs of U.S. Space-Based Operations:

An Inventory of Current and Projected Uses

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July 2021

EXECUTIVE SUMMARY

The United States is a global leader in the development and deployment of advanced, space-based technologies. Yet there is relatively little public awareness of the scope and scale or the economic benefits of these space-based technologies and even less recognition of the core public resource needed to operate and support them: radio-frequency spectrum. This report aims to provide basic information that will help increase public understanding of the scope and value of these space-based operations and the importance of their access to spectrum. It describes the wide range of government and commercial space-based operations and the value they provide to the economy and our quality of life, both here in the United States and globally. The report also contains detailed information about the specific frequencies used by these systems—a hopefully useful tool for policymakers and others going forward.

Every day, Americans use and depend on space-based technologies, whether they know it or not. Take the Global Positioning System (GPS), a U.S.-government satellite system, which is well known for the navigation services it provides to users of mobile phones and other devices. What is less well known, however, is the positioning, navigation, and timing applications GPS provides, such as synchronization of computer and financial networks and for satellite orbit maneuvers and orbit determination. Other important space-based technologies provide the data and images used to make accurate weather forecasts and the video we see of breaking news and live sports events. The progress we have made in predicting weather several days in advance—including real-time information on the path of hurricanes and tornados—is attributable in large part to advances in data from weather satellites. Similarly, our ability to see video from around the globe, whether on television or the Internet, depends to some extent on the ability of commercial satellites to transmit live images. For people in rural or remote areas, multichannel television and Internet access through satellite may be the only option available. The same is true for information about impending natural hazards and long-term monitoring of the climate, soil moisture, weather, precipitation, and pollination—each critically important concerns for the global community.

Less visible to most of us—but perhaps more vital for our security and prosperity—are the space-based technologies that drive our national security, public safety, space and earth exploration, and scientific infrastructures. Our military depends on space-based assets for planning, readiness, and tactical operations. The same goes for public safety entities at the national level, including the Department of Homeland Security (DHS), Federal Emergency Management Agency (FEMA), and the Forest Service, and at the state and local level, including government users, private agencies, and individual users. Air traffic control and the Emergency Alert System each depend on space-based systems.

Space-based systems and their services provide enormous economic benefits. Government services like GPS, weather forecasting, and air traffic control add hundreds of billions of dollars or more in productivity, efficiency, and safety, while improvements in national defense and science are incalculable. Communications enabled by space are equally valuable, particularly in rural areas and during emergencies.

Altogether, the space sector provides hundreds of thousands of high-paying jobs and the kind of innovation that must continue to characterize the American economy if we are to protect ourselves and stay at the forefront of the global economy. A recent review by the

Department of Commerce's Bureau of Economic Analysis (BEA) found the U.S. space economy added $108.9 billion value to the current-dollar GDP (0.5 percent of total U.S. current-dollar GDP). The BEA estimate included wages, salaries, and employer contributions to pensions and insurance, supporting more than 365,000 private sector jobs.

Space-based operations depend on access to spectrum for communications or observations—or both. Access to space itself—whether orbiting the Earth or travelling to the Moon and beyond—depends on the availability of spectrum. Spectrum is critical for rocket launches, to operate and communicate with Earth after launch, and to observe the Earth itself.

That access to spectrum is uniquely vulnerable to interference from other spectrum users, particularly when compared with ground-based systems that use spectrum. For ground-based operations, the distance between where a signal is transmitted and where it is received typically is measured in feet, miles, or tens of miles. In space-based operations, those distances are typically hundreds or thousands of miles and, for space exploration, millions of miles. As a result, the signals are relatively weak by the time they reach their destination. Additionally, some space-based operations, such as weather satellites and radio astronomy observatories, require a particularly quiet environment because they rely on receiving weak distant signals that cannot be boosted, for example from oxygen or water vapor molecules on Earth or from distant stars light years away.

In recent years, as many of these space-based operations have had to compete with each other and with the legitimate and rapidly growing demand for spectrum by other wireless users, there have been increasing concerns regarding the potential for interference to space operations. Those concerns have involved key space assets like GPS, weather satellites, radio astronomy, commercial operators, mobile networks, Wi-Fi, fixed microwave, and high-altitude platforms. To some extent, these kinds of concerns are inevitable as the demand for spectrum increases. Over time, technological innovation may help to increase the opportunities for spectrum sharing, but these laws of physics will always present challenges. A full appreciation for the value of space-based systems and their spectrum needs will enable policymakers to weigh necessary trade-offs.

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INTRODUCTION

The United States has been in space since the dawn of the Space Age in the 1950s. Indeed, America's domestic technology growth and global political leadership in the post-World War II era have strong ties to its pioneering role in space, as exemplified by the historic Moon landing in 1969. This report on spectrum access for space-based assets seeks to provide greater understanding of the role that spectrum access plays in supporting U.S. space-based activities.

To gather data for this report, in January 2019, the National Telecommunications and Information Administration ("NTIA") issued a Request for Comments (RFC) seeking stakeholder input.[1] Replying stakeholders emphasized:

- The importance of preserving stable and certain access to spectrum for space-based assets;[2]
- Protecting spectrum for GPS[3] and weather forecasting;[4]
- Providing access to spectrum bands needed for future consumer broadband satellite constellations;[5] and
- Affording sufficient spectrum access to enable a robust domestic space launch industry.[6]

NTIA also solicited and received non-public input from the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the Departments of Defense and Energy, and the National Science Foundation.[7] The Federal Communications Commission provided detailed information regarding the spectrum it has

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[1] NTIA, Comments on Developing a Sustainable Spectrum Strategy for America's Future, Docket No. 181130999-8999-01 (Jan. 29, 2019), https://www.ntia.gov/federal-register-notice/2019/comments-developing-sustainable-spectrum-strategy-america-s-future.

[2] *See* Comments of the Boeing Company, at 3-7; EchoStar Operating Corporation and Hughes Network Systems, at 2; Satellite Industry Association, at 1-2; SES Americom, Inc., and O3b Limited, at 3-4; and ViaSat, at 12-14. All of the comments are available at NTIA, Comments on Developing a Sustainable Spectrum Strategy for America's Future.

[3] *See* Comments of Boeing, at 12; *see generally* Comments of GPS Innovation Alliance.

[4] *See* Comments of Coalition of Aviation, Satcom, and Weather Information Users, at 11-13.

[5] *See* Comments of SES/O3b, at 7, 9, and 10; Space Exploration Technologies Corp. (SpaceX), at 9. Both companies said satellite allocations in the V- and Q-bands would speed broadband deployment across all technology platforms nationwide.

[6] *See* Comments of SIA, at 2-3; Comments of EchoStar & Hughes, at 3; Comments of Spire Global, at 5. Elsewhere, SpaceX also recommended increasing available launch spectrum. *See* SpaceX Notice of Ex Parte Communication, ET Docket No. 13-115 (May 30, 2017), https://ecfsapi.fcc.gov/file/105303042704142/SpaceX%20FCC%20Commissioner%20Chairman%20Pai%20Ex%20parte%205.25.17.pdf. These comments were concerned with the spectrum "available" to the commercial satellite industry (whether or not launching on a private launch vehicle).

[7] As of 2019, global government spending on space programs was $87 billion. *See* Space Foundation, "The Space Economy Scorecard" (Aug. 2020) ("Space Economy Scorecard"), https://www.thespacereport.org/scorecard/.

authorized for space-based operations, as reflected in Table 1 and the Appendix, the latter of which provides a spreadsheet of spectrum available for space-based uses. These public and private sector inputs have provided the nucleus for this report, which has been augmented by staff research and evaluation, as detailed in the remaining sections.

This paper provides information on government and commercial systems, respectively, and the value and breadth of services they provide to the U.S. public—a healthy, vibrant, and growing space sector. Notwithstanding the long-standing delineation of government and non-government spectrum use allocations, a distinction between government and private systems is not always clear, as many government systems rely on private industry and many of the commercial operations began with government support and count government as an important customer.

DISCUSSION

The United States government and an array of American companies use a wide variety and range of radio frequencies for critical, space-based operations.[8] Space-based communications include voice, data and video transmission — including entertainment, emergency alerts, broadband Internet access, financial transactions, tele-medicine and remote learning. Users of these communications systems are everywhere: on the ground, in the air, on ships, and in space, including eventually on the Moon and beyond. Space-based operations also are vital for science, taking measurements that are critical for weather forecasting, resource management, and astronomy. Looking ahead, government and commercial entities plan space manufacturing and mining, which will link to Earth via space-based networks.

Space-based networks have inherent capabilities when compared to terrestrial mobile networks. They provide:

- Coverage as wide as entire continents and oceans, including hard-to-serve rural and remote areas;[9]
- Service directly to an almost unlimited number of users at the same time, without extensive ground infrastructure;[10]

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[8] This report is limited to describing only unclassified systems and operations. Also, cybersecurity issues and "GPS-spoofing" concerns are beyond the mandate of this spectrum report.

[9] M. Sullivan, "This New Wave of Satellite Broadband Could Challenge Cable and Fiber," Fast Company (Mar. 13, 2018), https://www.fastcompany.com/40542241/this-new-wave-of-satellite-broadband-could-challenge-cable-and-fiber ("This new wave of satellite service may . . . let people in sparsely populated areas get fast, reliable broadband."). *Extending Wireless Telecommunications Services to Tribal Lands*, WT Docket No. 99-266, FCC 00-209, 15 FCC Rcd 11794, ¶ 13 (2000), https://docs.fcc.gov/public/attachments/FCC-00-209A1.pdf ("Satellites have large coverage areas and, in many cases, can reach an entire nation . . . . Satellites also provide communications opportunities for communities in geographically isolated areas, such as mountainous regions and deep valleys, where rugged and impassable terrain may make service via terrestrial wireless or wireline telephony economically impractical.").

[10] Intelsat, "Discover the True Benefits of 4K UHDTV with Satellite," (Oct. 2020), https://www.intelsat.com/wp-content/uploads/2020/10/intelsat-media-1west-4K-tipsheet.pdf ("Intelsat's wide-

- Observation of large portions of the Earth to collect scientific data; and
- Rapid deployment of user devices enabling near-immediate service to areas needing emergency connectivity when disaster impacts local infrastructure.

Today's space-based infrastructure mostly is based on satellite platforms. There are two basic types of satellites: Geostationary Orbit (GSO) satellites and Non-Geostationary Orbit (NGSO) satellites. GSO satellites orbit over a fixed point approximately 22,300 miles above the Equator, moving with the Earth's rotation so that they appear stationary. NGSO satellites orbit at different altitudes, including Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and highly elliptical orbits that can pass through the LEO and MEO regions.

These satellites come in a wide range of sizes and costs. At the large end are high throughput geostationary satellites (HTSs) that can weigh over 7 tons, cost over $600 million to build, require enormous rockets to launch, and have hundreds or thousands of gigabits of throughput capacity. These satellites typically are used to provide broadband and mobile communications. At the smaller end are NGSO CubeSats and other types of "SmallSats," which can weigh anywhere from less than a pound to a few hundred pounds.[11] SmallSats execute a wide range of tasks, including scientific, imaging, and communications missions. Traditionally, SmallSats were built by startups or academic researchers and launched as excess cargo on rockets used to put larger satellites into orbit,[12] but in recent years use of SmallSats for commercial and government operations has become more established, and some launches dedicated to SmallSats have become available.

In between are traditional GSO satellites and large constellations of NGSO satellites. The newest of these NGSO satellite constellations are "mega-constellations." Their proponents are beginning to launch systems with hundreds and even thousands of satellites to provide global broadband connectivity.[13]

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beam satellites easily cover the entire video neighborhood so distributors can easily get their content out to millions of viewers at one flat cost."); EUTELSAT, "A Guide To TV Distribution Models," https://www.eutelsat.com/en/blog/what-are-tv-distribution-models.html (last visited Dec. 31, 2020) ("While some infrastructure transmission costs increase based on the number of users, with satellite transmission, costs remain the same no matter how many viewers you reach").

[11] NASA defines SmallSats by weight: anything from about 0.001 kg (a "Femtosatellite") to a "Minisatelllite," weighing under 180 kg (400 pounds), roughly the mass of a small refrigerator. *See* NASA, "What are SmallSats and CubeSats?," https://www.nasa.gov/content/what-are-smallsats-and-cubesats (last modified Aug. 7, 2017). CubeSats are a modular form of SmallSats, with a standard size CubeSat unit, or "1U," measuring 10 x 10 x 10 centimeters, and are scalable to larger sizes consisting of multiple units.

[12] Scientists often launched them as low-cost projects. *See* L. Berthoud *et al.*, "University CubeSat Project Management for Success," 33rd Annual AIAA/USU Conference on Small Satellites (2019), https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=4362&context=smallsat; American Physical Society, "CubeSats prove their worth for scientific missions," Science Daily (Apr. 16, 2019), https://www.sciencedaily.com/releases/2019/04/190416132137.htm.

[13] G. Ritchie & T. Seal, "Why low earth orbit satellites are the new space race," Bloomberg Businessweek ("Bloomberg Space Race"), https://www.bloomberg.com/news/articles/2019-08-09/why-low-earth-orbit-satellites-are-the-new-space-race-quicktake (last modified July 10, 2020).

In addition to satellites, this report also covers radio astronomy facilities, which include radio telescopes on the ground and those planned to be in space, all of which listen for faint signals from space and rely on access to spectrum.

These space-based assets provide a wide variety of services, including the position, navigation and timing provided by the Global Positioning System (GPS), collecting data for weather forecasting, scientific exploration of the Earth and space, and critical communications used for national security and public safety, television and radio distribution, Internet access, flight safety, and space exploration. Satellites can provide links to fixed points on the ground, providing what is known as Fixed Satellite Service, or to stations or personal devices in motion, on land, sea, or in the air (Mobile Satellite Service). In recent years, as user terminals have become smaller, the distinction between Fixed Satellite Service and Mobile Satellite Service has blurred. Some satellites solely observe the Earth or provide communications on Earth, while others look out into space. Some space-based networks link satellites with each other or link the Earth with spacecraft such as the International Space Station.

Taken together, these space-based operations, public and private, are an essential and growing part of our everyday lives, our economy, and our national security,[14] and they warrant careful spectrum planning and management to sustain them. Table 1 provides a broad overview of the most relevant allocations of U.S. space-based spectrum use.

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[14] R. Bell, "Why is Mobile Having All the Fun?," Via Satellite (July 16, 2020), https://www.satellitetoday.com/opinion/2020/07/16/why-is-mobile-having-all-the-fun/ ("Commercial airlines can't fly without them. Computer networks won't run without them. Agriculture, energy, weather forecasting, trade, mining, military missions, national and border security, humanitarian relief — it is hard to find a critical part of the modern world that doesn't run on what I like to call the invisible, indispensable infrastructure of space and satellite.").

Table 1. Existing United States Space-Based Spectrum Use

Band	Frequency Range	Use Categories	Illustrative Systems
VHF **& Lower UHF**	**30-300 MHz** **300-1000 MHz**	Space Exploration	Int'l Space Station Systems (ISS), Mars Curiosity Rover, Mars Helicopter Scout, NASA IceCube
		Mobile Satellite Service	Orbcomm
		Defense/National Security	Space mission systems, Telemetry, Tracking, & Control (TT&C), active sensors
		Weather Observation/Earth Science	NOAA weather satellites, Polar/GSO Operational Environmental Satellite (POES/GSO), NASA RainCube
		Radio Astronomy	Goldstone Radio Telescope, Very Large Array (VLA), Owens Valley Long Wavelength Array
		Amateur Satellite	HUSKYSAT-1, Swampsat
L-Band	**1-2 GHz**	GPS/PNT	GPS
		Space Exploration	International Space Station (ISS)
		Mobile Satellite Service	Iridium, Globalstar, Inmarsat, Ligado
		Aircraft and Maritime Safety	Search and Rescue Satellite-Aided Tracking (SARSAT) System
		Defense/National Security	Positioning, Navigation and Timing (PNT), Space mission systems, TT&C, active sensors
		Weather Observation/Earth Science	NOAA weather satellites, (GOES, JPSS, and COSMIC-2); NASA CloudSatSMAP, Owens Valley Solar Array (OVSA)

Band	Frequency Range	Use Categories	Illustrative Systems
		Radio Astronomy	Arecibo Observatory, Green Bank Observatory (GBO)
S-Band	**2-3.6 GHz**	Space Exploration	Voyager 1 & 2, Hubble Space Telescope, Orion Multi-Purpose Crew Vehicle, TT&C
		Mobile Satellite Service	Globalstar, DISH
		Satellite Radio	Sirius XM
		Defense/National Security	Space mission systems, TT&C
		Weather Observation/Earth Science	NOAA weather satellites (POES, GOES, DMSP, DSCOVR); NASA Time-Resolved Observations of Precipitation (TROPICS), Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE)
		Radio Astronomy	VLA, OVSA
		Amateur Satellite	DTUSat-2 (Denmark), Es'hailSat-2 (Qatar), Reaktor Hello World (Finland)
C-Band	**3.6-7 GHz**	Space Exploration	NASA Tracking Radar (Launch vehicles, balloons, satellites, and aircraft)
		Fixed Satellite Service	Intelsat, Globalstar
		Defense/National Security	Space mission systems, TT&C
		Weather Observation/Earth Science	NOAA weather satellites, NASA Tropical Ocean Global Atmosphere (TOGA), JASON-CS, Surface Water and Ocean Topography (SWOT)
		Radio Astronomy	VLA, OVSA

Band	Frequency Range	Use Categories	Illustrative Systems
X-Band	**7-10 GHz**	Space Exploration	Voyager 1 & 2, NASA Lunar Reconnaissance Orbiter, Spitzer Space Telescope, Launch Operations Support
		Defense/National Security	Active sensor, mission, and TT&C space systems
		Weather Observation/Earth Science	Spire Global, Planet (Doves (Flock) and SkySats); Digital Globe; NOAA Weather Satellites (GOEES, JPL-CS); NASA EESS (ASA AQUA, AURA, Terra, Meteorological Radar)
		Radio Astronomy	VLBA, GBO, OVSA
Ku-Band	**10-17.8 GHz**	Space Exploration	Tracking Radar (Launch vehicles, balloons, satellites, and aircraft), Tracking and Data Relay Satellites (TDRS)
		Fixed/mobile Satellite	Intelsat, SpaceX, EchoStar, O3b
		Satellite TV	DirectTV, DISH
		Defense/National Security	Passive Sensors, Space mission systems, TT&C
		Weather Observation/Earth Science	NASA AQUA, Global Precipitation Measurement (GPM), High Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP), SWOT
		Radio Astronomy	VKA, GBO

Band	Frequency Range	Use Categories	Illustrative Systems
Ka-band	**17.8-40 GHz**	Space Exploration	ISS, TDRS, Deep Space Station 14 (DSS-14), Juno Deep Space Mission to Jupiter, Mars 2020
		Fixed Satellite	Intelsat, EchoStar, SpaceX, Telesat, ViaSat, O3b, OneWeb
		Satellite TV	DirecTV, Dish
		Aircraft Safety	Unmanned Aircraft Traffic Management Radar
		Defense/National Security	Passive sensors, space mission systems, TT&C
		Weather Observation (active & passive)/Earth Science	NOAA weather satellites: JASONs, NASA AQUA, GPM, WindSat, SWOT, HIWRAP
		Radio Astronomy	Very Long Base Array (VLBA), VLA
V-Band	**40-75 GHz**	Space Exploration	Deep Space Station 14 (DSS-14)
		Fixed/Mobile Satellite	EchoStar, SpaceX, Telesat, O3b
		Defense/National Security	Space mission systems, DSMP, TT&C
		Weather Observation/Earth Science	NOAA weather satellites, NASA, AQUA, JASON-3
		Radio Astronomy	VLA, GBO
W-band	**75-110 GHz**	Defense/National Security	Active and Passive Sensors and Space mission systems
		Weather Observation/Earth Science	NOAA atmospheric sensors, NASA cloud radar systems, AQUA, TROPICS, JASON-CS
		Radio Astronomy	VLBA, GBO, Haystack Radio Telescope

Band	Frequency Range	Use Categories	Illustrative Systems
mm band	**+110 GHz**	Weather Observation /Earth Science Radio Astronomy	NOAA atmospheric sensors; NASA AURA, TROPICS, GPM Arizona Radio Observatory, Smithsonian Millimeter Array

The following text explores in more detail these space-based systems, their uses, and their supporting spectrum allocations. The first section discusses government and non-commercial systems, which include the Global Positioning System, systems used for weather forecasting, defense, public safety, aviation, space exploration, and radio astronomy. It also describes non-commercial satellites operated by amateur radio and other entities. The next section discusses the vibrant American commercial space sector, a participant in the highly competitive global industry, characterized by increasing innovation. The description of commercial systems looks at those that provide consumer services, such as television and radio programming and Internet access, as well as those that are less visible but equally important, including those connecting much of our telecommunications infrastructure. It also describes such emerging systems and services as space tourism and space mining and manufacturing.

I. GOVERNMENT AND NON-COMMERCIAL SPACE SYSTEMS

A. Global Positioning System

It is hard to imagine a modern technology, space-based or otherwise, more integrated into daily life than the Global Positioning System ("GPS"). Operated and maintained by the U.S. Air Force, GPS consists of thirty operating satellites[15] flying in a variety of orbits and transmitting one-way radionavigation signals.[16] By combining sophisticated user devices and the signals from multiple satellites, users on Earth can derive:

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[15] NASA, "What is GPS?" (June 3, 2019), https://www.nasa.gov/directorates/heo/scan/communications/policy/what_is_gps.

[16] L1 C/A Band: 1575.42 MHz; L2C Band: 1227.60 MHz; L5 Band: 1176.45 MHz; and the L1C Band, also at 1575.42 MHz. *See* GPS.gov, "New Civil Signals," https://www.gps.gov/systems/gps/modernization/civilsignals/#L2C (last modified Aug. 10, 2020); U.S. Geological Survey (USGS) and U.S. Air Force, "Improving the GPS L1 Signal" (Feb. 18, 2012), https://www.gps.gov/multimedia/presentations/1997-2004/2004-04-ieee/5-ImprovingTheGPSL1Signal.pdf.

- *Positioning*. The ability accurately and precisely to determine a device's location and orientation;[17]
- *Navigation.* The ability to select from various routes; and
- *Timing*. The ability to acquire and maintain the most accurate and precise time anywhere in the world.[18]

Billions of devices incorporate GPS as a critical enabling technology for countless uses across multiple sectors of the economy.[19] The United States is committed to continuing to provide GPS without user fees.[20] The following are but a few examples of GPS-related benefits:

- *Agriculture.* GPS provides unique efficiencies in planning, soil sampling, field mapping, tracking pest infestations, and crop scouting, and gives farmers the ability to operate precision agriculture equipment even during low visibility conditions.[21]
- *Transportation.* Hundreds of millions of consumers use GPS to identify the best routes for driving, biking, or walking. Pilots use GPS to fly more efficient and safer routes and for precision landings.[22] GPS provides precision location coordinates that help steer huge container ships to the proper docks, and track containers from port of entry to exit.[23] The rail

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[17] GPS's operators commit to a 25-foot accuracy 95 percent of the time, but today's smartphones typically are accurate to within 16 feet. GPS.gov, "GPS Accuracy," https://www.gps.gov/systems/gps/performance/accuracy/ (last modified Apr. 22, 2020).

[18] U.S. Dep't of Transportation, "What is Positioning, Navigation and Timing (PNT)?," (June 13, 2017), https://www.transportation.gov/pnt/what-positioning-navigation-and-timing-pnt.

[19] Research Triangle Institute, "Economic Benefits of the Global Positioning System to the Private Sector Study" (Oct. 2, 2019), https://www.nist.gov/news-events/news/2019/10/economic-benefits-global-positioning-system-us-private-sector-study; *see also* F. van Diggelen and P. Enge, "The World's first GPS MOOC and Worldwide Laboratory using Smartphones," Proceedings of the 28th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS), at 361-69 (2015), https://www.ion.org/publications/abstract.cfm?articleID=13079 (4.9 meter accuracy); GPS.gov, "Timing," https://www.gps.gov/applications/timing/ (last modified November 5, 2019); C. Aguilera & J. Redelkiewicz, European GNSS Agency, "Where (exactly) are my things?" (Nov. 2018), https://aioti.eu/wp-content/uploads/2018/11/AIOTI-webinar-2018-002.pdf.

[20] *See* GPS.gov, "Program Funding," https://www.gps.gov/policy/funding/ (last modified Nov. 13, 2020).

[21] GPS.gov, "Agriculture," https://www.gps.gov/applications/agriculture/ (last modified Mar. 6, 2018). *See* R. Wilson *et al.*, "The Value of Space," Center for Space Policy and Strategy, at 3, 4, (May 21, 2020) ("Value of Space"), https://aerospace.org/sites/default/files/2020-05/Gleason-Wilson_ValueOfSpace_20200511.pdf ("Variable rate technology, as this practice is called, avoids overapplication of pesticides and nutrients . . . . Precision agriculture was used on less than 50 percent of acres planted with corn in 2005 but accounted for more than 72 percent 5 years later.").

[22] GPS.gov, "Aviation," https://www.gps.gov/applications/aviation/ (last modified Sept. 11, 2020); WAAS T&E Team, Atlantic City International Airport, NJ, "Global Positioning System (GPS) Standard Positioning Service (SPS) Performance Analysis Report," Submitted to FAA (Jan. 31, 2017), https://www.nstb.tc.faa.gov/reports/PAN96_0117.pdf.

[23] GPS.gov, "Marine," https://www.gps.gov/applications/marine/ (last modified Mar. 6, 2018).

industry uses GPS to track the movement of and maintain locomotives and rail cars. GPS is also part of Positive Train Control systems to make trains run safer and faster.[24] GPS enabled the development of rideshare services, which provide convenient and relatively low-cost transportation for many consumers.[25]

- *Public safety and disaster relief.* GPS is foundational to wireless communications providers determining the location of callers to 911 emergency services. The most critical component in any successful rescue operation is time. GPS is a key aid in getting rescuers to victims quickly. During landslides and volcano eruptions, GPS is used to map the scope of disaster and identify where pockets of survivors are most likely to be.[26] GPS is used, along with infrared cameras, to manage the response to wildfires.[27]
- *Timing.* GPS is widely used to synchronize large networks,[28] and as an additional cybersecurity countermeasure technique.[29]
- *Surveying.* The precision provided by GPS has greatly improved the efficiency and accuracy of property boundary surveying.[30]

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[24] GPS.gov, "Rail," https://www.gps.gov/applications/rail/ (last modified Mar. 6, 2018).

[25] *See* U.S. Department of Commerce and White House Office of Science and Technology Policy, "Driving Space Commerce Through Effective Spectrum Policy," at 5 (Mar. 26, 2019) ("Driving Space Commerce"), https://www.ntia.doc.gov/files/ntia/publications/drivingspacecommerce.pdf.

[26] R. Giraud & G. McDonald, "GPS Monitoring of Slow-Moving Landslides," Utah Geological Survey, 43 Survey Notes, No. 1, at 6 (Jan. 2011), https://ugspub.nr.utah.gov/publications/survey_notes/snt43-1.pdf.

[27] K. Kafi, M. Gibril, "GPS Application in Disaster Management: A Review," Asian J. of Applied Sci., Vol. 4, Issue 1 (Feb. 2016), https://www.researchgate.net/publication/296807030_GPS_Application_in_Disaster_Management_A_Review/ ("The importance of GPS application in monitoring and managing disaster events cannot be overemphasized. This is because GPS is used in providing real-time information of location with high precision that can help in managing each of the processes of disaster event starting from pre-disaster, during disaster and post-disaster event." (Internal citations omitted)). Many GPS satellites also are equipped to detect 406 MHz emergency beacons. *See* GPS.gov, "Public Safety and Disaster Relief," https://www.gps.gov/applications/safety/ (last modified June 14, 2019).

[28] *See* TimeTools, "The Importance of Accurate Time on Computer Networks" (Aug. 8, 2017), https://timetoolsltd.com/time-sync/network-time-sync/.

[29] M. Refan & H. Valizadeh, "Redundant GPS time synchronization boards for computer networks," at 904-07, Proceedings of the 19th Telecommunications Forum (TELFOR), Belgrade (2011), https://ieeexplore.ieee.org/document/6143691.

[30] North Surveying, "GPS, GNSS and GEODESY Concepts: Chapter 2, Navigation Satellites" (2020), https://northsurveying.com/index.php/soporte/gnss-and-geodesy-concepts#chapter-2-navigation-satellites; GPS.gov, "Surveying & Mapping," https://www.gps.gov/applications/survey/ (last modified Oct. 3, 2018). In recent years, GPS-enabled devices increasingly have been designed to operate with other GNSS signals. In 2018, the FCC approved non-Federal GPS-enabled devices to operate in the United States using certain Galileo GNSS signals. *See Waiver of Part 25 Licensing Requirements for Receive-Only Earth Stations Operating with the Galileo Radionavigation-Satellite Service*, IB Docket No. 17-16, FCC 18-158, 33 FCC Rcd 11322 (2018), https://docs.fcc.gov/public/attachments/FCC-18-158A1_Rcd.pdf.

- *Scientific applications.* High precision receivers are used to collect data for various science applications. These receivers are terrestrial- and space-based and collect data for geodetic/geodesy science (i.e., seismic/tectonic plate movement), weather prediction and climatology science (i.e., atmospheric perceptible water vapor measurement), hydrological and oceanic sciences (*i.e.*, water surface height measurements), and many more.[31]

Federal, state, and local governments depend on GPS: for example, the National Oceanic and Atmospheric Administration to assist precision surveying;[32] the National Science Foundation for viewing the impact of solar science on terrestrial weather (and the ability to rely on power generation, air travel, and—in turn—GPS itself);[33] NASA for "autonomous navigation in space;"[34] the Department of Defense for joint force war-fighting;[35] the U.S. Forest Service (a branch of USDA) for mapping existing fires;[36] the U.S. Geological Survey for, *inter alia*, the National Volcano Early Warning System;[37] and the Federal Emergency Management Agency to assess the scope and scale of damages after a disaster.[38]

This is not to minimize the private sector's contribution and continued involvement in GPS. Beginning in May 2000, when GPS "Selective Availability" was set to zero and precise location services opened to civilian use, an explosion of manufacturers and software

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[31] A. Witze, "GPS Is Doing More Than You Thought," Knowable Magazine (Oct. 30, 2019), https://www.scientificamerican.com/article/gps-is-doing-more-than-you-thought/.

[32] NOAA, National Geodetic Survey, "Continuously Operating Reference Station (CORS)" (Feb. 12, 2020), https://www.ngs.noaa.gov/CORS/ ("Surveyors, GIS users, engineers, scientists, and the public at large that collect GPS data can use CORS data to improve the precision of their positions. CORS enhanced post-processed coordinates approach a few centimeters relative to the National Spatial Reference System, both horizontally and vertically.").

[33] National Science Foundation, News Release 20-002, "NSF's newest solar telescope produces first images" (Jan. 29, 2020) ("NSF Solar Telescope"), https://www.nsf.gov/news/news_summ.jsp?cntn_id=299908 ("Activity on the sun, known as space weather, can affect systems on Earth. Magnetic eruptions on the sun can impact air travel, disrupt satellite communications and bring down power grids, causing long-lasting blackouts and disabling technologies such as GPS.").

[34] NASA will be able to use the GNSS for spacecraft in low earth orbit and, increasingly, in geostationary orbit. *See* J. Parker *et al.*, "The Multi-GNSS Space Service Volume" (Oct. 1, 2018), https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180006983.pdf.

[35] DoD Chief Information Officer, Principal Staff Assistant for PNT Policy, "Strategy for the Department of Defense Positioning, Navigation and Timing (PNT) Enterprise [Unclassified Version]," at 34 (Nov. 2018), https://rntfnd.org/wp-content/uploads/DoD-PNT-Strategy.pdf.

[36] USDA Forest Service Engineering, Remote Sensing: Forest Fire Control Applications, https://www.fs.fed.us/eng/remsense/firecontrol.htm (last visited Dec. 31, 2020).

[37] USGS, "The National Volcano Early Warning System (NVEWS) will help USGS better monitor nation's most dangerous volcanoes" (May 6, 2019), https://www.usgs.gov/news/national-volcano-early-warning-system-nvews-will-help-usgs-better-monitor-nation-s-most?qt-news_science_products=3#qt-news_science_products.

[38] FEMA, Preliminary Damage Assessment Guide (May 2020), https://www.fema.gov/sites/default/files/2020-07/fema_preliminary-disaster-assessment_guide.pdf.

designers began delivering GPS to all.[39] Today, there are nearly 700 companies operating in the arena—the most recent growth sub-sector being GPS applications.[40] Plus, GPS is an enabling technology: without GPS, the various ride application services available directly on your smartphone never could have been created.[41] Indeed, according to a 2019 estimate, 4 million jobs globally are linked to GPS.[42]

In nearly all these contexts, the accessibility of accurate GPS data either can directly save lives or, in the cases of scientific and development applications, can improve health, economic growth and quality of life immeasurably. Because the GPS system is available globally, it provides these benefits to people worldwide, expanding global goodwill toward the United States and toward the Americans who use it to assist in disaster relief, humanitarian assistance and development efforts, among other applications.

A 2019 study concluded that GPS provided $1.4 trillion in cumulative benefits to the private sector between 1984 and 2017.[43] A more recent study concluded that GPS had a $1.4 trillion economic impact on U.S. industry alone.[44] Another recent study calculated that a loss of GPS service would cost the U.S. economy $1 billion per day, and even more during the spring planting season.[45]

B. Weather Forecasting and Other Earth Observation

Satellites provide the most cost-efficient way to monitor the environment of the entire Earth, its atmosphere, and its surface. They can observe wide areas without intrusion and home in on any targets of interest. The information gathered is a critical input to computer

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[39] The Satellite Industry Association tabulates a 56 percent increase in GNSS satellite-enabled devices—including smartphones—sold in the five years between 2015 and 2019. Satellite Industry Association, "State of the Satellite Industry Report," at 41 (July 2020) ("2020 SIA Report"), *available for order at* https://sia.org/news-resources/state-of-the-satellite-industry-report/.

[40] Space Capital and Silicon Valley Bank, "The GPS Playbook: How a space-based technology generated the largest venture outcomes in history," at 8 (Mar. 18, 2020), https://spacecapital.docsend.com/view/r6655fe.

[41] *Id.* at 9.

[42] W. Ross, "Launching toward a $1 trillion space economy," Orlando Sentinel (Feb. 28, 2019) ("Ross Space Economy Speech"), https://www.orlandosentinel.com/opinion/os-op-wilbur-ross-space-1-trillion-20190228-story.html.

[43] Research Triangle Institute, "Economic Benefits of the Global Positioning System to the Private Sector Study" (Oct. 2, 2019), https://www.nist.gov/news-events/news/2019/10/economic-benefits-global-positioning-system-us-private-sector-study.

[44] The Space Foundation, "The Space Economy Scorecard" (Feb. 2021) ("Space Economy Scorecard"), https://www.thespacereport.org/scorecard/.

[45] National Institute of Standards and Technology, Prepared by RTI International, "Economic Benefit of the Global Positioning System (GPS) Final Report" (June 2019), https://www.rti.org/sites/default/files/gps_finalreport618.pdf?utm_campaign=SSES_SSES_ALL_Aware2019&utm_source=Press%20Release&utm_medium=Website&utm_content=GPSreport. *See also* I. Leveson, "Economic Studies of GPS and the NGS Gravity Program," at 11 (June 6, 2019), https://www.gps.gov/governance/advisory/meetings/2019-06/leveson.pdf.

models, which help assess climate, weather, resources monitoring, and disaster monitoring and mitigation.[46]

These satellites operate within the allocation for the Earth Exploration Satellite Service (EESS).[47] Broadly speaking, there are two types of sensors, active and passive:

- *Passive*: Most NGSO weather satellites rely on passive sensors to collect data.[48] Passive sensors emit no energy themselves;[49] instead, they measure natural emissions from molecules in the atmosphere and on the surface of the earth.[50] They can be likened to a giant thermometer in space, with instruments "tuned" to specific frequencies that detect the natural resonance of the particular properties of the scientific characteristics being sensed.[51] Because molecule resonance occurs

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[46] *See* ITU-R Report RS.2178-0, "The essential role and global importance of radio spectrum use for Earth observations and for related applications," at 7 (2010) ("ITU-R Rep. RS.2178"), https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-RS.2178-2010-MSW-E.docx ("Satellites provide the most cost-efficient, if not the only, way to monitor the environment of the entire Earth, both land, sea, and air. Unique capabilities of Earth exploration-satellite service (EESS) satellites include observing wide-areas non-intrusively and uniformly (by using the same instrument) with the ability to rapidly target any point on Earth, including remote and inhospitable places, and to continue with a series of observations over a long period of time. Through these capabilities, the EESS brings many benefits to society in both the non-profit and commercial sectors.").

[47] The Earth Exploration Satellite Service is defined as "A radiocommunication service between earth stations and one or more space stations, which may include links between space stations, in which:

> (1) Information relating to the characteristics of the Earth and its natural phenomena, including data relating to the state of the environment, is obtained from active sensors or passive sensors on Earth satellites;
>
> (2) Similar information is collected from airborne or Earth-based platforms;
>
> (3) Such information may be distributed to earth stations within the system concerned; and
>
> (4) Platform interrogation may be included. This service may also include feeder links necessary for its operation."
>
> 47 C.F.R. § 2.1(c).

[48] *See* NASA Earth Observatory Glossary, "radiometer," https://earthobservatory.nasa.gov/glossary/q/s ("An instrument that quantitatively measures electromagnetic radiation. Weather satellites carry radiometers to measure radiation from snow, ice, clouds, bodies of water, the Earth's surface, and the sun."); *see also* National Academies of Sciences, Engineering, and Medicine, Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses, at 12-14 (2nd ed. 2015) ("NAS Handbook"), *available for purchase at* http://www.nas.edu.

[49] In addition, EESS satellites typically employ two types of radio communication systems: TT&C systems used to operate the satellite itself, and data downlinks used to transport data from the satellite to the ground.

[50] Passive sensors typically measure resonant frequencies from particular elements or molecules to determine the percentage of such elements or molecules near the earth's surface, according to well-known sensitivity charts (which change from season to season). *See* 47 C.F.R. § 2.1(c) ("*Passive Sensor.* A measuring instrument in the earth exploration satellite service or in the space research by means of which information is obtained by reception of radio waves of natural origin.").

[51] Many of these frequencies are listed in Table 1 of ITU-R Recommendation RS.515-5 (Aug. 2012) ("ITU-R Rec. RS.515"), https://www.itu.int/dms_pubrec/itu-r/rec/rs/R-REC-RS.515-5-201208-I!!PDF-E.pdf.

naturally only on specific frequencies, it cannot be re-tuned to operate or sense on other frequencies. Some of the most important bands are restricted passive use, with no active signals permitted. Due to the extreme sensitivity required to sense physical phenomena such as water vapor—in different heights of the atmosphere—and sea salinity, passive sensing bands are extremely vulnerable to interference coming from transmitters operating in adjacent bands with unwanted emissions extending into the passive band.

- *Active*: Active sensors transmit a signal and receive the same signal, usually, by the same satellite. They can be likened to radar. The use of active sensing varies from measuring the characteristics of the sea surface such as wave height and winds, to measuring land topography, including changes due to land movement, and to determining the density of trees in the rain forest.[52]

Meteorological services form the first subset of the EESS. Almost all weather forecasting now relies heavily on space-based observations and measurements. Each day, for example, the National Weather Service acquires 140 million observations from satellites.[53] Weather satellites operate in both non-geostationary orbits[54] (most in low earth orbit between about 435-mile perigee to 730-mile apogee), and geostationary orbit.[55]

Typically, each weather satellite has multiple measurement instruments operating in the EESS using multiple frequencies. These space-borne sensors monitor environmental conditions repetitively on a global scale, typically via polar-orbiting satellites.[56] Forecasters

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[52] There are five main active space borne sensor types:

- Synthetic aperture radars (SAR) – produce a radar image of the Earth's surface that can be processed to provide altitudes and movements to a precision and accuracy of centimeters.
- Altimeters – measure the altitude of the Earth's Ocean, lakes, and large river surface waves.
- Scatterometers – determine the wind direction and speed on the Earth's Ocean surface.
- Precipitation radars – measure the rainfall rate over the Earth's surface and the three-dimensional structure of rainfall.
- Cloud profile radars – determine the cloud reflectivity profile over the Earth's surface.

[53] T. Brookes, "How's the Weather Out There? Forecasting the Chaos of Weather," National Geographic Magazine (June 21, 2019), https://www.nationalgeographic.com/environment/natural-disasters/weather-forecasting/.

[54] The majority are in polar or near-polar orbits that sweep through the same view of the earth (and its natural shadows) once per day. NOAA-20 is in such a "sun-synchronous" orbit. *See* WMO OSCAR, NOAA-20, https://www.wmo-sat.info/oscar/satellites/view/noaa_20 (last visited Dec. 31, 2020).

[55] GOES-17, launched in 2018, is in geostationary orbit. *See* WMO OSCAR, GOES-17, https://www.wmo-sat.info/oscar/satellites/view/goes_17 (last visited Dec. 31, 2020).

[56] Some weather spacecraft are owned by NASA, others are owned jointly by NASA and NOAA, or operated by NASA on behalf of NOAA, or "flown" by NOAA itself. Most often, NOAA is responsible for Earth weather forecasts; NASA for space weather forecasts; and DoD for its own Defense-related weather observations.

DoD and NOAA once jointly operated weather satellites—such as Coriolis, which still has useful sensors operating at 37 GHz +/- 0.5 GHz, *see* WMO OSCAR, Coriolis, https://www.wmo-rely on measurements taken by multiple satellite missions, observing the Earth in multiple frequency bands to determine the critical atmospheric conditions throughout the globe necessary to be confident in a forecast. EESS sensors measure factors such as, but not limited to:[57]

- *Atmosphere*: Temperature, water vapor, cloud, and trace gas profiles;
- *Water bodies*: Global and local water supply: height of lakes; snow water content and depth; ocean wind speed and salinity; sea ice; rainfall prediction;
- *Ecosystems*: Trends in observed leaf area and other indices including topological and soil moisture changes;
- *Agriculture*: Drought prediction, crop health; moisture, rain rate, oil slicks, and biomass at the land surface, as well as land surface temperature;
- *Biodiversity*: The ways species and ecosystems respond to climate change; [58] and
- *Human factors*: Population distribution and growth.

In other cases, sensors profile temperatures and water vapor—indirectly, through passive microwave sensors that read oxygen absorption in several bands.[59] Another type of measurement looks at the degree to which the Earth's atmosphere bends radionavigation signals such as GPS when viewed from varying orbital locations on opposite orbital "chord-lines" as the satellite passes behind the earth or re-appears above it.[60]

Other weather satellites have active sensors that receive signals they have transmitted after those signals are reflected by land or ocean surfaces or by rain drops or ice particles in

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sat.info/oscar/satellites/view/coriolis (last visited Dec. 31, 2020). For the past dozen or more years, however, the two programs split to meet each agency's separate missions.

In addition, U.S. agencies often cooperate with entities in Europe, India and Japan in joint packages on spacecraft flown by a foreign entity. New weather satellites are continually being launched to both replace existing satellites and provide improved capabilities.

Shared weather data became the norm after passage of World Metrological Organization (WMO) Resolution 40 and its Annexes, in 1995. WMO, Res. 40 (1995), https://www.wmo.int/pages/prog/www/ois/Operational_Information/Publications/Congress/Cg_XII/res40_en.html; *see also* J. Zillman, "Origin, Impact and Aftermath of WMO Resolution 40," 68 WMO Bull. 2 (2019), https://public.wmo.int/en/resources/bulletin/origin-impact-and-aftermath-of-wmo-resolution-40.

[57] ITU Radiocommunication Bureau, Handbook: Earth Exploration-Satellite Service (2011) ("ITU-R EESS Handbook"), https://www.itu.int/dms_pub/itu-r/opb/hdb/R-HDB-56-2011-PDF-E.pdf.

[58] *See generally* ITU-R Recommendation RS.1883-1, "Use of remote sensing systems in the study of climate change and the effects thereof" (Dec. 2018), https://www.itu.int/dms_pubrec/itu-r/rec/rs/R-REC-RS.1883-1-201812-I!!MSW-E.docx.

[59] Oxygen absorption normally is measured between 52 and 60 GHz. *See* ITU-R Rec. RS.515, *supra* note 51, Table 1, at 3.

[60] This technique is called "Radio Occultation." To refine measurements, Radio Occultation satellites observe the limb of the earth to see how much the atmosphere, "bends" the measured signal when skimming the earth's atmosphere. The result, a measure of density, allows conventional space-based weather prediction models to be still more accurate. E. Niller, "Weather Forecasts Will Soon Use Weird, Bendy GPS Signals," Wired (June 18, 2019), https://www.wired.com/story/weather-satellites-gps-radio-occultation/.

the Earth's atmosphere.[61] Sometimes active sensors can take images such as topographic maps, and multiple readings of the same terrain from the same location can be combined to map the surface movement associated with earthquakes, landslides, and volcanoes.[62] Other active and passive sensors assist in mapping and predicting the effects of natural disasters.[63]

These satellites use frequencies determined by the natural properties of the materials that each is observing; in most cases, no "substitute" spectrum could suffice.[64] The satellites have to be sensitive: in addition to only emitting at certain limited frequencies, these signals also often are very weak.[65] Some of the most important signals are used to measure:

- clouds, ice, snow, rain, lakes, and seas;[66]

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[61] *See* ITU-R Recommendation RS.1166-4, Annex 1, §§ 4, 6 (Feb. 2009) ("ITU-R Rec. RS.1166"), https://www.itu.int/dms_pubrec/itu-r/rec/rs/R-REC-RS.1166-4-200902-I!!MSW-E.doc. Because the return signal depends on the average of the mix of the various elements seen—the dialectic properties—the unique frequencies necessary for active sensing depend on the phenomena measured.

[62] NASA, "Spectrum 101: An Introduction to National Aeronautics and Space Administration Spectrum Management," at 31 (Feb. 2016) ("NASA Spectrum 101"), https://www.nasa.gov/sites/default/files/atoms/files/spectrum_101.pdf.

[63] ITU-R Recommendation RS.1859-1, "Use of remote sensing systems for data collections to be used in the event of natural disasters and similar emergencies" (Dec. 2018) ("ITU-R Rec. RS.1859"), https://www.itu.int/dms_pubrec/itu-r/rec/rs/R-REC-RS.1859-1-201812-I!!MSW-E.docx.

[64] Final Acts WRC-19, ITU-R Resolution 750, at 483 (rev. 2019) ("ITU-R Res. 750"), https://www.itu.int/dms_pub/itu-r/opb/act/R-ACT-WRC.14-2019-PDF-E.pdf ("[I]in many cases, the frequencies used by EESS (passive) sensors are chosen to study natural phenomena producing radio emissions at frequencies fixed by the laws of nature, and therefore shifting frequency to avoid or mitigate interference problems is not possible"). Examples of these are oxygen (temperature profile) and water vapor (humidity profile).

[65] Final Acts, WRC-19, ITU-R Resolution 657, at 453 (rev. 2019), https://www.itu.int/dms_pub/itu-r/opb/act/R-ACT-WRC.14-2019-PDF-E.pdf ("[*C*]*onsidering* a) that space weather observations are important for detecting solar activity events that impact services critical to the economy, safety and security of administrations and their population . . . c) that some of the sensors operate by receiving signals of opportunity, including, but not limited to, low level natural emissions of the Sun, Earth's atmosphere, and other celestial bodies, and therefore may suffer harmful interference at levels which could be tolerated by other radio systems . . . .").

[66] The 23.8 GHz band is "unique" because water vapor (whether ice, water, or steam) there "is not opaque at sea level." U.S. National Academies of Sciences, Engineering, and Medicine, "Views on Agenda Items of Interest to the Science Services at the World Radiocommunication Conference 2019," at 36-37 (2017) ("NAS WRC Review"), https://www.nap.edu/read/24899/chapter/3#36. This is among the most common passive observations made the by Advanced Technology Microwave Sounder (ATMS)/(ATMS-U) package on many satellites. *See* STAR Joint Polar Satellite System Website, "Advanced Technology Microwave Sounder (ATMS)," https://www.star.nesdis.noaa.gov/jpss/ATMS.php (last modified Sept. 25, 2018). It is also on newer satellites, such as NOAA-18 and NOAA 20. *See* WMO OSCAR, NOAA-18, https://www.wmo-sat.info/oscar/satellites/view/noaa_18 (last visited Dec. 31, 2020); *id.*, NOAA-20, https://www.wmo-sat.info/oscar/satellites/view/noaa_20 (last visited Dec. 31, 2020).

See also ITU-R Recommendation RS.1861, Annex 1, § 6.6 (Jan. 2010) ("ITU-R Rec. RS.1861"), https://www.itu.int/dms_pubrec/itu-r/rec/rs/R-REC-RS.1861-0-201001-I!!MSW-E.docx (water vapor content).

- sea ice, water vapor, oil spills, clouds, liquid water, and surface temperature;[67]
- global water circulation, rain rates, snow, sea ice, and clouds,[68] which are used to track tropical hurricanes and predict their severity and path;[69]
- a crucial "calibration band,"[70] detecting water vapor, among the most important because its readings are used to compare and correct readings from other channels on the same spacecraft, as well as multiple satellite sources;[71]
- clouds, oil spills, ice, snow, rain[72] and
- active vertical cloud profiling for predicting storms.[73]

Combining many such observations in different bands produces higher quality data. Improvements in the reliability and precision of data collection by space-based assets has extended the length of a reliable Northern Hemisphere weather forecast by roughly 50 percent.[74] In other words, with the use of space-based assets and their access to protected spectrum, weather forecasts that otherwise would be accurate for no more than four days ahead, are now accurate for six days. Such increased predictability improves the lives of millions of people and the profitability of millions of businesses. Two extra days of

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[67] This is the 31.4 GHz band. *See* ITU-R Rec. RS.515, *supra* note 51, at Table 1.

[68] This is the 36-37 GHz band. *See* ITU-R Rec. RS.1861, *supra* note 66, § 6.8. The Global Precipitation Measurement (GPM) package 36.5 GHz +/- 1 GHz monitors sea surface winds speed and percentage of water vapor in clouds. *See* NASA, "GPM Microwave Imager (GMI)," https://gpm.nasa.gov/missions/GPM/GMI (last visited Dec. 9, 2020). Measurements at this frequency helped, track and predict, for example, 2019's Hurricane Dorian.

[69] *See* NASA, "The Global Precipitation Measurement Mission (GPM)," https://gpm.nasa.gov/GPM (last visited Dec. 31, 2020).

[70] This is the 50.2-50.4 GHz band, which the FCC called "essential for the calibration of other passive band data." *Amendment of Parts 1, 2, 15, 74, 78, 87, 90, and 97 of the Commission's Rules Regarding Implementation of the Final Acts of the World Radiocommunication Conference (Geneva, 2007) (WRC-07), Other Allocation Issues, and Related Rule Updates*, Notice of Proposed Rulemaking and Order, ET Docket No. 12-338, FCC 12-140, 27 FCC Rcd 14598, ¶ 107 (2012), https://docs.fcc.gov/public/attachments/FCC-12-140A1_Rcd.pdf. *See also* Letter from Assistant Secretary of Commerce for Communications and Information David Redl to FCC Chairman Ajit Pai, at 4-5 (Apr. 11, 2019), https://ecfsapi.fcc.gov/file/1041195772176/NTIA%20Redl%20Letter%20to%20Chairman%20Pai%20in%20GN%20Dkt%20No.%2014-177%20and%20AU%20Dkt%20No.%2019-59.pdf. As the ITU-R explained, "The band is exclusively passive and further protected by restrictions placed on active services operating in adjacent bands." ITU-R EESS Handbook, *supra* note 57, at 59.

[71] NAS WRC Review, *supra* note 66, at 21. *See* ITU-R Recommendation RS.1861, *supra* note 66, § 4; *see id.*, § 6.7 ("[the 31.3-31.8 GHz band] is one of the bands used . . . in conjunction with the bands such as 23.8 GHz and 50.3 for the characterization [of] each layer of the Earth's atmosphere").

[72] This is the 89 GHz band. ITU-R Recommendation RS.515, *supra* note 51, Table 1, at 3. *See* National Research Council of the National Academies, "Spectrum Management for Science in the 21st Century" (2010) ("NAS Spectrum Management Science"), https://www.nap.edu/read/12800/chapter/4#29.

[73] This is measured in the 94.0-94.1 GHz band. *See* ITU-R EESS Handbook, *supra* note 57, at 42; NASA Spectrum 101, *supra* note 62, at 31.

[74] NAS Spectrum Management Science, *supra* note 72, at 25-26. The comparable figure in the Southern hemisphere is at least a doubling in length of an accurate forecast. *Id.* at 25.

preparedness can enable better planning for routine activities and save the lives of people who need to escape flood or hurricane zones and allow additional time to pre-stage relief.

Although three recent NOAA satellites (GOES-17, GOES-T—set for launch in about a year—and NOAA-20) cost a total of about $11 billion,[75] the benefits are enormous. One study found that the total value of weather data in the U.S. in 2016 was $13 billion.[76] Another found that weather forecasts annually generate $31.5 billion in value for U.S. households.[77]

U.S. utilities save over $150 million annually using 24-hour temperature forecasts to meet electricity demands more efficiently.[78] Reducing the length of coastline evacuations when hurricanes threaten has saved up to $1 million per coastal mile in evacuation and other preparedness costs.[79]

As the 2019 National Space Weather Strategy and Action Plan remarked, the U.S. space weather network observes natural phenomena that have the potential to adversely affect critical functions, assets, and operations in space and on Earth.[80] Yet, "[e]xtreme space weather events can degrade or damage critical infrastructures, which may result in direct or cascading failures across key services such as electric power, communications, water supply,

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[75] F. Konkel, "Next-Gen Weather Satellite Operational over Western U.S.," NextGov (Feb. 12, 2019), https://www.nextgov.com/analytics-data/2019/02/next-gen-weather-satellite-operational-over-western-us/154821/. *Cf.* NOAA, "NOAA's GOES's-T Satellite Undergoes Testing to Simulate Launch and Orbit Conditions" (Sept. 29, 2020), https://www.nesdis.noaa.gov/content/noaa%E2%80%99s-goes-t-satellite-undergoes-testing-simulate-launch-and-orbit-conditions.

[76] National Weather Service, "National Weather Service Enterprise Analysis Report" (June 8, 2017), https://www.weather.gov/media/about/Final_NWS%20Enterprise%20Analysis%20Report_June%202017.pdf.

[77] NOAA Chief Economist Team, "NOAA by the Numbers," at 8 (June 2018), https://www.performance.noaa.gov/wp-content/uploads/NOAA-by-the-Numbers-Accessible-Version-Corrected-17-JUL-18.pdf.

[78] American Meteorological Society, "Weather Analysis and Forecasting" (Mar. 25, 2015), https://www.ametsoc.org/ams/index.cfm/about-ams/ams-statements/statements-of-the-ams-in-force/weather-analysis-and-forecasting/.

[79] *See id.*

[80] Executive Office of the President, "National Space Weather Strategy and Action Plan," at 1 (Mar. 2019) ("National Space Weather Strategy"), https://www.whitehouse.gov/wp-content/uploads/2019/03/National-Space-Weather-Strategy-and-Action-Plan-2019.pdf.

Extreme weather events, such as solar flares, can jam electronics, including cellphones, and temporarily degrade GPS accuracy. NASA, "Impacts of Strong Solar Flares" (May 13, 2013), https://www.nasa.gov/mission_pages/sunearth/news/flare-impacts.html. They also can disrupt electric power transmission. *See* NOAA, Space Weather Prediction Center, "Electric Power Transmission," https://www.swpc.noaa.gov/impacts/electric-power-transmission. *See* ITU-R Report RS.2456-0, at 28 (June 2019) (listing characteristics of the five types of solar flares), https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-RS.2456-2019-MSW-E.docx.

healthcare, and transportation."[81] So weather satellites also help to prevent damage to infrastructure *before* it occurs.[82]

NOAA's operational meteorological component is complemented by NASA's longer-term research role within the overall EESS.[83] For starters, NASA develops most of NOAAs EESS weather satellites, pursuant to specifications worked out between the two agencies.[84] NASA also provides NOAA satellites with minimal solar X-ray observations from NASA's suite of solar observing spacecraft in their common quest to predict solar storms (flares that may affect Earth in other, less obvious ways).[85]

As described above, NOAA's principal mission is weather forecasting and extreme weather disaster prediction. By contrast, NASA's mission is more long term, including the refinement of weather forecasting tools[86] and climatology.[87] Both kinds of research projects evolved into operational tools used routinely to forecast weather. One example of study that covered both categories is measurement of ocean height, initially research carried out by the joint NASA-French Space Agency satellite Topex-Poseidon,[88] which led to the ability to forecast *El Niño*/*La Niña* regional climatological/weather events. This mission in turn evolved into the JASON series[89] that extended the measurements.

Soon, NOAA began using those data to forecast *El Niño/La Niña* events routinely. Today, the European meteorological organization (EUMETSAT) and space agency (ESA) have joined the effort with the Sentinel series,[90] and the next mission, Sentinel-6 Michael Freilich, will be a joint NASA/NOAA/European effort, scheduled for a November 2020

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[81] National Space Weather Strategy, *supra* note 80, at vii.

[82] *Cf.* NSF Solar Telescope, *supra* note 33.

[83] *See* NASA, "Earth Science at Ames - Weather," https://www.nasa.gov/centers/ames/earthscience/programs/researchandanalysis/weather (last visited Jan. 25, 2021).

[84] *See, e.g.*, NOAA, "Lift Off! NOASS's JPSS -1 Heads to Orbit" (Nov. 17, 2017), https://www.jpss.noaa.gov/launch.html ("Together, NOAA and NASA oversee the development, launch, testing and operation [sic] all the satellites in the JPSS program. NOAA funds and manages the program, operations and data products. On behalf of NOAA, NASA develops and builds the instruments, spacecraft and ground system and launches the satellites.").

[85] *See infra* text accompanying notes 106-107.

[86] *See* NASA, "Global Modeling and Assimilation Office (GMAO)," https://gmao.gsfc.nasa.gov/.

[87] ITU-R Report RS.2178, *supra* note 46, at 33.

[88] *See* NASA-JPL, "TOPEX/Poseidon," https://sealevel.jpl.nasa.gov/missions/topex/.

[89] See NASA/JPL's Jason-3, "Ocean Surface Topography from Space," https://sealevel.jpl.nasa.gov/missions/jason3/; *see also* WMO OSCAR, JASON-3, https://www.wmo-sat.info/oscar/satellites/view/jason_3 (last modified July 18, 2020).

[90] *See, e.g.,* WMO OSCAR, Sentinel-3B, https://www.wmo-sat.info/oscar/satellites/view/sentinel_3b (last modified Aug. 21, 2020).

launch.[91] Similarly, the joint NASA-Japanese Tropical Rainfall Measurement Mission (TRMM), was limited to low latitude observations,[92] but evolved into the Global Precipitation Measurement Mission (GPM).[93] GPM involves many instruments on many satellites operated by many nations, all sharing the data and providing current–within a few hours-rainfall measurements covering the entire Earth's surface.[94]

EESS monitoring of the health of the planet can provide early warning of natural disasters, thereby potentially decreasing the death toll. For example, EESS detects earthquakes; tracks floods, coastal hazards, tsunamis, and hurricanes; forest fires; oil leaks; droughts; ocean pollution; wildfires; and ground movements associated with landslides and volcanoes.[95]

Should a disaster occur, EESS has a crucial role in disaster management. EESS data shows heat levels, as well as sea and lake ice levels, to help identify the areas affected, plan relief operations, and monitor the recovery from a disaster.[96] For example, the MODIS instrument flown on NASA's TERRA and AQUA satellites proved capable of spotting forest fire hot spots through the smoke and haze.[97] These observations were transmitted as they were made, and were (and are) available to any ground station within line-of-sight of either satellite. Hence, this data could be immediately processed and used to guide firefighters on the ground. Dozens of such ground stations were installed around the globe to help identify and fight wildland fires, and a follow-on instrument being flown on the NOAA JPSS satellites is carrying this capability into the future.

Today, the demand for more spectrum for large-scale usage, both for terrestrial and space services, is putting increasing pressure on the frequency bands used for Earth observation purposes. A cooperative and coordinated approach towards the use of frequencies is critically important.

C. National Security

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[91] *See* WMO OSCAR, Jason_CA-1/Sentinel-6A, https://www.wmo-sat.info/oscar/satellites/view/sentinel_6a (last modified Nov. 22, 2020); M. Freilich, "Copernicus: Sentinel-6 Michael Freilich Mission," EO Portal (2020), https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/copernicus-sentinel-6-michael-freilich%20.

[92] *See* NASA, "TRMM: Tropical Rainfall Measuring Mission" (Feb. 22, 2018), https://trmm.gsfc.nasa.gov/.

[93] *See* NASA, "Global Precipitation Measurement," https://www.nasa.gov/mission_pages/GPM/main/index.html; *see also* WMO OSCAR, GPM Core Observatory, https://www.wmo-sat.info/oscar/satellites/view/gpm_core_observatory (last modified Dec. 29, 2019).

[94] *See* NASA, "The GPM Constellation," https://gpm.nasa.gov/missions/GPM/constellation (last visited Dec. 31, 2020).

[95] ITU-R Rep. RS.2178, *supra* note 46, at 30-31.

[96] *Id.* at 32-33; *see also* ITU-R Rec. RS.1859, *supra* note 63.

[97] *See* NASA Earth Observation Data, "Active Fire Data," https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms/active-fire-data (last modified May 12, 2020).

Space-based operations play a critical role in our national security. Although the Defense Department's use of space-based systems and spectrum warrants its own report and some of these operations are classified, this document will survey some of the major unclassified uses and systems and their value to U.S. national security. The Appendix to this report further illustrates the substantial spectrum needs of this sector.

Not surprisingly, one of the Defense Department's primary space systems and uses is GPS. As described above, one primary use of GPS is navigation—by ships,[98] soldiers,[99] and each service's logistics train.[100] GPS also is integrated into Department of Defense (DoD) offensive capabilities, including precision weapon systems, such as mortar shells and air-to-ground missiles.[101] Increased accuracy is the "sharp end of the spear" for the military to carry the fight to the enemy with decisive effect, shortening conflicts and ultimately saving the lives of U.S. service men and women. Accurate location and targeting helps to minimize harm to civilian non-combatants, as well as "friendly fire" mishaps. The combination allows U.S. forces to sustain a "high operations tempo and maximizes commanders' ability to deploy forces efficiently."[102]

DoD operates space networks for communications, command and control, and remote sensing. With military personnel spread across the globe, communications include everything from sensitive tactical communications to broadcasts of Armed Forces Radio/TV and providing the opportunity for a service member to phone home. The goal of protected military satellite communications is to provide reliable links, with a low probability of interception or exploitation. Satellites offer transmission pipes for secure, encrypted

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[98] T. Callender, "The Naval Warfare Domain," Military Strength Topical Essays (Oct. 4, 2017), https://www.heritage.org/military-strength-topical-essays/2018-essays/the-naval-warfare-domain ("Satellite navigation systems such as the Global Positioning System (GPS) provide a highly accurate real-time ship's position for both military and commercial vessels. GPS and related technologies have afforded military naval vessels the required positioning, navigation, and timing (PNT) accuracy that enables use of precision-guided munitions and coordinated military operations.").

[99] D. Hambling, "The Overloaded Soldier: Why U.S. Infantry Now Carry More Weight Than Ever," Popular Mechanics (Dec. 26, 2018), https://www.popularmechanics.com/military/research/a25644619/soldier-weight/.

[100] Lt. Col. J. Bates, "Joint Force Logistics: Understanding Location Basics," Army Logistician (Mar.-Apr. 2006), https://alu.army.mil/alog/issues/marapr06/location_basics.html ("GPSs are helping to transform logistics.").

[101] *See, e.g.,* "Raytheon, US Army upgrade Excalibur precision guided projectile," Global Defense Security (Oct. 9, 2018), https://web.archive.org/web/20181011140355/https://www.armyrecognition.com/october_2018_global_defense_security_army_news_industry/raytheon_us_army_upgrade_excalibur_precision_guided_projectile.html; Boeing, Small Diameter Bomb (SDB), GBU-39-B Weapon (2015), http://www.boeing.com/resources/boeingdotcom/defense/weapons-weapons/images/small_diameter_bomb_product_card.pdf ("Near-precision INS/GPS navigation with Anti-jam GPS").

GPS systems originally were designed to detect nuclear detonations ("NUDET"), although that function has not been included on the most recent generation of GPS spacecraft. *See* D. Mcrady & P. Phipps, U.S. Dep't of Energy, "The GPS Burst Detector W-Sensor" (1994), https://www.osti.gov/servlets/purl/10176800.

[102] Value of Space, *supra* note 21, at 14.

information that can be sent directly between base and battlefield. To accomplish this, DoD uses both government and commercial systems[103] and both GSO and NGSO networks.[104]

DoD also operates an array of both active and passive sensors[105] in support of warfighting and humanitarian-response capabilities. Most of the sensors are part of the Defense Department's own weather satellite program. Others help detect underground nuclear testing by other nations. A third type points toward the heavens, to measure solar flares (which can interfere with electronic equipment)[106] or gamma rays produced by neutron stars and pulsars.[107]

DoD's space-based weather network is extensive. That is in addition to the data it obtains from agencies with weather spacecraft, including NASA and NOAA.[108] DoD is investing in new systems like the Weather System Follow-on Microwave (WSF-M) Satellite[109] and investing in or contracting with new commercial networks[110] and is a customer of data generated from unaffiliated NASA, NOAA, European and Japanese spacecraft.[111]

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[103] S. Williams & C. Badgett, "The Growing Convergence of DoD and Commercial Protected Satcom Requirements," 32nd Space Symposium, at 3 (Apr. 11-12, 2016) ("Convergence of DoD/Commercial Protected SATCOM"), https://www.spacesymposium.org/wp-content/uploads/2017/10/Williams-Steve-THE-GROWING-CONVERGENCE-OF-DoD-AND-COMMERCIAL-PROTECTED-SATCOM-REQUIREMENTS.pdf.

[104] Apart from the mission communications links, DoD uses inter-satellite links. DoD has associated space communications and tracking, telemetry and control ("TT&C"). *See, e.g.*, Los Angeles Air Force Base, "Milstar" (Feb. 11, 2014), https://web.archive.org/web/20141006085339/http://www.losangeles.af.mil/library/factsheets/factsheet.asp?id=5328.

[105] *See, e.g.*, Appendix.

[106] *See* National Space Weather Strategy, *supra* note 80.

[107] Gamma ray bursts can act like a lighthouse "beam of energy," more deadly than previously believed. *See* K. Jones, "Gamma Ray Burst Radiation is Deadlier than We Thought," Asgardia (Dec. 23, 2019), https://asgardia.space/en/news/Gamma-Ray-Burst-Radiation-Is-Deadlier-Than-We-Thought (*citing* M. Ahlers & L. Hasler, "Neutrino Fluence from Gamma-Ray Bursts: Off-Axis View of Structured Jets," Arxiv (Dec. 2, 2019), https://arxiv.org/pdf/1908.06953.pdf). *See also supra* note 80.

[108] NAS Spectrum Management Science, *supra* note 72, at 45.

[109] J. Keller, "Ball Aerospace wins half-billion-dollar contract to build first WSF-M microwave imaging weather satellite," Military & Aerospace Electronics (Nov. 12, 2018), https://www.militaryaerospace.com/unmanned/article/16726604/ball-aerospace-wins-halfbilliondollar-contract-to-build-first-wsfm-microwave-imaging-weather-satellite.

[110] T. Hitchens, "'GEOINT Singularity:' There'll Be Nowhere for DoD to Hide," Breaking Defense (Aug. 8, 2019), https://breakingdefense.com/2019/08/geoint-singularity-therell-be-nowhere-for-dod-to-hide-exclusive/.

[111] Data from DoD, NOAA, Japanese, European or other national weather satellites are analyzed at several places within the U.S. and abroad, including, for the Air Force, in Nebraska. *See* GAO Briefing to Congressional Defense Committees, Department of Defense (DOD) Weather Satellites, GAO-16-252R DOD Weather Satellite Alternatives (Mar. 10, 2016), https://www.gao.gov/assets/680/675725.pdf. *See also* U.S. Air Force, "Air Force Weather Agency" (Mar. 24, 2005), https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104580/air-force-weather-agency/.

Together, sensors, communications, and intelligence from these space-based assets are among "the Army's six modernization priorities."[112] They already are transforming Navy carrier groups[113] and contracts have been awarded to upgrade Army satellite capabilities with secure, networked, battle-command communications down to the tactical level.[114] The DoD's Defense Space Strategy states that "[s]pace is both a source of and conduit for national power, prosperity, and prestige."[115] The "rapid expansion of allied, partner, and commercial activities in space in recent years have . . . transformed space into a warfighting domain."[116]

The Defense Department uses a variety of government and commercial systems. By law,[117] DoD's first choice is to "buy commercial"—in other words, to lease capacity from the commercial space industry—where frequency and classification requirements make it possible.[118]

Looking to the future, DoD is acting assertively to maximize its access to, and control over, space as a strategic theater of operations. The 2019 National Defense Authorization Act[119] established a unified United States Space Command "to conduct, all affairs of such command relating to joint space warfighting operations."

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[112] D. Vergun, "Army network modernization efforts spearheaded by new Cross-Functional Teams," Army News Service (Mar. 27, 2018), https://www.army.mil/article/202500/army_network_modernization_efforts_spearheaded_by_new_cross_functional_teams.

[113] *See* SBIR-STTR, "C3I, Inc." (July 17, 2017), https://www.sbir.gov/node/1308543.

[114] Satnews Daily, "Kratos Defense & Security to Work on U.S. Army Advance Comms Systems" (Jan. 21, 2020), http://www.satnews.com/story.php?number=1769499596. M. Rogers & G. Nye, "Securing the Highest Ground: Integrating Commercial Space Innovation Into National Security Missions," Center for the Study of the Presidency and Congress, at 15 (Apr. 2019) ("Securing the Highest Ground"), https://static1.squarespace.com/static/5cb0a1b1d86cc932778ab82b/t/5d5ecda75489fb0001d85500/1566494123916/CSPC+NSSP+Report+Digital+Version+-+Securing+the+Highest+Ground%5B235%5D.pdf (finding it critical that the U.S. government form "a coherent strategy for investment in, acquisition from, or partnership with the commercial sector."); *see also* G. Willmer, "How telcos serve military communications," Capacity (Mar. 10, 2016), https://www.capacitymedia.com/articles/3536673/ANALYSIS-How-telcos-serve-military-communications.

[115] U.S. Dep't of Defense, "Defense Space Strategy Summary," at 3 (June 2020), https://media.defense.gov/2020/Jun/17/2002317391/-1/-1/1/2020_DEFENSE_SPACE_STRATEGY_SUMMARY.PDF.

[116] *Id.*

[117] *See* 10 U.S.C. § 2377 (2020); 41 U.S.C. § 3307 (2020).

[118] *See* U.S. Dep't of Defense, "Guidebook for Acquiring Commercial Items, Part A: Commercial Item Determination," at 25-26 (2018), https://www.acq.osd.mil/dpap/dars/pgi/docs/DoD_Guidebook_PartA_Commercial_Item_Determination_07_10_19.pdf.

[119] Pub. L. No. 115-232, 132 Stat 1636, 2104, Sec. 1602 (Aug. 13, 2018) ("2019 National Defense Reauthorization Act"), https://www.congress.gov/115/plaws/publ232/PLAW-115publ232.pdf. *See also* Conference Report to Accompany H.R. 5515, at 1040 (July 25, 2018),

D. Public Safety

Public safety increasingly relies on several space-based systems. Two of these, the GPS system and the network of weather forecasting satellites, have been described above. Many other critically important space-based public safety services systems are provided by the private sector and discussed in the section on Commercial Systems.

Emergency beacons have been around for a long time, most operated via terrestrial radio. But in 1979 the International Maritime Organization,[120] a U.N. specialized agency, adopted a Convention on Maritime Search and Rescue (SAR Convention) to standardize automatic distress protocols, and gradually shift them to satellite.[121] Collectively, those protocols were the earliest critical global system, known as the Global Mobile Distress and Safety System (GMDSS), which were mandated on all major passenger and cargo ocean-going vessels by 1999.[122] GMDSS began as an extensive terrestrial radio-based system—via Ship-to-Shore, Ship-to-Ship communications, and Search and Rescue aircraft—then morphed into several space-based maritime-focused distress satellite systems.[123]

GMDSS's first space-based component is COSPAS-SARSAT, composed of a U.S./Canada/France LEO system and a Russian LEO system, with 43 other nation-signatories.[124] The satellites listen for three types of beacons: ELTs (Emergency Locator Transmitters, from aircraft), EPIRBs (Emergency Position Indication Radio Beacons),[125] and PLBs (Personal Locator Beacons for general outdoor uses, such as hiking and climbing).

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https://www.govinfo.gov/content/pkg/CRPT-115hrpt874/pdf/CRPT-115hrpt874.pdf. The new law also gives DoD more flexibility in contracting with commercial entities for the use of space-based assets.

[120] *See* International Maritime Organization, "Introduction to the IMO," http://www.imo.org/en/About/Pages/Default.aspx (last visited Dec. 31, 2020).

[121] SAR Convention (1979), https://onboard-aquarius.org/uploads/2018/08/SAR-Convention-1979.pdf; *see* International Maritime Organization, "Radiocommunications and Search and Rescue," https://www.imo.org/en/OurWork/Safety/Pages/RadiaCommunicationsSearchRescue-Default.aspx (last visited Jan. 12, 2021).

[122] SOLAS Convention (1974), http://www.mar.ist.utl.pt/mventura/Projecto-Navios-I/IMO-Conventions%20(copies)/SOLAS.pdf.

[123] Changes in the IMO's GMDSS requirements were incorporated into the 1974 Amendments to the International Convention for the Safety of Life at Sea (SOLAS), which entered into force in 1980. *See* International Maritime Organization, "International Convention for the Safety of Life at Sea (SOLAS) 1974" (Nov. 1, 1974), https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx.

[124] *See* COSPAS-SARSAT, "Participants," https://cospas-sarsat.int/en/about-us/participants (last visited Dec. 31, 2020).

[125] An EPIRB is a battery powered, position-indicating beacon "designed to save your life if you get into trouble by alerting rescue authorities and indicating your location." U.S. Dep't of Homeland Security, U.S. Coast Guard Navigation Center, "Emergency Position Indication Radiobeacon (EPIRB)," https://www.navcen.uscg.gov/?pageName=mtEpirb (last visited Dec. 31, 2020). EPRIBS operate at 406 MHz and 1544.5 MHz.

COSPAS-SARSAT also works with NOAA[126] so that emergency alerts can be detected by NOAA's GOES-series satellites equipped search and rescue capabilities.[127] Since 1982, SARSAT has facilitated 41,000 rescues.[128]

A newer EPIRB frequency is 1544.5 MHz,[129] which also detects positions by Doppler shift. GMDSS services provided by commercial satellite operators are described *infra* at page 42.

E. Aviation

The future of government-mandated aviation safety and other services is based in large part on the increasing use of space-based systems.[130] In the U.S., the new system, mandated by the FAA, is called Next Generation Air Transportation System (NextGen).[131] The FAA

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[126] In addition to the bands mentioned in the footnotes, some weather observing satellites—both geostationary and polar orbiters—also are capable of receiving the international distress signal at 406 MHz and participate in search and rescue activities, "to help first responders locate people in distress worldwide, whether from a plane crash, a boating accident or other emergencies." NASA, "Weather Satellites Aid Search and Rescue Capabilities" (Mar. 7, 2018), https://www.nasa.gov/feature/goddard/2018/weather-satellites-aid-search-and-rescue-capabilities. Some examples are India's INSAT-3DR, Europe's Metop-B, and the U.S. GOES-15, GOES-16 and GOES-17. *See* WMO OSCAR, List of Radio Frequencies, set to active satellites from 0 to 500 MHz, https://www.wmo-sat.info/oscar/satellitefrequencies (last visited Dec. 31, 2020). For example, on April 2, 2017, a small General Aviation aircraft crashed in a snow-covered, isolated part of the Olympic Mountains in Washington State. A distress signal from the plane's Emergency Locator at 406 MHz was detected by the GOES West satellite, and the message was relayed to the NOAA-operated SARSAT U.S. Mission Control Center. Within minutes, a U.S. Navy Rescue Team from Whidbey Island Naval Air Station Search and Rescue was dispatched to the crash site. Both pilot and passenger survived. *See* NOAA, "NOAA Satellites Facilitate Rescues on Land and Sea," https://www.nesdis.noaa.gov/content/noaa-satellites-facilitate-rescues-land-and-sea (last visited Dec. 31, 2020).

[127] *See* NOAA, "Welcome to SARSAT: Search and Rescue Satellite Aided Tracking" (Dec. 13, 2019), https://www.sarsat.noaa.gov/.

[128] Value of Space, *supra* note 21, at 9. NOAA, "NOAA Satellites Helped Save 307 Lives in 2016" (Jan. 19, 2017), https://www.noaa.gov/stories/noaa-satellites-helped-save-307-lives-in-2016#:~:text=Since%20the%20program's%20inception%20in,emergency%20beacons%20with%20NOAA%20online.

[129] *See* U.S. Table of Allocations, 47 C.F.R. § 2.106, Footnote 5.356.

[130] The need for satellite-based aircraft positioning became plain by the horrifying loss of Malaysia Airlines Flight 370. MA370 lost contact with ground ATC 40 minutes after take-off, disappearing from radar before veering wildly off-course, and crashing into the southern Indian Ocean, killing 227 passengers and 12 crew. *See* BBC News, "Flight MH370 'crashed in south Indian Ocean' – Malaysia PM" (Mar. 24, 2014), https://www.bbc.com/news/world-asia-26716572. Thereafter, the global aviation and spectrum community assembled to try to prevent recurrence of such disasters, most notably at the ITU's 2015 World Radio Conference, which allocated 1087.7-1092.3 MHz for aeronautical mobile satellite service global flight tracking. *See* ITU Press Release, "Radio spectrum allocated for global flight tracking" (Nov. 11, 2015), http://www.itu.int/net/pressoffice/press_releases/2015/51.aspx#.XhNVIGRKi70.

[131] NextGen represents a suite of technology improvements. "This initiative is one of the most ambitious infrastructure projects in U.S. history. NextGen goes beyond simply making minor upgrades to aging infrastructure. . .. NextGen is halfway through a multi-year investment and implementation plan." Federal Aviation Administration, NextGen FAQs, Question 1, https://www.faa.gov/nextgen/faqs/#q1 (last modified

began by mandating installation of GPS, or a transponder with similar altitude-resolution capabilities, on all commercial or private aircraft flying by instrument in U.S. airspace.[132] Starting in January 2020, all aircraft flying in U.S. controlled airspace were required to install Automatic Dependent Surveillance-B Out (ADS-B Out); the principal ADS-B Out frequency is 1090 MHz.[133] ADS-B Out reports, once per second,[134] the aircraft's GPS location, altitude (both barometric and GPS), air speed, and aircraft tail number to satellites that then relay the information back to the FAA.

In the near future, aircraft will be required to use space-based systems to allow the crew to communicate with ground control.[135] Once completed, the FAA anticipates NextGen will avoid more than 15,000 hours of air delays through improved reroutes around weather and congestion; indeed, the average scheduled passenger aircraft delay (16.6 minutes) in 2018 was unchanged from 2017 despite an increase in bad weather and passenger/cargo traffic.[136]

A portion of the 5 GHz C-band spectrum is allocated for multiple uses, including aeronautical and satellite services that potentially can be used by Unmanned Aircraft Systems for beyond-line-of-sight operations.[137] Although there now are a few tests taking place in that band, the FAA, NASA, and private sector contractors are defining transmission characteristics for such systems, while the FAA decides how to integrate UAS with the "rules of the road" for areas near airports.[138]

Aug. 10, 2020). *See* Press Release, L3Harris, "Harris Corporation Awarded $291 Million Contract to Provide Federal Aviation Administration's New National Air Traffic Control Communications Systems" (Aug. 28, 2012), https://www.businesswire.com/news/home/20120828006394/en/Harris-Corporation-Awarded-291-Million-Contract-to-Provide-Federal-Aviation-Administration%E2%80%99s-New-National-Air-Traffic-Control-Communications-System.

[132] 14 C.F.R. §§ 91.215, 217, 219; 14 C.F.R. § 121.349, *et seq.* ADS-B signals from aircraft are received by commercial satellite systems and forwarded to the relevant Civil Aviation Authority.

[133] 14 C.F.R. § 91.225(a) (2019). *See* Federal Aviation Administration, "Automatic Dependent Surveillance-Broadcast (ADS-B)," https://www.faa.gov/nextgen/programs/adsb/ (last modified Aug. 4, 2020). Universal Access Transceivers, operating at 978 MHz, will be permitted on some General Aviation aircraft for a transitional period. Federal Aviation Administration, Advisory Circular 20-165B, "Airworthiness Approval of Automatic Dependent Surveillance – Broadcast OUT Systems," at 3 (Dec. 7, 2015), https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_20-165B.pdf.

[134] Federal Aviation Administration, "Ins and Outs," https://www.faa.gov/nextgen/equipadsb/capabilities/ins_outs/ (last modified Jan. 2, 2020).

[135] Federal Aviation Administration, Advisory Circular 20-172B, "Airworthiness Approval for ADS-B in Systems and Applications," at 4-5 (May 20, 2015), https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_20-172B.pdf.

[136] Federal Aviation Administration, "Modernization of U.S. Airspace," https://www.faa.gov/nextgen/ (last modified Aug. 6, 2020); Federal Aviation Administration, "FAQ: Weather Delay," https://www.faa.gov/nextgen/programs/weather/faq/ (last modified Aug. 17, 2020); Federal Aviation Administration, "How NextGen Works," https://www.faa.gov/nextgen/how_nextgen_works/ (last modified Aug. 21, 2020).

[137] This is the 5030-5091 MHz band.

[138] *See* NASA, "NASA Armstrong Fact Sheet: Unmanned Aircraft Systems Integration in the National Airspace System," https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-075-DFRC.html (last modified

F. Space Exploration

Every NASA mission depends on access to spectrum, from spacecraft launch to telemetry, tracking and control of objects in space, to mission communications. NASA often contracts with the private sector for construction of components, and sometimes for the operation of systems. Altogether, NASA's missions rely on a sophisticated global communications infrastructure, consisting of several component networks, including:

- Deep Space Network, used to support scientific spacecraft;
- Near Earth Network, ground stations that provide tracking telemetry and control services for NASA itself and for commercial entities;[139] and the
- Space Network, also known as the Tracking and Data Relay Satellite (TDRS) System.

NASA's Space Communications and Navigation (SCaN) manages operations for all three NASA's networks: the Jet Propulsion Laboratory (JPL) has the lead role on the Deep Space Network (DSN),[140] and Goddard Space Flight Center (GSFC) takes the lead for the Near Earth Network (NEN) and Space Network (SN).[141]

The NEN is a series of more than 15 globally located NASA-owned and -contracted commercial ground terminals that provide comprehensive communications services to satellites from near-Earth orbit to a million miles from Earth. Built to manage both the TT&C and the data downlink operations of NASA's own spacecraft, the NEN can communicate with a variety of GSO and NGSO satellites—as well as communications to the International Space Station (ISS)—and is used by NASA itself as well as commercial entities and foreign governments.[142]

NASA's uses the DSN to communicate with its inter-planetary spacecraft,[143] and as a "back-up" to the NEN and the SN.[144] It does this from three facilities (approximately 120

Oct. 22, 2020) ("In June 2018, a collaboration among Armstrong, General Atomics-Aeronautical Systems Inc., (GA-ASI), Honeywell and the FAA led to the first remotely-piloted aircraft, Ikhana, to fly in the national airspace without a safety chase plane.").

[139] NASA Spectrum 101, *supra* note 62, at v.

[140] NASA, "What is the Deep Space Network," https://www.nasa.gov/directorates/heo/scan/services/networks/deep_space_network/about (last modified July 1, 2020).

[141] NASA, "Goddard Space Flight Center 2019 Annual Report," at 23, https://www.nasa.gov/sites/default/files/atoms/files/2019goddardannualreportfinalpages.pdf.

[142] NASA, "Near Earth Network (NEN)," https://www.nasa.gov/directorates/heo/scan/services/networks/nen (last modified July 24, 2018).

[143] NASA Spectrum 101, *supra* note 62, at 28. TDRS is available for inter-planetary communications in favorable configurations.

[144] NASA, "Deep Space Network (DSN)," https://www.nasa.gov/directorates/heo/scan/services/networks/dsn (last modified Nov. 5, 2020).

degrees apart) in Goldstone, California; Madrid, Spain; and Canberra, Australia, each with a 70-meter antenna, a 34-meter High Efficiency antenna, and one or more 34-meter Beam Wave Guide antennas.[145] For example, at present, NASA uses the DSN for two-way communications with the Juno Deep Space Mission to Jupiter,[146] and for communications with the Parker Solar Probe,[147] and other important science missions.[148] The DSN communicates with the Mars orbiters that carry out space-based meteorology of Mars[149] and the Mars rovers.[150]

The SN originally was established in the early 1980s to replace NASA's worldwide network of ground tracking stations.[151] The SN, however, now consists of the Tracking and Data Relay Satellite (TDRS) fleet. First launched in the early 1980s, TDRS includes 10 on-orbit satellites (4 first generation; 3 second generation and 3 third generation spacecraft).[152] TDRS satellites communicate in multiple bands[153] that collectively provide a continuous

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[145] *Id.* These support a range of transmit/receive activities, including at VHF, S, X Ku, and Ka bands. For a view of what each of the six antennas are doing in real time, *see* NASA, "Deep Space Network *Now*," https://eyes.nasa.gov/dsn/dsn.html (last visited Dec. 31, 2020).

[146] This is accomplished in the 32-35 GHz band and the 34.2 to 34.7 GHz band, with X-band TT&C links. *See* NASA, "Juno Telecommunications," at 12-14, 35 (Oct. 2012), https://descanso.jpl.nasa.gov/DPSummary/Juno_DESCANSO_Post121106H--Compact.pdf (two-way X-band for telecommand, two-way Ka-band for downlinking gravity science information to NASA's Deep Space Network).

[147] *See* NASA, "NASA's Parker Solar Probe Sheds New Light on the Sun" (Dec. 4, 2019), https://www.nasa.gov/feature/goddard/2019/nasas-parker-solar-probe-sheds-new-light-on-the-sun.

[148] Such communications use the 31.89-32.3 GHz band. *See* Sharing Earth Observation Resources, "Parker Solar Probe," https://directory.eoportal.org/web/eoportal/satellite-missions/p/psp (last visited Dec. 31, 2020).

[149] *See* NASA, MARS InSight Mission, "Communications with Earth," https://mars.nasa.gov/insight/mission/communications/ (last visited Dec. 31, 2020); *see also* NASA, MARS InSight Mission, "Mars Weather," https://mars.nasa.gov/insight/weather/ (last visited Dec. 31, 2020).

[150] *See* NASA Science, MARS 2020 Mission Perseverance Rover News, https://mars.nasa.gov/mars2020/news/, last updated Jan. 6, 2021; NASA, MARS 2020/Perseverance, NASA Facts (Mar. 2020), https://mars.nasa.gov/files/mars2020/Mars2020_Fact_Sheet.pdf; NASA, Mars Curiosity Rover, "Communications with Earth," https://mars.nasa.gov/msl/mission/communications/ (last visited Dec. 31, 2020); *see also* K. Chang, "How NASA's Curiosity Rover Weighed a Mountain on Mars," N.Y. Times (Jan. 31, 2019), https://www.nytimes.com/2019/01/31/science/mars-curiosity-rover-mount-sharp.html.

[151] NASA, "Space Network (SN)," https://www.nasa.gov/directorates/heo/scan/services/networks/sn (last modified Nov. 5, 2020).

[152] *See* NASA, "Tracking and Data Relay Satellite (TDRS)," https://www.nasa.gov/directorates/heo/scan/services/networks/tdrs_main (last modified Mar. 11, 2019).

[153] TDRS operates in several bands: 137-155 MHz, 2.0-2.3 GHz (mostly s-t-s), 13.7-15.0 GHz, and most of 22.5-27.5 GHz, this last—except for a small spectrum carve-out—being co-channel with a

[153] *See* NASA, "Tracking and Data Relay Satellite (TDRS)," https://www.nasa.gov/directorates/heo/scan/services/networks/tdrs_main (last modified Mar. 11, 2019).

[153] TDRS operates in several bands: 137-155 MHz, 2.0-2.3 GHz (mostly s-t-s), 13.7-15.0 GHz, and most of 22.5-27.5 GHz, this last—except for a small spectrum carve-out—being co-channel with a new terrestrial mobile designation. *See also* NASA, "Tracking and Data Relay Satellite (TDRS) Fleet,"

global link between spacecraft and the ground. NASA uses TDRS to communicate with NASA spacecraft, with the International Space Station (ISS), and with missions and payloads to and from the ISS. NASA relies on access to this system almost every moment of every day to communicate with its various un-manned systems, mostly within lunar distances, both to transmit instructions and to receive data the systems are collecting.[154] The SN provides tracking and data relay for spacecraft, satellites; and expendable launch vehicles using space and ground segments,[155] and immediate, anywhere, 24 hours a day emergency communications to suitably equipped satellites.[156] The SN is available to the private sector via contract.[157]

NASA's Commercial Crew Program is working with U.S. companies to design, build, test and operate safe, reliable and cost-effective human transportation systems to low-Earth orbit. On May 30, 2020, NASA achieved an important milestone when a SpaceX Falcon-9 rocket and its Dragon Crew spacecraft launched two NASA astronauts.[158] The pair quickly docked with and joined the International Space Station then returned safely to Earth[159]—the first NASA astronauts to do so on a fully privately built vehicle.

Yet more challenges are to come, and NASA's reliance on spectrum will continue as it increases its activity. On July 30, 2020, NASA launched an Atlas V rocket, carrying the

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https://www.nasa.gov/directorates/heo/scan/services/networks/tdrs_third_gen (last modified Oct. 4, 2017). Third generation TDRS can use the same frequencies for launch operations, and flight communications, providing near-continuous communications with low earth orbiting satellites.

[154] TDRS is protected from interference from fixed service interference in the 25.25-27.50 MHz band. *See* ITU-R Recommendation SA.1276-5 (July 2017), https://www.itu.int/dms_pubrec/itu-r/rec/sa/R-REC-SA.1276-5-201707-I!!MSW-E.docx. It is difficult to imagine that any less protection would be due from terrestrial mobile services. Indeed, the ITU has specific criteria for interference protection from (mobile) airborne transmitters to the Deep Space Network. *See* ITU-R Recommendation SA.1016-1 (Aug. 2019), https://www.itu.int/dms_pubrec/itu-r/rec/sa/R-REC-SA.1016-1-201908-I!!MSW-E.docx.

[155] *See* NASA, "What kind of communications do NASA missions require?," https://www.nasa.gov/directorates/heo/scan/communications/outreach/funfacts/txt_communications.html (last modified Aug. 7, 2017).

[156] This is in contrast with the NEN, which can communicate only when a spacecraft or satellite is in line-of-sight of an NEN ground station.

[157] *See* Memorandum from NASA Space Communications and Navigation Deputy Program Manager for Operations to Goddard Space Flight Center Associate Director for Flight Projects (Oct. 1, 2019), https://www.nasa.gov/sites/default/files/atoms/files/signed_space_network_rates_fy20_memo.pdf (providing NASA's fleet-wide communications rates for FY 2020).

[158] NASA, "NASA Astronauts Launch from America in Historic Test Flight of SpaceX Crew Dragon" (May 30, 2020), https://www.nasa.gov/press-release/nasa-astronauts-launch-from-america-in-historic-test-flight-of-spacex-crew-dragon. SpaceX was able to recover its Falcon-9 first stage on this launch. M. Wall, "SpaceX rocket returns to shore after historic astronaut launch," Space.com (June 3, 2020), https://www.space.com/spacex-falcon-9-rocket-returns-shore-after-astronaut-launch.html.

[159] NASA, "International Space Station Welcomes First SpaceX Crew Dragon with NASA Astronauts," https://www.nasa.gov/feature/international-space-station-welcomes-first-spacex-crew-dragon-with-nasa-astronauts (last modified June 1, 2020); NASA, "Crew Dragon Safely Returns Astronauts," https://www.nasa.gov/image-feature/crew-dragon-safely-returns-astronauts (last modified Aug. 2, 2020).

Perseverance rover, which successfully landed on Mars February 18, 2021.[160] A lunar orbiter is undergoing testing with an unmanned launch scheduled for late 2021[161] and a crewed mission planned in 2023.[162] NASA landed an additional rover; both use radio spectrum for communications[163] with NASA's Mars orbiters,[164] and with links back to Earth via the DSN.[165]

This need for spectrum will accelerate as human spaceflight seeks further benchmarks. NASA is preparing its Artemis mission, to land the next man and first woman on the Moon by 2024[166] and taking the first steps to use the lunar region to ascend and leapfrog manned missions on Mars.[167] For human spaceflight, NASA's "programs have required, and will continue to require, extremely complex and critical radio systems. These radio systems will require bands of frequencies spanning the spectrum from about 100 MHz up to more than 30 GHz."[168]

NASA's activities, and those of its contractors, contribute to U.S. economic growth and job creation. During Fiscal Year 2019, NASA estimates its efforts (in all 50 states and the District of Columbia) generated a total economic output of more than $64 billion, and resulted in nearly $7 billion in federal, state, and local tax revenue.[169] Perhaps more significantly, NASA's efforts in that single year supported more than 312,000 American jobs.

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[160] NASA, "Touchdown! NASA's Mars Perseverance Rover Safely Lands on Red Planet," https://mars.nasa.gov/news/8865/touchdown-nasas-mars-perseverance-rover-safely-lands-on-red-planet/ (last modified Feb. 18, 2021).

[161] NASA, "NASA Mega Moon Rocket Passes Key Test, Readies for Launch," https://www.nasa.gov/press-release/nasa-mega-moon-rocket-passes-key-test-readies-for-launch (last modified Mar. 25, 2021). Orion will communicate via S-band with Earth and, eventually, on UHF with Mars orbiters.

[162] NASA, "NASA's First Flight With Crew Important Step on Long-term Return to Moon, Missions to Mars," https://www.nasa.gov/feature/nasa-s-first-flight-with-crew-important-step-on-long-term-return-to-the-moon-missions-to (last updated Sep. 28, 2020).

[163] NASA will use the 400 MHz frequency. NASA, Mars 2020 Mission, "Communications," https://mars.nasa.gov/mars2020/spacecraft/rover/communications/ (last visited Dec. 31, 2020).

[164] NASA, Mars 2020 Mission, "Communications: Ultra-High Frequency Antenna," https://mars.nasa.gov/mars2020/mission/rover/communications/#UHF-Antenna (last visited Dec. 31, 2020).

[165] NASA, Mars 2020 Mission, "Communications: The X-Band High-Gain Antenna," https://mars.nasa.gov/mars2020/mission/rover/communications/#High-Gain-Antenna (last visited Dec. 31, 2020).

[166] NASA, Artemis, https://www.nasa.gov/specials/artemis/ (last visited Dec. 31, 2020).

[167] NASA, "Explore Moon to Mars," https://www.nasa.gov/topics/moon-to-mars (last modified Sept. 25, 2020).

[168] NASA Spectrum 101, *supra* note 62, at 35.

[169] Figures in this paragraph are available in NASA's first-ever Economic Impact Report. NASA, "Economic Impact Report – FY19," at 3, (Sep. 2020), https://www.nasa.gov/sites/default/files/atoms/files/2020_nasa_eir_brochure_for_fy19.pdf.

As noted above, NASA relies on the private sector—particularly aerospace contractors—for the construction and deployment of its space-based assets.[170] Increasingly, as discussed in the second half of this section, space exploration also is being undertaken by private enterprises directly.[171] For example, NASA is asking private companies "to help the space agency collect dirt and rocks from the moon."[172] All of these operations will require access to spectrum.

G. Radio Astronomy

Many components of the Universe are so distant that they can be studied only by means of their radio frequency signatures.[173] Like weather satellites, radio astronomers "listen" for emissions, in this case distant cosmic emissions, including galactic atoms or molecules, at fixed frequencies. In this way, radio astronomers seek to unlock the mysteries of the origin of the universe,[174] understand galaxy and star formation, and detect black holes, nebulae, and quasars. Some of this listening is done from space itself, but many scientific observations are accomplished using enormous, highly sensitive, ground-based radiotelescopes, often constructed in remote and/or high-altitude areas.[175] Radio telescopes include large single dishes and interferometers, which are many telescopes acting in unison as a "virtual" larger

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[170] *See* Walter A. McDougall, ". . . the Heavens and the Earth: A Political History of the Space Age" (rev. 1997).

[171] *See, e.g.*, J. Keller, "NASA surveys industry for atmospheric monitoring CubeSat that will push the bounds of SWaP in spacecraft," Military & Aerospace Electronics (Oct. 21, 2019), https://www.militaryaerospace.com/sensors/article/14069015/cubesat-atmospheric-monitoring.

[172] M. Kramer, "NASA wants to buy Moon dirt from private companies," Axios (Sep. 10, 2020), https://www.axios.com/nasa-moon-samples-private-companies-cdd4aea1-48d8-42bf-a2f0-2be5431fb4c0.html.

[173] ITU-R, Handbook on Radio Astronomy, 3rd Edition, at 1 (2013) ("ITU Radio Astronomy Handbook"), https://www.itu.int/dms_pub/itu-r/opb/hdb/R-HDB-22-2013-PDF-E.pdf.

[174] NAS Handbook, *supra* note 48, at 16 ("Study of the radio emission from celestial sources provides unique insight into the formation, evolution, and physical characteristics of a wide range of astronomical objects and objects [including those] at the farthest limits of the known universe.").

[175] *Id.* at 92 ("An important degree of protection from ground-based transmitters can be obtained by choosing observatory sites and Earth stations in locations of low population density and taking advantage of shielding by mountains or other terrain features.").

NASA recently provided initial support for development of a radiotelescope that would fill a 2-to-3-mile crater on the dark (back) side of the moon, and thus be isolated from Earth-based interference. NASA, "Lunar Crater Radio Telescope (LCRT) on the Far-Side of the Moon," https://www.nasa.gov/directorates/spacetech/niac/2020_Phase_I_Phase_II/lunar_crater_radio_telescope/ (last modified Apr. 7, 2020). This ultimate in terrain shielding would take perhaps a decade to complete, even were it funded.

telescope.[176] U.S. radio astronomy telescopes strive to detect signals that, by the time they reach the observatory, are under one percent of a billionth of a billionth of a single watt.[177]

Radio telescopes observe the cosmos almost continuously from less than 100 MHz up to 1 THz. Some spectrum ranges are more heavily utilized, where the atmosphere is most transparent to radio waves.[178] Radio astronomers also monitor higher frequencies, and have been doing so for many decades, observing solar system, galactic, and extragalactic events.[179]

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[176] One example of an interferometer is the Very Long Baseline Array (VLBA) comprised of ten telescopes located across the United States. *See* National Radio Astronomy Observatory, "Very Long Baseline Array" (2020), https://public.nrao.edu/telescopes/vlba/. The VLBA is one system of the more general Very Long Baseline Interferometry (VLBI) technique. "By linking together widely separated radio telescopes, VLBI allows astronomers to see the universe in more detail than ever." *See* C. Crockett, "How VLBI reveals the universe in amazing detail," EarthSky (July 5, 2012), https://earthsky.org/astronomy-essentials/how-vlbi-reveals-the-universe-in-amazing-detail. *See also* M. Thomasson, "Radio astronomical use of the electromagnetic spectrum at Onsala Space Observatory," at 3 (May 2013) https://www.chalmers.se/en/researchinfrastructure/oso/Documents/Other%20reports/RadioAstronomicalFrequenciesOnsala.pdf ("the VLBI technique is used to increase the spatial resolution (the current record is 28 microarcseconds, corresponding to 5 cm on the Moon as seen from the Earth)"). Relative astrometric precision of ~10 microarcseconds is achievable; *see* National Radio Astronomy Observatory, "Introduction to the VLBI" (May 15, 2019), https://science.nrao.edu/facilities/vlba/introduction-to-the-VLBA. VLBI observations routinely are made between 1 and 100 GHz; however, millimeter VLBI at higher frequencies (*e.g.*, 230 GHz) has been successful for astronomical discoveries. *See* Event Horizon Telescope, "Astronomers Capture First Image of a Black Hole" (Apr. 10, 2019), https://eventhorizontelescope.org/press-release-april-10-2019-astronomers-capture-first-image-black-hole (observed at λ 1.3 mm or 231 GHz).

[177] *See* Comments of the National Academy of Sciences' Committee on Radio Frequencies, *Use of Spectrum Bands Above 24 GHz for Mobile Radio Services*, GN Docket 14-177, at 3 (Sept. 29, 2016) ("CORF 2016 NPRM Comments"), https://ecfsapi.fcc.gov/file/10929535912548/CORF%20FNPRM%20Comments%20Dkt%2014-177%2009.29.16%20(00973462xB3D1E).pdf.

[178] These include 23-6.24.0 GHz and 48.94-49.04 GHz. *See* National Radio Astronomy Observatory, "Introduction to Radio Astronomy: Atmospheric Windows," https://www.cv.nrao.edu/course/astr534/Introradastro.html (displaying atmospheric transmission as a function of frequency at the ALMA telescope). The atmosphere becomes more opaque to radio waves at higher frequencies, including some bands where molecules in the atmosphere—such as water—impede virtually any observation.

In some spectrum ranges such as 23.6-24.0 GHz and 48.94-49.04 GHz, there is overlap between passive weather satellite frequency allocations and radio-astronomy frequency allocations. A principal difference is that radio astronomers also must account for the "Doppler Shift," which may require observations at different frequencies than the spectral line frequency. *See* J. Condon & S. Ransom, Essential Radio Astronomy, Chapter 7 (2018) ("Essential Radio Astronomy"), https://www.cv.nrao.edu/~sransom/web/Ch7.html ("Spectral lines are powerful diagnostics of physical and chemical conditions in astronomical objects. Their rest frequencies identity the specific atoms and molecules involved, and their Doppler shifts measure radial velocities."). Radio Astronomers also observe broadband emission from sources (*e.g.*, thermal and non-thermal emission like synchrotron) and the protected radio astronomy bands are helpful in obtaining a spectral energy distribution (SED); *see* Essential Radio Astronomy, Chapters 2, 4, 5, & 7; *see also* Appendix.

[179] These include 84–116 GHz, 125– 63 GHz, 211–275 GHz, 275–373 GHz, 385–500 GHz, 602–720 GHz, and 787-950 GHz. Recently, the SuperWASP-North telescope on the Canary Islands, Spain, made the first observation of two planets orbiting a distant sun. *See* N. Anderson, "Two Interacting Gas Giants Orbit Sun-

Radio astronomy is critical to understanding our solar system and the sun itself. Radio astronomy discovered pulsars,[180] extra-solar planets, black holes,[181] quasars, and supernovae.[182] Monitoring solar radio flares provides critical advance warning of geomagnetic disturbances that can affect the operation of GPS and terrestrial power grids.[183] They also measure Earth's plate tectonics and polar wandering via the global VLBI network.[184] Radio astronomy also drives technological breakthroughs that spread throughout the economy. Spinoff technologies from radio astronomy include Wi-Fi,[185] CT scans,[186] improvements to laser eye surgery,[187] and elements of the extremely low-noise receiver used to deliver Enhanced 911 emergency services.[188]

Like Star WASP-148," SCI News (July 9, 2020), http://www.sci-news.com/astronomy/two-interacting-gas-giants-sun-like-star-wasp-148-08619.html. Much of this observation is accomplished at dishes—or series in of dishes–in the high desert in Chile. Both the Smithsonian Submillimeter Array and the Arizona Radio Observatory have been examining these bands for decades. *See* Smithsonian Astrophysical Observatory, "The Submillimeter Array," https://www.cfa.harvard.edu/sma/ (last visited Dec. 31, 2020); University of Arizona, "Arizona Radio Observatory" (2020), https://www.as.arizona.edu/arizona-radio-observatory. ALMA is building receivers to observe from 163–211 GHz. *See* Atacama Large Millimeter/submillimeter Array, "Receivers," https://www.almaobservatory.org/en/about-alma-at-first-glance/how-alma-works/technologies/receivers/ (last visited Dec. 31, 2020). Understanding planet formation is one of the scientific motivations. For an example of some of the discoveries made, s*ee* National Radio Astronomy Observatory, "The Epoch of Planet Formation, Times Twenty" (Dec. 12, 2018), https://public.nrao.edu/news/2018-alma-survey-disks/.

[180] NAS Handbook, *supra* note 48, at 39-40.

[181] Inquiries into the relativistic impacts on matter near black holes continues to be one of the leading areas of inquiry in radio astronomy.

[182] NAS Handbook, *supra* note 48, at 32-33, 44-45.

[183] ITU-R Radio Astronomy Handbook, *supra* note 173, § 0.4.3.2.

[184] *See* ITU Recommendation RA.769-2 (2003) ("ITU-R Rec. RA.769"), https://www.itu.int/dms_pubrec/itu-r/rec/ra/R-REC-RA.769-2-200305-I!!MSW-E.doc ("[*C*]*onsidering* a) that many of the most fundamental astronomical advances made in the past five decades (*e.g.*, the discovery of radio galaxies, quasars, and pulsars, the direct measurement of neutral hydrogen, the direct measurement of distances of certain external galaxies . . . have been made through radio astronomy, and that radio astronomical observations are expected to continue making fundamental contributions to our understanding of the Universe, and that they provide the only way to investigate some cosmic phenomena."). Radio Astronomy can experience severe harmful interference from terrestrial or satellite transmitters in the same or adjacent bands. *See* ITU-R Rec. RA.769, Annex 1, Sec 2.

[185] ABC Science, "The Story of Wi-Fi: How a team of Australian radio astronomers solved the problem of high-speed wireless internet" (Mar. 5, 2015), https://www.abc.net.au/science/articles/2015/03/05/4183467.htm.

[186] ITU Radio Astronomy Handbook, *supra* note 173, § 0.3.2.4.

[187] NAS WRC Review, *supra* note 66, at 9.

[188] E. Bryerton, "Low Noise Amplifiers – Pushing the limits of low noise," National Radio Astronomy Observatory (May 15, 2015), https://science.nrao.edu/facilities/cdl/low-noise-amplifiers. *See also* ITU-R Rec. RA.769, *supra* note 184 ("*considering* b) that the development of radio astronomy has also led to major technological advances, particularly in receiving and imaging techniques, and to improved knowledge of fundamental radio noise limitations of great importance to radiocommunication, and promises further important results"); NAS Handbook, *supra* note 48.

Additionally, radio astronomy contributes important knowledge to other space-critical applications. One of the most important collaborations is the use of global VLBI observations for obtaining the most precise Earth-orientation. For high-precision GPS, it is imperative to know the Earth's exact orientation with respect to the background stars. The challenge is that the stars in the Milky Way galaxy are also moving. By combining observations of many background radio galaxies outside the local galaxy group, which essentially are fixed in space, we can obtain the most precise Earth-orientation.[189] For this reason, the Department of the Navy funds about half the VLBA network, an example of how fundamental, curiosity-driven research and development eventually leads to very practical and useful techniques.

Internationally, U.S. radio astronomers, working with NTIA, have taken leadership roles at the ITU, and in the Inter-American Telecommunication Commission's (CITEL's) Permanent Consulting Group II on Radiocommunication. This is vital, as many critical American radio astronomy investments in the Western Hemisphere are outside the United States, including the ACAMA Large Millimeter Array (ALMA) in the high desert of Chile;[190] others in Chile;[191] and the Large Millimeter Telescope in Mexico.[192]

H. Amateur Radio and Academic and Research Satellite Missions

The first amateur radio satellite was launched in 1961.[193] Now, there are dozens of amateur satellites in operation,[194] and many more satellites that operate for academic and research purposes. Many of these satellites are Cubesats that are built inexpensively and launched as secondary payload either directly from a rocket or from the International Space Station. Satellites in the amateur-satellite radio category may operate within allocated

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[189] *See* J. Dickey, "How and Why to Do VLBI on GPS," IVS General Meeting Proceedings, at 65-69 (2010), https://ivscc.gsfc.nasa.gov/publications/gm2010/dickey.pdf. Similarly, all satellites in orbit rely on general relativistic corrections to keep their orbits from degrading over time.

[190] Located in the Atacama Desert—one of the highest and driest places in the world—ALMA currently is the largest radio telescope in the world and is made available for U.S. researchers both physically and by remote operation. Atacama Large Millimeter/submillimeter Array, "About ALMA, at First Glance," https://www.almaobservatory.org/en/about-alma-at-first-glance/.

[191] These include the Cosmology Large Angular Scale Surveyor (CLASS) is the, observing the sky at 40 GHz, 90 GHz, 150 GHz and 220 GHz and the Simons Observatory, scheduled to become operational in 2020. *See* Johns Hopkins University, "Cosmology Large Angular Scale Surveyor" (2020), https://sites.krieger.jhu.edu/class/; *and* "Important Milestones for SO: Preliminary Design Review for the Large Aperture Telescope" (Mar. 28, 2018), https://simonsobservatory.org/news.php.

[192] This bi-national project between the United States and Mexico is the world's largest single-dish steerable millimeter-wavelength telescope cable of observation between about 75 GHz and 353 GHz. It is exploring the physical processes that lead to the formation and evolution of planetary systems, stars, black holes, and galaxies throughout the 13.7-billion-year history of the Universe. Large Millimeter Telescope, "Large Millimeter Telescope *Alfonso Serrano*," http://lmtgtm.org/?lang=en (last visited Dec. 31, 2020).

[193] AMSAT, "A Brief History of AMSAT," https://www.amsat.org/amsat-history/ (last visited Dec. 31, 2020).

[194] AMSAT Live OSCAR Satellite Status Page, https://www.amsat.org/status/ (last visited Dec. 31, 2020).

amateur-satellite frequencies,[195] and amateur radio licensees on the ground are able to communicate with them whenever they are within range.

Amateur, academic, and research satellites serve a wide range of purposes, including providing back-up communications for the International Space Station itself, offering disaster communications in remote regions. They also serve as a testing ground for new satellite technology and as a platform for, science experiments, and providing educational opportunities for hands-on learning by students at universities[196] and students as young as elementary school age.[197] Many of the educational experimental satellites are ephemeral near-earth orbit LEOs.[198] One of the more significant science missions successfully determined GPS signals can be used by other space-based systems even when they are located above the GPS satellites. This finding has enabled weather satellites and missions thousands of miles above the geostationary arc to use GPS signals to manage and improve their performance.[199] Currently, the amateur radio community is planning to use its spectrum to communicate with the upcoming lunar mission.[200]

II. COMMERCIAL SPACE SYSTEMS

The private sector is a major player in the operation of space-based systems and the provision of their many services, particularly in the United States.[201] Commercial space industries bring the United States both enormous international prestige and quantifiable benefits in terms of job creation and innovation. According to the Space Foundation, the 2021 global space economy is valued at $424 billion, of which $337 billion is commercial space revenue.[202] In addition to the leading role it takes in areas that are outside the scope of this report, including the manufacture of the space assets themselves and the associated

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[195] *See* Table 1 & Appendix.

[196] ARISS News Release, "10 US Schools Moved Forward in ARISS Selection Process" (Feb. 3, 2020), https://www.ariss.org/press-releases/february-4-2020.

[197] *See, e.g.*, TERRIERS, "The Tomographic Experiment using Radiative Recombinative Ionospheric EUV and Radio Sources," http://www.astronautix.com/t/terriers.html (last visited Dec. 31, 2020).

[198] *See* B. Marshall, "Build a CubeSat Satellite that actually works, Part 1: Make it Resilient," DesignSpark (Nov. 19, 2018), https://www.rs-online.com/designspark/build-a-cubesat-satellite-that-actually-works-part-1-make-it-resilient.

[199] *See* M. Moreau *et al.*, "Results from the GPS Flight Experiment on the High Earth Orbit AMSAT OSCAR-40 Spacecraft" (Sept. 2002), https://emergentspace.com/wp-content/uploads/AO40IonGps2002_final.pdf.

[200] *See* AMSAT, "AMSAT and ARISS Designing Amateur Radio System for Lunar Gateway" (Aug. 6, 2019), https://www.amsat.org/amsat-and-ariss-designing-amateur-radio-system-for-lunar-gateway/.

[201] K. O'Connell, Director, Office of Space Commerce, U.S. Dep't of Commerce, "Remarks on the Trillion Dollar Space Economy" (Nov. 27, 2018) ("O'Connell Remarks"), https://www.space.commerce.gov/remarks-on-the-trillion-dollar-space-economy/; NASA, "Space Commercialization," https://www.nasa.gov/centers/hq/library/find/bibliographies/space_commercialization (last modified Dec. 16, 2020).

[202] Space Economy Scorecard, *supra* note 44.

ground equipment and launch vehicles, it provides a wide range of services that rely directly on access to spectrum.

Despite the COVID-19 pandemic and resultant economic slowdown, 2020 saw the biggest private investment in space to date.[203] A recent review by the Department of Commerce's Bureau of Economic Analysis (BEA) found the U.S. space economy added $108.9 billion value to the current-dollar GDP (0.5 percent of total U.S. current-dollar GDP).[204] The BEA estimate included wages, salaries, and employer contributions to pensions and insurance, supporting more than 365,000 private sector jobs.[205] Another report noted as of the first quarter of 2021, investment in the commercial space sector had grown from essentially nothing in 2011 to a cumulative total of more than $186 billion; 47 percent of that investment went to U.S. companies.[206]

Space commerce revenues amount to tens of billions of dollars for U.S. companies and the prospects for substantial future growth are promising.[207] Morgan Stanley Research foresees global space industry revenues growing to over $1 trillion by 2040, with second-order impacts ultimately equal to consumer TV, satellite launch, and consumer broadband combined.[208] The U.S. Chamber of Commerce predicts slightly greater growth: it calculates commercial space will generate $1.5 trillion by 2040.[209]

This investment allows U.S. firms to innovate for U.S. and foreign customers. U.S. companies accounted for 42 percent of global satellite revenues in 2019, highlighted by 63 percent of both satellite manufacturing and launch revenues.[210] Total U.S. launch revenues were $2.3 billion in 2019, 35 percent of the global launch industry.[211] With GPS, the United States invented an enormous product market that has expanded to include an estimated 6.4 billion devices (including every smartphone). The U.S. share of this market is 42 percent. Space "applications" as a whole—a category dominated by position, navigation and timing hardware and software, but extending to communications devices and software, space

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[203] Morgan Stanley Research, "5 Key Themes in the New Space Economy" (Feb. 4, 2021), https://www.morganstanley.com/ideas/space-economy-themes-2021.

[204] T. Highfill, A. Jouard, & C. Franks, BEA, "Preliminary Estimates of the U.S. Space Economy, 2012-2018," 100 Surv. of Current Bus. Centennial 12, at 3, 7 (Dec. 2020), *available at* https://apps.bea.gov/scb/2020/12-december/pdf/1220-space-economy.pdf.

[205] *Id*. at 4, 7. Of those 365,000 total jobs, almost half—176,000—were in service industries such as "information" and "education." *Id*. at 4.

[206] Space Capital, "Space Investment Quarterly, Q1 2021," at 4 ("Space Capital 1Q 2021"), https://spacecapital.docsend.com/view/6x3sub6i74sitwie.

[207] *See* O'Connell Remarks, *supra* note 201.

[208] Morgan Stanley Research, "Space: Investing in the Final Frontier" (July 24, 2020), https://www.morganstanley.com/ideas/investing-in-space.

[209] B. Higginbotham, "The Space Economy: An Industry Takes Off" (Oct. 18, 2018), https://www.uschamber.com/series/above-the-fold/the-space-economy-industry-takes.

[210] 2020 Satellite Industry Report, *supra* note 39, at 23, 34.

[211] *Id.* at 37.

component manufacturing, and earth observation applications—totaled $148 billion since 2012, 44 percent of which went to U.S. firms.[212] Such opportunities for innovation attract top talent[213] for high-paying jobs.[214] Indeed, "no country enjoys as robust and dynamic a commercial space industry as does the United States."[215]

In the past ten years, more than $25.7 billion has been invested in 535 space companies globally, including $5.8 billion in 2019 alone—the largest investment year ever.[216] Today, the geostationary arc, with satellites of many nations, represents a staggering $168 billion investment in satellites. NGSO satellites represent the potential for substantial additional investment of about the same order or more.[217] Further, these numbers do not include the value of the ground segment, both in the United States and globally. This demonstrates space spectrum is valuable to venture capitalist and corporate investors.

The services most familiar to consumers are fixed offerings, such as rooftop and backyard satellite dishes used to provide video programming directly to households, or relatively new offerings of broadband to homes and businesses in suburban and rural areas. Moreover, there are services for mobile users: satellite radio service, which offers a wide variety of music, news, sports, and information to consumers in their cars and trucks; and nascent satellite broadband offerings, designed for users on the go.

Other commercial services are less well-known, but critically important. These include the satellite services that are a key part of our communications infrastructure, as well as remote sensing and satellite imagery, and emerging businesses in space tourism and space mining and manufacturing. And, as mentioned above, many government sectors—the military, aviation, public safety—depend on commercial space spectrum providers for part, or even the bulk of their needs. Indeed, today's high-throughput satellites have employed

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[212] Space Capital 1Q 2021, *supra* note 206, at 10.

[213] C. Herrera, "The growing space industry is scrambling to find workers—but it can't take foreigners," Orlando Sentinel (Oct. 26, 2018), https://phys.org/news/2018-10-space-industry-scrambling-workersbut-foreigners.html.

[214] Statement of Tim Hughes, Senior VP, SpaceX, Before the Subcommittee on Space, Science & Technology, Committee on Commerce, Science & Technology, United States Senate, at 8 (July 13, 2017), https://www.hq.nasa.gov/legislative/hearings/7-13-17%20HUGHES.pdf.

[215] G. Nye III & M. Rogers, "Securing the Highest Ground," Center for the Study of the Presidency & Congress (Mar. 31, 2019), https://www.thepresidency.org/securing-the-highest-ground.

[216] M. Sheetz, "Space companies raised a record $5.8 billion in private investments last year," CNBC (Jan. 14, 2020), https://www.cnbc.com/2020/01/14/space-companies-including-spacex-raised-5point8-billion-in-2019.html.

[217] M. Sheetz, "Why in the next decade companies will launch thousands more satellites than in all of history," CNBC (Dec. 15, 2019), https://www.cnbc.com/2019/12/14/spacex-oneweb-and-amazon-to-launch-thousands-more-satellites-in-2020s.html; A. Boyle, "Amazon to offer broadband access from orbit with 3,236-satellite 'Project Kuiper' constellation," GeekWire (Apr. 4, 2019), https://www.geekwire.com/2019/amazon-project-kuiper-broadband-satellite/; D. Mosher, "Amazon is building a giant factory to make internet satellites and compete with SpaceX," Business Insider (Dec. 18, 2019), https://www.businessinsider.com/amazon-project-kuiper-satellite-internet-factory-redmond-washington-2019-12.

such state-of-the-art technology that their spectrum efficiency approaches theoretical physical limits.[218]

Given its reach and capabilities, satellites are expected to become a central component of the 5G ecosystem. The next 3GPP standard, Release 17, scheduled to be completed in 2022, is planned to include integration of satellite in 5G systems, especially for specific applications (*e.g.*, non-low latency applications such as IoT).[219]

A. Consumer Services

1. Television

In the United States, the most well-known space-based systems after GPS are probably the satellite services that deliver hundreds of channels of video and audio programming directly to consumers' satellite dishes. Two satellite television services have about 28.5 million U.S. subscribers at the end of 2020.[220] This segment generated $92 billion in revenue in 2019.[221] Because these satellite services have nationwide coverage, satellite television can be received in rural and remote areas just as well as in big cities. Satellite-delivered services compete with and complement broadcast and cable, increasing innovation and reducing prices to consumers.[222]

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[218] *Cf.* M. Viswanathan, "Shannon limit on power efficiency – demystified," GaussianWaves (Nov. 20, 2019), https://www.gaussianwaves.com/2019/11/shannons-limit-on-power-efficiency/.

[219] 3GPP, "Release 17" (Sept. 4, 2019), https://www.3gpp.org/release-17; 3GPP, "5G in Release 17 – strong radio evolution" (Dec. 14, 2019), https://www.3gpp.org/news-events/2098-5g-in-release-17-%E2%80%93-strong-radio-evolution ("GPP RAN will now start normative work on 5G NR enhancements to support non-terrestrial access (NTN): satellites and High-Altitude Platforms (HAPs). Initial studies will be performed for IoT as well, paving the way to introduce both NB-IoT and eMTC support for satellites."). *See also* X. Lin *et al.*, "5G from Space: An Overview of 3GPP Non-Terrestrial Networks," Arxiv (2021), https://arxiv.org/ftp/arxiv/papers/2103/2103.09156.pdf.

[220] Dish reported 11.3 million subscribers (including Sling) at the end of 2020. *See* Statista, "Dish Network: No. of Video Subscriber in the U.S. 2012-2020," https://www.statista.com/statistics/497299/dish-network-number-subscribers-usa/#:~:text=As%20of%20the%20fourth%20quarter%20of%202020%2C%20Dish,Sling%20TV%2C%20had%20around%202.47%20million%20subscribers%20 (last visited Apr. 30, 2021). DirecTV (now owned by AT&T) reported about 788,000 subscribers at the end of the first quarter of 2021 (including AT&T TV). *See* What toWatch, "AT&T TV Now subscribers and earnings," https://www.whattowatch.com/news/directv-now-subscribers-earnings (last viewed Apr. 30, 2021). AT&T since has spun a 70% interest in DirecTV to a third company, 30 percent held by the private equity firm TPG. "AT&T to spin off DirecTV, AT&T TV Now and U-Verse into new company valued at $16.25 billion," CNBC, https://www.cnbc.com/2021/02/25/att-to-spin-off-directv-att-tv-now-and-u-verse-into-new-company.html, *last updated* (Feb. 25, 2021).

[221] *See* Satellite Industry Association, "2019 Top-Level Global Satellite Industry Findings," at 2 (July 2020), https://sia.org/wp-content/uploads/2020/07/2020-SSIR-2-Pager-20200701.pdf.

[222] See *Communications Marketplace Report,* Report, GN Docket 18-231, FCC 18-181, 33 FCC Rcd 12558, ¶ 117 & nn.327-29 (2018) ("FCC 2018 Communications Competition Report"), https://docs.fcc.gov/public/attachments/FCC-18-181A1.pdf.

2. Radio

Satellite radio is another mass-market commercial, space-based system.[223] The United States provider operates a constellation of two satellites, plus in-orbit spares, with two additional satellites scheduled to launch on a Falcon-9 in mid-late 2020.[224] The satellites cover a large part of North America, providing well over 175 channels of programming and competition for terrestrial broadcasting. Satellite radio had almost 35 million subscribers[225] generating $7.53 billion in revenue in 2020.[226] The programming includes a huge range of music formats, news and opinion, comedy, and sports programming that includes play-by-play of the full schedule of the major sports leagues.

The system also provides unique and critical public safety services. One such service provides real-time weather data to businesses and general aviation pilots that was previously unavailable during flight. This permits them to avoid emerging weather systems that would otherwise threaten their flight safety.[227] Another distinctive capability of satellite radio is as part of the FCC's national Emergency Alert System (EAS), where it serves as an inexpensive and efficient relay to notify broadcast stations around the country of an emergency.[228]

During emergencies, the systems operator makes The Weather Channel™ available to all satellite radios regardless of whether the owner is currently a subscriber. Because the signal is transmitted via satellite, this provides continuous service during natural disasters even after local stations are knocked off the air.[229]

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[223] SiriusXM's broadcast transmissions to users are in S-band, at 2320-2345 MHz, with service uplinks in X band.

[224] *See* SpaceX Missions, Falcon 9, https://www.spacex.com/vehicles/falcon-9/ (last visited Dec. 31, 2020).

[225] *See* Statista, "Number of Sirius XM Subscribers in the United States from 1st quarter 2011 to 4th Quarter 2020" (Mar. 24, 2021), https://www.statista.com/statistics/252812/number-of-sirius-xms-subscribers/.

[226] *See* Statista, "Sirius XM Holdings' annual revenue from 2003 to 2020," (Mar. 24, 2021), https://www.statista.com/statistics/205719/revenue-of-sirius-xm-radio/ (figure includes Pandora revenues).

[227] *See* SiriusXM, "Weather & Entertainment All Flight Long," https://www.siriusxm.com/sxmaviation?intcmp=GN_FOOTER_NEW_MoreSiriusXM_ForPlanes (last visited Dec. 31, 2020); SiriusXM Aviation, "SiriusXM vs. ADS-B/FIS-B Weather," https://siriusxmcommunications.com/sxmaviation/daretocompare.html#METAR (last visited Dec. 31, 2020).

[228] SiriusXM, *Further Supplement to Petition for Reconsideration and Request for Limited Waiver*, EB Docket 04-296 (Sept. 24, 2018), https://ecfsapi.fcc.gov/file/10924819802710/SiriusXM%20EAS%20Further%20Supplement%20to%20Recon%20Petition%20FINAL%209.24.18.pdf.

[229] *Compare* M. Bettes, "Listen to @weatherchannel live on @SIRIUSXM for Hurricane #Irma coverage" (Sept. 8, 2017), https://twitter.com/mikebettes/status/906335974283780096 *with* FCC, *Communications Status Report for Areas Impacted by Hurricane Irma* (Sept. 11, 2017), https://docs.fcc.gov/public/attachments/DOC-346655A1.pdf.

3. *Broadband to Homes and Businesses*

Two satellite companies provide Internet access to consumers throughout the United States.[230] In many rural areas, these two are the sole broadband providers.[231] These operators deliver broadband service to consumers through GSO satellites operating at approximately 22,300 miles from Earth, and both plan to add additional HTS GSO capacity to meet growing demand.[232] The consolidated revenues for both companies totaled about $4 billion in 2019.[233] Distribution of satellite broadband terminals to homes has increased commensurately, up 22 percent between 2015 and 2019.[234] Over the past few years, the FCC awarded three such companies almost a combined $1 billion to provide fixed and broadband services to unserved homes and businesses in high-cost areas.[235]

A new development in the satellite industry is the idea of "megaconstellations" of LEOs that could provide global broadband Internet with low latency. Several companies plan multi-satellite NGSO constellations to provide broadband services. The proposed systems

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[230] *See* M. Sheetz, "SpaceX's Starlink wins nearly $900 million in FCC subsidies to bring internet to rural areas," CNBC (Dec. 7, 2020), https://www.cnbc.com/2020/12/07/spacex-starlink-wins-nearly-900-million-in-fcc-subsidies-auction.html; Viasat, "Services+Systems, Residential," https://www.viasat.com/services/residential (last visited Dec. 31, 2020); HughesNet, "HughesNet Internet FAQs," https://www.satelliteinternet.com/providers/hughesnet/faqs/ (last visited Dec. 31, 2020). ViaSat now is licensed to add an NGSO constellation to its existing GSO system. *See ViaSat, Inc., Petition for Declaratory Ruling Granting Access for a Non-U.S.-Licensed Non-Geostationary Orbit Satellite Network,* Order and Declaratory Rulemaking, IBFS File No. SAT-PDR-201611115-00120, FCC 20-56 (Apr. 23, 2020), https://docs.fcc.gov/public/attachments/FCC-20-56A1.pdf.

[231] FCC 2018 Communications Competition Report, *supra* note 222.

[232] *See* J. De Loor, "Embracing HTS Connectivity Services: Your HTS Platform Benefits," Newtec (Sep. 28, 2018) ("HTS Connectivity"), https://www.newtec.eu/article/article/embracing-hts-connectivity-services-your-hts-platform-benefits (estimating that by 2021, broadband would account for 51 percent of HTS revenue).

[233] *See* Viasat, "2019 Annual Report," at 1 (2019), http://investors.viasat.com/node/20736/pdf; Hughes Press Release, "EchoStar Announces Financial Results for Three and Twelve Months Ended December 31, 2019" (Feb. 20, 2020), https://www.hughes.com/resources/press-releases/echostar-announces-financial-results-three-and-twelve-months-ended-december-2019.

[234] 2020 Satellite Industry Report, *supra* note 39, at 41. *See also* SIA President's Midyear Member News (Mar. 2021), https://sia.org/wp-content/uploads/2021/03/REVISED-Presidents-Rep21-Member-News-Update-March-V1.0.pdf

[235] J. Hill, "FCC Awards Viasat $19.9 Million for Broadband Services in Rural Pennsylvania," Via Satellite (July 17, 2020), https://www.satellitetoday.com/broadband/2020/07/17/fcc-awards-viasat-19-9-million-for-broadband-services-in-rural-pennsylvania/; R. Jewett, "Hughes Network Systems Continues to Receive FCC Support to Connect Rural America," Via Satellite (Feb. 13, 2020), https://www.satellitetoday.com/broadband/2020/02/13/hughes-network-systems-continues-to-receive-fcc-support-to-connect-rural-america/; J. Brodkin, "No-fiber zone: FCC funds 25 Mbps, data-capped satellite services in rural areas," Ars Technica (Dec. 17, 2019), https://arstechnica.com/information-technology/2019/12/no-fiber-zone-fcc-funds-25mbps-data-capped-satellite-in-rural-areas/.

range from a few hundred satellites[236] to tens of thousands in various orbits.[237] Predictions suggest "High Volume Production" of such satellites could dramatically reduce spacecraft manufacturing time and cost.[238]

These megaconstellations are at varying stages of development and deployment.[239] The aim of these systems is to provide global, low-latency broadband connectivity, anywhere, anytime, including Alaska, Hawaii, Caribbean islands, and underserved areas in CONUS, as well as globally.[240] They expect to have the capacity and speeds to compete with a wide range of terrestrial providers.[241]

4. Phone, Emergency, and Mobile Communications

Several companies provide space-based service in the United States to small mobile devices capable of operating on land, in the air, or on inland and coastal waters for narrowband voice and data services. They operate on a variety of frequencies. Each of these systems provide an important communications capability, particularly in rural and remote areas where ground-based communications may be unavailable and during emergencies when local networks may be destroyed or overloaded.[242] Two of the systems also have been

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[236] C. Henry, "Viasat, lured by broadband subsidy opportunity, eyes 300-satellite LEO constellation," SPACENEWS (May 28, 2020), https://spacenews.com/viasat-lured-by-broadband-subsidy-opportunity-eyes-300-satellite-leo-constellation/ (300 satellites).

[237] *See* Application of Space Exploration Holdings, LLC for Deployment of and Operating Authority for the SpaceX Gen2 NGSO Satellite System, at 10 (May 26, 2020), https://licensing.fcc.gov/myibfs/download.do?attachment_key=2378669 (30,000 satellites).

[238] D. Eccles *et al.*, "Effects of High-Volume Production (HVP) on Space Systems," Center for Space Policy and Strategy (June 2020), https://aerospace.org/sites/default/files/2020-06/Eccles-HPV-20200610.pdf.

[239] The FCC last year approved Amazon's "Kuiper" application for 3329 satellites, in 98 orbital planes, at three different altitudes about 380 miles above earth. *See Kuiper Systems, LLC*, *Application for Authority to Deploy and Operate a Ka-band Non-Geostationary Satellite Orbit System*, Order and Authorization, IBFS File No. SAT-LOA-20190704-00057, FCC 20-102 (July 30, 2020), https://docs.fcc.gov/public/attachments/FCC-20-102A1.pdf. *Cf. Space Exploration Holdings, LLC*, IBFS File No. SAT-MOD-20200417-00037, FCC 21-48 (Apr. 27, 2021), https://docs.fcc.gov/public/attachments/FCC-21-48A1.pdf (authorizing SpaceX to add over 2,000 new satellites in low earth orbit).

[240] *See* Bloomberg Space Race, *supra* note 13.

[241] *See* D. Grossman, "Amazon Kuiper: What You need to know about Starlink's Latest Competition," Inverse (Aug. 3, 2020), https://www.inverse.com/innovation/amazon-kuiper; M. Koziol, "Amazon's Project Kuiper is More than the Company's Response to SpaceX," IEEE Spectrum (Aug. 17, 2020), https://spectrum.ieee.org/tech-talk/aerospace/satellites/amazons-project-kuiper-is-more-than-the-companys-response-to-spacex (cloud); Intelligence Brief, "How will OneWeb collapse impact the future of LEO satellites?," GSMA Mobile World Live (Apr. 22, 2020), https://www.mobileworldlive.com/blog/intelligence-brief-how-will-oneweb-collapse-impact-the-future-of-leo-satellites (mobile).

[242] These satellite companies include Globalstar (operating in the L- and S-bands), Inmarsat (operating in the Ku- and Ka-bands), Ligado (operating in L-band), and Iridium (operating in L-band). *See* Appendix.

certified for service as part of the Global Maritime Distress and Safety System, discussed in Section I.D.[243]

Another provider offers a service that can be used to both send an "SOS" and connect with the GOES Emergency Response Coordination Center to confirm when first responders have been dispatched.[244] Plus, when hurricanes Irma and Maria hit Puerto Rico and the Virgin Islands in 2017, most of the mobile phone infrastructure was knocked out. The Federal Emergency Management Agency relied on satellites (and drones) for emergency communications.[245] Indeed, a single satellite phone provided the only communications link for a Puerto Rican town of 45,000, whose populace lined up at the local drugstore—the sole satellite phone connection—for hours to assure their families they were safe.[246]

Commercial space-based systems also provide service as part of a U.S. Coast Guard-mandated Ship Security Alert System that requires vessels near the United States, or intending to dock at a U.S. port-of-call, to announce that intention well off the coast.[247] Another space-based service is Long Range Identification and Tracking, which collects and disseminates vessel position information.[248] And, there are satellite-provided systems delivering ship's captain alerts of conditions that require a change in course.[249]

Medical providers are among the users of these systems. Many rural ambulances are satellite-equipped, so that doctors can analyze patient telemetry before the ambulance arrives. At least two companies sell pre-equipped helicopter ambulances containing compact satellite terminals to forward data on the patient to the destination hospital (all while monitoring the

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[243] Inmarsat long has provided such services; Iridium became the second satellite service permitted to provide GMDSS service. *See* Iridium, "Iridium is Now Formally Authorized to Provide GMDSS Services" (Jan. 13, 2020), https://investor.iridium.com/2020-01-13-Iridium-is-Now-Formally-Authorized-to-Provide-GMDSS-Service.

[244] Globalstar, "SPOT X," https://www.globalstar.com/en-us/products/personnel-safety/spotx (last visited Dec. 31, 2020). In addition, hikers headed beyond the reach of mobile coverage can clip a device onto their mobile phone and communicate emergency messages (such as being caught in landslides or threatened by dangerous wildlife) even when traveling "off the grid."

[245] Remarks of FCC Chairman Ajit Pai at the Satellite Industry Association's 21st Annual Leadership Dinner, at 1 (Mar. 12, 2018), https://docs.fcc.gov/public/attachments/DOC-349676A1.pdf.

[246] *Id*.

[247] That Inmarsat-based system, implemented after 9/11, requires U.S. flagged vessels to transmit continuous position reports; foreign flag vessels to transmit position reports once the vessel announces an intent to enter a U.S. port; and foreign flag vessels within 1,000 nautical miles of the baseline of the United States to transmit continuously. *See* 33 C.F.R. § 169.210.

[248] LRIT is an IMO-standardized service designed to collect and disseminate vessel position information. Satellite based; it provides an "enhanced level of Maritime Domain Awareness that is the first of its kind." U.S. Dep't of Homeland Security, U.S. Coast Guard Navigation Center, "Long Range Identification and Tracking (LRIT) Overview," https://www.navcen.uscg.gov/?pageName=lritMain (last visited Dec. 31, 2020); *see also* International Maritime Resolution, Maritime Safety Committee Resolution MSC.263(84), Annex 9, § 11.2 (May 2008), https://www.navcen.uscg.gov/pdf/lrit/ref_docs/MSC.263(84).pdf. Because SSAS and LRIT are satellite based, they especially can be useful in Polar Regions.

[249] Iridium, "Preparing for the Unexpected with Iridium Connected 'Tender Watch'" (May 14, 2019), https://www.iridium.com/blog/2019/05/14/prepare-for-unexpected-ship-iridium-connected-tender-watch/.

helicopter's own performance).[250] Portable mobile satellite terminals often are erected at emergency sites, cut-off from local communications and power, and used to coordinate response actions, especially in remote areas beyond the reach of terrestrial mobile networks.

Several of these space mobile satellite-system companies also serve the data needs of businesses. Mobile satellites are already serving remote fixed points for meter reading.[251] Satellite IoT revenues are forecasted to grow to almost $3 billion worldwide by 2026.[252] In addition, mobile satellites have been adept in moving into the Internet of Things (IoT) submarket.[253] NASA is considering using one of the systems to supplement the system it uses to communicate with its space assets, providing an alternate space-to-space link.[254]

More recently, conventional fixed satellite-service systems are being used to provide service to mobile users. This especially has been facilitated by the development of "high throughput satellites" (HTS) offering substantially higher power with narrow spot beams that allow customers to choose exactly where to transmit (and not to transmit) their intended signals.[255] HTS spacecraft often serve mobile users via innovative antenna designs called Earth Stations in Motion (ESIMs) to reach passengers, or crew, on jets or cruise ships, or provide high-speed entertainment to either platform. Land-based vehicles, such as trains and buses, can take advantage of these same capabilities for connectivity or fleet tracking.

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[250] Honeywell, "Health and Usage Monitoring Systems (HUMS)," https://aerospace.honeywell.com/en/learn/products/health-and-usage-monitoring (last visited Dec. 31, 2020); *see* Inside Viasat, "Viasat technology behind advances in telemedicine, better en route care" (Jan. 15, 2019), https://corpblog.viasat.com/viasat-technology-behind-advances-in-telemedicine-better-en-route-care/.

[251] Ardmore, Florida, installed satellite-water reader units in 2019. *See* D. Butler, "City of Ardmore installing satellite-linked meters to track water usage," The Daily Ardmoreite (July 21, 2019), https://www.ardmoreite.com/news/20190721/city-of-ardmore-installing-satellite-linked-meters-to-track-water-usage.

[252] IEEE ComSoc Technology Blog, "NSR: Satellite IoT market forecast at $2.9B by 2026" (Oct. 1, 2017), https://techblog.comsoc.org/2017/10/01/nsr-satellite-iot-market-forecast-at-2-9b-by-2026/.

[253] *See, e.g.,* Ligado Networks, "Solutions: Standards-Based Satellite IoT" (Apr. 20, 2020), https://ligado.com/solutions/standards-based-satellite-iot/ (last visited Dec. 31, 2020); Iridium, "Iridium's Internet of Things," https://www.iridium.com/solutions/iot/ (last visited Dec. 31, 2020); A new entrant, Omnispace, combines connectivity from an NGSO system with conventional terrestrial wireless to serve its IoT customers. *See* Omnispace, "Enabling IoT on a massive new scale," https://omnispace.com/services/ (last visited Dec. 31, 2020).

[254] NASA Webinar, "Topics in Advanced Communications and Design in the TES-n Nanosatellite Flight Series: Use of Iridium as a Primary Command/Control Gateway" (Mar. 18, 2020), https://www.nasa.gov/smallsat-institute/use-of-iridium-as-a-primary-command-control-gateway.

[255] According to the Satellite Industry Association, these HTS spacecraft have lowered the cost of new geostationary capacity from $30M/Gbps to under $5M/Gbps in between 2014 and 2019. 2020 Satellite Industry Report, *supra* note 39, at 13. Northern Sky Research, a consulting firm, says "a significantly higher value can be achieved from [HTS] in terms of capacity per sellable bits by using Software Defined Satellites." S. Sachdeva, "What Drives Satellite Flexibility: Necessity or Opportunity?,' Northern Sky Research (Aug. 17, 2020), https://www.nsr.com/what-drives-satellite-flexibility-necessity-or-opportunity/.

Mobile HTS customers can pay for a shaped satellite spot beam reaching exactly where they are and handing off from cell-to-cell as they travel.[256]

B. Infrastructure Communications

1. *Video*

Video content distribution has been a key market for the satellite industry, driven by satellites' unique ability to cover entire continents. The first successful commercial communications geostationary satellites provided point-to-multipoint downlink communications, including for video and data distribution. Some of the largest customers of this service are video networks that rely on satellites to transmit their broadcast programming to cable head-ends and to television stations.[257] HBO began this way, as a pay TV fill-in for cable TV subscribers in rural Pennsylvania and, within a year, it was distributing its signal to multiple cable TV head-ends, including New York City, via satellite.[258] According to HBO statistics from 2017, HBO is seen in over 142 million households worldwide,[259] most of which receive it either directly or indirectly via satellite. Other broadband offerings, such as streaming video, also are carried via satellite and compete with terrestrial broadcasting and cable TV.

2. *Data*

Another huge market for satellites is data transmission. Via satellite, data can be transmitted and received nationwide to networks of users each equipped with only a small terminal.[260] These networks enable automatic teller machines at banks and convenience stores and credit (or debit) card machines at gas stations and coffee shops.[261] Millions of

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[256] *See* HTS Connectivity, *supra* note 232, estimating that by 2021, mobility would account for 18 percent of HTS revenue.

[257] ITU-R Report M.2640-0, "Key elements for integration of satellite systems into Next Generation Access Technologies" (July 2019), https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2460-2019-PDF-E.pdf; Y. Zeller & T. Beutelspacher, "Signal Transmission from Antenna to Receiver: Transmission and distribution of satellite signals in large facilities," Microwave Journal (Aug. 2, 2018), https://www.microwavejournal.com/articles/30796-signal-transmission-from-antenna-to-receiver.

[258] Time Warner Cable, "HBO & Satellites," *archived at* https://archive.ph/20130412002347/http://m.history.timewarnercable.com/the-twc-story/era-1970s/Story.aspx?story=45.

[259] Digital Intheround, "How Many Subscribers Does HBO Have?" (Mar. 17, 2021), https://digitalintheround.com/how-many-subscribers-does-hbo-have/#Basic_HBO_Stats_and_Facts.

[260] X2nSat, "About VSAT," https://x2nsat.com/network/about-vsat/ (last visited Dec. 31, 2020).

[261] K. Hassan & A. Mustafa, "VSAT Network Overview," 10 J. of Electron. & Comm. Engineering 18, 21 (Jan.-Feb. 2015), http://iosrjournals.org/iosr-jece/papers/Vol.%2010%20Issue%201/Version-3/D010131824.pdf. *See also* CorpSkies, "Explanation of internet access and private VSAT networks," http://www.satsig.net/corp-skies/internet-vsat-private-networks.htm (last visited Dec. 31, 2020).

these terminals operate in various satellite bands.[262] HTS spacecraft further improve the service these networks can provide.

Satellites also provide essential connectivity for mobile service towers in remote areas. This "backhaul" capability is in place for 3G and 4G connections,[263] and is expected to provide a similar function for 5G, and follow-on 6G, architectures.[264]

A subset of data distribution is SCADA, an acronym for supervisory control and data acquisition. It is a technology used to monitor and control plants and equipment in industries such as water and waste control, energy (oil and gas), transportation, and telecommunications. Satellite delivery of SCADA helps companies that operate nationwide and in rural and remote areas do so more efficiently.

C. Imaging

Satellite imaging – the photographing of objects from space – is a technology that has existed from the earliest days of spaceflight. With recent advances, it permits amazingly sharp resolution and frequent updates. Originally a technology for spy agencies, satellite imagery now is used for a wide range of applications, including by farmers deciding when to plant, geologists and others identifying natural resources, and financial analysts looking at trends in economic activity.[265]

Commercial expansion of the satellite imaging market is forecast as commercial products can augment military capabilities and the availability of new technologies such as high-resolutions cameras, light detection and ranging (LIDAR) and electric propulsion.[266] The

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[262] As one example of the scale of VSAT operations, the EchoStar/Hughes VSAT system claims to support over 100,000 lottery terminals. Hughes, "Hughes Lottery Systems Solutions" (Nov. 2015), https://www.hughes.com/sites/hughes.com/files/2018-03/Hughes%20Lottery%20System%20Solutions.pdf.

[263] Intelsat, "On Demand: The Future Begins Here: How Satellite Backhaul Enables a Brighter Tomorrow" (2020), https://www.intelsat.com/events/the-future-begins-here-how-satellite-backhaul-enables-a-brighter-tomorrow.

[264] Nokia, "5G from space: The role of satellites in 5G," (2020), https://www.nokia.com/networks/insights/5g-space-satellites/.

[265] Satellite Imagery has monitored Amazonian deforestation from space. *See* T. Betwick & S. Ruiz, "Smartphones and Satellite Imagery: Bringing Environmental Enforcement to the Peruvian Amazon," Global Forest Watch (Mar. 27, 2019), https://blog.globalforestwatch.org/people/smartphones-and-satellite-imagery-bringing-environmental-enforcement-to-the-peruvian-amazon. Satellite imagery, and even GPS, also can present national security concerns to countries, including in the United States. A. McKenna, A. Gaudion & J. Evans, "The Role of Satellites and Smart Devices: Data Surprises and Security, Privacy and Regulatory Challenges," 123 Penn. St. L. Rev. 591, 622-31 (2019), http://www.pennstatelawreview.org/wp-content/uploads/2019/06/Penn-StatimMcKenna-Formatted-FINAL.pdf.

[266] Research and Markets, Press Release, Global Commercial Satellite Imaging Market Outlook, 2020 (July 31, 2020), https://www.globenewswire.com/news-release/2020/07/31/2070947/0/en/Global-Commercial-Satellite-Imaging-Market-Outlook-2020.html. Imaging satellites operate at various frequencies including 401-402 MHz, 420-450 MHz, and 8025-8400 MHz. *See* Appendix.

best resolution available on the commercial market is just below 0.5 meters.[267] New commercial satellite ventures are accomplishing even finer imaging from NGSO orbits.[268] Indeed, some are deploying constellations of SmallSats, including CubeSats,[269] as an efficient way to collect and provide specialized data. U.S. national defense relies on information from commercial imaging providers.

Ocean monitoring is one example of how federal and commercial entities can combine space spectrum systems to create a needed product. Remote sensing satellites "are now integral to what oceanographers do."[270] Combined with GPS, the imaging satellites provide tailored products streaming real-time and predictive data for fisherman.[271] Satellites also assist in sustainable fishery management: polar orbiting satellites provide NOAA observations on ocean color, which is a proxy for phytoplankton, the base of the sea's food chain.[272] NOAA uses the same technology to set "tags" on certain birds, seals, fish, sea turtles, and whales—allowing both animal tracking and issuing advisories to help vessels avoid endangered species during migration.[273] Complementing NOAA, the LANDSAT series of satellites observed the Earth's surface since 1973, and provided benchmark data for detecting ground surface changes worldwide, including monitoring crop health and identifying disaster-struck areas. LANDSATs are operated by the United States Geological Survey and provided, in orbit, by NASA.[274]

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[267] For example, DigitalGlobe states its WorldView-3 satellite offers 31 cm resolution, and that its GeoEye-1 satellite offers 46 cm resolution. *See* Satellite Imaging Corporation, "Worldview-3 Satellite Sensor," https://www.satimagingcorp.com/satellite-sensors/worldview-3/ (last visited Dec. 31, 2020); *and* Satellite Imaging Corporation, "GeoEye-1 Satellite Sensor," https://www.satimagingcorp.com/satellite-sensors/geoeye-1/ (last visited Dec. 31, 2020). The Airbus Pleiades 1B, marketed through the French company SPOT, claims 50 cm accuracy. *See* Satellite Imaging Corporation, "Pleiades-1B Satellite Sensor," https://www.satimagingcorp.com/satellite-sensors/pleiades-1b/ (last visited Dec. 31, 2020).

[268] *See, e.g.*, M. Wall, "Surface Rupture from Ridgecrest Earthquake Spotted from Space (Photo)," Space.com (July 9, 2019), https://www.space.com/ridgecrest-earthquake-satellite-photos-planet.html.

[269] The company Planet, for example, has over 100 CubeSats in orbit. Planet, "Our Constellation," https://storage.googleapis.com/planet-ditl/day-in-the-life/index.html (last visited Dec. 31, 2020).

[270] Value of Space, *supra* note 21, at 5.

[271] *See* V. Klemas, "Fisheries Applications of Remote Sensing: An Overview," Fisheries Research Vol. 148 (Nov. 2013), https://www.sciencedirect.com/science/article/pii/S0165783612001075.

[272] *See* M. Behrenfeld *et al.*, "Carbon-based ocean productivity and phytoplankton physiology from space," Global Biogeochemical Cycles Vol. 19, Issue 1, at 2-3 (Jan. 25, 2005), https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2004GB002299.

[273] Value of Space, *supra* note 21, at 6.

[274] *See* USGS, "Landsat Missions," https://www.usgs.gov/land-resources/nli/landsat/landsat-satellite-missions?qt-science_support_page_related_con=2#qt-science_support_page_related_con (last visited Dec. 31, 2020).

D. Launch Services

In recent years, American companies have paved the path of innovation and growth in commercial launch services to meet the increased demand for space exploration, space tourism, and the deployment of thousands of additional satellites. Recognizing the development of the commercial launch industry, the U.S. decreased regulatory burdens on commercial space transport. Congress passed legislation that streamlined launch approvals, promoted private sector roles in launch and reentry,[275] federalized liability claims for launch service providers, and directed the Department of Transportation to set a launch liability ceiling.[276] In the launch process, several space spectrum bands have been used to track the rockets and control their engines.[277]

According to the Director of National Intelligence, the number of satellites launched worldwide nearly quadrupled between 2016 and 2018 alone, from just over 100 to more than 400 launched.[278] Between 2012 and year-end 2019, over 1,700 SmallSats were launched.[279] U.S. companies created only in the past decade have been driving this growth. Between 2018 and 2019, the United States increased its market share of satellite launches to 63 percent.[280] This industry proved remarkably flexible, so that a single launch vehicle can launch a variety of payloads: manned missions to the International Space Station: six dozen SmallSats; or resupply the International Space Station with over 5,700 pounds of cargo.[281] These new entrants have driven down launch costs. U.S. achievements were capped this

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[275] *See* 51 U.S.C. § 50918 (2020) note ("It is the sense of Congress that eliminating duplicative requirements and approvals for commercial launch and reentry operations will promote and encourage the development of a commercial space sector.").

[276] *See* 51 U.S.C. § 50914 (2020).

[277] Those bands include: 420-430 MHz for sending self-destruct commands, if necessary, during launch; 2200-2290 MHz to send performance data space-to-Earth to ground controllers; and 5650-5925 MHz for radar transponders to track the launch vehicle. *See Allocation of Spectrum for Non-Federal Space Launch Operations,* ET Docket No. 13-115, ¶ 4 (Apr. 22, 2021) (Report and Order and Further Notice of Proposed Rulemaking), https://docs.fcc.gov/public/attachments/FCC-21-44A1.pdf. *See also* Appendix.

Many launch providers such as SpaceX and Blue Origin have moved away from using the 420-430 MHz and 5650-5925 MHz bands during launches while some legacy use by other providers may continue. *See* SpaceX Notice of Ex Parte Communications, Exhibit, ET Docket No. 13-115 (July 6, 2020), https://ecfsapi.fcc.gov/file/10706003157598/Launch%20Spectrum%20Ex%20Parte%20(7-6-2020).pdf; Blue Origin Notice of Ex Parte Communication, FCC Docket No. 13-115, Exhibit at 11-14 (July 23, 2020) ("Blue Origin Ex Parte"), https://ecfsapi.fcc.gov/file/1072396509074/Blue%20Origin%20FCC%20Docket%2013-115%20Ex%20Parte%20Communication.pdf.

[278] Statement for the Record of Daniel Coats, Director of National Intelligence, "Worldwide Threat Assessment of the U.S. Intelligence Community," Senate Select Committee on Intelligence at 17 (Jan. 29, 2019), https://www.dni.gov/files/ODNI/documents/2019-ATA-SFR---SSCI.pdf.

[279] Bryce Space and Technology, "SmallSats by the Numbers, 2020," at 2, https://brycetech.com/reports/report-documents/Bryce_Smallsats_2020.pdf (defining SmallSats as those satellites with a mass of 600 kg or less).

[280] 2020 SIA Report, *supra* note 39, at 34.

[281] S. Clark, "SpaceX resupply mission reaches International Space Station," Spaceflight Now (Dec. 8, 2019), https://spaceflightnow.com/2019/12/08/spacex-resupply-mission-reaches-international-space-station/.

spring when two NASA astronauts were launched to the ISS, and returned, in a private-sector capsule on a private sector rocket.[282]

The benefits include the creation of thousands of high-tech jobs; regaining U.S. dominance in the sector; and securing America's high-tech supply chain by reducing the need to launch from, for example, Kazakhstan on Russian-made rockets. One U.S. launch provider grew to over 6,000 employees in 2018;[283] by mid-2020, employment had jumped to 8,000.[284] That same company launched two astronauts to the International Space Station and back, hundreds of satellites for its megaconstellation, and made successful re-entry and landing of reusable rocket first stages, potentially "reducing the cost of traveling to space by a hundredfold."[285] Other U.S.-based[286] companies[287] are fabricating and testing launch vehicles, and undergoing similar growth. These companies are trusted sufficiently to launch for the U.S. intelligence community.[288] Indeed, U.S. law and policy require launch vehicles for U.S. government satellites to be manufactured in the United States.[289]

As it grows, the launch industry provides hundreds of higher-salary employment

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[282] *See supra* text accompanying notes 158-159.

[283] M. Sheetz, "The rise of SpaceX and the future of Elon Musk's Mars dream," CNBC (Mar. 20, 2019), https://www.cnbc.com/2019/03/20/spacex-rise-elon-musk-mars-dream.html.

[284] M. Sheetz, "Elon Musk tells SpaceX employees that its Starship rocket is the top priority now," CNBC (June 7, 2020), https://www.cnbc.com/2020/06/07/elon-musk-email-to-spacex-employees-starship-is-the-top-priority.html.

[285] H. Groenendaal, "Reusable rockets will reduce cost to space," EE Publishers (Apr. 18, 2016), https://www.ee.co.za/article/reusable-rockets-will-reduce-cost-space.html. SpaceX's gain has been Russia's loss. Private sector built, truly reusable first stage reduces launch costs enormously. Neither Russia nor China, suffocated by State Owned Enterprises, had accomplished this. *See* E. Berger, "Russia appears to have surrendered to SpaceX in the global launch market," Ars Technica (Apr. 18, 2018), https://arstechnica.com/science/2018/04/russia-appears-to-have-surrendered-to-spacex-in-the-global-launch-market/.

[286] *See* Blue Origin, Launch. Land. Repeat., https://www.blueorigin.com/our-mission (last visited Dec. 31, 2020). *See also* A. Boyle, "Blue Origin's expansion plans rush ahead at its Seattle-area HQ – and in Los Angeles," GeekWire (Nov. 29, 2019), https://www.geekwire.com/2019/blue-origins-expansion-plans-rush-ahead-seattle-area-hq-los-angeles/ ("Just three and a half years ago, Blue Origin's workforce amounted to 600 employees . . . . Now the employee count is at around 2,500, heading toward 3,500 in the next year.").

[287] *See* Virgin Galactic Vision, https://www.virgingalactic.com/vision/ (last visited Dec. 31, 2020) ("We are at the vanguard of a new industry, pioneering the next generation of reusable space vehicles. We aim to transform the current cost, safety and environmental impact of space-launch. In doing so we are helping to create, for the first time, a basic space access infrastructure that will act as an enabler for scientists and entrepreneurs.").

[288] Rocket Lab, "Rocket Lab To Launch National Reconnaissance Office Mission" (Jan. 20, 2020), https://www.rocketlabusa.com/about-us/updates/media-release-rocket-lab-to-launch-national-reconnaissance-office-mission/.

[289] *See* 51 U.S.C. § 50131 ("the Federal Government shall acquire space transportation services from United States commercial providers . . .."). *See also* FAA.gov, "Space - Frequently Asked Questions," https://www.faa.gov/space/additional_information/faq/ (last modified Mar. 31, 2021).

opportunities and attracts top talent to America.[290] The same is true for U.S. satellite manufacturers—63 percent of all commercially procured satellites launched last year were built in the United States.[291] This "generates a lot of employment for engineers, mathematicians, physicists, chemists, biologists and similar professions."[292]

E. Over the Horizon: Developing Space Commerce Markets

Although longstanding space commerce markets are enjoying a resurgence, highlighting the importance of spectrum access, there also are tantalizing new technologies that could provide still more avenues for economic growth and U.S. high-tech leadership throughout this century.

1. Tourism

Space tourism – human spaceflight for recreational purposes – is another promising area of development. Multiple countries have successfully offered suborbital flight. Orbital tourism to date has been significantly more expensive.[293] Some of these "private spaceflight participants" have even paid for brief stays on the International Space Station (ISS). Since the end of the U.S. Shuttle program, all these flights to the ISS were delivered via the Russian Space agency (Roscosmos),[294] until the recent successful SpaceX launch, which sent and returned two NASA astronauts to and from the ISS in 2020.[295]

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[290] The U.K.'s Rocket Lab July 4, 2020, launch from New Zealand experienced a second-stage failure, stranding payloads from Cannon Electronics Inc., Planet, and Inspace. R. Jewett, "Rocket Lab Fails Mission, Loses Payloads for Canon, Planet," Via Satellite (July 5, 2020), https://www.satellitetoday.com/launch/2020/07/05/rocket-lab-fails-mission-loses-payloads-for-canon-planet/.

[291] 2020 SIA Report, *supra* note 39, at 23.

[292] "Industry Insight: Space Jobs of the Future," Space Report (last visited Dec. 31, 2020), https://www.thespacereport.org/uncategorized/industry-insight-space-jobs-of-the-future/.

[293] In 2002, South African Mark Shuttleworth spent over 9 days orbiting in a Russian spacecraft. *See* Biographies of International Astronauts, "Mark Shuttleworth," http://www.spacefacts.de/bios/international/english/shuttleworth_mark.htm (last modified Apr. 20, 2018). He paid $20 million (almost $30 million in 2020 dollars) for the flight. *See "*Ubantu: The Entrepreneur who wants to give it all away," Financial Times (Jan. 20, 2006), *archived at* https://web.archive.org/web/20101115224130/http://www.benking.co.uk/art/Ubuntu_the_entrepreneur_who_wants_to_give_it_all_away.php.

[294] "Roscosmos and Space Adventures Sign Contract for Orbital Space Tourist Flight," Space Adventures (Feb. 19, 2019), https://spaceadventures.com/blog/roscosmos-and-space-adventures-sign-contract-for-orbital-space-tourist-flight/; L. Matignon, "Space Tourism Legal Aspects," Space Legal Issues (Mar. 5, 2019), https://www.spacelegalissues.com/space-law-space-tourism-legal-aspects/.

[295] *See supra* text accompanying notes 158-159.

Future opportunities suggest a much larger market. There is already a "Spaceport America" in New Mexico,[296] built with commercial operations, in mind.[297] At least two[298] American-based[299] companies and a U.K. competitor[300] seek to provide space tourism in the medium term. Forecasts predict this market getting off the ground in 2022 and generating $14 billion in cumulative revenues by 2028.[301]

Commercial development of space tourism is already a reality, and some in the private sector would go further than orbiting Earth to develop privately funded missions to the Moon and Mars.[302] To that end, NASA recently issued a Request for Information for establishing data communications between the Earth and Moon and on the Moon[303]—Internet for the Moon using SmallSats.[304] Soon, commercial actors may augment or fly side-by-side with government systems in the next phase of exploration of the solar system.

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[296] *See* SpaceportAmerica, "FAQs," https://www.spaceportamerica.com/faq/ (last visited Dec. 31, 2020) (claiming over 300 launches).

[297] *See* SpaceportAmerica, "Do Business With Us," https://www.spaceportamerica.com/business/ (last visited Dec. 31, 2020).

[298] M. Kramer, "SpaceX inks deal to fly space tourists to orbit," Axios (Feb. 18, 2020) ("Space Tourism Update"), https://www.axios.com/spacex-space-tourism-deal-a464e9b4-ff33-472f-8c10-bda6ec2db5ea.html.

[299] Blue Origin uses 2250 MHz for its launch, granted by a series of one-time grants of Special Temporary Authority. *See*, *e.g*., FCC Application for Special Temporary Authority, Call Sign WP9XVN, File No. 2385-EX-ST-2019 (Jan. 3, 2020), https://apps.fcc.gov/oetcf/els/reports/STA_Print.cfm?mode=current&application_seq=97256&RequestTimeout=1000. Blue Origin's New Shepard NS-15 executed a perfect unmanned test mission in mid-April 2021—landing both the first stage (reused from an earlier flight) and the empty capsule. That puts Blue Origin on course to sell tickets for public sub-orbital lights in 2022. M. Bartels, "Blue Origin aces 'astronaut rehearsal' New Shepard test flight," Space.com (Apr. 14, 2021), https://www.space.com/blue-origin-new-shepard-ns-15-launch-landing-success.

[300] Virgin Galactic, the space tourism company created by entrepreneur Richard Branson, expects to re-open ticket sales in 2020. M. Sheetz, "Virgin Galactic is seeing strong demand for tourist flights to space, will re-open ticket sales," CNBC (Jan. 9, 2020), https://www.cnbc.com/2020/01/09/virgin-galactic-ticket-sales-will-re-open-this-year-ceo-says.html. Virgin Galactic's founder, Richard Branson, promised to fly sub-orbital later in 2020. Space Tourism Update, *supra* note 298, at 1. Previously, the company sold over 600 space tourism tickets, before a test rocket crashed five years ago. *See* K. Chang & J. Schwartz, *Virgin Galactic's SpaceShip Two Crashes in New Setback for Commercial Spaceflight*, N.Y. Times, at A1 (Nov. 1, 2014), https://www.nytimes.com/2014/11/01/science/virgin-galactics-spaceshiptwo-crashes-during-test-flight.html.

[301] Northern Sky Research, "Suborbital and Orbital Tourism to Begin Services in 2020 & 2021, will Generate $14B by 2028" (Dec. 17, 2019), https://www.nsr.com/nsr-report-space-tourism-market-ready-to-take-off/.

[302] M. McFall-Johnsen & D. Mosher, "Elon Musk says he plans to send 1 million people to Mars by 2050 by launching 3 Starship rockets every day and creating 'a lot of jobs' on the red planet," Business Insider (Jan. 17, 2020), https://www.businessinsider.com/elon-musk-plans-1-million-people-to-mars-by-2050-2020-1.

[303] *See* NASA, "Lunar Communications Relay and Navigation Services," Notice ID GSFC-CIS-RFI-0002 (Oct. 3, 2020), https://www.govcb.com/government-bids/LUNAR-COMMUNICATIONS-RELAY-AND-NBD00159526947335055.htm.

[304] D. Israel *et al.*, "LunaNet: a Flexible and Extensible Lunar Exploration Communications and Navigation Infrastructure and the Inclusion of SmallSat Platforms," SSC-20-XII-03 (34th Annual Small Satellite Conference Aug. 2020), https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=4773&context=smallsat.

2. Resource Recovery and Manufacturing

Another exciting prospect for commercial space operations (which has been called "the next gold rush"[305]) is recovery of space resources (such as Helium-3, a clean-burning fuel), or distribution of solar power.[306] This could be either from the Moon or from asteroids via a base on the Moon.[307] A Moon base is likely the first necessary step and represents a potential jumping-off point for future manned travel to Mars. In the future, the Moon's surface itself might be turned into oxygen via electro-deoxidation of powdered solid-state lunar dust and rocks.[308]

Space manufacturing represents yet another opportunity. Today, the International Space Station is being used to conduct experiments in space-manufacturing, benefiting from its natural advantages (zero gravity and an immediate testbed for repeatable, long-term use).[309] NASA has had good initial results, including tests of 3D printing in Zero-G.[310] Preliminary speculation suggested that, under the right conditions, it could be cheaper to cut[311] or drill[312] metal or other materials in the vacuum of space. Research suggests the use of space to

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[305] J. Pandya, "The Race to Mine Space," Forbes (May 13, 2019), https://www.forbes.com/sites/cognitiveworld/2019/05/13/the-race-to-mine-space/#19e351441a70.

[306] M. Wall, "No Digging Required: Space Mining on the Moon and Beyond May be Solar Powered," Space.com (Sept. 4, 2019), https://www.space.com/moon-asteroid-space-mining-with-concentrated-sunlight.html; "How to make oxygen from moondust," The Economist (Jan. 25, 2020), https://www.economist.com/science-and-technology/2020/01/25/how-to-make-oxygen-from-moondust.

[307] *See* B. Weichert, "Nationalism is the Key Ingredient for Space Exploration," Center for American Greatness (Aug. 10, 2019), https://amgreatness.com/2019/08/10/nationalism-is-the-key-ingredient-for-space-exploration/ ("The energy sector stands to benefit also, as things like space-based solar power and even, potentially, Helium-3-fueled nuclear fusion become a reality. Other industries, such as biomedicine and computing, also could be catapulted to new heights of innovation as the growing human presence in space demands more out of these attendant sectors." (Internal citations omitted)).

See also USGS, "Feasibility Study for the Quantitative Assessment of Mineral Resources in Asteroids," Report 2017-1041 (2017), https://pubs.usgs.gov/of/2017/1041/ofr20171041.pdf.

[308] *See* B. Lomax *et al.*, "Proving the viability of an electrochemical process for the simultaneous extraction of oxygen and production of metal alloys from lunar regolith," 180 Planetary & Space Sci. 104748 (Jan. 2020), https://www.sciencedirect.com/science/article/pii/S0032063319301758?via%3Dihub.

[309] NASA, "In-Space Manufacturing," https://www.nasa.gov/oem/inspacemanufacturing (last modified May 22, 2019).

[310] T. Prater *et al.*, "Summary Report on Phase I and Phase II Results from the 3D Printing in Zero-G Technology Demonstration Mission, Volume II" (Mar. 1, 2018), https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180002403.pdf.

[311] Permanent, "Vapor and Droplet Deposition in Vacuum," https://www.permanent.com/space-industry-vapor-deposition.html (last visited Dec. 31, 2020).

[312] Permanent, "Cutting in a Vacuum," https://www.permanent.com/space-industry-cutting.html (last visited Dec. 31, 2020).

produce ultra-light printed circuit boards might also be advantageous.[313] Others have suggested certain Binder Jetting or Material Extrusion processes might be less expensive on the Moon or Mars.[314]

One former NASA space shuttle commander recently predicted that space manufacturing capabilities will be a transformative step in commercial space, and orbital debris could be raw material for orbital satellite manufacturing, which has a somewhat longer time horizon.[315] NASA is in Phase 2 of a challenge designed to develop robots for in-situ resource utilization (ISRU) to be feasible on the Moon or Mars.[316] The Chief Counsel of the Department of Commerce Office of Space Commerce recently spoke before two United Nations' Committees, saying other entrepreneurs are bringing forth wholly new capabilities like space-based manufacturing, on-orbit servicing, and space tourism, even in addition to capabilities designed to help us explore the heavens to the Moon and Mars and beyond."[317]

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[313] R. Clinton, "Overview of Additive Manufacturing Initiatives at NASA Marshall Space Flight Center - In Space and Rocket Engines" (Feb. 22-23, 2017), https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170001772.pdf.

[314] J. Thangavelautham *et al.*, "Autonomous Multirobot Technologies for Mars Mining Base Construction and Operation," IAC-19-D3.18 (2019), https://arxiv.org/ftp/arxiv/papers/1910/1910.03829.pdf.

[315] "More Space Company M&A, Failures Seen Coming," Communications Daily (Jan. 15, 2020) (subscription only). China has more ambitious plans, including manned Moon landings, resource mining, and Mars missions, in a shorter timeframe. C. Tai, "China's Plan to Conquer the Moon, Mars, and More," Wall Street Journal Video (July 17, 2020), https://www.wsj.com/video/china-plan-to-conquer-the-moon-mars-and-more/202774E8-3A3C-4A8B-99C7-9455D2D58477.html.

[316] NASA, "Space Robotics Challenge Phase 2" (2019) (Phase 1 submissions ended in December of 2019), https://www.challenge.gov/challenge/space-robotics-challenge-phase-2/.

[317] Diane Howard, Chief Counsel, Office of Space Commerce, U.S. Dep't of Commerce, "OSC Remarks at UN General Assembly" (Oct. 31, 2019), https://www.space.commerce.gov/osc-remarks-at-un-general-assembly/.

Appendix: Allocations and Systems

Separate Enclosure

Acknowledgements

We gratefully acknowledge the input and review by the following individuals from Executive Branch and Independent Agencies, as well as many others who supported their efforts: Kenneth Turner and Brian Jordan (DoD); Scott Heckman (for ODNI); Jerry Ulcek (Coast Guard); Ivan Navarro, Al Wissman, and Fred Mistichelli (NOAA); Rene Balanga, William Horne, and Frank Bauer (NASA); Ashley Zauderer and Jonathan Williams (NSF); and Jose Albuquerque, Karl Kensinger, and Merissa Velez (FCC). This Report is the product of cooperation between these agencies and staff of the Office of Spectrum Management, particularly: Bruce Jacobs, Carl Frank, Brandon Mitchell, and John Alden; and contractors Jay Chauhan, Christian Kuzdak, and Martha Alemu at Freedom Technologies.