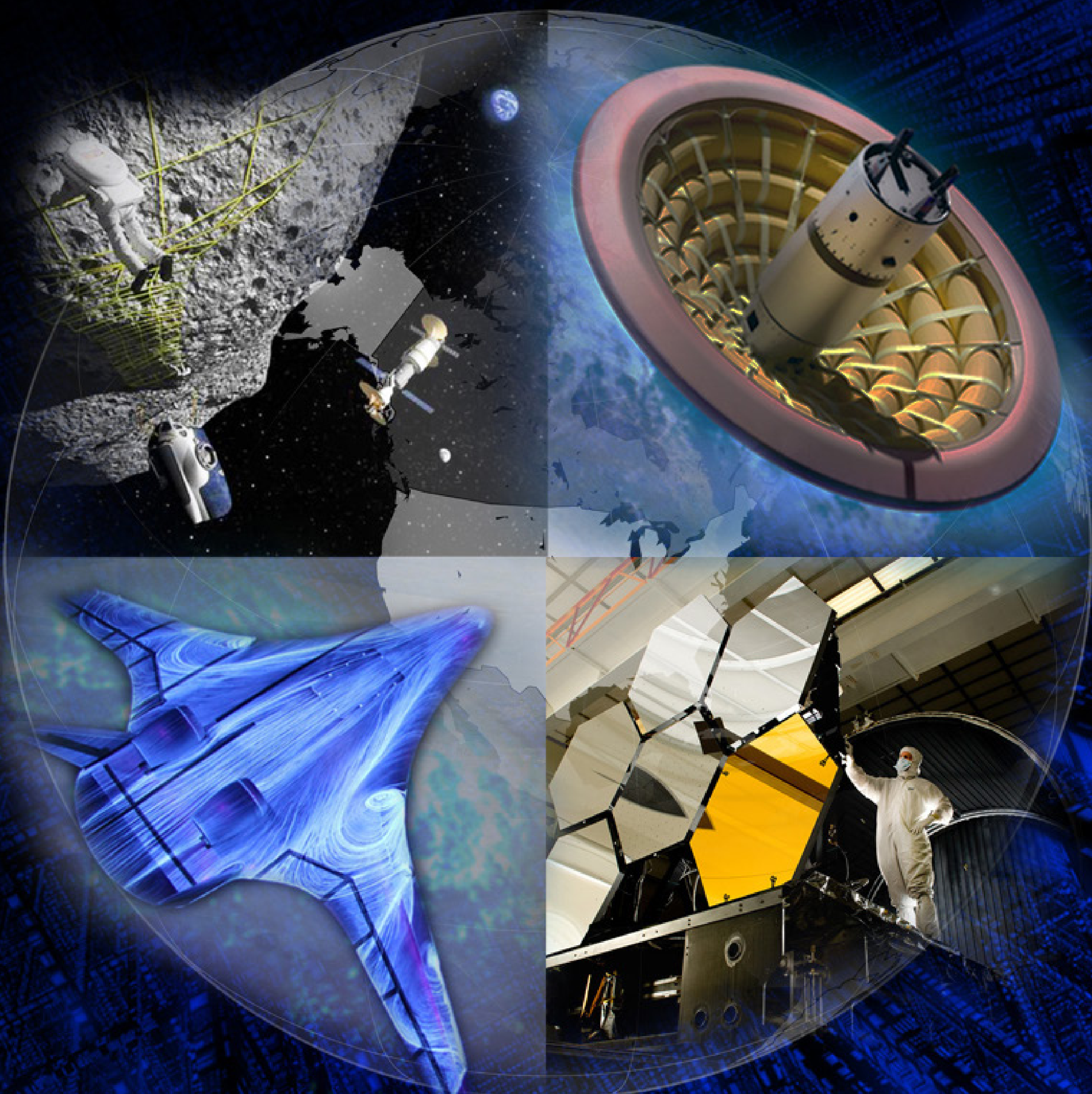
National Aeronautics and Space Administration

NASA Technology Roadmaps

TA 5: Communications, Navigation, and Orbital Debris Tracking and Characterization Systems



July 2015

Foreword

NASA is leading the way with a balanced program of space exploration, aeronautics, and science research. Success in executing NASA's ambitious aeronautics activities and space missions requires solutions to difficult technical challenges that build on proven capabilities and require the development of new capabilities. These new capabilities arise from the development of novel cutting-edge technologies.

The promising new technology candidates that will help NASA achieve our extraordinary missions are identified in our Technology Roadmaps. The roadmaps are a set of documents that consider a wide range of needed technology candidates and development pathways for the next 20 years. The roadmaps are a foundational element of the Strategic Technology Investment Plan (STIP), an actionable plan that lays out the strategy for developing those technologies essential to the pursuit of NASA's mission and achievement of National goals. The STIP provides prioritization of the technology candidates within the roadmaps and guiding principles for technology investment. The recommendations provided by the National Research Council heavily influence NASA's technology prioritization.

NASA's technology investments are tracked and analyzed in TechPort, a web-based software system that serves as NASA's integrated technology data source and decision support tool. Together, the roadmaps, the STIP, and TechPort provide NASA the ability to manage the technology portfolio in a new way, aligning mission directorate technology investments to minimize duplication, and lower cost while providing critical capabilities that support missions, commercial industry, and longer-term National needs.

The 2015 NASA Technology Roadmaps are comprised of 16 sections: The Introduction, Crosscutting Technologies, and Index; and 15 distinct Technology Area (TA) roadmaps. Crosscutting technology areas, such as, but not limited to, avionics, autonomy, information technology, radiation, and space weather span across multiple sections. The introduction provides a description of the crosscutting technologies, and a list of the technology candidates in each section.

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Executive Summary

This is Technology Area (TA) 5: Communications, Navigation, and Orbital Debris Tracking and Characterization, one of the 16 sections of the 2015 NASA Technology Roadmaps. The Roadmaps are a set of documents that consider a wide range of needed technologies and development pathways for the next 20 years (2015-2035). The roadmaps focus on “applied research” and “development” activities.

TA 5 supports all NASA space missions with the development of new capabilities and services that make missions possible and safe. NASA’s space communications and navigation infrastructure provides the critical lifeline for all space missions. It is the means of transferring commands, spacecraft telemetry, mission data, and voice for human exploration missions, while maintaining accurate timing and providing navigation support. Orbital debris can be tracked and characterized by some of the same systems used for spacecraft communications and navigation, as well as by other specialized systems. Advancements in communications and navigation technologies will allow future missions to implement new and more capable science instruments, greatly enhance human missions beyond Earth orbit, and enable entirely new mission concepts. This will lead to more productivity in science and exploration missions, as well as provide high-bandwidth communications links that will enable the public to be a part of NASA’s exploration and discovery programs. Orbital debris tracking and characterization systems can be improved using radio frequency and optical techniques similar to those used in communications and navigation systems, as well as other dedicated systems, and will make crewed and robotic missions in Earth orbit safer for longer durations.

Goals

The high-level goals of communications, navigation, and orbital debris tracking and characterization technology development are increased performance and efficiency in the systems that provide these capabilities for all mission classes.

In communications, these goals translate to:

- Increased data rates (e.g., 10 to 100 times) without increasing the mission burden in mass, volume, power, and/or spectrum;
- Increased security without increased complexity; and
- Assured data delivery via robust, low latency, automated or autonomous, and networked connectivity throughout the solar system.

For navigation and timing, the goals are to provide:

- More accurate vehicle tracking to reduce the errors in trajectories; entry, descent, and landing; and rendezvous and docking;
- The ability to track more vehicles in less time with equivalent accuracy;
- Automated or autonomous trajectory and maneuver planning; and
- More accurate and stable time or frequency references for timekeeping to facilitate more precise navigation and autonomous operations.

Orbital debris tracking and characterization will require the ability to:

- Track and characterize debris that is 10 to 100 times smaller than debris that is currently being tracked; and
- Reduce tracking time to accommodate the larger number of targets being tracked.

Increased reliability is an underlying goal for both performance and efficiency. In all of these technology developments, the goals of increased efficiency and performance must ultimately translate into an overall mission lifecycle cost reduction.

The immediate goal of the communications and navigation technology development effort is to address any deficiencies identified by established missions. A secondary, longer-term goal is to provide NASA with advanced communications and navigation capabilities that the missions can then infuse to provide new mission capabilities, including enhanced public engagement and, potentially, spinoffs to commercial endeavors.

As mission capabilities grow, the space communications infrastructure must grow faster to avoid constraints on missions and enable missions never before imagined. The vision of the future will transform the present NASA space communications and navigation capability from being a connection provider to being a flexible service provider as NASA extends Internet-worked technologies and techniques throughout the solar system and beyond. This vision includes enabling spacecraft to autonomously navigate and communicate back to Earth over self-forming, adaptive networks that are tolerant of disruptions and delays.

In order to bring about this transformation in space communications capability, NASA must continue to develop new technologies. There is still enormous potential to further develop radio frequency technology, which will help provide the higher data rates that will be needed in the future to avoid constraining new mission capabilities. There is also an enormous potential to develop optical communications to a level of availability that matches that of radio frequency communications and unbridles the unrestricted optical bandwidth for orders of magnitude advances over present radio frequency capabilities. Position, navigation, and timing technology advancement will allow spacecraft to navigate autonomously anywhere in the solar system. Extending the Internet to space will require the development of new protocols and network topologies, but also new ways of providing a secure environment for the vital communications links that will be needed in the future. Some of the revolutionary concepts in this TA have the potential to enable “game changing” capabilities for future mission architectures.

The ability to track and characterize orbital debris smaller than what is currently tracked and do it more quickly than it is currently being done will allow NASA to better protect space assets, including the crews in or in-transit to beyond Earth orbit.

Table 1. Summary of Level 2 TAs

5.0 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	Goals:	Increase performance and efficiency in the systems that provide communications, navigation, and orbital debris tracking and characterization capabilities for all mission classes.
5.1 Optical Communications and Navigation	Sub-Goals:	Provide higher data rate links for near-Earth and enable more efficient photon-starved links for deep-space.
5.2 Radio Frequency Communications	Sub-Goals:	Enable higher data rates and data throughput for near-Earth and deep-space to ground communications. Provide communications through harsh environments, such as rocket plumes and reentry ionization.
5.3 Internetworking	Sub-Goals:	Provides dynamic, high-speed internetworked communications and navigation services for space applications
5.4 Position, Navigation, and Timing	Sub-Goals:	Reduce reliance on Earth-based systems for ground-based tracking, ranging, trajectory and orbit determination, and maneuver planning and execution functions.
5.5 Integrated Technologies	Sub-Goals:	Develop highly integrated, multifunctional systems to reduce mass and power requirements on spacecraft, and reduce dependence on manual control from Earth.
5.6 Revolutionary Concepts	Sub-Goals:	Provide orders of magnitude increase in data throughput, guaranteed data integrity, and robust navigation for near-Earth and deep-space applications.
5.7 Orbital Debris Tracking and Characterization	Sub-Goals:	Maintain detailed knowledge of orbital debris characteristics in order to predict future collisions and potentially take action to avoid them.

Benefits

Communications and navigation are enabling services that are required by all spacecraft. Developments in communications and navigation technology will ensure that future NASA missions are not constrained by deficiencies in communications or navigation. It will allow missions to take advantage of more capable science instruments that will evolve in the future. Orbital debris tracking and characterization are fundamental to the safety of Earth-orbiting assets and crews, thus making technology development in this area important for safety.

Technology developments in Position, Navigation, and Timing (PNT) will benefit both human and robotic spaceflight. More precise positioning will facilitate higher quality data return from science instruments, such as high-resolution cameras, and will enable mission operations concepts, such as precise landing and deep-space formation flying, that are not possible with today's navigation capability. Extending networking to space will decrease the cost of missions through autonomous transfer of data, where today such transfers involve high levels of Earth-based scheduling and scripting. This will be analogous to how the terrestrial Internet autonomously transfers information without human intervention.

Developments in PNT technologies will also improve autonomous navigation, which will ultimately reduce the cost of mission operations and enable mission capabilities, such as, autonomous rendezvous, proximity operations, and docking. The benefits that would accrue to human spaceflight include reduced mission risk; lowered operations costs through significantly less ground control intervention; and new capabilities for robotic pre-positioning, assembly, and servicing of key assets and cargo.

NASA space communications technology and orbital debris tracking and characterization have traditionally been of interest to other agencies in the U.S. government. This is evidenced by the fact that many past space communications technology developments and orbital debris tracking and characterization activities have been joint projects with other agencies. There is reason to believe that this trend will continue. For example, cybersecurity has been identified as an area of critically important research and development (R&D) that should be pursued by all U.S. government agencies, and will be a driving requirement as the terrestrial Internet is extended into space.

Many advances in space communications technology are transferable to the commercial communications environments. For example, spectrum-efficient technology is a prime concern of the telecommunications industry and to those U.S. government agencies that manage spectrum. Similarly, advanced networking that can autonomously deal with communications disruptions has potential terrestrial commercial Internet applications. In general, communications technology developed for space applications can be implemented in the commercial sector, even though the actual spectrum frequencies may differ.

Due to commonality in many of its components and methods, NASA's communications technology has always been synergistic with the radio astronomy community. Many government, non-profit, and academic organizations can benefit from space communications technology development by participating in the challenging opportunities for researchers and through educational outreach programs.

Development of communications technology will also benefit the average American citizen through improved Agency outreach to the public and educational institutions. Space communications technology development can allow an average citizen to view from his or her living room—in an immersive, virtual three dimensional (3D) audio, video, and haptic environment—the exploration activities of NASA's robots and astronauts on their missions of discovery. Improvements in communications will allow exploration experiences to be extended into the homes and classrooms of the general public. Data can be disseminated to experimenters in near real-time to allow for improved experiments and provide telescience capability. Live audio and video delivery allow for direct public involvement into the engineering challenges and excitement of scientific discovery.

Technology Area 5
Communications, Navigation, and Orbital Debris Tracking and Characterization Systems Roadmap 1 of 2

Enabling Technology Candidates Mapped to the Technology Need Date

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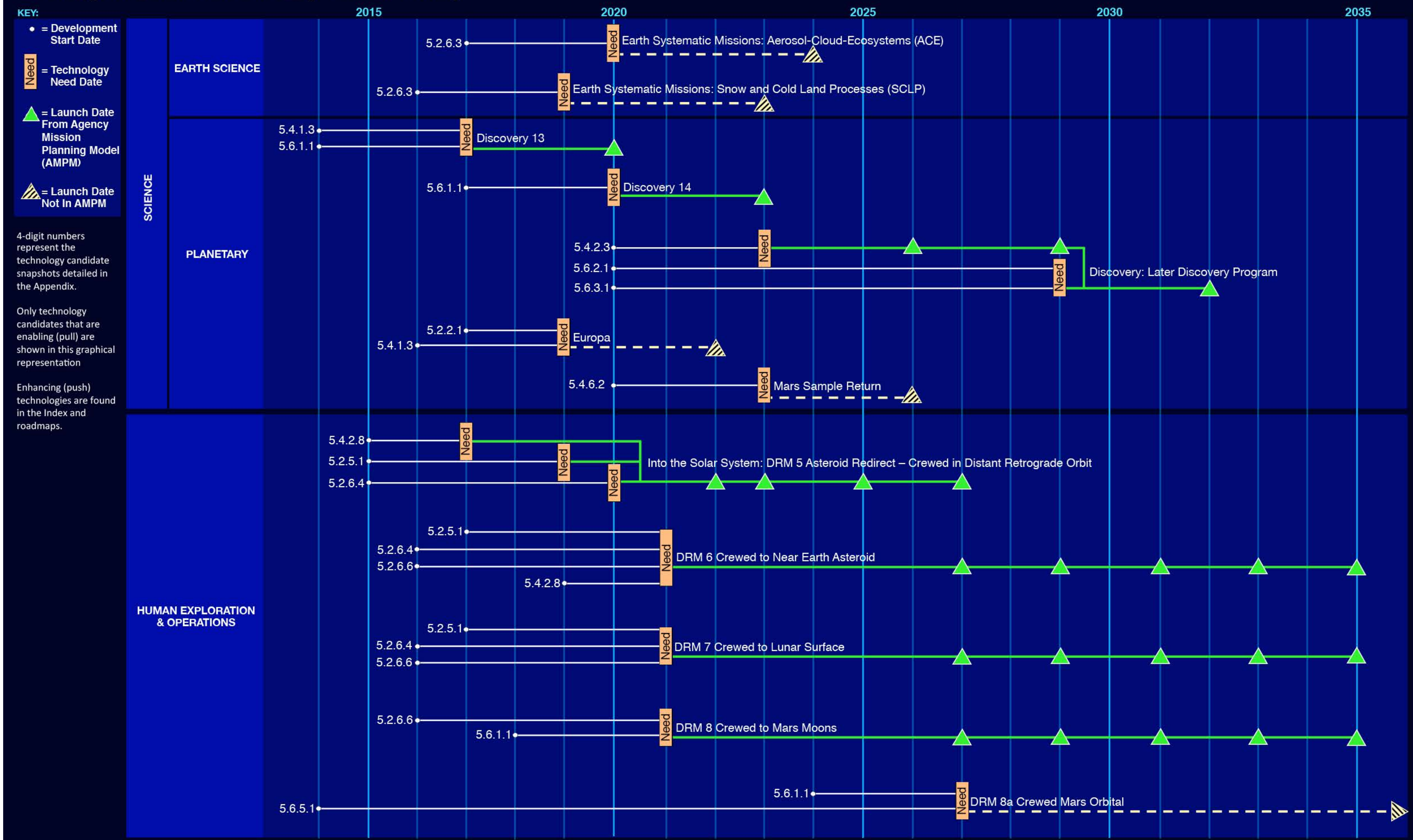
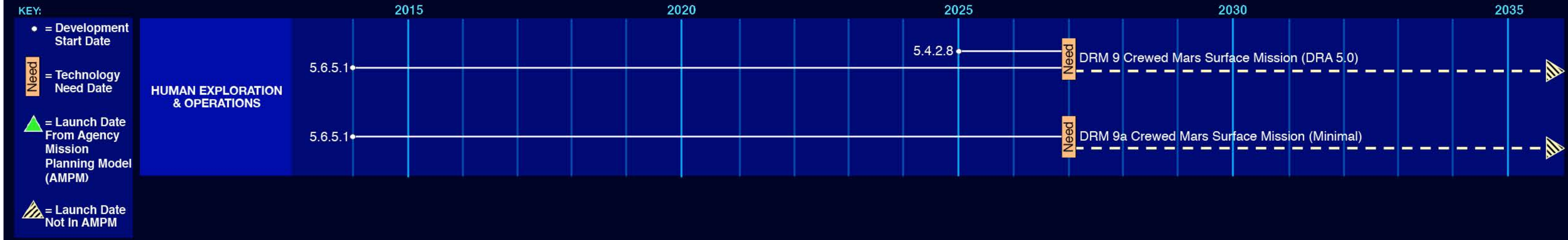


Figure 1. Technology Area Strategic Roadmap

Technology Area 5
Communications, Navigation, and Orbital Debris Tracking and Characterization Systems Roadmap 2 of 2

Enabling Technology Candidates Mapped to the Technology Need Date

National Aeronautics and Space Administration



4-digit numbers represent the technology candidate snapshots detailed in the Appendix.

Only technology candidates that are enabling (pull) are shown in this graphical representation

Enhancing (push) technologies are found in the Index and roadmaps.

Figure 1. Technology Area Strategic Roadmap (Continued)

Introduction

Figure 2 shows the Technology Area Breakdown Structure (TABS) for Communications, Navigation and Orbital Debris Characterization Systems.

TA 5 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

5.1 Optical Communications and Navigation
- 5.1.1 Detector Development
- 5.1.2 Large Apertures
- 5.1.3 Lasers
- 5.1.4 Acquisition and Tracking
- 5.1.5 Atmospheric Mitigation
- 5.1.6 Optical Tracking
- 5.1.7 Integrated Photonics

5.2 Radio Frequency Communications
- 5.2.1 Spectrum-Efficient Technologies
- 5.2.2 Power-Efficient Technologies
- 5.2.3 Propagation
- 5.2.4 Flight and Ground Systems
- 5.2.5 Earth Launch and Re-Entry Communications
- 5.2.6 Antennas

5.3 Internetworking
- 5.3.1 Disruption-Tolerant Networking
- 5.3.2 Adaptive Network Topology
- 5.3.3 Information Assurance
- 5.3.4 Integrated Network Management

5.4 Position, Navigation, and Timing
- 5.4.1 Timekeeping and Time Distribution
- 5.4.2 Onboard Auto Navigation and Maneuver
- 5.4.3 Sensors and Vision Processing Systems
- 5.4.4 Relative and Proximity Navigation
- 5.4.5 Auto Precision Formation Flying
- 5.4.6 Autonomous Approach and Landing

5.5 Integrated Technologies
- 5.5.1 Radio Systems
- 5.5.2 Ultra Wideband
- 5.5.3 Cognitive Networks
- 5.5.4 Science from the Communications System
- 5.5.5 Hybrid Optical Communications and Navigation Sensors
- 5.5.6 Radio Frequency and Optical Hybrid Technology

5.6 Revolutionary Concepts
- 5.6.1 X-Ray Navigation
- 5.6.2 X-Ray Communications
- 5.6.3 Neutrino-Based Navigation and Tracking
- 5.6.4 Quantum Key Distribution
- 5.6.5 Quantum Communications
- 5.6.6 Superconducting Quantum Interference Filter Microwave Amplifier
- 5.6.7 Reconfigurable Large Apertures

5.7 Orbital Debris Tracking and Characterization
- 5.7.1 Tracking Technologies
- 5.7.2 Characterization Technologies

Figure 2. Technology Area Breakdown Structure Technology Areas for Communications, Navigation, and Orbital Debris Characterization Systems

NASA's technology area breakdown structure (TABS) is in wide use in technology organizations around the globe. All sections that are in the previous structure have been retained for traceability, and new sections have been appended to reflect the growth in technology areas. There are sections within the roadmaps with no identified technology candidates. This is either because there are no identified technologies which coupled with NASA's mission needs (either push or pull) within the next 20 years, or because the technologies are now being addressed elsewhere in the roadmaps. These sections are noted in gray above and are explained in more detail within the write-up for this roadmap.

5.1 Optical Communications and Navigation

Optical Communications and Navigation deals with the various technologies required to make communications and navigation with light practical and seeks to take advantage of the virtually unconstrained bandwidth available in the optical spectrum.

Optical communications and navigation technologies can be grouped into the following general categories:

- **5.1.1 Detector Development:** Development of high detection efficiency, low-dark-count, low-jitter photon counting detectors for both ground and flight applications.
- **5.1.2 Large Apertures:** Multi-meter diameter optical apertures for both ground (> 10 meters diameter) and flight (> 5 meter diameter) applications.
- **5.1.3 Lasers:** High direct current (DC)-to-optical power efficiency, high peak-to-average power, reliable, flight-qualified lasers.
- **5.1.4 Acquisition and Tracking:** Techniques and technologies for efficient, accurate pointing of the optical terminal—primarily in flight—but may include interaction with the ground terminals or be "beaconless."
- **5.1.5 Atmospheric Mitigation:** Measurement and modeling of the atmospheric channel and its effects on optical propagation, and techniques and technologies for mitigating atmospheric effects.
- **5.1.6 Optical Tracking:** Optical techniques for ranging and Doppler measurement derived from the optical communications signal.
- **5.1.7 Integrated Photonics:** The next generation of highly integrated systems including lasers, optics, modulators, demodulators, encoding, and decoding.

5.2 Radio Frequency Communications

Radio Frequency (RF) Communications strives to dramatically accelerate techniques in use today for NASA's missions. RF technology development concentrates on getting more productivity out of the constrained spectrum bands that are allocated to space users. Although it is quite a bit more mature than optical communications, there is still a great deal of promise for technology breakthroughs in the RF domain. The focus of RF technology development will be on the RF spectrum allocated and needed for space use by the International Telecommunication Union (ITU), where adequate bandwidth would provide a useful service, or where the application is beyond the near-Earth environment.

RF communications technologies can be grouped into the following general categories:

- **5.2.1 Spectrum-Efficient Technologies:** Flight and ground techniques and technologies that allow more efficient utilization of the RF spectrum.
- **5.2.2 Power-Efficient Technologies:** Flight and ground techniques and technologies that make more efficient use of the available system power.
- **5.2.3 Propagation:** Measurement and modeling of the RF channel and its effects on RF propagation, and techniques and technologies for mitigating these effects.
- **5.2.4 Flight and Ground Systems:** Technologies are addressed in TA 5.5 Integrated Technologies.
- **5.2.5 Earth Launch and Re-Entry Communications:** Technologies to mitigate the communications and tracking effects occurring during Earth launch and reentry.
- **5.2.6 Antennas:** Flight and ground antennas providing larger effective apertures than those currently in operation, with high efficiency but lower mass per unit area and accurate pointing.

5.3 Internetworking

Internetworking deals with the adaptation of the Earth's Internet technology and processes throughout the solar system. The expansion of internetworking will help lower operational costs of systems by replacing manual scripting and commanding of individual spacecraft communications links with autonomous handling of data distribution similar to that of the terrestrial Internet. It will also enable space vehicles (free flyers, extravehicular activity (EVA) crew members, wireless cameras, etc.) to communicate with other space vehicles independently, without relying on ground support to manage communications.

Internetworking technologies can be grouped into the following general categories:

- **5.3.1 Disruption-Tolerant Networking:** Networking techniques and technologies that provide data delivery across multiple data links that may be disrupted and/or have long delays.
- **5.3.2 Adaptive Network Topology:** Topologies and protocols, including mesh networking, capable of optimizing data connectivity among elements in spaceflight or on planetary surfaces.
- **5.3.3 Information Assurance:** Security techniques and technologies to ensure system safety, data integrity, availability, and confidentiality and to enable use of all available links and networks – some of which may be provided by other agencies or countries.
- **5.3.4 Integrated Network Management:** Architectures and protocols to effectively support network operations when network topology includes nodes with disrupted and/or long delay links.

5.4 Position, Navigation, and Timing

PNT provides all the technologies required to know where spacecraft and targets are, understand their trajectories, and synchronize all systems. The PNT area addresses the key technology efforts necessary to improve navigation through developments in timing accuracy and distribution, as well as make autonomous navigation available for precise maneuvers, such as rendezvous and docking, anywhere in the solar system.

PNT technologies can be grouped into the following general categories:

- **5.4.1 Timekeeping and Time Distribution:** Integrated, space-qualified systems with ultra-high time accuracy and frequency stability, as well as technologies and architectures for distributing precise time and frequency signals or information to distributed points in a network.
- **5.4.2 Onboard Auto Navigation and Maneuver:** Technologies to implement autonomous onboard navigation and maneuvering to reduce dependence on ground-based tracking; ranging; trajectory, orbit, and attitude determination; and maneuver planning support functions.
- **5.4.3 Sensors and Vision Processing Systems:** Technologies include optical navigational sensor hardware (such as high resolution flash Light Detection and Ranging (LIDAR) sensors, visible and infrared cameras), radar sensors, radiometrics, fine guidance sensors, laser rangefinders, high-volume and high-speed electronics for LIDAR and other imaging sensor data processing, sensor measurement processing algorithms, synthetic vision hardware and software, and situational awareness displays.
- **5.4.4 Relative and Proximity Navigation:** Technologies include those that enable the ability to perform multi-platform relative navigation (such as determine relative position, relative velocity, and relative attitude or pose), which directly supports cooperative and collaborative space platform operations.
- **5.4.5 Auto Precision Formation Flying:** Technologies to enable precision formation flying requirements imposed by envisioned distributed observatories, such as planet-finding interferometers. Technologies include differential (relative) navigation, sensors and vision processing systems, space clocks and time or frequency distribution systems, onboard system navigation, and autonomous orbit and attitude maneuvering.

- **5.4.6 Autonomous Approach and Landing:** Technologies to perform safe and controlled precision landings on or contacts with any solid body in the solar system.

5.5 Integrated Technologies

Realizing that there may be advantages to integrating technologies developed across the communications and navigation areas, Integrated Technologies deals with crosscutting technologies that work in combination with the other areas to maximize the efficiency of missions. This focus area also includes the integration of communications and navigation technology developed in other technology areas, such as computing technology and advanced sensors.

Integrated technologies can be grouped into the following general categories:

- **5.5.1 Radio Systems:** Exploit technology advances in RF communications, PNT, cognition, and space internetworking to develop advanced, integrated space and ground systems that increase performance and efficiency while reducing cost. For example, a multipurpose, software-defined radio might be developed that can change its function with mission phase and requirements or autonomously sense and adapt to its RF environment to improve communications.
- **5.5.2 Ultra Wideband (UWB):** Provides a method of spectrum reuse in modern communications systems by transmitting extremely narrow pulses. Such extremely narrow time pulse systems can be used for communications, networking, and tracking.
- **5.5.3 Cognitive Networks:** Communications system in which each communications node on the network is dynamically aware of the state and configuration of the other nodes to autonomously optimize their operational parameters in response to changes in user needs or environmental conditions.
- **5.5.4 Science from the Communications Systems:** Enhance the use of RF communications systems and develop the capability to use optical communications links to perform science measurements. Using RF and optical in combination can improve the science data collection potential.
- **5.5.5 Hybrid Optical Communications and Navigation Sensors:** Optical sensor systems that are dual-use in nature, providing a synergistic benefit to both communications and navigation functions.
- **5.5.6 Radio Frequency and Optical Hybrid Technology:** A system that can be used to support hybridized RF and optical communications in the same asset, in diverse atmospheric (weather) and in-space conditions. This includes both the electronics and the complex integration of collinear antenna and weather elements within the system. Potential benefits include size, weight, and power (SWaP) savings and provision of an RF beacon for acquisition and pointing.

5.6 Revolutionary Concepts

Revolutionary Concepts are those technology ideas that are truly on the cutting edge. These ideas are so “far out” that the development approaches are not yet well understood. These are typically items that are simultaneously very high risk, but very high payoff if they materialize. As items mature, they might be moved to other appropriate areas of the roadmap. Much of this focus area is currently at a low-Technology Readiness Level (TRL) concept development stage. It is recognized that some of these may not come to fruition in the timeframe of this roadmap.

Revolutionary concept technologies can be grouped into the following general categories:

- **5.6.1 X-Ray Navigation:** Uses X-ray emitting pulsars to provide the ability to autonomously determine position anywhere in the solar system, just as the Global Positioning System (GPS) does for users on Earth.

- **5.6.2 X-Ray Communications:** Exploits extremely low beam divergence of X-rays to provide high-rate, deep-space, low-transmit-power, highly-secure data links, and enable new penetrating communications capabilities.
- **5.6.3 Neutrino-Based Navigation and Tracking:** Neutrino sources as navigation beacons enable navigation and tracking directly through normal matter. Accordingly, they could be used for long-distance signaling when line-of-sight cannot be guaranteed.
- **5.6.4 Quantum Key Distribution (QKD):** Promises absolute secure transmission of the key codes that are essential to encrypt messages with tamper proof information assurance.
- **5.6.5 Quantum Communications:** The art of transferring quantum states (which encode information) between two points, potentially leading to much more efficient communications.
- **5.6.6 Superconducting Quantum Interference Filter Microwave Amplifier:** Represents a significant paradigm shift by using magnetic field detection instead of electric field detection and capitalizes on techniques demonstrated in the sensors community. It incorporates a superconducting quantum interference device (SQUID) array for detecting extremely weak magnetic fields to enable a new type of signal detection process.
- **5.6.7 Reconfigurable Large Apertures:** The vision is to form large space apertures using constellations of nanosatellite systems. This will require advances in nanotechnologies, semiconductor processors, computing architectures, advanced materials power and propulsion, miniaturized communications components, ad hoc or wireless network protocols, and cognitive swarm operations.

5.7 Orbital Debris Tracking and Characterization

Tracking and characterizing the “remains” of manmade objects in orbit around Earth is critical to the safe and reliable operation of spacecraft in Earth orbit. This Orbital Debris Tracking and Characterization focus area can be grouped into two categories:

- **5.7.1 Tracking Technologies:** Tracking of orbital debris is accomplished by ground-based radars operating in S- through X-bands, as well as passive optical observation. Future radar systems are considering Ka-band for increased resolution.
- **5.7.2 Characterization Technologies:** Determination of orbit and type of debris, as well as large-scale modeling of orbital debris based on input from many different sensors.

TA 5.1: Optical Communications and Navigation

NASA is in the process of migrating its high-data-rate mission communications to Ka-band as part of a continuing trend in the demand for high data returns from science missions. The transition reflects the need for higher data rates and the necessity of moving away from S-band services. However, it is expected that the trend toward higher data rates will continue in the future and will eventually surpass the capacity available with Ka-band. NASA will migrate from Ka-band to optical communications, which provides access to an open spectrum that will support the data rates needed by the future generation of science instruments and crewed missions. This migration will be valuable to both near-Earth and deep-space missions, which will be able to realize data rates greater than or equal to RF communications with flight terminals that will impose an equal, or lower, power and mass burden on spacecraft and have significantly less aperture size than RF antennas. Optical terminals, developed by foreign space agencies, are progressing toward operational capability in the next year providing high-rate communications – up to 6 gigabit per second (Gb/s) for low-Earth orbit (LEO) and geosynchronous Earth orbit (GEO) crosslinks, and 1.8 Gb/s for LEO-GEO crosslinks. It should also be noted that optical communications has the side benefit of centimeter (cm)-level ranging, an order of magnitude better than RF.

NASA continues development of optical communications technology. In 2013, a new capability was demonstrated by the Lunar Laser Communications Demonstration (LLCD) on the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft. It proved fundamental concepts and transferred up to 622 megabits per second (Mb/s) from lunar distance, roughly three to six times the rate of the Ka-band system on the Lunar Reconnaissance Orbiter (LRO). The system demonstrated Serially Concatenated Pulse-Position Modulation (SCPPM) and superconducting nanowire photon counting detectors, which will be key factors in optical communications from deep-space locations in the future. The optical terminal flown on LADEE is now the basis for demonstrating optical communications capability in near-Earth missions. The flight terminal's optical module technology is applicable to use in LEO and GEO. However, with the shorter distance and power available in a near-Earth environment, coherent modulation is more appropriate and will be used as the primary modulation—potentially augmented with the SCPPM capability. With coherent modulation, these systems will be able to operate at the multi-Gb/s level at GEO and below. The downlinks use 1,550 nanometer (nm) wavelength, though high power uplinks for deep-space are currently in the 1,030-1,080 nm wavelength region. Also, use of optical communications for in-situ relay links can improve performance by several orders of magnitude.

While not explicitly captured here as a technology area, the flight implementation of signal processing and storage (electrical or photonic) for modulation, demodulation, encoding, decoding, and routing functions are also significant challenges as bit rates approach 100 Gb/s.

Sub-Goals

Technology development efforts begin with supporting near-Earth (including lunar) optical communications. This technology progresses from near-Earth capabilities to the development of larger terminals to support deep-space optical communications. Later in the optical communications development process, beaconless tracking will be developed that will enable optical communications for the outer planets. Also, in order to enhance deep-space optical communications, technology will be developed to enable Earth-based satellites to relay deep-space optical communications to Earth.

The intensity of a laser signal decreases rapidly as the receiver gets farther and farther from the source. This is a major concern, especially for deep-space applications, because data transmission rates decline as the density of received photons is reduced. Extraneous "noise photons," such as those that might occur when pointing close to the Sun, drive the need to distinguish the transmitted photons. The narrow beam widths involved require precise acquisition and tracking, as well as vibration mitigation. Increasing laser lifetime is critical for long-duration missions. At the same time, increasing laser power efficiency from the current 10 to 15 percent to around 30 percent while decreasing mass and cost will be an important factor in moving the optical communications capability forward, especially for deep-space applications. Atmospheric conditions including clouds, clear air moisture content, and atmospheric turbulence can be a major challenge to eventual operational acceptance of optical communications. High-performing, space-based optical receiver systems will be required for space-based uplinks and relay applications.

Table 2. Summary of Level 5.1 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
5.0 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	Goals:	Increase performance and efficiency in the systems that provide communications, navigation, and orbital debris tracking and characterization capabilities for all mission classes.
Level 2		
5.1 Optical Communications and Navigation	Sub-Goals:	Provide higher data rate links for near-Earth and enable more efficient photon-starved links for deep-space.
Level 3		
5.1.1 Detector Development	Objectives:	Improve photon-counting detectors.
	Challenges:	Increasing detector array area, saturation limitations, efficiency, and number of pixels while decreasing jitter and improving radiation tolerance.
	Benefits:	Enables at least a 10x increase in data rate over current deep-space radio frequency systems for science and exploration missions.
5.1.2 Large Apertures	Objectives:	Provide lower-cost, large apertures for deep-space-to-Earth optical communications.
	Challenges:	Clouds, attenuation, and background radiance disrupting transmission through Earth's atmosphere.
	Benefits:	Increases the data rate, and hence the data return, on deep-space optical communications links.
5.1.3 Lasers	Objectives:	Provide efficient downlinks from any mission using optical communications.
	Challenges:	In-band pumping, pump laser diode efficiency, fiber damage mitigation, parts selection, radiation, and packaging, including thermal design.
	Benefits:	Paves the way for higher power lasers needed for communications from deep-space. Improves laser beam pointing capability.
5.1.4 Acquisition and Tracking	Objectives:	Provide accurate pointing, acquisition, and tracking to support high-data-rate, deep-space communications
	Challenges:	Stabilizing small optical payloads by lowering mass and implementing active-passive techniques. Improving radiation tolerance, detection efficiency, and number of pixels.
	Benefits:	Supports high data rate, deep-space communications.
5.1.5 Atmospheric Mitigation	Objectives:	Develop efficient daytime adaptive optics to operate at the highest data rates in the daytime.
	Challenges:	Atmospheric compensation for > 10 meter apertures with low losses.
	Benefits:	Increases data throughput.

Table 2. Summary of Level 5.1 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
5.1.6 Optical Tracking	Objectives:	Generate range, range-rate, and bearing products from the optical communications link for spacecraft navigation.
	Challenges:	Faster detector readout and time stamping for flight side. Ranging modulation signals for ground-based lasers.
	Benefits:	Increases tracking precision for better orbit determination for any mission carrying an optical communications system.
5.1.7 Integrated Photonics	Objectives:	Provide highly integrated systems combining lasers, modulators and demodulators, encoders and decoders, detectors, and associated electronics to combine photonic and digital systems into one unit.
	Challenges:	Attenuation, blockage by clouds, background noise from atmospherically-scattered solar radiation, and scintillation from Earth's atmosphere.
	Benefits:	Ensures extremely high data rates for Inter-Satellite Links (ISLs).

TA 5.1.1 Detector Development

Photon counting detectors are key to efficiently operating optical communications on "photon-starved" links—either for deep-space or very-low-power, near-Earth links. Current ground-based photon counting systems use superconducting nanowire detectors of either niobium nitride (NbN) or tungsten silicide (WSi) with detector element efficiencies of 90 percent or better. Since they have been used for 1 meter (m) class receive terminals, the total area and number of pixels is small relative to the need for > 10 meter class receive apertures. It is also expected that detector efficiency, jitter, and saturation rates will improve. Higher operating temperature, high bandwidth (> Gigahertz) photon counting detectors are needed for spaceflight laser communications receivers. Promising technologies include mercury cadmium telluride and indium antimonide avalanche photodiodes. Coherent systems require fiber or integrated photonics with optically pre-amplified PIN diodes (> 10 Gb/s).

Technical Capability Objectives and Challenges

The goal of detector development is to improve photon-counting detectors by increasing detector array area, saturation limitations, efficiency, and the number of pixels. The primary challenge in the development of superconducting detectors is the ability to fabricate large area detector arrays with high yield. The primary challenge for the flight detectors is design for radiation tolerance. In both cases, increased detection efficiency, increased photon saturation thresholds, and reduced dark count rates are key challenges.

Benefits of Technology

Improved photon counting detectors are part of the overall flight and ground optical communications architecture that will enable an increase in data rate by at least 10 times (e.g., 250 Mb/s versus 25 Mb/s) over current deep-space RF systems for science and exploration missions of the future while not increasing spacecraft burden (e.g., SWaP).

Table 3. TA 5.1.1 Technology Candidates – not in priority order

TA	Technology Name	Description
5.1.1.1	Tungsten Silicide (WSi) Photon Counting Detector Array	Tungsten Silicide (WSi) large-area superconducting nanowire single photon counting detector array.
5.1.1.2	Indium Gallium Arsenide (InGaAs) Flight Photon Counting Detector Array	Indium gallium arsenide (InGaAs) kilopixel radiation-tolerant photon counting detector array.

TA 5.1.2 Large Apertures

Current plans for deep-space-to-Earth optical communications rely on large-aperture (> 10 meter effective) antennas. These do not need to be diffraction limited like a Keck telescope, which helps reduce the cost. Lower-cost, large-aperture antennas are needed for the future, and this can be accomplished by innovative monolithic apertures or by using arrays of smaller aperture antennas.

Technical Capability Objectives and Challenges

The goal of this TA is to provide lower-cost, large-aperture antennas for deep-space-to-Earth optical communications. The key challenge in all cases is increased aperture with lower mass per unit area and reduced cost relative to current technologies without compromising optical performance.

Benefits of Technology

These large-aperture antennas are key to increasing data rate, and hence the data return, on deep-space optical communications links. Since these antennas are on the "Earth end" of the link, the cost will be amortized across multiple missions and a longer time period.

Table 4. TA 5.1.2 Technology Candidates – not in priority order

TA	Technology Name	Description
5.1.2.1	Virtual, Large, Ground-Based Apertures	Arrays of smaller telescopes to provide a larger equivalent aperture.
5.1.2.2	Lightweight, Space-Based, Large Aperture Optics	Lightweight space-based large aperture optics.
5.1.2.3	Space-Based Optical Arrays	Arrays of optical telescopes to provide larger equivalent aperture.

TA 5.1.3 Lasers

Flight laser transmitters are key to efficient downlinks from any mission using optical communications. Specifically, improvement in the DC-to-optical conversion efficiency (e.g., a goal of up to 30 percent) is paramount, whether for transmitters in the 1 Watt (W) output class for CubeSats or tens of Watts for larger, higher-data-rate applications. In addition, maintaining this efficiency for low-duty-cycle optical communications modulation formats, like SCPPM, which require high peak-to-average power, is critical. Lifetimes of up to 10 years will be necessary for operational space systems. Fiber and integrated photonics laser transmitters with small SWaP (1 W) are required for near-Earth LEO and GEO flight terminals that support coherent and direct detection laser communications modulation formats (e.g., Pulse-Position Modulation (PPM) and Differential Phase Shifting Key (DPSK)).

Technical Capability Objectives and Challenges

The near-term goal in this TA is to develop a 4 W average power laser transmitter with 640 W peak-to-average, while the longer-term goal is for up to 100 W average, 1 milliWatt (mW) peak, with 30 percent DC-to-optical efficiency. The technology challenges include: in-band pumping, efficient pump laser diode development, fiber damage mitigation, parts selection, electromagnetic radiation, and packaging, including thermal design.

Benefits of Technology

Laser power efficiency improvements will pave the way for higher-power lasers needed for communications from deep-space. Addressing spacecraft-induced jitter will improve laser beam pointing. Improving space-based lasers should include improvements in amplifiers that enable higher power operations and also focus on extending the lifetime of the terminal. The near-term effort should include improving pump diode lifetime and increasing laser power to 5 W and above for high-data-rate, deep-space applications, as well as developing more power-efficient lasers.

Table 5. TA 5.1.3 Technology Candidates – not in priority order

TA	Technology Name	Description
5.1.3.1	High Direct Current (DC)-Optical Efficiency, Space-Qualified Pulse-Position Modulation (PPM) Laser Transmitter	Laser transmitter for photon efficiency communications at deep-space ranges.
5.1.3.2	Outer Planet/Oort Cloud Laser Transmitter	Laser transmitter for multi-Mb/s communications beyond Saturn.

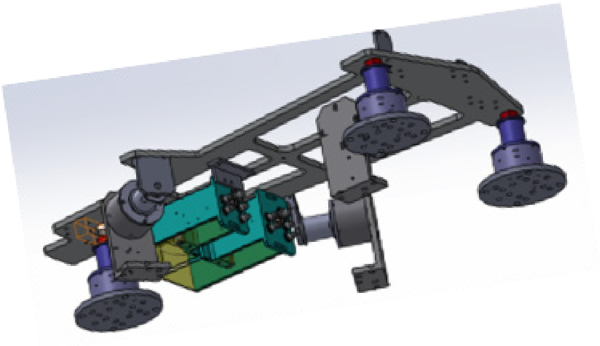
TA 5.1.4 Acquisition and Tracking

When using the extremely narrow beamwidths (relative to RF systems) in optical communications, it is essential that both ends of the link are capable of pointing, acquisition, and tracking (PAT). This is most critical on the spacecraft end of the link. Current space vibration isolation systems tend to be massive and are not appropriate for rejecting the low-frequency vibrations. The PAT systems typically assume two-way optical signals (beacon, communications, ranging, etc.), but in cases where it is desirable not to have an optical uplink, beaconless pointing will be needed.

A number of initiatives are needed in order to improve acquisition and tracking of the optical signal, including better vibration mitigation through either passive or active means; improved stabilization systems, such as introducing Fiber Optic Gyro (FOG) technology, which could effectively extend beacon-aided acquisition beyond Mars; and eventual development of a beaconless pointing capability, which would allow the use of optical communications technology throughout the solar system.

Technical Capability Objectives and Challenges

The goal of Acquisition and Tracking is to support high-data-rate, deep-space communications by providing a system that can accurately point, acquire, and track within the extremely narrow beamwidth limits required by optical communications. The key challenges related to the ability to point microradian optical beams are isolating the telescope from the spacecraft vibrations and providing accurate pointing information to the pointing system while keeping the mass, volume, and power of the necessary systems below current solutions.



Disturbance-Free Platform

Benefits of Technology

Improved acquisition and tracking systems are key to supporting high-data-rate, deep-space communications.

Table 6. TA 5.1.4 Technology Candidates – not in priority order

TA	Technology Name	Description
5.1.4.1	Disturbance-Free Platform	Non-contact isolation of laser terminal from spacecraft disturbances.
5.1.4.2	Autonomous High-Accuracy Star Tracker	Highly accurate, advanced celestial attitude determination technology.

TA 5.1.5 Atmospheric Mitigation

Optical communications signals transiting Earth's atmosphere are subject to effects like attenuation, blockage by clouds, background noise from atmospherically-scattered solar radiation, and scintillation. It is important to be able to measure and model these effects as well as combat them with techniques like adaptive optics. Optical communications techniques must operate in both daytime and nighttime regimes, unlike optical astronomy, which is limited to nighttime use. This includes experimenting with reception of signals from spacecraft terminals in varying atmospheric conditions and developing methods for handling the handover of the signal from space to alternate ground stations in the event that clouds or other atmospheric conditions disrupt a link. In addition, the development of adaptive optics or large detector arrays to mitigate atmospheric turbulence effects on optical signals is needed. In order to accelerate this work, models of optical communications signal performance in the Earth's atmosphere will be developed and validated through experimentation. Subsequent model development will extend the modeling capability to atmospheres of other bodies in the solar system.

Technical Capability Objectives and Challenges

The goal of atmospheric mitigation for optical communications is to develop efficient daytime adaptive optics to operate at the highest data rates in the daytime. The challenge for the Solar Differential Image Motion Monitor (DIMM) is to develop an accurate, autonomous, reliable, cost-effective DIMM that works during the daytime that can be deployed at remote terminal locations. The key challenges for the development of daytime adaptive optics are the derivation of the correction signal and cost-effective deformable mirrors for applying the correction to the received signal.

Benefits of Technology

Mitigating the atmospheric disturbances will increase the data throughput. Techniques developed in this TA will also provide a benefit to the optical astronomy community.

Table 7. TA 5.1.5 Technology Candidates – not in priority order

TA	Technology Name	Description
5.1.5.1	Solar Differential Image Motion Monitor (DIMM)	Daytime atmospheric optical channel characterization.
5.1.5.2	Daytime Adaptive Optics	Daytime adaptive optics for > 10 meter apertures with < 1 dB Strehl loss.

TA 5.1.6 Optical Tracking

Optical communications signals can be used for deriving tracking information similar to "radiometrics" derived from RF signals; specifically, range and range rate or Doppler. Due to the higher fundamental frequency (shorter wavelength) and data rates, greater precision is expected. The key to realizing this goal is the ability to measure pulse arrival times with the photon counting detectors and readout integrated circuits. The stability of the laser is also critical, because instability can lead to miscounts of the photons.

Technical Capability Objectives and Challenges

The goal of this technology area is to provide the ability to generate range, range-rate, and bearing products from the optical communications link for spacecraft navigation. Challenges include the development of fast detector readout and time stamping on the flight side, and ground-based lasers capable of ranging modulation signals.

Benefits of Technology

Improvements in optical tracking will increase the tracking precision for better orbit determination for any mission carrying an optical communications system.

Table 8. TA 5.1.6 Technology Candidates – not in priority order

TA	Technology Name	Description
5.1.6.1	Embedded Optical Tracking for Spacecraft Navigation	Generate range, range-rate, delta range rate, and bearing products from optical communications link for spacecraft navigation.

TA 5.1.7 Integrated Photonics

The cost and SWaP efficiency of optical communications systems of the future will depend upon more highly integrated photonic systems replacing multiple bulky and power hungry systems all requiring individual testing and integration. Ideally, these will be derivatives of similar technology being developed in commercial fiber optic systems of 40 to 100 Gb/s data rates.

Technical Capability Objectives and Challenges

The goal of this TA is to provide highly integrated systems combining lasers, modulators and demodulators, encoders and decoders, detectors, and associated electronics in one combined unit. The challenge is to take technology being developed for the fiber optic world—space qualify it with potential modifications—and integrate it with the spacecraft data systems.

Benefits of Technology

Meeting these challenges will ensure extremely high data rates for ISLs.

Table 9. TA 5.1.7 Technology Candidates – not in priority order

TA	Technology Name	Description
5.1.7.1	Multi-Mode Coherent Transceivers	Integrated photonics providing lasers, modulators, detectors, encoding, decoding, and electronics for coherent Inter-Satellite Links (ISL).

TA 5.2: Radio Frequency Communications

RF communications is used on all of NASA's current space missions. Near-Earth missions drive the state of the art (SOA) for data rates, data volume, and bandwidth efficiency. With today's technology, downlink data rates can be more than 1 Gb/s. The standard operational data rate available to NASA is 258 Mb/s through the Tracking and Data Relay Satellite System (TDRSS). Higher data rates have been demonstrated from the TDRSS, but are not currently ready for operational use.

Since communications performance is inversely proportional to the distance squared, deep-space missions tend to push the art in other directions – particularly in power efficiency. The Mars Reconnaissance Orbiter (MRO) is the SOA in deep-space communications, and can return 6 Mb/s when Mars and Earth are at their closest distance. Currently, there are critical phases of missions where standard RF techniques do not work, which include communications through launch plumes and communications through plasma during Earth reentry. NASA needs to mitigate these problems to ensure mission safety and success.

Sub-Goals

Near-term RF communications development will focus on advancing the reprogrammable, software-defined radios that can then be used as an infusion path for subsequent developments. The mid-term focus is on reducing SWaP for major components.

RF communications will develop new techniques that will allow at least two orders of magnitude increase over current data rate capabilities in deep-space. Communications through harsh environments, such as rocket plumes and reentry ionization, will be addressed with technology approaches like UWB radios and variable magnetic field in conjunction with conformal antenna to make the reentry plasma transparent for L- to Ka-band RF frequencies.

The major challenge is to provide a data return capability at or beyond the needs of the mission. In addition, it is important to make significant strides in increasing uplink and developing innovative approaches to conduct emergency communications, which will enable safe and efficient human exploration and autonomous robotic space operations. Since radio spectrum is controlled by international law, the challenge is to get as much use out of the allocated spectral bands as possible. RF links between spacecraft (for example, crosslinks or support of in-situ exploration) will become more prevalent in future mission concepts. NASA will also need to increase the performance of in-situ surface wireless communications on bodies other than Earth and in the proximity of space vehicles. Communications through harsh environments provides a major challenge during critical phases of missions. Finally, NASA must manage these new technologies together with the increase in number of spacecraft and ever more complex mission operations without huge increases in operations or maintenance costs. Since this technology area is more mature than optical communications, developments should also focus on more efficient use of power, available spectrum, mass, and volume.

Table 10. Summary of Level 5.2 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
5.0 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	Goals:	Increase performance and efficiency in the systems that provide communications, navigation, and orbital debris tracking and characterization capabilities for all mission classes.
Level 2		
5.2 Radio Frequency Communications	Sub-Goals:	Enable higher data rates and data throughput for near-Earth and deep-space to ground communications. Communicate through harsh environments, such as rocket plumes and reentry ionization.

Table 10. Summary of Level 5.2 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
5.2.1 Spectrum Efficient Technologies	Objectives:	Spectrally efficient technologies to allow for packing more bits per second in a given bandwidth.
	Challenges:	Inefficiency of orthogonal partitioning of time and frequency to avoid links interfering with each other. Allowing multiple links to operate at the same time and in the same frequency band.
	Benefits:	Achieves high data rate from the International Space Station (ISS) via TDRSS to ground using approaches that provide operational data rates of at least 1 Gb/s or higher.
5.2.2 Power Efficient Technologies	Objectives:	Provide RF power for near-Earth and deep-space missions with improved overall efficiency and reduced mass.
	Challenges:	Integrating advanced data compression, coding, and modulation techniques with data sampling.
	Benefits:	Provides power for deep-space and near-Earth missions with improved efficiency and reduced mass.
5.2.3 Propagation	Objectives:	Develop better-performing transmission and detection algorithms, including atmospheric modeling and simulation.
	Challenges:	LEO propagation studies limited to short passes, often during non-meaningful times of the day, resulting in lack of statistically significant data.
	Benefits:	Provides ability to design high reliability Earth-space LEO communications systems.
5.2.4 Flight and Grounds Systems	Flight and Ground Systems is covered in section TA 5.5 Integrated Technologies.	
5.2.5 Earth Launch and Re-Entry Communications	Objectives:	Efficiently transmit and receive RF communications and receive GPS navigational information through the hypersonically induced plasma enveloping a reentering space vehicle.
	Challenges:	Operational testing opportunities of communications through reentry ionization may be limited.
	Benefits:	Supports multiple missions, such as the Multi-Purpose Crew Vehicle (MPCV) mission as well as the Space Launch System (SLS) and Orion Asteroid Redirect Mission.
5.2.6 Antennas	Objectives:	Develop deployable antennas or antenna arrays that are efficient and can be pointed.
	Challenges:	Integrating deployable structures and antennas into flight systems; adaptively combining apertures; combining antennas in the transmit direction; lowering mass; and improving efficiency and control of fields across the antenna aperture.
	Benefits:	Supports multiple missions such as Mars Relay Satellite, Next Generation Communications and Navigation Architecture Systems, future Discovery class missions, New Frontiers, near-Earth object detection missions, and missions extending reach beyond LEO into the solar system.

TA 5.2.1 Spectrum Efficient Technologies

Spectral bandwidth is a precious and legally-enforced commodity. In order to get as much use from the allocated bandwidth as possible, innovative ways of fitting more bits into the same number of Hertz will need to be developed. Technology to reduce RF interference also needs to be advanced as the spectral bandwidth becomes more crowded. High-order modulation schemes (e.g., eight phase shift keying (PSK) and 16 quadrature amplitude modulation (QAM)), as well as careful pulse shaping (e.g., Gaussian Minimum Shift Keying) are examples of current technologies being developed in this area.

Technical Capability Objectives and Challenges

While efficient traveling wave tube amplifier technology is already space-qualified and in place, space-qualified modem technology must be developed, and advancement in space-qualified field-programmable gate arrays (FPGAs) is required. A major source of spectral inefficiency is the orthogonal partitioning of time and frequency to avoid links interfering with each other. Advanced interference management strategies that allow multiple links to operate at the same time and in the same frequency band could lead to many-fold gains in spectral efficiency. Examples of such interference management strategies include: multi-user, multiple input multiple output (MIMO); interference alignment; user cooperation; and full-duplex communications.

The overall approach to overcome the challenges is to continue maturing, via laboratory demonstration and test in relevant environment, spectrally-efficient technologies like spectrally-efficient modem, advanced coding and modulation, amplifier non-linearity compensation, adaptive equalizers, cross-polarization cancellers, and traveling-wave tube amplifier technologies. Full development of these technologies also requires advancement in space-qualified FPGAs.

Benefits of Technology

The primary benefit of the technologies associated with this TA is to achieve high data rate from the International Space Station (ISS) via TDRSS to ground, using approaches like spectrally-efficient modems, advanced coding and modulation, amplifier non-linearity compensation, and traveling-wave tube amplifier technologies to provide operational data rates of at least 1 Gb/s or higher as compared to current operational data rates of 258 Mb/s. The technology will also be of relevance to the Earth science missions identified in the decadal survey.

Table 11. TA 5.2.1 Technology Candidates – not in priority order

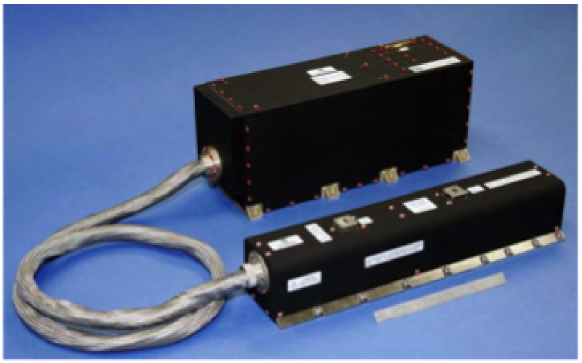
TA	Technology Name	Description
5.2.1.1	Advanced Interference Management	Signaling strategies (e.g., coding and signal processing) to enable multiple wireless links to operate at the same time and in same band.

TA 5.2.2 Power-Efficient Technologies

Spacecraft power is a precious commodity for many missions, and the communications system is a traditional major user of this power. NASA must continually strive to reduce the amount of power required to return each bit from space. Efficient traveling wave tube amplifiers (TWTA), solid-state power amplifiers (SSPA), and error-correcting codes are three standard techniques for advancing power efficiency. Another is the use of higher carrier frequencies, such as moving from X-band (~8 GHz) to Ka-band (~32 GHz) in deep-space. Further gains are possible by using advanced data compression, coding, and modulation techniques, and by carefully combining and creatively integrating these with data sampling.

Technical Capability Objectives and Challenges

The overall approach to overcome the challenges will be to continue improving the overall efficiency and reliability of SSPA and TWTA and reduce the mass. For the TWTA, the objective is to achieve an efficiency of 70 to 75 percent and target reduction in mass by 1 kilogram (kg) (approximately a 20 percent reduction in mass), while for SSPAs the objective is to achieve an efficiency of 35 to 40 percent and target reduction in mass by 0.5 kg (approximately a 25 to 50 percent reduction in mass).



Ka-Band Traveling Wave Tube Amplifier

Benefits of Technology

The primary benefit of the TWTA and SSPA amplifier technology will be to provide power for deep-space and near-Earth missions, with improved efficiency and reduced mass. SSPAs and TWTAs are currently flying on a variety of missions.

Table 12. TA 5.2.2 Technology Candidates – not in priority order

TA	Technology Name	Description
5.2.2.1	Traveling Wave Tube Amplifiers (TWTAs)	Vacuum electronics-based helical traveling-wave tube amplifier.
5.2.2.2	Solid-State Power Amplifiers (SSPAs)	Gallium-Arsenide (GaAs) and Gallium-Nitride (GaN) high electron mobility transistor (HEMT) and monolithic microwave integrated circuit (MMIC) technology based SSPAs.

TA 5.2.3 Propagation

The more that is understand about how signals move through space and atmospheres in the allocated frequency bands, the more innovative NASA can be in developing better-performing transmission and detection algorithms. This knowledge, including atmospheric modeling and simulation, is needed to develop future concepts for arraying spacecraft and ground antennas, as well as robust reentry communications. Furthermore, there is a need to increase understanding of LEO propagation parameters, which is currently lacking. Accordingly, studies of Ka-band propagation as they apply to LEO satellites for system design margins are desirable.

Technical Capability Objectives and Challenges

Studies of Ka-band propagation as they apply to LEO satellites for system design margins are required. LEO propagation studies are limited to short passes, and often during non-meaningful times of the day, resulting in a lack of statistically significant data. For example, the total known cumulative ground station data collected per year for LEO propagation is approximately 30 days for a specific site. Accordingly, the performance objective is to characterize enough events to separate atmospheric and orbital dynamics effects in order to obtain statistically significant models for the design of high-reliability LEO communications systems.

The overall approach to overcome the challenges and achieve technical capability objectives will be to install many fast tracking ground stations (e.g., 1 meter-class antenna) at various Earth locations to obtain enough passes for meaningful, long-term beacon data for a LEO spacecraft's beacon. Ka-band beacons on LEO payloads, required for the aforementioned campaign, will also be developed. Successful establishment of the LEO propagation studies campaign will result in at least a 12-fold enhancement in data collection station years, equivalent to a minimum of 1 station-year of data, or higher for propagation campaigns of longer duration, such as 1 to 5 years.

Benefits of Technology

Currently, GEO propagation statistics at Ka-band are used to predict atmospheric effects for LEO systems. Characterizing propagation effects at Ka-band on LEO paths through the atmosphere provides the ability to design high-reliability Earth-space LEO communications systems. Future Earth observation missions will benefit from this technology, since these missions have in common the intent to use Ka-band direct-to-Earth data downlinks.

Table 13. TA 5.2.3 Technology Candidates – not in priority order

TA	Technology Name	Description
5.2.3.1	Low-Earth Orbit (LEO) Ka-Band Propagation Studies	Studies of Ka-band propagation as they apply to low-Earth orbiting satellites for system design margins.

TA 5.2.4 Flight and Ground Systems

Flight and Ground Systems technologies are addressed in section TA 5.5 Integrated Technologies.

TA 5.2.5 Earth Launch and Re-Entry Communications

This area involves characterizing the harsh atmospheric reentry environment and developing solutions to mitigate its effects on RF communications, telemetry, and navigation from re-entering vehicles during one of the most critical portions of an exploration mission.

Technical Capability Objectives and Challenges

The theory of using a variable magnetic field in conjunction with a conformal antenna to make the reentry plasma transparent for L- to Ka-bands of RF frequencies has been demonstrated. Accordingly, the overall approach to overcome the challenges and achieve technical capability objectives are to design and implement conformal antenna technology that could be placed in an adaptably controllable magnetic field, based on already-developed formalisms and theoretical analysis, which can operate in an ablative environment like a reentry plasma. The ablation mechanism can be minimized through proper aerodynamic shaping.

Benefits of Technology

Continuous communications with reentry vehicles currently being developed by NASA and other government agencies is critical for their real-time health monitoring, command, and control. Accordingly, the proposed “magnetic window” concept will impact the design and functionality of the next generation of reentry vehicles through the integration of a ‘magnetic’ conformal antenna thereby enabling uninterrupted RF communications in a plasma ablative environment. This technology could support exploration missions including the Asteroid Redirect Mission.

Table 14. TA 5.2.5 Technology Candidates – not in priority order

TA	Technology Name	Description
5.2.5.1	Mitigation of Reentry Plasma Effects	Maintain RF communications to re-entering vehicles during one of the most critical portions of an exploration mission.

TA 5.2.6 Antennas

Both flight and ground antennas are considered in this area. As NASA moves to higher carrier frequencies, there is a need to develop antennas that are efficient and can be pointed. NASA also needs to consider arrays of antennas as an option to building ever-larger single dishes. For flight systems, various forms of deployable structures, as well as techniques for adaptively combining apertures, needs to be investigated. Combining antennas for receiving signals is already advanced. However, focused technology development should be directed towards antenna combining in the transmit direction.

Technical Capability Objectives and Challenges

NASA will pursue novel materials, design, and manufacturing methods that enable lower mass, greater efficiency, and greater control of fields across the antenna aperture. Game-changing advances in component technologies could enable significant advances in antenna array performance and enable alternate, higher-performance architectures.

Benefits of Technology

There are numerous benefits to developing these technologies, including:

- Supporting Mars Relay Satellite and next-generation TDRSS (Universal Communications and Navigation architecture);
- Ka-band multiple-access phased arrays for NASA’s Next Generation Communications and Navigation Architecture Systems (such as the TDRSS follow-on relay and user terminal) and future Discovery class missions;

- Deep-space missions like New Frontiers and Mars missions, as well as near-Earth object (NEO) detection missions; and
- Providing greater fields-of-view and often reduced mass relative to conventional antenna elements.

Table 15. TA 5.2.6 Technology Candidates – not in priority order

TA	Technology Name	Description
5.2.6.1	Deployable Antennas	≥ 5 m diameter deployable mesh or shape memory polymer microwave reflectors.
5.2.6.2	Phased Array Antennas	Electronic beam steering.
5.2.6.3	Atmospheric Phase Compensation for Uplink Arrays at Ka-Band	Compensation of atmospheric turbulence effects to maximize transmit power of ground based arrays.
5.2.6.4	Small-Satellite Distributed Multiple Input Multiple Output (MIMO)	Distributed communications architecture based on deployment of MIMO antenna arrays on multiple small satellites.
5.2.6.5	Conformal, Low-Mass Antenna Systems	Conformal, low mass antenna systems.
5.2.6.6	Antenna Array Architecture Enablers	RF components, beamformers, and algorithms for enabling antenna arrays.

TA 5.3: Internetworking

To date, most space communications scenarios have involved fundamental point-to-point links between a spacecraft and Earth. Today's specialized link-layer protocols and carefully planned and scheduled link operations have thus far been adequate to meet the needs of missions. Currently, there is a rudimentary relay network supporting the Mars rovers and a separate Internet Protocol (IP)-based internetworking capability between the ISS and the ground. There have also been a number of technology demonstrations of space-based internetworking technologies that demonstrated mobile IP and experiments that placed delay or disruption tolerant networking (DTN) protocols in deep-space and LEO. The ISS is in the process of incorporating DTN services onboard to support science payloads and mission support applications.

Sub-Goals

Early focus will capitalize on developments made by NASA in DTN technology that will enable future networking capabilities throughout the solar system. Expanding functionality to include a broader spectrum of communications and navigation services that exploit autonomous and cognitive technologies will follow.

Earth-based internetworking technologies will be migrated to space with DTN and selective use of IP, which will help deal with latency issues and automate distribution of data wherever spacecraft and humans operate. Challenges include:

Availability: The terrestrial Internet assumes that there is always a real-time and reliable path between the source and destination, even when the path is across multiple hops. In space, nodes are often not available for communications, either because the spacecraft (free-flyer or EVA crew member) is not in view or because it is busy doing other tasks. Messages must be able to pass through this network even when intermediate nodes appear and disappear.

Latency: Because of the long distances involved, space links are not conducive to standard Internet solutions. In addition, the long latency makes many real-time adaptive techniques impossible.

Autonomous operations: As missions become more complex and further from Earth's resources, there will be a need to support more autonomous operations with minimal Earth contact. With increasing levels of autonomy, entirely new classes of missions are also being envisioned where assets would routinely coordinate among themselves without ground intervention to achieve mission objectives. There will be a need for remote communications networks to enable communications between platforms, as well as a need to configure and maintain dynamic routes, manage intermediate nodes, and provide quality of service functionality.

Complex network topologies: Earth science, astrophysics, human origins, and solar-terrestrial missions will require multiple communications and networking topologies to meet future missions, to include multiple spacecraft flying in formation (e.g., to create unprecedented telescope apertures and interferometers for imaging fainter, smaller, and more distance objects). Commercial in-space servicing and orbital debris removal, heavy-lift vehicle stacking, and assembly of separately launched telescope mirrors require precise navigation and proximity communications. Complex and time-varying networks of spacecraft and sensors must be capable of sharing rich, near-real-time streams of information.

Minimizing spacecraft burden: Spacecraft systems are continually seeking to reduce the burden of spacecraft bus systems, such as the communications systems, to reduce spacecraft size and increase allocations for instruments or other payloads. Therefore, minimizing the implementation footprint of the internetworking software, memory, and processing for spacecraft nodes is essential for space implementation.

Table 16. Summary of Level 5.3 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
5.0 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	Goals:	Increase performance and efficiency in the systems that provide communications, navigation, and orbital debris tracking and characterization capabilities for all mission classes.
Level 2		
5.3 Internetworking	Sub-Goals:	Provide dynamic, high-speed internetworked communications and navigation services for space applications.
Level 3		
5.3.1 Disruption-Tolerant Networking	Objectives:	Provide space internetworking capable of supporting high data rate and data storage requirements that is tolerant to disruptions.
	Challenges:	High speed flight qualified processors and FPGAs; high speed and high volume flight qualified memory.
	Benefits:	Provides more reliable and automated data flows and data availability.
5.3.2 Adaptive Network Topology	Objectives:	Allow data to be routed and prioritized on planetary surfaces or over disrupted links. Maximize quality of service.
	Challenges:	Protocols allowing nodes to relay data to other nodes in a multi-hop fashion across changing topologies. Adaptive routing that can discover resources and adapt to failures. Methods to distinguish traffic according to timeliness, importance, and robustness; and queuing and routing protocols.
	Benefits:	Allows networks to automatically adjust in size and data paths as they become increasingly complex.
5.3.3 Information Assurance	Objectives:	Develop security and key management protocols and techniques for DTN networks. Protect science and information assets and operations.
	Challenges:	Information is vulnerable to many factors, including hardware corruption, software corruption, viruses and malware, and intentional human intervention. Providing information assurance without significant impact to bandwidth utilization and processing requirements, as well as the management and distribution of keys in a disconnected or delayed environment.
	Benefits:	Allows networking-based space communications to operate securely.
5.3.4 Integrated Network Management	Objectives:	Develop integrated network management architectures and protocols to effectively support autonomous operations.
	Challenges:	Allow network style operations and control in this unique space-internetworking scenario.
	Benefits:	Provides effective support of network operations when network topology includes nodes with disrupted or long delay links.

TA 5.3.1 Disruption-Tolerant Networking

The fundamental DTN protocols, Bundle Protocol (BP) and Licklider Transmission Protocol (LTP), have been implemented and demonstrated in both LEO and deep-space. An experimental implementation on the ISS is in the process of being upgraded for operational support of science payloads and mission support applications. The ISS implementations will run on laptops, which will provide the storage and processing required in the ISS environment. Implementations providing storage and processing for future relays and robotic and human exploration missions still need to be developed.

Technical Capability Objectives and Challenges

Internetworking protocols (e.g., surface wireless and proximity, quality of service, network management, information assurance, ad hoc networking, etc.) are critical to enable automation of connections and data flows and disconnection (store-and-forward) and multi-hop friendly applications. Advances in space-based, high-speed routing technologies will also be necessary to enable internetworking across future high-bandwidth links (proximity and end-to-end). The fundamental DTN protocols, BP and LTP, will be implemented into platforms capable of providing higher data rates and data storage in space environments.

Benefits of Technology

The terrestrial Internet has demonstrated that networking technology can enhance existing applications and enable functions that the originators could not have imagined. Extending the capabilities of networking to space will provide more reliable and automated data flows and data availability.

Table 17. TA 5.3.1 Technology Candidates – not in priority order

TA	Technology Name	Description
5.3.1.1	Disruption Tolerant Networking (DTN) Basic Services	Algorithms and software or firmware implementations of basic DTN services, such as Licklider Transport Protocol and Bundle Protocol.

TA 5.3.2 Adaptive Network Topology

Because most space communications are planned well in advance, there has been little need for the development of routing protocols for space applications. The introduction of constellations of CubeSats, surface networks, modular exploration systems, and other future scenarios have led to the need for protocols that will allow nodes to relay data to other nodes in a multi-hop fashion across changing topologies. The ISS has now deployed onboard wireless networks to handle the dynamic aspects of personal devices, wireless sensors, and the need for communications connectivity where the onboard data network does not exist. When circumstances differ from the analogous terrestrial applications, new technologies need to be developed that will allow data to be routed and prioritized on planetary surfaces or over disrupted links.

Technical Capability Objectives and Challenges

The objective of this TA is to develop standardized, robust, ad hoc, and mesh networking of mobile elements to coordinate timing, position, and spacing within the operational needs of human and robotic missions. Advanced methods of channel access, including multiple and demand access, will be considered. Quality of service across the dynamic network will also be maintained. Traffic modeling and simulation will be critical tools to define and validate topologies.

Adaptive routing in DTN networks, which can discover resources and adapt to failures to form routes, expand connectivity coverage, and increase end-to-end capacity and latency performance, need to be developed. To maximize Quality of Service (QoS), communications systems also need methods to distinguish traffic according to timeliness, importance, and robustness; and queuing and routing protocols. Routing and QoS work in DTN is ongoing, with ad hoc and mesh networking identified as future areas of technology development.

Benefits of Technology

These technologies will allow networks to automatically adjust in size and data paths as they become increasingly complex.

Table 18. TA 5.3.2 Technology Candidates – not in priority order

TA	Technology Name	Description
5.3.2.1	Ad Hoc and Mesh Networking of Mobile Elements	Algorithms for establishment of ad hoc and mesh networks for coordinated communications among mobile elements.
5.3.2.2	Disruption Tolerant Networking Routing	Adaptive routing in disruptive networks to enable discovery of resources and adapt to failures to form routes expanding connectivity coverage and increasing end-to-end capacity and latency performance.
5.3.2.3	Disruption Tolerant Networking Quality of Service	Extensions of differentiated services.

TA 5.3.3 Information Assurance

NASA is not currently advancing any Information Assurance technologies within the timeframe of this Roadmap. The area of information assurance is broad in scope and mission operations concepts are still being defined. Information assurance technologies for space-based communications are dependent upon the requirements defined in the mission operations concepts, and as such no specific technologies were identified for advancement. Some discussion of this area is, however, included below.

Technical Capability Objectives and Challenges

Network security for missions with limited connectivity, processing power, and possibly great distances, poses unique challenges requiring the development of security and key management protocols and techniques for DTN networks.

The objectives of this TA would be to develop information assurance architecture technologies to: a) ensure system safety, data integrity, availability, and, when required, confidentiality; and b) enable dual use of all available links and networks, some which may be provided by other agencies or countries (perhaps unsecure). Space information assurance protocols will also enable system self-awareness of actual versus expected patterns of operation to detect anomalies that may indicate information assurance breaches, system failures, or safety hazards, and have the ability to automatically execute plans to reroute critical traffic in the event that critical systems are compromised or destroyed.

Information is vulnerable to many factors, including hardware corruption, software corruption, viruses and malware, and intentional human intervention. As NASA's science and information sources become interweaved with terrestrial public domain networks to support initiatives such as Science, Technology, Engineering, and Mathematics (STEM) education and international collaboration, it will be imperative to protect assets and operations, facilitate seamless authentication of users, and ensure that all messages are transferred without compromise.

DTN development has included the Bundle Security Protocol (BSP). Development challenges include providing information assurance without significant impact to bandwidth utilization and processing requirements, as well as the management and distribution of keys in a disconnected or delayed environment. Near-term development focuses on BSP, while longer-term development will encompass Agency requirements for end-to-end information assurance.

Benefits of Technology

Developing these technologies would allow networking-based space communications to operate securely.

TA 5.3.4 Integrated Network Management

NASA is not currently advancing any Integrated Network Management technologies within the timeframe of this Roadmap. As with the information assurance technology area, information network management is broad in scope and dependent upon the mission operations concept. As such no specific information network management technologies were identified as in-need of advancement for the current space-based communications requirements. Some discussion of this area is, however, included below.

Technical Capability Objectives and Challenges

Network management is typically envisioned as methods that allow a network operator to see the state of a network's performance and take any required actions to correct issues. This becomes a challenge when all of the network nodes are not continuously connected or when they are connected and their "real-time" status data is many minutes old due to distance and speed-of-light delays.

The objective of this TA would be to develop integrated network management architectures and protocols to effectively support autonomous operations with network monitoring, configuration, and control mechanisms.

Benefits of Technology

Developing these technologies would provide effective support of network operations when a network topology includes nodes with disrupted or long delay links.

TA 5.4: Position, Navigation, and Timing

NASA's current PNT SOA relies on both ground-based and space-based radiometric tracking, laser ranging, and optical navigation techniques (e.g., star trackers, target imaging). A variety of radiometric ranging and Doppler techniques are used throughout the NASA communications networks. Post-processed GPS position determination performance is at the centimeter level at LEO distances and meter-level at high Earth orbit (HEO) distances. Autonomous, real-time GPS performance can achieve accuracies of at least 20 meters.

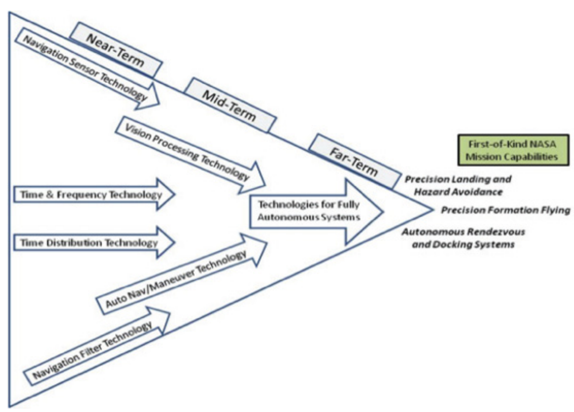
Position determination performance is better than 10 meters at near-Earth distances, and is a few kilometers at approach to Mars, while Mars orbital determination accuracies are better than 100 meters. The Deep-Space Network (DSN) employs a high-accuracy, very-long-baseline interferometry (VLBI) method that yields position determination performance of 1 kilometers at Mars, a few kilometers at Jupiter, and hundreds of kilometers at distances beyond Jupiter. Optical navigation methods yield position determination performance of 1 kilometer at near-Earth distance and tens of kilometers at Mars distance.

Navigation relies on precision time and frequency distribution and synchronization. The Earth-orbit GPS-based time and frequency reference and time transfer capabilities are in the nanosecond range and the microsecond range, respectively. The use of quartz resonators for onboard time and frequency generation is most common. The GPS satellites employ rubidium and/or cesium atomic clocks for ultra-stable timekeeping. The short-term and medium-term stability performance of the current generation of space clocks, in terms of Allan Variance, currently spans the 10^{-12} to 10^{-13} range for intervals of 1 to 10 seconds and is within the 10^{-13} to 10^{-14} range for intervals greater than 100 seconds.

All the above PNT methods are technically and operationally mature and have thus far been adequate for NASA's mission needs.

Sub-Goals

The early focus is on increasing PNT accuracy and precision, with the later focus on autonomy. An overall goal of these technology developments is to position NASA to conduct human spaceflight missions beyond LEO.



PNT Development Timeline

As notionally depicted in the adjacent figure, "PNT Development Timeline," NASA envisions a phased PNT technology development effort over the next 15 to 20 years that starts with foundational work in timekeeping and time and frequency distribution or time synchronization, coupled with developments in navigational sensors and filters. Development into the next generation of multi-purpose navigation filtering techniques is needed. The development of component-level PNT technology building blocks will permit the synthesis and implementation of early semi-autonomous (e.g., supervised autonomy) PNT flight systems. Based on flight results of the semi-autonomous missions, together with developments in autonomous systems technology, NASA will be in an excellent position to fly missions having fully autonomous PNT functions. Attaining this goal will have benefits for human and robotic spaceflight in all flight regimes: near LEO, beyond LEO, and in deep-space. There will be interaction between the TAs identified in the above figure as NASA works towards the goal of having fully autonomous PNT functions available where needed. The convergence of the TAs will culminate in first-of-a-kind NASA capabilities for autonomous rendezvous and docking (AR&D) and precise formation flying (PFF) missions, which absolutely require the highest level of autonomy and PNT performance.

Fundamental to the improvement of NASA's navigation capability is the improved accuracy and stability of space clocks. Algorithms for autonomous rendezvous, docking, landing, and formation flying are needed.

Future missions will require precision landing, rendezvous, formation flying, cooperative robotics, proximity operations (e.g., servicing), and coordinated platform operations. This drives the need for increased precision in absolute and relative navigation solutions.

As NASA operates farther from Earth and performs more complex navigational maneuvers, it will be necessary to reduce reliance on Earth-based systems for real-time decisions. This will require reducing dependence on ground-based tracking, ranging, and trajectory or orbit determination support functions (to minimize latency and availability constraints). Since timing is a fundamental parameter for adequate navigation, NASA will need increased precision in reference time and frequency generation, time and frequency distribution, and synchronization. Space-qualified clocks with the precision required for future missions are not available today. Reducing reliance on Earth systems also requires clocks that are orders of magnitude more precise than the best space-qualified clocks today. Increased precision in each individual node's PNT system will be required in order to minimize the error contributions of each hop to the final node's PNT solutions.

The platforms that are "first down" on a near-Earth asteroid (NEA) or a planetary surface, may have limited ground inputs and no surface or orbiting navigational aids. NASA currently does not have the navigational trajectory and attitude flight control technologies that permit the fully autonomous capabilities for approach and landing without navigation support from Earth.

Table 19. Summary of Level 5.4 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
5.0 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	Goals:	Increase performance and efficiency in the systems that provide communications, navigation, and orbital debris tracking and characterization capabilities for all mission classes.
Level 2		
5.4 Position, Navigation, and Timing	Sub-Goals:	Reduce reliance on Earth-based systems for ground-based tracking, ranging, trajectory/orbit determination, and maneuver planning and execution functions.
Level 3		
5.4.1 Timekeeping and Time Distribution	Objectives:	Reduce atomic-based space clock complexity and cost while maintaining their high-end performance. Provide nanosecond-level time transfer capability across the solar system.
	Challenges:	Reducing sensitivity to onboard thermal environment conditions and susceptibility to magnetic and electric field, gravitational force, and ionizing radiation effects for space clocks using quartz resonators. Reducing complexity while maintaining high-end performance for atomic clocks.
	Benefits:	Couples ability to perform precise time and frequency transfer with technology developments for space clocks.

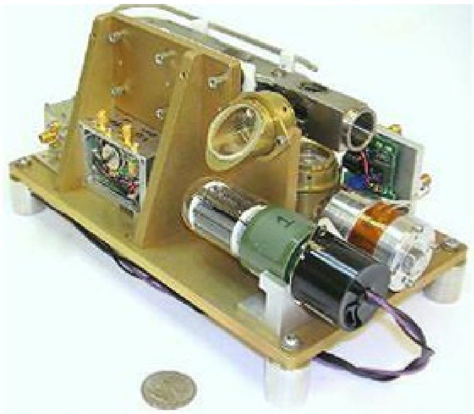
Table 19. Summary of Level 5.4 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
5.4.2 Onboard Auto Navigation and Maneuver	Objectives:	Develop mission management flight software for use onboard space systems that is robust enough to detect and handle hardware and software failures without compromising the success or safety of the mission.
	Challenges:	Failure Detection, Isolation, and Recovery (FDIR) for similar and dissimilar sensor architectures; using optimizers to autonomously plan and replan missions.
	Benefits:	Reduces dependence on ground-based tracking; ranging; trajectory, orbit, and attitude determination; and maneuver planning support functions. Reduces the burden of routine navigational support and communications requirements on network services in the near-term. Increases platform's operational agility, and enables near real-time re-planning and opportunistic science. Enables classes of missions that are freed from round-trip light time constraints in the long-term.
5.4.3 Sensors and Vision Processing Systems	Objectives:	Develop sensors and vision processing systems to improve image acquisition and processing, and to increase the amount of useful data that is extracted for navigation.
	Challenges:	Characterizing active sensors; providing both intensity and range imagery across entire operational range; providing relative navigation systems that operate with respect to active and passive target vehicles or bodies.
	Benefits:	'Noise radars,' yields benefits with respect to power, volume, and mass. Radiation-hardened or tolerant FPGAs and Graphical Processing Units (GPUs) that have fast processing speeds that yield benefits as algorithms get more sophisticated in order to meet stringent mission requirements.
5.4.4 Relative and Proximity Navigation	Objectives:	Provide high resolution or high frame rate visible and infrared imaging sensors, and high-speed sensor data processing electronics to support cooperative and collaborative space platform operations.
	Challenges:	Understanding (as to basic physics) high frame rate data; processing high frame rate data; per pixel range accuracy of better than 1 centimeter.
	Benefits:	Provides mission safety and success at lower cost.
5.4.5 Auto Precision Formation Flying	Objectives:	Provide autonomous planning and optimization algorithms and higher performance relative navigation sensors to enable precision formation flying.
	Challenges:	Off-nominal performance, particularly in the presence of sensor and effector failures.
	Benefits:	Allows more precise placement of the chaser relative to the target than can be obtained from ground-based formation flying paradigm. Precludes ground involvement, other than possibly higher-level plan approval and authority to proceed, thus reducing costs.
5.4.6 Autonomous Approach and Landing	Objectives:	Provide real-time situational awareness and platform response in uncertain operational environments.
	Challenges:	Avoiding hazards while simultaneously identifying safe landing sites; handling large quantities of images, incorporating known terrain models, and generating safe sites reliably and accurately.
	Benefits:	Enables crews to walk less than 1,000 meters to their habitat, transporter, and return vehicles without damaging prepositioned assets.

TA 5.4.1 Timekeeping and Timing Distribution

In the Earth-orbit domain, GPS is the primary timekeeping and timing distribution method. As mentioned above, the primary GPS timekeeping system is based on cesium or rubidium standards. The next generation of these standards for both near-Earth and deep-space will be based on trapped mercury ions in a vacuum tube, such as the Deep-Space Atomic Clock (DSAC). The next challenge will be to develop optical clocks that have much-reduced SWaP and lifecycle cost, relative to the room-sized clocks of today, and to flight qualify them.

Technical Capability Objectives and Challenges


Deep-Space Atomic Clock

The development of a new, integrated, space-qualified timekeeping system with ultra-high accuracy and frequency stability performance is to be considered not only for PNT functions, but also for fundamental physics, time and frequency metrology, geodesy and gravimetry, and ultra-high resolution VLBI science applications. The advanced timekeeping systems sought could be based on highly stable quartz crystal resonators or on techniques that measure atomic transitions to establish the frequency standard for the timing system, including optical clocks. Major technical challenges for space clocks that use quartz resonators include reducing their sensitivity to the onboard thermal environment conditions and their susceptibility to magnetic and electric field, gravitational force, and ionizing radiation effects. The primary technical challenges for atomic-based space clocks are to reduce their complexity and cost while maintaining their high-end performance. Common technical challenges include reducing the overall timekeeping system SWaP resource requirements; radiation-hardened, low-noise clock readout electronics; and software algorithms that process the clock measurements and estimate or propagate the timekeeping model that generates time and frequency signal outputs. Advanced time-keeping systems will require technology developments to address the aforementioned technical challenges. Development is also needed into new timekeeping system architectures in which outputs of an ensemble of clocks are weighed and software filtered to synthesize an optimized time estimate.

Technology development is needed to provide the service function of collecting, formatting to a common interface standard, and communicating PNT data across a heterogeneous network of space- and ground-based platform nodes. Development is required at three levels:

- Systems development, such as time and frequency distribution architectures, techniques, and methodologies; system error and uncertainty modeling;
- Hardware component development, such as RF or optical communications devices to affect time/frequency transfers; and
- Software component developments, such as filtering algorithms to propagate real-time estimates of the common time and frequency reference.

Nanosecond-level time transfer capability across the solar system is envisioned as a long-term objective, given that this level of time and frequency transfer is the SOA on Earth. NASA will also need to develop methods for accurate time and frequency distribution in the space-internetworking environment, especially when there is not a direct real-time path back to Earth.

Benefits of Technology

NASA mission applications, both for navigational functions and in the fundamental science realm, will benefit from having a robust and reliable common time and frequency reference that can be shared precisely across the solar system. The ability to perform precise time and frequency transfer is coupled with the anticipated technology developments for space clocks. As the frequency stability of space clocks improves, the need for precise time and frequency transfer will increasingly emerge as the driving 'timing' problem.

Table 20. TA 5.4.1 Technology Candidates – not in priority order

TA	Technology Name	Description
5.4.1.1	Trapped Mercury Ion Clock	High-stability clock based upon microwave interrogation of high-Q mercury trapped ion "filter."
5.4.1.2	Trapped Ion Optical Clocks	High-stability clock based upon optical interrogation of high-Q trapped ytterbium ion "filter."
5.4.1.3	Cold Atom Lattice Optical Clocks	High-stability clock based upon holding cold atoms in a dipole lattice trap during optical interrogation.

TA 5.4.2 Onboard Auto Navigation and Maneuver

Orion will serve as the SOA in autonomous Guidance, Navigation, and Control (GN&C) systems once its technologies have been demonstrated in space. The sensors and associated algorithms and flight software are designed to be robust and stable. Along with the associated flight software, Orion is designed to have the ability to rendezvous and dock with target vehicles anywhere in the solar system, independent of communications with the ground.

With respect to autonomous onboard planning and execution, Orion once again serves as the SOA. The entry guidance laws, by their very nature, are autonomous and are designed to achieve tight landing accuracies. The orbit guidance and targeting algorithms, particularly the deorbit and Trans-Earth Injection (TEI), as well as the deep-space rendezvous guidance and targeting algorithms, provide Orion with the ability to carry out missions without communications with the ground.

The asteroid sample return mission Origins Spectral Interpretation Resource Identification Security – Regolith Explorer (OSIRIS-Rex) will serve as an example of the SOA development for performing onboard deep-space autonomous navigation and maneuvering once its technologies have been demonstrated in space. The mission is designed to use a 3D Flash LIDAR sensor to perform real-time, onboard navigation functions to update the a priori ground-determined CheckPoint and MatchPoint propulsive maneuvers during the critical touch and go (TAG) phase of the mission when the spacecraft descends near the surface of the asteroid. The 3D Flash LIDAR is also designed to serve as the relative navigation sensor during the TAG phase to ensure the spacecraft flies within its established range and range rate safety corridor.

Technical Capability Objectives and Challenges

The principal mission drivers for autonomy are servicing and assembly, sample return, formation flying, natural body fly-around, non-cooperative object capture, and pinpoint landing. Autonomous navigation and maneuvering technologies will be needed for all classes of space platforms, from robotic spacecraft and planetary landers to crewed exploration vehicles and planetary surface rovers. Further development in the following technologies will be needed:

- Autonomous navigation system architectures and techniques;
- Autonomous navigational planning and optimization algorithms, including highly-reliable approaches for fault management;
- Sensors for onboard autonomous navigation;
- Navigation filter algorithms;
- Onboard maneuver planning and sequencing algorithms;
- Fault-tolerant attitude control systems for autonomously orienting the platform;
- Efficient autonomous navigation system verification and validation methodologies;

- Ground-based hardware-in-the-loop systems test bed; and
- In-space demonstration test beds.

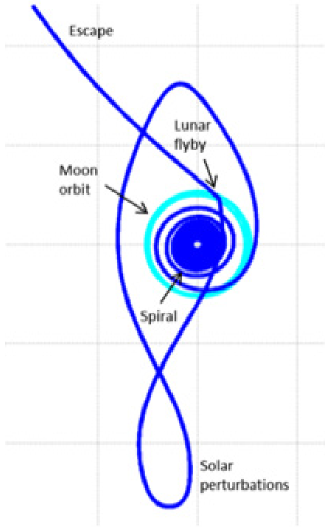
NASA needs to continue development in both autonomous navigation and maneuvering. Addressed here are the algorithms and software that are needed for spacecraft to operate outside the confines of LEO. In such cases, the one-way light time or loss-of-communications due to either communications failure or being in occultation, would necessitate increasing autonomy. To this end, GN&C systems must be designed to be self-sufficient. At the highest level, the objective is to develop and implement space system mission management onboard flight software that is robust enough to detect and handle hardware and software failures without compromising the success or safety of the mission. With regard to navigation, failure detection, isolation, and recovery (FDIR) must be robust enough to detect sensor-level failures, as well as algorithm failures. This may include hardware-level self-tests, measurement quality indicators, comparison between similar (and dissimilar) sensors, and residual edit checks, as well as persistent error checks. At the algorithm level, this may necessitate several instantiations of the same set of software, perhaps being 'fed' with different sensor inputs. This is a high-level architecture design development that will yield significant benefits. At the next level, sensor-level redundancy needs to be addressed, either by instantiating several copies of the same sensor or dissimilar sensors that produce similar measurements. Examples of dissimilar sensors that that are used for FDIR include cameras versus LIDARs. The FDIR responsibilities for dissimilar sensors are exceedingly complex and need to be addressed.

The maneuver planning aspect of missions can be approached in a variety of ways. At the most complex application, a trajectory optimization can be performed onboard to plan the mission, satisfying the myriad of mission constraints and onboard resources, as exemplified by a low-thrust trajectory from deep-space into a Lagrangian point halo orbit. At the next level is the implementation of a mission trajectory planner that manages the modes, segments, and activities—including targeting of maneuvers according to a specified plan—provided externally to the mission trajectory planner. This includes contingencies and may also include authority to proceed points requiring inputs from the crew or the ground. At the lowest level is a typical 'sequencer' that steps through actions and will require crew or ground intervention in case of problems.

Effort needs to be made to develop a robust, efficient, and flexible mission planning system that can be implemented onboard. For example, a potential solution is to implement a 'stripped-down' version of an optimizer on a flight processor. At the same time, attention must be given to FDIR for similar and dis-similar sensor architectures, as well as the number of sensors needed to meet mission requirements. When sufficient confidence is gained along both of these lines, the next challenge of using the optimizers to autonomously plan and re-plan missions can be addressed. In this case, the mission manager would be given the responsibility of supervising the mission planner, as well as the health and status of the navigation system, and be able to confidently make decisions in cases of hardware and software failures.

Benefits of Technology

Developing technologies to implement autonomous onboard navigation (and maneuvering) will reduce dependence on ground-based tracking; ranging; trajectory, orbit, and attitude determination; and maneuver planning support functions. As NASA's human exploration and science missions progress farther from Earth, the Agency must minimize and eventually overcome the impacts of latency on the navigation and maneuver planning or execution for varied space systems, such as spacecraft and planetary rovers. In the near-term, gradually increasing levels of autonomous navigation capabilities will allow platforms to go longer between time and state vector updates from the Earth. A significant benefit to be attained in this case will be a reduction in the burden of routine navigational support. Less



Low-Thrust Trajectory

reliance on the ground-based navigational support will reduce communications requirements on network services, making them available for missions with less onboard autonomy. An additional benefit that will accrue from having autonomous onboard navigation and maneuvering capabilities will be an increase in a platform's operational agility, enabling near-real-time re-planning and opportunistic science. In the longer term, fully autonomous navigational capabilities will enable classes of missions that would otherwise not be possible due to round-trip light time constraints.

Table 21. TA 5.4.2 Technology Candidates – not in priority order

TA	Technology Name	Description
5.4.2.1	Low-Thrust Trajectory Optimization in a Multi-Body Dynamical Environment	Algorithms and software for efficient preliminary and high-fidelity design and optimization of low-thrust trajectories in a multi-body dynamical environment.
5.4.2.2	Fault-Resistant, High Performance Navigation Architectures	Fault-resistant, high-performance navigation architectures using advanced dis-similar sensor navigation FDIR for error detection from robust, high-performing sensors.
5.4.2.3	Onboard Trajectory Planning and Optimization Algorithms	Neural net trajectory planning; genetic algorithm-based trajectory planning.
5.4.2.4	Advanced Onboard Navigation Algorithms	Gaussian mixture model-based estimation; multiple-model estimation, Sigma Point Kalman filters, cauchy-based filters.
5.4.2.5	Onboard, Real-Time Mission Re-Sequencing	Onboard maneuver planning and sequencing algorithms.
5.4.2.6	Autonomous Outer Planet Tour Navigation	Techniques and algorithms for estimating and controlling spacecraft trajectories in outer planet satellite tours, based on data derived and computations performed onboard.
5.4.2.7	Advanced Deep-Space Trajectory Design Techniques	Advanced deep-space trajectory design techniques.
5.4.2.8	Deep-Space Positioning System (DPS)	A compact, low-mass, low-power hardware and software system capable of performing deep-space autonomous navigation for robotic and human missions virtually anywhere in the solar system.
5.4.2.9	High Rate Spacecraft Guidance, Navigation, and Control (GN&C)	A highly capable spacecraft GN&C system capable of accurately controlling a spacecraft during rendezvous phase with an uncooperative target with high relative velocities.

TA 5.4.3 Sensors and Vision Processing Systems

The list of onboard navigation sensors include Inertial Measurement Units (IMUs), GPS receivers, Star Trackers, as well as cameras for absolute (inertial) navigation, and cameras, radiometric ranging, and Flash LIDARs for relative navigation. In addition, infrared (IR) cameras are being used to provide images, particularly for relative navigation that is not as dependent on solar illumination; the thermal inertia of the target vehicle provides enough photons to 'image' the target in the absence of solar illumination. Today's sensors (Star Trackers, Cameras, LIDARs) produce imagery that necessitates robust image processing algorithms as well as the vision (image) processing hardware (usually containing FPGAs).

Technical Capability Objectives and Challenges

Specific technologies to be developed in this area include optical navigational sensor hardware (such as high resolution Flash LIDAR sensors, visible and IR cameras), radar sensors, radiometrics, fine guidance sensors, laser rangefinders, high-volume and high-speed electronics for LIDAR and other imaging sensor data processing, sensor measurement processing algorithms, synthetic vision hardware or software, and situational awareness displays.

Image processing is an increasingly vital part of new sensor systems, and significant work needs to be done in extracting the maximum amount of information from these images. This necessitates both sophisticated algorithms, as well as hardware necessary to carry out the function. In particular, active sensors, which provide both intensity and range imagery, need to be well characterized across their entire operational range. Additionally, relative navigation systems must be designed to operate with respect to active and passive target vehicles or bodies.

Benefits of Technology

Modest development in navigation sensors can yield enormous benefits with respect to power, volume, and mass. Additionally, a new class of small sensors is being developed called 'noise radars' that operate in the RF spectrum and also provide imagery, which have the potential to provide SWaP savings.

There is significant potential benefit with respect to the redundancy and SWaP of IMUs by developing 'swarm sensing' technology. The principle of swarm sensing involves strategically packaging five to seven low-cost micro-electrical mechanical system (MEMS) IMUs, and could yield performance close to 'inertial grade' IMUs.

Vision processing algorithms are computation-intensive, yet can be massively parallelized; as such, they are uniquely suited to FPGAs or GPUs. Radiation-hardened or tolerant FPGAs and GPUs that have fast processing speeds will yield tremendous benefits as algorithms become more sophisticated in order to meet stringent mission requirements.

Table 22. TA 5.4.3 Technology Candidates – not in priority order

TA	Technology Name	Description
5.4.3.1	Improved Deep-Space Network (DSN) Radiometric Data	Improvement of deep-space tracking systems and calibrations to yield more accurate, robust, and timely Doppler, ranging, and interferometric tracking data.
5.4.3.2	Optimetric Data for Navigation	Data types derived from an optical communications signal that are analogous to or improve upon tracking techniques using communications signals' microwave frequencies.
5.4.3.3	Miniature, High-Accuracy, Multi-Function Star Tracker	Celestial attitude and orbital object detection sensor.
5.4.3.4	Fast Light Optical Gyroscopes for Precision Inertial Navigation	Enhanced-performance optical gyroscopes.

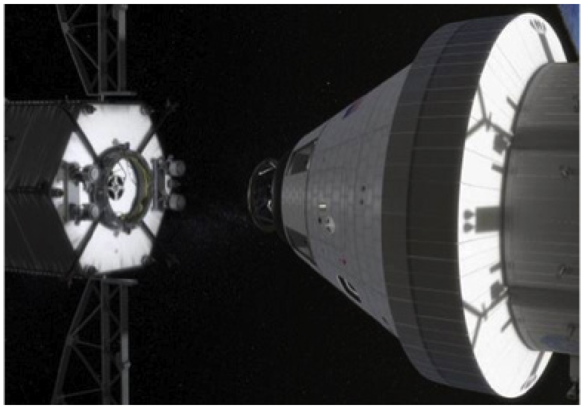
TA 5.4.4 Relative and Proximity Navigation

The ability to perform multi-platform relative navigation (such as determine relative position, relative velocity, and relative attitude or pose) directly supports cooperative and collaborative space platform operations. There is a crosscutting mission 'pull,' from both the envisioned human exploration missions as well as the robotic science missions, for relative navigation technologies. One such cooperative operation that relative navigation enables is AR&D of two or more space platforms. The collaborative operation of satellite formations or coordinated surface rovers operations with orbiting spacecraft are other missions enabled by relative navigation.

Relative navigation sensors (with the exception of GPS and radiometric ranging) are image-based. These include Star Trackers and star cameras that are used at long ranges, cameras (visible and IR) that are used at medium and short ranges, and LIDARs. Mission requirements may necessitate the use of active sensors like LIDARs (if there is a lighting-independent or direct ranging requirement); if such direct ranging requirements are not levied, then passive sensors (cameras) may be sufficient to meet mission requirements.

Technical Capability Objectives and Challenges

The specific component-level technologies to be developed for this technology area include, but may not be limited to, high resolution and high frame rate visible and IR imaging sensors, high-speed sensor data processing electronics, precision narrow beam laser rangefinder sensors, navigation filters (e.g., adaptive filters) and associated algorithms to sort and selectively weight data from multiple relative sensor input sources, mid-to-short range RF or optical inter-spacecraft communications systems for transmission of relative navigation state information, and other data between cooperating spacecraft.


Orion Docking to the Asteroid Redirect Robotic Vehicle

NASA must continue to develop technology for relative navigation hardware and software. Image-based sensors, such as, but not limited to, LIDARs, cameras (visible and IR), and 'noise radars,' provide high frame-rate data that need to be understood (as to the basic physics), well-calibrated, and processed. Additionally, the sensors will be required to have more stringent performance. For example, the per-pixel range accuracy for LIDAR must be better than 1 centimeter (3 sigma) in order to meet the docking requirements of some planned missions. This requirement may necessitate different types of detectors, and different chemistry of these detectors. Moreover, future missions will require larger resolution detectors, which will subsequently increase the volume of imagery data from these larger detectors.

Benefits of Technology

Relative navigation systems consist of both the hardware (sensors) and software (including algorithms). Sensors must be available to provide measurements across the entire range of operation. The benefits are primarily mission safety and success, at lower cost. Depending on where the rendezvous occurs, there may be significant one-way light-time issues that may preclude ground involvement. If the relative navigation sensors are onboard the vehicle, it will likely be prudent to perform the relative navigation onboard. The resulting system will be robust, and in the long run, cheaper. Capable relative navigation sensors will offer a level of safety and reliability that will be crucial to future missions.

Table 23. TA 5.4.4 Technology Candidates – not in priority order

TA	Technology Name	Description
5.4.4.1	Optical-Navigation-Grade Cameras	Optical-navigation-grade cameras that can be used as sensors for onboard autonomous navigation.
5.4.4.2	High-Resolution Infrared Cameras	High-resolution infrared cameras that can be used as sensors for onboard autonomous navigation.
5.4.4.3	Flash Light Detection and Ranging (LIDAR), Scanning LIDARs	Rendezvous LIDARs and landing LIDARs.
5.4.4.4	High-Performance Light Detection and Ranging (LIDARs)	Improved performance in LIDARs as sensors for onboard autonomous navigation.

TA 5.4.5 Auto Precision Formation Flying

This system capability builds on and coalesces several of the PNT technologies previously described. The supporting technologies include differential (relative) navigation, sensors and vision processing systems, space clocks and time or frequency distribution systems, onboard system navigation, and autonomous orbit and attitude maneuvering.

Precision formation flying invariably requires a high level of autonomy. The relative sensors and the time-critical processing of the sensor measurements reside on the vehicles to avoid delays in the transmission of safety-critical information and avoid safety concerns. As such, the guidance and targeting algorithms and software and the control system software would reside on the vehicles. SOA challenges include integrated radiometric crosslink sensors and navigation processing to maintain formations with more than two vehicles.

Technical Capability Objectives and Challenges

In this TA, a much higher level of PNT performance is needed to satisfy the stringent PFF requirements imposed by envisioned distributed observatories, such as planet-finding interferometers. Advances in mainstream PNT technologies are necessary but not sufficient to enable an autonomous PFF capability. The PNT technologies sought are for autonomous planning and optimization algorithms; higher performance relative navigation sensors; lower noise, higher speed sensor-processing electronics; and enhanced relative navigation filters.

Mission planning algorithms commensurate with the mission requirements are needed to advance this technology. The level of autonomy granted to these algorithms and systems is a function of the aforementioned mission requirements, as well as the venue of operation (for example, PFF at Mars will require more autonomy than in LEO). Extensive testing to cover all conceivable contingencies will require a great deal of attention. This technology necessitates FDIR algorithms, not only for sensor reconfiguration but also for effector reallocation. Whereas adequate attention needs to be given to the nominal performance and requirements' satisfaction, the off-nominal performance (particularly in the presence of sensor and effector failures) is the primary challenge facing PFF systems of the future.

Benefits of Technology

The benefits of developing autonomous PFF are myriad. As demands for more accurate relative navigation systems are made, the requirements on precisely controlling trajectories become more stringent. The earlier section outlined the benefits of precise relative navigation systems; this section will briefly mention the need for algorithms and sensors to make such systems. Planning and execution algorithms will allow more precise placement of the chaser relative to the target than can be obtained from ground-based formation flying paradigms. The time constants associated with future PFF missions along with the requirements levied on the systems may themselves preclude ground involvement, other than possibly higher level plan approval and authority to proceed.

Table 24. TA 5.4.5 Technology Candidates – not in priority order

TA	Technology Name	Description
5.4.5.1	Rapid Trajectory Design Near Small Bodies	Prototype software and algorithmic framework to support rapid exploration of transfer options near small bodies and close-proximity operations of small body missions.
5.4.5.2	Embedded Software Defined Radio (SDR), Antenna, and Protocol	SDR for bearing measurements to AR&D targets and to natural quasar and planetary RF sources for navigation and timing.

TA 5.4.6 Autonomous Approach and Landing

The SOA of approach and landing technology is the Autonomous Landing and Hazard-detection and Avoidance Technology (ALHAT) project, which consists of a suite of sensors, including terrain navigation and hazard-relative navigation and avoidance. This sensor suite, which also consists of image processing algorithms, has matured and has performed Earth-based flight tests. It will be instrumental to landing on planetary bodies.

Technical Capability Objectives and Challenges

An integrated ensemble of active and passive optical and RF sensor hardware with supporting real-time vision processing algorithms will be a fundamental part of any autonomous GN&C system intended to perform safe and controlled precision landings on or contacts with the surface of any solid body in the solar system. Precision terrain-relative navigation while simultaneously detecting and avoiding surface hazards is a multidisciplinary technology challenge focused on improving real-time situational awareness and platform response in uncertain operational environments. Technologies that allow an increased reliance on in-situ observations, data fusion, and autonomous PNT are needed to support future mission requirements. Significant development in technologies for vehicle onboard sensing, perception, reasoning, planning, and decision making are needed to improve the efficiency, accuracy, and precision of autonomous approach and landing systems. This is a system-level capability built strongly, but not solely, upon several PNT technologies that enable autonomous maneuvering, sensors and vision processing systems, and onboard navigation. These PNT technologies include:

- Sensors and algorithms for path planning and optimization and constraint handling;
- Integrated system health management and fault management (e.g., FDIR);
- Event sequencing and optimal resource allocations;
- Collaborative sensor fusion and sensor image motion compensation and processing;
- Pattern recognition and matching;
- Hazard search and detection strategies;
- Feature (e.g., hazards) location and mapping;
- High-performance inertial sensors and celestial sensors;
- Accurate and fast converging vehicle state estimation filters; and
- Adaptive flight control systems that provide precise and agile maneuvering.

One other particular TA that has synergy between the navigation on and around NEAs or planetary bodies, as well as conducting scientific surveys, is the development of a new generation of high-performance gravimetric and gravity gradiometer sensors using emerging cold atom sensor technology. System architectures and supporting technologies for navigational beacons and optical targets that aid spacecraft approach and landing are needed. The navigational beacons and targets can be deployed on early exploration satellites, landers, and rovers. Navigational beacons can be integrated into the precursor satellites, which will be used to map and study planet and NEA surface characteristics. These orbiting beacons can be part of a navigation constellation for improved vehicle positioning during the approach and landing mission phase. Likewise, body-based beacon landing systems derived from GPS pseudolite technologies and landing optical targets can be used for accurate landing systems. A pre-landing mission can deploy three to five beacons or targets. These beacons and targets can land in rough, unknown locations using air bags or parachutes. Through repeated observation, beacons' and targets' positions can be precisely determined. With knowledge of beacon and target location, future landing craft can use precise timing beacons and optical targets for improved navigation accuracy similar to GPS pseudolites and ISS proximity and docking targets.

Autonomous precision landing and hazard avoidance will be needed for both crewed and robotic missions to planets and small bodies. Future planetary landing systems will need sensors not only to land at a specified location within a particular accuracy, but also to avoid hazards. Therefore, sensors must be developed to detect hazards, and algorithms must be developed to avoid these hazards while at the same time identifying safe landing sites. These sensors include Doppler velocimeters, laser altimeters, and flash LIDARs—all of which have large fields of view, high accuracy, and the ability to operate in the midst of dust clouds generated by engine plumes. Additionally, the algorithms need to be able to handle large quantities of images (of range and intensity), to incorporate known terrain models, and to be able to generate safe sites reliably and accurately. These navigation and image processing algorithms will need to be designed using advanced techniques to minimize the computational burden on the onboard flight processor.

Benefits of Technology

Future landing missions will operate far from Earth. These missions will be required to achieve landing precisions that are commensurate with precision Earth landing. The ability to land close to prepositioned assets is a prerequisite to carrying out extensive scientific inquiry and exploration of planetary bodies without damaging the prepositioned assets, but still enabling crews to walk less than 1,000 meters to their habitat, transporter, and return vehicles.

Table 25. TA 5.4.6 Technology Candidates – not in priority order

TA	Technology Name	Description
5.4.6.1	Primitive Body/Lunar Proximity Operations and Pinpoint Landing	Techniques and algorithms for estimating and controlling spacecraft trajectories in proximity to the Moon or small bodies (including pinpoint landing scenarios), based on data derived and computations performed onboard.
5.4.6.2	Multi-Altitude Terrain Recognition Navigation (TRN) Sensor System	Imager, altimeter, and image processor.

TA 5.5: Integrated Technologies

This area integrates technologies developed in the other areas with the goal of reducing SWaP and enabling multi-purpose systems while at the same time enhancing mission autonomy.

Current NASA flight transceivers are capable of performing communications and radiometrics. However, they are not aware of their environment and do not react to it. There are only limited network-level capabilities. Ground systems have just begun integrating network functionality. NASA missions can take advantage of the RF communications link as a science instrument, gleaning information about intervening atmospheres, gravity fields, and surface terrains. LIDARs have demonstrated the potential for similar capability on optical links. Today, RF and optical systems are developed and operated separately, even though there are components that could be shared. Modeling and simulation is used today to develop communications and navigation systems. Finally, the location and status of astronauts and their implements is determined through manual means on the ground.

Sub-Goals

Development of hybrid optical and RF communications systems should reduce mass and power requirements on spacecraft. Integrating knowledge engineering with future networking radios could provide cognitive networking functionality, which would further reduce dependence on manual control from Earth. Techniques will be developed to improve the use of the RF link as a science instrument (measuring perturbations along its path or in the spacecraft trajectory) and enable these kinds of measurements using optical links.

Challenges include reducing the user burden and ground infrastructure by integrating technologies, reducing costs through innovative systems-level analysis, exploiting optical communications links of science instruments while increasing performance over the RF equivalent, and increasing the flexibility of communications and navigation systems.

Table 26. Summary of Level 5.5 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
5.0 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	Goals:	Increase performance and efficiency in the systems that provide communications, navigation, and orbital debris tracking and characterization capabilities for all mission classes.
Level 2		
5.5 Integrated Technologies	Sub-Goals:	Develop highly integrated, multifunctional systems to reduce mass and power requirements on spacecraft, and reduce dependence on manual control from Earth.
Level 3		
5.5.1 Radio Systems	Objectives:	Develop an intelligent, multi-purpose software defined radio that provides increased performance and efficiency while reducing cost.
	Challenges:	Supporting multiple signal formats and interfacing with different ground and space assets during the various mission phases. Efficiently integrating different capabilities and components, unexpected radio or system decisions or behavior, and methods to verify decision-making algorithms as compared to known, planned performance.
	Benefits:	Allows for more autonomous operations by reducing dependence on Earth-based control. Helps manage the complexity brought on by the reconfigurable systems. Enables ground control oversight of the system with less needed direct manual interaction. Enables low cost ground assets that support human exploration missions as well as short duration CubeSat and small satellite missions.

Table 26. Summary of Level 5.5 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
5.5.2 Ultra Wideband	Objectives:	Develop radio technology that provides high-data-rate communications; high-precision, real-time location estimation; and high-precision time synchronization for proximity applications.
	Challenges:	Radio frequency (RF) interference with other onboard RF systems. Coordination of spectrum allocation and usage with regulatory agencies.
	Benefits:	Provides non-interfering local area networks as well as high precision location technology.
5.5.3 Cognitive Networks	Objectives:	Develop communications and navigation subsystems that can interpret information about their situation autonomously, understand their options, and select the best means to communicate or navigate without relying on communications with the ground.
	Challenges:	Ensuring each node is dynamically aware of the state and configuration of the other nodes to autonomously optimize their operational parameters in response to changes in user needs or environmental conditions.
	Benefits:	Optimizes performance for networks of spacecraft, increasing data return and making communications more resilient to changing conditions.
5.5.4 Science from the Communications System	Objectives:	Enhance the use of RF communications systems to perform science measurements. Develop the capability to use optical communications links to make science measurements.
	Challenges:	Using software defined radio, highly stable timing sources on the spacecraft, higher effective isotropic radiated power (EIRP), and resolution from the ground radars in RF science and communications assets.
	Benefits:	Enhances scientific knowledge for much less than a dedicated instrument.
5.5.5 Hybrid Optical Communications and Navigation Sensors	Objectives:	Develop dual-use sensor systems that can provide both communications and navigation functions.
	Challenges:	Component integration without sacrificing performance while maintaining advantages in SWaP.
	Benefits:	Reduces SWaP and lifecycle cost for multiple functions.
5.5.6 Radio Frequency and Optical Hybrid Technologies	Objectives:	Provide hybridized RF and optical communications in the same asset that functions in diverse atmospheric (weather) and in-space conditions.
	Challenges:	Optimizing architecture; integrating components.
	Benefits:	Creates SWaP savings and provision of an RF beacon for acquisition and pointing.

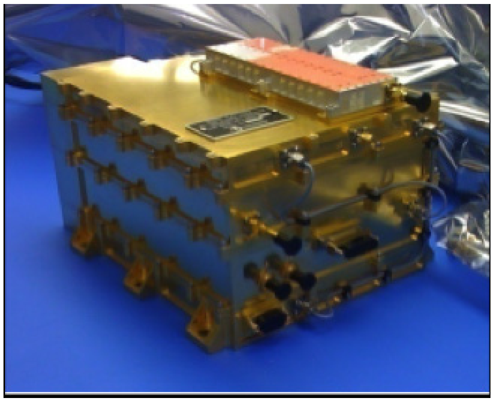
TA 5.5.1 Radio Systems

As human and science exploration missions move further from Earth and become increasingly more complex, they present unique challenges to onboard communications systems and networks. The missions will require systems that support multiple signal formats and interface with different ground and space assets during the various mission phases. Intelligent radio systems will help manage the increased complexity and provide greater capability to the mission to return more science data. Crewed missions pose a unique challenge in that they need communications during all mission phases starting from launch and ascent, through the return to Earth. Currently, this is accomplished by having a different radio for each mission phase. Reconfigurable radio systems that capitalize on technology advancements in RF communications, space networking and tracking, and spectrum and power efficiencies have the potential to significantly improve performance using a single system while reducing cost and SWaP. An adaptive system could autonomously optimize the RF links, network protocols, and modes used based on the needs of the various mission phases. A cognitive radio system would sense its RF environment and adapt and learn from its various configuration changes to optimize the communications links throughout the system in order to maximize science data transfer, enable substantial efficiencies, and reduce latency. The challenges in this area are in the efficient integration of different capabilities and components, unexpected radio or system decisions or behavior, and methods to verify decision-making algorithms as compared to known, planned performance.

Technical Capability Objectives and Challenges

The objective of this TA is to exploit technology advances in RF communications, PNT, cognition, and space internetworking to develop advanced, integrated space and ground systems that increase performance and efficiency while reducing cost. For example, an intelligent, multi-purpose software defined radio (SDR) that can change its function with each mission phase and requirements or autonomously sense and adapt to its RF environment to improve the communications. An SDR, as described, will significantly reduce SWaP and cost for crewed exploration missions while enabling it to interface with different infrastructure assets including Space Network, GPS Satellites, and DSN. Individual technology advancements are called for in areas of

- spectrum and power-efficient waveform design,
- advanced coding schemes,
- adaptive mode control (cognitive technology) based on mission phases,
- channel and network conditions,
- system-wide awareness of cognitive or autonomous behavior,
- design and validation of space-to-space RF ranging (range, range rate) for rendezvous and proximity tracking, and
- miniaturization to reduce SWaP and to be compatible for EVA communications system needs.



Software-Defined Radio

RF electronics SWaP can be reduced with advancements in functionality, packaging, and the ability to withstand the harsh spaceflight environments. Spacecraft SWaP will be improved overall if microelectronics are developed with wider temperature operational ranges, radiation tolerance, and higher performance, such as what could be achieved with radio frequency integrated circuits (RFICs) and metal-semiconductor field effect transistors (MESFETs) with wide operational temperature ranges.

Development of ground-based and flight SDRs encompassing highly capable multiband radios, as well as more focused radios for smaller satellites (e.g., CubeSats) and short-lived applications, will be necessary. Most missions going forward are likely to fly SDRs. Increased intelligence within the radio system and throughout the communications system will increase data volume return by improving efficiencies and making optimal use of network connectivity.

Benefits of Technology

Reconfigurable systems, while reducing spacecraft SWaP, can also provide the ability to adaptively adjust the data rate, transmit power, and the coding scheme used by sensing the channel and vehicle conditions. This allows for more autonomous operation, which will be critical as future missions call for increased autonomy and reduced dependence on Earth-based control. Intelligent radio systems will also help manage the complexity brought on by reconfigurable systems, enable ground control oversight of the system, and enable less need for direct manual interaction.

Another benefit of reconfigurable systems is that they enable low-cost, ground assets that can support human exploration missions, as well as short-duration CubeSat and small satellite missions.

Table 27. TA 5.5.1 Technology Candidates – not in priority order

TA	Technology Name	Description
5.5.1.1	Intelligent, Multipurpose Software Defined Radio	Software-based communications and navigation functions in a reprogrammable signal processing platform, which sense and adapt to link and system conditions, to efficiently increase data transfer and reduce user burden.

TA 5.5.2 Ultra Wideband

Currently, missions rely on different systems to provide tracking, data communications, and time synchronization. Examples include spread-spectrum radiometrics, satellite navigation systems, and continuous-wave communications systems. These multiple application-specific systems incur high cost, high SWaP, and relatively low precision location estimation and time-synchronization accuracy. Future missions call for low cost and lower SWaP systems that can provide high-data-rate communications; high-precision, real-time location estimation; and high-precision time synchronization for proximity applications. Proximity applications encompass communications over short ranges, such as between a rover and during EVAs on the surface of the Moon and between a spacecraft and external free-flyers.

The development of ultra-wideband radio systems using impulsive modulation with bandwidth in excess of 500 megaHertz (MHz) can provide high-data-rate communications, high-precision location estimation, and high-precision temporal synchronization capability. The exact frequency band of operation for this system will need to be coordinated with NASA's Frequency Management team.

Technical Capability Objectives and Challenges

The objective of this TA is to develop radio technology for short-range, high-bandwidth communications and navigation. This ultra-wide band subsystem would integrate the latest technologies to support high-data-rate communications; high-precision, real-time location estimation; and high-precision time synchronization for proximity applications, such as formation flying of small satellites, distributed cooperative beam-forming and MIMO communications using small satellite constellations, surface operations in GPS-deprived environments, and intra-vehicular activity (IVA) and EVA asset tracking and telemetry transport. For example, a surface explorer may carry an ultra-wideband transceiver and subsystem, which enables it to (in a single burst) communicate with another rover or orbiter in proximity, determine a precise range to the other element (positioning), and listen for returns from the same burst to produce a navigation map for the terrain in proximity to the rover (navigation). This would not only reduce the mass of the rover, consolidating three functions into a single system, but may also reduce power by using a single burst to perform all three functions. Any potential RF interference of the UWB system with other onboard RF systems will need to be addressed.

Benefits of Technology

UWB systems can provide potentially non-interfering local area networks, as well as high-precision location technology.

Table 28. TA 5.5.2 Technology Candidates – not in priority order

TA	Technology Name	Description
5.5.2.1	Ultra-Wideband Impulse Radio	Ultra-wideband impulse radio for real-time location estimation, time synchronization, and data transport.

TA 5.5.3 Cognitive Networks

The goal of this TA is to develop cognitive networks in which each node can sense the other nodes in the network and their capabilities and adjust the network topology or capability on the fly. These networks are still in the research stage.

Technical Capability Objectives and Challenges

The objective of this TA is to develop a system in which each node is dynamically aware of the state and configuration of the other nodes to autonomously optimize their operational parameters in response to changes in user needs or environmental conditions. Today, most of the decisions in space communications and navigation are made on the ground. Communications and navigation subsystems on future missions should be capable of interpreting information about their situation autonomously, understanding their options, and selecting the best means to communicate or navigate without relying on communications with the ground. For example, a node in such a network might be aware of the positions and trajectories of all other nodes, inferring this entirely through networked communications and modeling. Another example would be dynamically changing displays of information for the human receiver, based on needed response times informed by the cognitive network.

Benefits of Technology

Autonomously adaptive systems can optimize performance for networks of spacecraft, increasing data return and making communications more resilient to changing conditions.

Table 29. TA 5.5.3 Technology Candidates – not in priority order

TA	Technology Name	Description
5.5.3.1	Automated Intelligent Networked Systems	Develop a system in which each communications node on the network is dynamically aware of the state and configuration of the other nodes to autonomously optimize their operational parameters in response to changes in user needs or environmental conditions.

TA 5.5.4 Science from the Communications System

NASA is not currently advancing any Science from the Communications System technologies within the timeframe of this Roadmap. A number of related technologies that enable science measurements with the communication system are being advanced under other technology areas. For example a software defined radio in TA 5.5.1, Radio Systems, can be reprogrammed to process a communication signal in different ways, which could extract useful science data, such as perturbations on the signal caused by gravity or the atmosphere. Some discussion of this area is, however, included below.

Science from the Communications System has a long history using the RF assets on Earth and in space for both radio science and radar observations of solar system bodies. The near-term challenge is to continue to evolve these applications using technologies in other TAs, such as TA 5.5.1 Radio Systems, TA 5.4.1 Timekeeping and Time Distribution, and TA 5.7.1 Tracking Technologies. The future challenge is to develop science capability compatible in future optical communications systems and the optimetric capabilities.

Technical Capability Objectives and Challenges

The objective of this TA would be to enhance the use of RF communications systems to perform science measurements. It involves developing the ability to use optical communications links to make science measurements; leveraging the combination of RF systems, optical systems, and science instruments to improve accuracy; and expanding the spectral width of the signals to enable more information about sub-surfaces. For example, with further technology development, it may be possible to determine the Earth's wobble using the same technology being developed for the arraying of TDRSS satellites. This would provide a continuous real-time measurement of the wobble as a by-product of tracking TDRSS with this new technology.

Benefits of Technology

Use of existing communications and navigation systems for science enhances scientific knowledge for much less than a dedicated instrument.

TA 5.5.5 Hybrid Optical Communications and Navigation Sensors

NASA is not currently advancing any Hybrid Optical Communications and Navigation Sensors technologies within the timeframe of this Roadmap. Related technologies for optical communications and optical navigation are being advanced in TA 5.1, Optical Communications and Navigation. No technologies specific to hybrid or dual use of optical communications and navigation were identified for advancement. Some discussion of this area is, however, included below.

Many missions already use optical sensors for science and navigation. Integrating these functions with optical communications capability and using, for example, a single aperture will reduce SWaP and lifecycle cost.

Technical Capability Objectives and Challenges

This TA includes sensor systems that are dual-use in nature, providing a synergistic benefit to both communications and navigation functions. Innovative approaches could include exploiting an optical communications terminal to perform navigational measurements, such as star sighting, or a Star Tracker technology developed to communicate at very high data rates. Such advances will decrease the SWaP burden to users.

Benefits of Technology

Combining the optical systems for communications and navigation can reduce SWaP and lifecycle cost for multiple functions.

TA 5.5.6 Radio Frequency and Optical Hybrid Technologies

Integrating RF and optical communications capability into a single system may reduce the complexity of operations and SWaP on flight systems. There have been demonstrations of small, ground-based integrated RF-optical apertures, but these have not made it into operations. There is ongoing development of larger (5 to 8 meter) ground-based hybrid apertures for deep-space application. Integrated flight systems are still in the laboratory development stage—including a hybrid aperture and integrated electronics (e.g., SDRs).

Technical Capability Objectives and Challenges

The objective of this TA is to optimize the architecture and integrated components into a system that can be used to support hybridized RF and optical communications in the same asset and in diverse atmospheric (weather) and in-space conditions. This includes both the electronics and the complex integration of collinear antenna and weather elements within the system.

Benefits of Technology

Potential benefits include SWaP savings and provision of an RF beacon for acquisition and pointing.

Table 30. TA 5.5.6 Technology Candidates – not in priority order

TA	Technology Name	Description
5.5.6.1	Large Aperture Combined Radio Frequency (RF)/Optical Apertures	Develop required technology to enable ground-based large combined optical and RF apertures to utilize large infrastructure development and reduce operating costs.

TA 5.6: Revolutionary Concepts

This roadmap also identifies revolutionary concepts for potential development. None of these technologies are "pulled" by any future mission. These are inherently risky concepts with a high probability of failing to achieve their goal, but they can have very high payoff if they are successful. Technologies that show promise will be transitioned to the appropriate communications and navigation area for infusion into missions or enabling infrastructure.

Sub-Goals

This area provides innovations and game-changing solutions that will provide mission planners and scientists with the freedom to develop and implement more complex missions and enable new science and exploration goals. Several revolutionary concepts that could enable new classes of missions have been identified as examples of possible tasks.

The critical thrust for this TA is to develop new ways of approaching the key communications and navigation challenges that radically improve the performance. Changes should typically be several orders of magnitude in increased performance or decreased user burden to be considered.

Table 31. Summary of Level 5.6 Sub-Goals, Objectives, Challenges, and Benefits

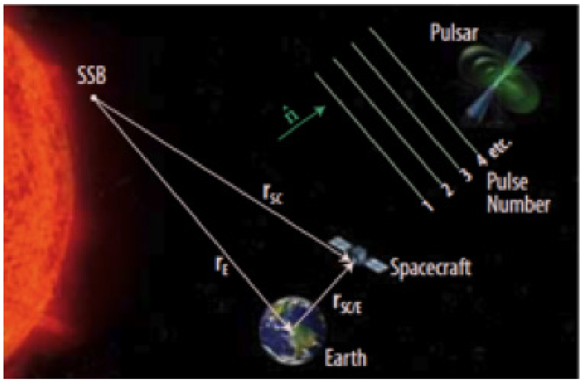
Level 1		
5.0 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	Goals:	Increase performance and efficiency in the systems that provide communications, navigation, and orbital debris tracking and characterization capabilities for all mission classes.
Level 2		
5.6 Revolutionary Concepts	Sub-Goals:	Provide orders of magnitude increase in data throughput, guaranteed data integrity, and robust navigation for near-Earth and deep-space applications.
Level 3		
5.6.1 X-Ray Navigation	Objectives:	Autonomously determine position anywhere in the solar system using X-ray emitting pulsars.
	Challenges:	Volume and pointing constraints.
	Benefits:	Provide the ability to autonomously determine position anywhere in the solar system.
5.6.2 X-Ray Communications	Objectives:	Provide high-rate deep-space, low transmit power, and highly physically secure data links and enable new penetrating communications.
	Challenges:	Platform isolation and pointing accuracy.
	Benefits:	Provides high rate deep-space, low transmit power and highly physically secure data links; enables new penetrating communications capabilities and communications through harsh environments; and enables secure space-to-space links.
5.6.3 Neutrino-Based Navigation and Tracking	Objectives:	Provide long-distance signaling when line-of-sight cannot be guaranteed. Determine position and attitude of spacecraft anywhere in the universe.
	Challenges:	Neutrino generator and detector sizes and event detection rates are currently orders of magnitude removed from practicality for either deep-space communications or navigation.
	Benefits:	Uses angle of arrival (AoA) to known sources for attitude and position knowledge and is an enabling technology in support of Discovery Missions as identified in the decadal survey.

Table 31. Summary of Level 5.6 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
5.6.4 Quantum Key Distribution	Objectives:	Provide absolute secure transmission of the key codes that are essential to encrypt messages with tamper-proof information assurance.
	Challenges:	Improve the quantum key distribution rate.
	Benefits:	Provides more efficient secure communications links.
5.6.5 Quantum Communications	Objectives:	Enable long-range quantum communications.
	Challenges:	Generating entangled photons.
	Benefits:	Provides more efficient communications performance when integrated with optical communications systems.
5.6.6 Superconducting Quantum Interference Filter Microwave Amplifier	Objectives:	Develop a superconducting quantum interference filter to detect extremely weak magnetic fields to enable a new type of signal detection.
	Challenges:	Develop and optimize superconducting quantum interference filter (SQIF) technology to achieve quantum limited noise performance.
	Benefits:	Provides low noise front-end for space communications—ground or flight, changes the paradigm for RF communications to detecting the magnetic field instead of the electric field, and provides magnitude of improvement in communications systems.
5.6.7 Reconfigurable Large Apertures	Objectives:	Develop large, space-based apertures from smaller apertures or multiple spacecraft.
	Challenges:	Miniaturizing communications components.
	Benefits:	Provides low-cost reconfigurable apertures for RF or optical communications systems.

TA 5.6.1 X-Ray Navigation

The X-ray navigation (XNAV) concept uses a collection of pulsars—stellar “lighthouses”—as a time and navigation standard just like the atomic clocks of the GPS. Unlike GPS satellites, XNAV pulsars are distributed across the galaxy, providing an infrastructure of precise timing beacons that can support navigation throughout the solar system. Since their discovery in 1967, pulsars have been envisioned as a tool for deep-space navigation. An XNAV system measures the arrival times of pulses from pulsars through the detection of individual X-ray photons.



X-Ray Navigation

Technical Capability Objectives and Challenges

Technology development will focus on the first demonstration of real-time, onboard X-ray pulsar based navigation using an X-ray timing instrument. The primary challenges to the development are reducing the volume of the system and reducing the pointing constraints.

Benefits of Technology

Advancement of XNAV using X-ray emitting pulsars could provide the ability to autonomously determine position anywhere in the solar system, just as GPS does for Earth inhabitants.

Table 32. TA 5.6.1 Technology Candidates – not in priority order

TA	Technology Name	Description
5.6.1.1	X-Ray Navigation (XNAV)	Pulsed X-ray signals from millisecond pulsars (MSPs) enable GPS-like absolute position determination to support autonomous navigation throughout the solar system and beyond.

TA 5.6.2 X-Ray Communications

Space-based communications can benefit dramatically from technological mastery of the X-ray portion of the spectrum. Fundamentally, two major advantages of X-rays (relative to optical, microwave, or RF technologies) should be exploited. First, the short wavelength offers very low divergences, which has the potential to lower requirements on SWaP relative to longer wavelength technologies, and to provide secure inter-satellite communications. Second, the exceedingly high carrier frequency means significantly larger bandwidths for information transmission if technologies for modulating X-rays are further developed.

Technical Capability Objectives and Challenges

The objective of this TA is a space demonstration over 100 kilometers using the Neutron star Interior Composition Explorer (NICER) X-ray timing instrument as a receiver with modified X-ray source (MXS) and optic combination as a transmitter (telemetry rate limited by NICER). After the NICER demonstration, development will continue to advance Gb/s communications capability to address challenges like platform isolation and pointing accuracy.

Benefits of Technology

This technology exploits extremely low beam divergence of X-rays to provide high-rate, deep-space, low transmit power, highly physically secure data links, and enable new penetrating communications capabilities. Accordingly, it should address communications constraint mitigation for deep-space (gigabits per Watt (Gbits/W)) and should enable communications through harsh environments (e.g. hypersonic plasma shroud), as well as secure space-to-space links.

Table 33. TA 5.6.2 Technology Candidates – not in priority order

TA	Technology Name	Description
5.6.2.1	X-Ray Communications (XCOM)	Exploit extremely low beam divergence of X-rays to provide high-rate deep-space, low transmit power, highly physically secure data links, and enable new penetrating communications capabilities.

TA 5.6.3 Neutrino-Based Navigation and Tracking

Neutrinos are small, near-light-speed particles with no electric charge. Neutrinos can be generated through nuclear reactors or particle accelerators. Detection of neutrinos currently requires massive detectors made of thousands of tons of liquid buried in the ground. Since neutrinos can travel through most matter, they could be used for long-distance signaling when line-of-sight cannot be guaranteed. A possible ranging method using neutrinos is to modulate the neutrino output from a nuclear reactor or particle accelerator on a spacecraft and detect this output at an Earth base station. The modulation would encode timing information from an atomic clock synchronized to Earth, which can be used to calculate range. NASA and its partners have demonstrated the use of neutrinos for communications.

Technical Capability Objectives and Challenges

Using neutrino sources as navigation beacons enables navigation and tracking directly through normal matter. The desired capability needed is to determine position and attitude of spacecraft anywhere in the universe. This capability depends on detector performance. Current neutrino detectors have fairly high accuracy in estimating angle of arrival, but they are massive and have very low rates of detection. Hence, the size and power consumption of neutrino detectors need to be significantly reduced for practical in-space navigation applications. The objective is to achieve 100- to 1,000-fold improvement in detector SWaP. Detection of neutrinos currently requires massive detectors made of thousands of tons of liquid buried in the ground. Neutrino generator and detector sizes and event detection rates are currently orders of magnitude removed from practicality for either deep-space communications or navigation.

Overcoming the challenges and achieving the technical capability objectives mentioned above require developing new concepts for efficiently generating and detecting neutrinos. The development of suitcase-sized neutrino detectors, with power consumption way below 100 W, is needed. While there is no specific due date for the technology due to its potential impact, ongoing efforts should be maintained within NASA, other government agencies, and academia to achieve the aforementioned objectives.

Benefits of Technology

This technology can provide position-fixing capabilities from angular estimates of sources. Current neutrino observatories provide angular accuracy of approximately 10 to 20 milliradian (mrad). Neutrino detectors are able to determine AoA and differentiate between types of neutrinos. AoA to known sources can be used for attitude and position knowledge. This capability could be an enabling technology in support of Discovery Missions, as identified in the decadal survey.

Table 34. TA 5.6.3 Technology Candidates – not in priority order

TA	Technology Name	Description
5.6.3.1	Neutrino-Based Navigation and Tracking Technologies	Neutrino sources as navigation beacons enable navigation and tracking directly through normal matter.

TA 5.6.4 Quantum Key Distribution

Encryption schemes entail distribution of a secret key among legitimate users and, as such, are susceptible to interception by an unwanted eavesdropper and, at worst, subject to damage or corruption. While traditional encryption schemes and codes can be compromised or intercepted, QKD promises absolute secure transmission of the key codes that are essential to encrypt messages with tamper-proof information assurance. A quantum communications channel is inherently secure, since the mere act of observing the communications channel will be apparent to both parties. While it is acknowledged that other government agencies have the technical lead in investigating this concept, NASA should be cognizant of the advances of QKD and quantum entanglement as a potential stepping-stone for quantum communications.

Technical Capability Objectives and Challenges

One of the keys to QKD is the need to generate entangled photons. Techniques such as backward quasi-phase matched interaction in waveguide and single photon waveguide source generation are potential solutions.

Benefits of Technology

Developing QKD will provide efficient secure communications links.

Table 35. TA 5.6.4 Technology Candidates – not in priority order

TA	Technology Name	Description
5.6.4.1	Entangled Photon Sources	Creation of entangled photons by backward quasi-phase matched interaction in waveguide.
5.6.4.2	Waveguide Single Photon Source	Single photon waveguide source for quantum key distribution.

TA 5.6.5 Quantum Communications

Quantum communications is the art of transferring quantum states (which encode information) between two points. It should be noted that there is significant debate in the scientific community as to whether this technology will enable faster-than-light communications. While quantum entanglement has been demonstrated at a few tens of kilometers, long-range communications face critical challenges.

Technical Capability Objectives and Challenges

High-flux single photon sources, as well as entangled photon sources, need significant development in order to enable long-range communications. NASA should stay abreast of development in this area to determine if the purported advantages make sense for space applications (e.g., no antenna needed, no broadcast power, very secure with high data rates, no line of sight, etc.).

Benefits of Technology

This technology can potentially be integrated with optical communications systems and provide more efficient communications performance.

Table 36. TA 5.6.5 Technology Candidates – not in priority order

TA	Technology Name	Description
5.6.5.1	Quantum Communications	Quantum communications to utilize linkage across space of entangled photons for improved data rates.

TA 5.6.6 Superconducting Quantum Interference Filter Microwave Amplifier

This revolutionary concept represents a significant paradigm shift by using magnetic field detection instead of electric field detection and capitalizes on techniques demonstrated in the sensors community. From a fundamental physics point of view, the magnetic field detection process holds promise for a significant advantage in sensitivity. This concept incorporates a SQUID array for detecting extremely weak magnetic fields to enable a new type of signal detection process. Though fundamental principles have already been demonstrated, it is not known how much of the theoretical sensitivity improvement can be realized. Integration of a "flux concentrator" at frequencies of interest to NASA and a practical SQIF has not been demonstrated. Issues such as flux motion within the superconducting film, which reduces sensitivity, and system benefits with the refrigeration system included need to be assessed.

Technical Capability Objectives and Challenges

The objective is to achieve quantum limited noise performance; that is, a 10-fold improvement in sensitivity and noise temperature with respect to those attained with state of practice devices (e.g., current 20 Kelvin (K), 0.1 µm high electron-mobility transistor (HEMT) low noise amplifier temperature is about 15 K at Ka-band).

Benefits of Technology

This technology will provide low-noise front-end for space communications—ground or flight. The concept could benefit receiver concepts required by the NASA Universal Communications and Navigation Architecture, as well as astrophysics missions. Successful development of SQIF technology would change the paradigm for RF communications to detecting the magnetic field instead of the electric field and provide magnitudes of improvement in communications systems.

The technology has been proven at ultra-high frequency (UHF), and basic SQIF devices have been demonstrated at X-band. The work ahead will concentrate on optimizing X-band SQIF devices in laboratory environments to achieve very low inductance superconducting loops, high critical current, and yield over large chip size, as well as development of integrated flux concentrator. Based on the outcome of these efforts, development of Ka-band SQIF will follow.

Table 37. TA 5.6.6 Technology Candidates – not in priority order

TA	Technology Name	Description
5.6.6.1	Superconducting Quantum Interference Filter (SQIF) Microwave Amplifier	SQUID devices permit the detection of magnetic fields as small as 10^{-15} Tesla. An integrated array of (N x N) SQUIDs of incommensurate area forms a SQIF demonstrating a noise temperature that is inversely proportional to the square root of N.

TA 5.6.7 Reconfigurable Large Apertures

Large, space-based apertures formed from smaller apertures on multiple spacecraft have the ability to quickly respond to changing needs. The use of small satellites—potentially nanosatellites—can make these apertures affordable.

Technical Capability Objectives and Challenges

The objective of this TA is to form large space apertures using constellations of nanosatellite systems. This will require advances in nanotechnologies, semiconductor processors, computing architectures, advanced materials power and propulsion, miniaturized communications components, ad hoc or wireless network protocols, and cognitive swarm operations. In addition, large deployable, reconfigurable apertures are needed for single spacecraft applications. Apertures for radar, remote sensing, and RF and optical communications that have optimized SWaP or are multipurpose (e.g., solar array and communications) will enable future exploration.

Benefits of Technology

This technology will provide low-cost, reconfigurable apertures for RF or optical communications systems.

Table 38. TA 5.6.7 Technology Candidates – not in priority order

TA	Technology Name	Description
5.6.7.1	Reconfigurable Large Aperture Technologies	Large, space-based apertures formed from smaller apertures on multiple spacecraft that have the ability to quickly respond to changing needs.

TA 5.7: Orbital Debris Tracking and Characterization

After more than 50 years of human space activities, orbital debris—defunct manmade objects orbiting the Earth—has become a serious problem in the near-Earth environment. As of 2014, the total mass of debris in orbit has exceeded 6,000 tons. The U.S. Space Surveillance Network is currently tracking more than 22,000 objects larger than 10 centimeters. Additional optical and radar data indicate that there are approximately 500,000 objects larger than 1 centimeter, and more than 100 million larger than 1 millimeter in the environment. Because of the high impact speeds between orbiting objects, debris as small as 0.2 millimeter poses a realistic threat to human spaceflight and robotic missions in the near-Earth environment. As highlighted in the President's 2010 National Space Policy, the orbital debris problem is creating a major challenge for Space Situational Awareness (SSA) and the safe operation of U.S. space assets. In order to address this challenge, development of technologies and techniques in many areas is needed to better define the orbital debris population for near-term debris impact risk assessments and protect critical space assets and for far-term sustainability of the environment. The following are examples of technologies that will be needed to address the challenge:

- Radar and optical detection to better characterize the orbital debris population from large (> 10 centimeter) to small (> 0.1 millimeter) objects and from LEO to GEO. A critical data gap is for debris between 0.5 and 3 millimeter in LEO, and
- Modeling the current and future orbital debris environment (theory, algorithms, etc.).

This section identifies technologies to measure and model orbital debris for those activities that are related to communications and navigation.

NASA's current measurement program uses both RF and optical techniques. Ground-based RF measurements are primarily made by the Haystack X-band Radar augmented by limited observations at the Goldstone Solar System Radar (GSSR), among others. Ground-based optical measurements are to be made by the Meter Class Autonomous Telescope on Ascension Island.

The key technical challenges are to provide radars with increased RF power, bandwidth, and sensitivity for detecting even smaller debris; increased sensitivity, wide field-of-view optical telescopes; autonomous data acquisition; and improved modeling of orbits and distribution.

Sub-Goals

The ultimate goal is to maintain detailed knowledge of orbital debris characteristics in order to predict future collisions and potentially take action to avoid them.

Table 39. Summary of Level 5.7 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
5.0 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	Goals:	Increase performance and efficiency in the systems that provide communications, navigation, and orbital debris tracking and characterization capabilities for all mission classes.
Level 2		
5.7 Orbital Debris Tracking and Characterization	Sub-Goals:	Maintain detailed knowledge of orbital debris characteristics in order to predict future collisions and potentially take action to avoid them.

Table 39. Summary of Level 5.7 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
5.7.1 Tracking Technologies	Objectives:	Maintain detailed knowledge of orbital debris characteristics in order to predict future collisions and potentially take action to avoid them.
	Challenges:	Increasing output power, size of effective aperture, and bandwidth.
	Benefits:	Increases capability to identify and track orbital debris thus increasing the number of items identified and the ability to track smaller sizes.
5.7.2 Characterization Technologies	Objectives:	Provide a better understanding of the orbital debris and prediction of potential effects upon orbital assets.
	Challenges:	No challenges identified.
	Benefits:	Allows better understanding of the orbital debris and prediction of potential effects upon orbital assets.

TA 5.7.1 Tracking Technologies

Tracking systems are the key to locating orbital debris, and both radio and optical frequency systems are used to track orbital debris. The RF systems are active (e.g., radars) and the key to their performance is driven by the effective isotropic radiated power, bandwidth, and beamwidth. Range and Doppler are the two key radiometric observables needed. In the optical domain, the key tracking metrics are angular location and rate of change in angle against the background star field—driven by the "gain" of the optical system and ability to "see" the debris.

Technical Capability Objectives and Challenges

Ground-based radars will benefit from greater output power, larger effective aperture, and increased bandwidth. This includes the development of 500-kilowatt (kW) X-band klystrons with 120 MHz bandwidth for upgrading current systems. The development of such high power klystrons and their associated high voltage power supplies are challenging due to their unique nature and the "art" of design. An array of 12 meter antennas can also provide high-power uplinking at Ka-band, where much more bandwidth is available. The key challenge here is the ability to maintain uplink coherence through the atmospheric turbulence that is much more pronounced at Ka-band than at lower frequencies.

Benefits of Technology

These technologies will greatly increase the ability to identify and track orbital debris, increasing the number of items identified and the ability to track smaller sizes.

Table 40. TA 5.7.1 Technology Candidates – not in priority order

TA	Technology Name	Description
5.7.1.1	High-Power Wideband X-Band Klystron	High-power wideband X-band klystron.
5.7.1.2	Ka-Band Objects Observation and Monitoring	A ground-based phased array of widely separated antennas operating in the Ka-band that can provide both high range and spatial resolution.

TA 5.7.2 Characterization Technologies

Characterization of orbital debris takes the information from the tracking systems and transforms it into a "picture" of the spatial distribution of the debris and predictions of how the orbital debris "cloud" will evolve with time. These characterizations rely upon very precise models taking into account all of the forces acting upon the debris.

Technical Capability Objectives and Challenges

This TA develops the models and algorithms to take input from tracking sensors and fuse them into the ability to predict current and future orbital characteristics, such as size distribution and orbits versus time. The fundamental challenges are the development of software that can handle larger quantities of data from better tracking systems, better physical models of the large quantities of debris and do it all efficiently for reduced runtime.

Benefits of Technology

These technologies will allow better understanding of the orbital debris and prediction of potential effects upon orbital assets.

Table 41. TA 5.7.2 Technology Candidates – not in priority order

TA	Technology Name	Description
5.7.2.1	Improved Modeling	Improved modeling of orbital debris characteristics, such as orbits, size, and density.

Appendix

Acronyms

3D	Three-Dimensional
ALHAT	Autonomous Landing and Hazard Avoidance Technology
AoA	Angle of Arrival
AR&D	Automated Rendezvous and Docking
BP	Bundle Protocol
BSP	Bundle Security Protocol
CFLOS	Cloud Free Line of Sight
CGR	Contact Graph Routing
CMOS	Complementary Metal-Oxide-Semiconductor
DC	Direct Current
DIMM	Differential Image Motion Monitor
DOR	Differential One-way Ranging
DPS	Deep-space Position System
DPSK	Differential Phase Shifting Key
DSAC	Deep-Space Atomic Clock
DSN	Deep-Space Network
DTN	Disruption (or Delay) Tolerant Networking
EIRP	Effective Isotropic Radiated Power
EKF	Extended Kalman Filter
EO-1	Earth Observing-1
EVA	ExtraVehicular Activity
FDIR	Failure Detection, Isolation, and Recovery
FDM	Frequency Division Multiplexing
FOG	Fiber Optic Gyro
FOV	Field Of View
FPGA	Field-Programmable Gate Array
GEO	Geosynchronous Earth Orbit
GN&C	Guidance, Navigation, and Control
GPS	Global Positioning System
GPU	Graphical Processing Unit
GSSR	Goldstone Solar System Radar
HEMT	High Electron-Mobility Transistor
HEO	High-Earth Orbit
IMU	Inertial Measurement Unit
IP	Internet Protocol
IR	InfraRed
IRU	Inertial Reference Unit

ISL	Inter-Satellite Links
ISS	International Space Station
ITU	International Telecommunication Union
IVA	Intra-Vehicular Activity
LADEE	Lunar Atmosphere and Dust Environment Explorer
LCRD	Laser Communications Relay Demonstration
LEO	Low-Earth Orbit
LEGEND	LEO-to-GEO ENvironment Debris
LIDAR	LIght Detection And Ranging
LKF	Linear Kalman Filter
LLCD	Lunar Laser Communications Demonstration
LRO	Lunar Reconnaissance Orbiter
LTP	Licklider Transmission Protocol
MEMS	Micro-Electrical Mechanical System
MESFET	MEtal-Semiconductor Field Effect Transistor
MIMO	Multiple-Input Multiple-Output
MMIC	Monolithic Microwave Integrated Circuit
MPCV	Multi-Purpose Crew Vehicle
MRO	Mars Reconnaissance Orbiter
MSP	MilliSecond Pulsar
MTTF	Mean Time To Failure
MU-MIMO	Multi-User Multiple Input Multiple Output
MXS	Modulated X-ray Source
NEA	Near-Earth Asteroid
NEO	Near-Earth Object
NICER	Neutron star Interior Composition ExploreR
OCT	Office of the Chief Technologist
ORDEM	ORbital Debris Engineering Model
OSIRIS-REx	Origins Spectral Interpretation Resource Identification Security – Regolith Explorer
PA	Power Amplifier
PAT	Pointing, Acquisition, and Tracking
PFF	Precise Formation Flying
PNT	Position, Navigation, and Timing
PPM	Pulse-Position Modulation
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QKD	Quantum Key Distribution
QoS	Quality of Service
R&D	Research and Development
RF	Radio Frequency
RFIC	Radio Frequency Integrated Circuits
ROIC	ReadOut Integrated Circuit

SCaN	Space Communications and Navigation
SCPPM	Serially Concatenated Pulse Position Modulation
SDR	Software-Defined Radio
SLS	Space Launch System
SNR	Signal-to-Noise Ratio
SOA	State Of the Art
SPHERES	Synchronized Position Hold, Engage, Reorient, Experimental Satellites
SPKF	Sigma Point Kalman Filter
SQUID	Superconducting QUantum Interference Device
SQIF	Superconducting Quantum Interference Filter
SSA	Space Situational Awareness
SSPA	Solid State Power Amplifier
STEM	Science, Technology, Engineering, and Mathematics
STIP	Strategic Technology Implementation Plan
SWaP	Size, Weight, and Power
TA	Technology Area
TABS	Technology Area Breakdown Structure
TAG	Touch And Go
TDM	Time Division Multiplexing
TDRSS	Tracking and Data Relay Satellite System
TEI	Trans-Earth Injection
TRL	Technology Readiness Level
TRN	Terrain Recognition Navigation
TWTA	Traveling Wave Tube Amplifier
UHF	Ultra High Frequency
U.S.	United States
UWB	Ultra WideBand
VLBI	Very Long Baseline Interferometry
XCOM	X-ray COMmunications
XNAV	X-ray NAVigation

Abbreviations and Units

Abbreviation	Definition
%	Percent
AU	Astronomical Unit
b/s/Hz	bits per seconds per Hertz
cm	Centimeter
cm^3	Cubic centimeters
dB	Decibel
dBi/K	Decibels-isotropic per Kelvin
dBW	Decibel Watt
DE	Detection Efficiency
deg	Degrees
g	Acceleration normalized to Earth surface gravity
GaAs	Gallium Arsenide
GaN	Gallium Nitride
GB	Gigabyte
Gb/s	Gigabit per second
Gbits/W	Gigabits per Watt
GHz	GigaHertz
G/T	Gain-to-noise-Temperature
InGaAs	Indium Gallium Arsenide
K	Kelvin
kb/s	Kilobits per second
kg	Kilogram
kg/m^2	Kilograms per square meter
km	Kilometer
krad	Kilorad
kW	KiloWatt
lbm	Pounds mass
m	Meter
M	Million
MB	Megabyte
Mb/s	Megabit per second
MHz	MegaHertz
μm	Micrometer
μs	Microsecond
mm	Millimeter
MP	Megapixel
mrad	Milliradian

Abbreviation	Definition
MW	MegaWatt
mW	MilliWatt
NbN	Niobium Nitride
nm	Nanometer
nrad	Nanoradian
ps	Picosecond
R	Radial distance
s or sec	Seconds
TB	Terabyte
Tb/s	Terabit per second
W	Watt
WSi	Tungsten Silicide

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Technology Candidate Snapshots

5.1 Optical Communications and Navigation
5.1.1 Detector Development

5.1.1.1 Tungsten Silicide (WSi) Photon Counting Detector Array

TECHNOLOGY

Technology Description: Tungsten Silicide (WSi) large-area superconducting nanowire single photon counting detector array.

Technology Challenge: Fabrication yield and material physics are challenges.

Technology State of the Art: Medium format free-space-coupled array.

Parameter, Value:
160 x 160 micron 64 pixel array;
40% detector efficiency (DE);
100 ps jitter;
< 3 dB saturation loss at 0.4 Gigaphotons/sec

TRL 3

Technology Performance Goal: Free-space-coupled photon counting detector for PPM 16-128 for 12 meter telescope.

Parameter, Value:
640 x 640 micron 256 pixel array;
70% DE;
50 ps jitter;
< 3 dB saturation loss at 2.0 Gigaphotons/sec

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Photon counting arrays for ground receivers.

Capability Description: Provide large active area, low jitter, high detection efficiency, low dark-count, high saturation rate detector array operating in the 1.0-1.5 micron band for multi-meter telescopes for Gb/s data rates.

Capability State of the Art: Multi-mode fiber coupled photon counting detector for PPM 16 (Lunar Laser Communications Demonstration) 62 micron diameter.

Parameter, Value:
62 x 62 μm, 16 pixel array at 155 Mb/s;
100 ps jitter, 60% DE;
< 10 kHz dark count rate;
< 3 dB saturation loss at 0.1 Gigaphotons/sec

Capability Performance Goal: Match atmospheric blurred spot of > 10 meter optical ground receivers. Support multi-GHz modulation formats. Reduce spacecraft transmitter power and mass requirements. Support daytime operations and multi-GHz modulation formats.

Parameter, Value:
1 mm area;
< 50 ps jitter;
> 80 DE;
< 1 MHz dark count;
< 3 dB saturation loss at 5 Gigaphotons/sec

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.1 Optical Communications and Navigation
5.1.1 Detector Development

5.1.1.2 Indium Gallium Arsenide (InGaAs) Flight Photon Counting Detector Array

TECHNOLOGY

Technology Description: Indium Gallium Arsenide (InGaAs) kilopixel radiation-tolerant photon counting detector array.

Technology Challenge: Reducing avalanche volume and stray capacitance is a challenge.

Technology State of the Art: 32 x 32 radiation-tolerant flight photon counting array.

Parameter, Value:

~1 Megaphoton/pixel with < 1 dB saturation ~300 ps jitter 32 x 32 array size;

~40% detection efficiency;

~5 krad tolerant

TRL: 4

Technology Performance Goal: High-flux, 128 x128 radiation-tolerant flight photon counting array.

Parameter, Value:

> 10 Megaphoton/pixel with < 1 dB saturation;

< 150 ps jitter;

> 128 x 128 array size;

> 40% detection efficiency;

> 10 krad tolerant

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Photon counting detector arrays for flight receivers.

Capability Description: Provide high flux capable radiation-tolerant flight photon counting array for uplink beacon tracking and communications.

Capability State of the Art: None

Parameter, Value:

Not applicable

Capability Performance Goal: High-rate uplink communications rates. Precision pointing of the terminal. Precision ranging.

Parameter, Value:

100 Mb/s uplink data rates;

Sub-microradian pointing < 1 centimeter precision ranging at interplanetary ranges.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	2 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.1 Optical Communications and Navigation
5.1.2 Large Apertures

5.1.2.1 Virtual, Large, Ground-Based Apertures

TECHNOLOGY

Technology Description: Arrays of smaller telescopes to provide a larger equivalent aperture.

Technology Challenge: Minimizing synchronization loss between multiple apertures and quasi-static piston compensation for > 100 Mb/s data rates are challenges.

Technology State of the Art: Lunar Laser Communications Demonstration (LLCD) ~ 1 meter effective aperture ground terminal.

Parameter, Value: | **TRL**
Effective aperture: 1 meter | 6

Technology Performance Goal: > 10 meter effective aperture.

Parameter, Value: | **TRL**
Effective aperture: 10 meter | 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low-cost receiver apertures.

Capability Description: Provide equivalent > 10 meter diameter ground receiver aperture at lower cost than single segmented mirror telescope, low loss synchronizaton between multiple receivers.

Capability State of the Art: LLCD ~ 1 meter effective aperture ground terminal.

Parameter, Value:
Effective aperture: 1 meter

Capability Performance Goal: > 10 meter effective aperture.

Parameter, Value:
Effective aperture: 10 meter

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	4 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.1 Optical Communications and Navigation
5.1.2 Large Apertures

5.1.2.2 Lightweight, Space-Based, Large Aperture Optics

TECHNOLOGY

Technology Description: Lightweight space-based large aperture optics.

Technology Challenge: Achieving an extreme reduction in mass for large aperture using thin membranes is a challenge.

Technology State of the Art: Laboratory concepts.

Parameter, Value:	TRL
~1 meter class segments	3

Technology Performance Goal: Multiple meter-class segments forming complete aperture.

Parameter, Value:	TRL
Aperture: 10 meter; Mass: 100 kilograms	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: > 10 meter diameter orbital receiver aperture.

Capability Description: Provide equivalent > 10 meter diameter ground receiver aperture at lower cost than ground based single segmented mirror telescope. For optical communications—not necessarily requiring diffraction limited performance.

Capability State of the Art: James Webb Space Telescope: 6.5 meter aperture.

Parameter, Value:

Aperture: 6.5 meter

Mass: 705 kilograms

Capability Performance Goal: 10 meter lightweight aperture.

Parameter, Value:

Aperture: 10 meter

Mass: < 100 kilograms

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Later Discovery Program	Enhancing	--	2029	2026	9 years

5.1 Optical Communications and Navigation
5.1.2 Large Apertures

5.1.2.3 Space-Based Optical Arrays

TECHNOLOGY

Technology Description: Arrays of optical telescopes to provide larger equivalent aperture.

Technology Challenge: Combining signals from multiple apertures with minimal synchronization loss and precision formation flying to eliminate data rate limits from piston errors are challenges.

Technology State of the Art: Ground-based.	TRL	Technology Performance Goal: Space-based.	TRL
Parameter, Value: Number of telescopes: 4; Aperture: ~1 meter	2	**Parameter, Value:** Number of telescopes: 100; Aperture: ~10 meters	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Lightweight, small, space-based telescopes, and alignment capability.

CAPABILITY

Needed Capability: > 10 meter diameter equivalent orbital receiver aperture.

Capability Description: Provide equivalent > 10 meter diameter space receiver aperture at lower cost than single mirror telescope. For optical communications—not necessarily requiring diffraction limited performance.

Capability State of the Art: Ground-based.	Capability Performance Goal: Space-based.
Parameter, Value: Number of telescopes: 4; Aperture: ~1 meter	**Parameter, Value:** Number of telescopes: 100; Aperture: ~10 meters

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Later Discovery Program	Enhancing	--	2029	2026	9 years

5.1 Optical Communications and Navigation
5.1.3 Lasers

5.1.3.1 High Direct Current (DC)-Optical Efficiency, Space-Qualified Pulse-Position Modulation (PPM) Laser Transmitter

TECHNOLOGY

Technology Description: Laser transmitter for photon efficiency communications at deep-space ranges.

Technology Challenge: In-band pumping; efficient pump laser diode development; fiber damage mitigation; and parts selection, radiation, and packaging (including thermal design) are all challenges.

Technology State of the Art: Thermal-Vac tested PPM laser amplifier.

Parameter, Value:

4 W average power, 640 W peak power;

2 GHz modulation bandwidth;

~10% efficient

TRL: 5

Technology Performance Goal: PPM laser transmitter suitable for 0.3 Gb/s at 0.4 A.U. throught 22 centimeter transmit aperture.

Parameter, Value:

4 W average power, 640 W peak power;

> 20% DC-optical efficiency;

> 20,000 hours mean time to failure (MTTF)

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Efficient 1.5 μm space qualified pulse-position modulation (PPM) laser transmitter.

Capability Description: 1.5 μm space qualified PPM laser transmitter with equivalent or higher (> 20% direct current-optical) efficiency than present 1.06 μm lasers; need > 2 GHz modulation bandwidth, 5 to 20 W average power, > 1 kW peak power.

Capability State of the Art: PPM laser transmitter suitable for 622 Mb/s at 0.003 A.U. through 10.8 centimeter transmit aperture.

Parameter, Value:

0.5 W average power, 8 W peak power;

5 GHz modulation bandwidth;

~10% efficient

Capability Performance Goal: PPM laser transmitter suitable for 1 Gb/s at 1 A.U. through 40 centimeter transmit aperture.

Parameter, Value:

20 W average power, 3,200 W peak power;

> 20% DC-optical efficiency;

> 50,000 hours MTTF

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	2 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.1 Optical Communications and Navigation
5.1.3 Lasers

5.1.3.2 Outer Planet/Oort Cloud Laser Transmitter

TECHNOLOGY

Technology Description: Laser transmitter for multi-Mb/s communications beyond Saturn.

Technology Challenge: Nonlinear damage thresholds are a challenge.

Technology State of the Art: Pulse-position modulation (PPM) laser transmitter suitable for 622 Mb/s at 0.003 A.U. through 10.8 centimeter transmit aperture.

Parameter, Value:	TRL
0.5 W average power, 8 W peak power; 5 GHz modulation bandwidth; ~10% efficient	2

Technology Performance Goal: MW outer planets transmitter.

Parameter, Value:	TRL
1 MW peak power, > 100 W average power with data modulation capability	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Outer planets laser transmitter.

Capability Description: kW average power, MW peak power, low average duty cycle laser transmitter to avoid 1 / R^4 loss regime.

Capability State of the Art: PPM laser transmitter suitable for 622 Mb/s at 0.003 A.U. through 10.8 centimeter transmit aperture.

Parameter, Value:

0.5 W average, 8 W peak;

5 GHz modulation bandwidth;

~10% efficient

Capability Performance Goal: MW outer planets transmitter.

Parameter, Value:

1 MW peak power, > 100 W average power with data modulation capability;

1 Mb/s at 100 A.U.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	5 years

5.1 Optical Communications and Navigation
5.1.4 Acquisition and Tracking

5.1.4.1 Disturbance-Free Platform

TECHNOLOGY

Technology Description: Non-contact isolation of laser terminal from spacecraft disturbances.

Technology Challenge: Low-mass/power inertial reference unit (IRU) mechanisms for active softening and Earth-based performance verification are challenges.

Technology State of the Art: Active-passive, low-frequency vibration isolation platform with low break frequency.

Parameter, Value: 0.3 Hz break frequency

TRL: 4

Technology Performance Goal: Very low break frequency for low-mass payloads capable of surviving launch.

Parameter, Value:
0.1 Hz effective break frequency;
5 to 20 kilogram payload;
> 35 g root mean square launch vibration specification

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Vibration isolation platform.

Capability Description: Decrease receive and transmit beam jitter; increase beacon tracking range.

Capability State of the Art: IRU used in Lunar Laser Communications Demonstration flight terminal.

Parameter, Value: 4 Hz break frequency

Capability Performance Goal: Very low break frequency.

Parameter, Value: 0.1 Hz break frequency

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	2 years
Planetary Flagship: Europa	Enhancing	---	2022*	2019	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.1 Optical Communications and Navigation
5.1.4 Acquisition and Tracking

5.1.4.2 Autonomous High-Accuracy Star Tracker

TECHNOLOGY

Technology Description: Highly accurate, advanced celestial attitude determination technology.

Technology Challenge: Faster acquisition time through higher resolution detectors.

Technology State of the Art: Multiple-head star trackers and distributed processing units.

Parameter, Value:	TRL
0.2 arc-second capability, but at 120 W and 25 kilograms	5

Technology Performance Goal: The technology's goal is to achieve 0.1 arc-seconds for utilization with large instrumentation and optical communications apertures.

Parameter, Value:	TRL
0.1 arc-seconds, less than 10 W and under 5 kilograms	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Beaconless optical pointing.

Capability Description: Provide the ability to resolve attitude at 0.1 arc-seconds for the purpose of precision attitude determination and optical communications beam pointing without relying upon an uplink beacon from Earth.

Capability State of the Art: 0.2 arc-second capability, but at 120 W and 25 kilograms.

Parameter, Value:

Angular resolution to 0.2 arc seconds

Capability Performance Goal: Increased autonomy and intelligence in spacecraft attitude determination.

Parameter, Value:

0.1 arc-seconds, less than 10 W and under 5 kilograms

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	5 years

5.1 Optical Communications and Navigation
5.1.5 Atmospheric Mitigation

5.1.5.1 Solar Differential Image Motion Monitor (DIMM)

TECHNOLOGY

Technology Description: Daytime atmospheric optical channel characterization.

Technology Challenge: Reproducible, low-cost, accurate differential image motion measurement for daytime application.

Technology State of the Art: Optical propagation studies are limited to weather-based statistics for cloud free line of sight (CFLOS) and some surface-based turbulence measurements at specific sites. Lack of data for full optical channel characterization.

Parameter, Value:
Turbulence: 5 centimeters

TRL 4

Technology Performance Goal: Need to fully characterize attenuation and wavefront errors due to daytime atmospheric channel.

Parameter, Value:
Turbulence: 2 centimeters

TRL 5

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Need to fully characterize attenuation and wavefront errors (scintillation, irradiance, etc.) due to daytime atmospheric channel.

Capability Description: Provide characterization of propagation effects on optical links through the atmosphere provides the capability to design high reliability Earth-space optical communications systems.

Capability State of the Art: CFLOS statistics, surface turbulence measurements, and local weather data are currently used to predict minimal set of atmospheric effects for optical systems.

Parameter, Value:
Ground-based characterization of turbulence effects, CFLOS statistics.

Capability Performance Goal: Characterize daytime atmospheric effects on the optical channel, including phase front distortions, Gaussian beam shape deformations, and particulate effects (such as sand and dust) on optical links.

Parameter, Value:
Need to fully characterize attenuation and wavefront errors due to daytime atmospheric channel.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	2 years

5.1 Optical Communications and Navigation
5.1.5 Atmospheric Mitigation

5.1.5.2 Daytime Adaptive Optics

TECHNOLOGY

Technology Description: Daytime adaptive optics for > 10 meter apertures with < 1 dB Strehl loss.

Technology Challenge: Cost effective wavefront sensing and compensation for wavefront errors.

Technology State of the Art: 1 meter class teleoscopes.

Parameter, Value:
1 meter class teleoscopes with < 1 dB Strehl loss

TRL
4

Technology Performance Goal: 10 meter class telescopes.

Parameter, Value:
10 meter class telescopes with < 1 dB Strehl loss

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Adaptive optics.

Capability Description: Mitigates atmospheric turbulence effects on optical signals; improves daytime data rates > 10 times.

Capability State of the Art: 1 meter class.

Parameter, Value:
1 meter class, < 1 dB Strehl loss

Capability Performance Goal: 10 meter class.

Parameter, Value:
10 meter class, < 1 dB Strehl loss

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	5 years

5.1 Optical Communications and Navigation
5.1.6 Optical Tracking

5.1.6.1 Embedded Optical Tracking for Spacecraft Navigation

TECHNOLOGY

Technology Description: Generate range, range-rate, delta range rate, and bearing products from optical communications link for spacecraft navigation.

Technology Challenge: Faster detector readout and time stamping in the flight terminal and kW class ground laser transmitters with ranging modulation.

Technology State of the Art: Ground-based optical ranging using giant-pulse laser and optical retroreflector ($1/R^4$ loss).

Parameter, Value:

3 centimeter precision ranging via retroreflector

TRL: 2

Technology Performance Goal: Space-based ranging using communications signal.

Parameter, Value:

Range accuracy, centimeter level

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: TA 5.1.1.2 and TA 5.4.1.1

CAPABILITY

Needed Capability: Spacecraft tracking using an optical link.

Capability Description: Generate range, range-rate, and delta range rate products from optical communications link for spacecraft navigation.

Capability State of the Art: Range, Doppler, and delta-differential one-way ranging (DOR) using radio frequency (RF) links.

Parameter, Value:

30 centimeter ranging accuracy;

1 nanoradian angular accuracy

Capability Performance Goal: Provide spacecraft tracking data products with similar or superior precision to present RF tracking data products.

Parameter, Value:

Range precision: 1 centimeter;

Sub nanoradian angular accuracy

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	2 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.1 Optical Communications and Navigation
5.1.7 Integrated Photonics

5.1.7.1 Multi-Mode Coherent Transceivers

TECHNOLOGY

Technology Description: Integrated photonics providing lasers, modulators, detectors, encoding, decoding, and electronics for coherent inter-satellite links (ISL).

Technology Challenge: Frequency/spatial mode multiplexing; flight-qualified multiple-input multiple-output (MIMO) receiver with less than a few hundred W power dissipation. Efficient operation at 1,550 nm; long-term stability (> 50,000 hours); develop receiver topology; signaling/coding/bandwidth filtering mass, pointing, and launch accomodations.

Technology State of the Art: Single-mode coherent transceivers. Narrow linewidth lasers “brick-wall” coherent receiver. Diffraction limited large aperture.

Parameter, Value:	**TRL**
5.6 Gb/s milliHertz linewidth, not flight, 1.44 bits/photon limit (heterodyne); 2.89 bits/photon limit (homodyne), 2.4 meter (Hubble)	2

Technology Performance Goal: Multi-mode flight coherent transceiver 100 Hz linewidth flight laser photon counting coherent receiver 10 meter diffraction limited flight optical transceiver aperture.

Parameter, Value:	**TRL**
100 Gb/s geosynchronous Earth orbit (GEO)-GEO < 100 Hz linewidth; > 40 W average power; > 20% direct current-optical efficiency; 5 bits/incident photon coherent receiver; 10 meter or > diameter; < 0.1 wave total optical wavefront error at 1 μm	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Coherent modulation/demodulation systems for ISL and ultimately for direct-to-Earth communications with adaptive optics receivers.

Capability Description: 10 to 100 Gb/s ISL in Earth orbit 0.1 to 1 Mb/s links to planetary orbiters.

Capability State of the Art: Earth orbiting ISL.

Parameter, Value:

1.2 Gb/s GEO (2017 NASA Laser Communications Relay Demonstration).

Capability Performance Goal: Multi-mode coherent transceivers. Deep-space coherent orbital transmitter. Deep-space coherent orbital receiver.

Parameter, Value:

40 to 1,000 Gb/s point-to-point links < 100 Hz linewidth flight lasers;

Photon counting coherent receiver > 10 meter diffraction limited apertures

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.2 Radio Frequency Communications
5.2.1 Spectrum Efficient Technologies

5.2.1.1 Advanced Interference Management

TECHNOLOGY

Technology Description: Signaling strategies (e.g., coding and signal processing) to enable multiple wireless links to operate at the same time and in same band.

Technology Challenge: Translation from theory to implementation; major hurdle is obtaining channel state information about interfering links.

Technology State of the Art: Multi-user multiple input multiple output (MU-MIMO) implemented in 802.11 ac. Full-duplex prototypes and user-cooperation prototypes demonstrated. Interference alignment demonstrated only in theory.

Parameter, Value: Spectral efficiency gain: ~2x

TRL 6

Technology Performance Goal: Comprehensive solution for interference management: including implementations of MU-MIMO, full-duplex, user cooperation, and interference alignment.

Parameter, Value: Spectral efficiency gain: ~10x

TRL 3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Many-fold increase in spectral efficiency.

Capability Description: Links that operate in same band, but resolve interference with advanced signaling strategies.

Capability State of the Art: Time division multiplexing (TDM) and frequency division multiplexing (FDM). Currently, each wireless link is allocated its own frequency band (FDM), or links share the same frequency band are operated at different times (TDM).

Parameter, Value:
Spectral efficiency: log (1 + signal-to-noise ratio (SNR)) b/s/Hz

Capability Performance Goal: Many-fold gain in spectral efficiency (e.g., 10x) by leveraging advanced signal processing to operating links at the same time and in the same frequency band.

Parameter, Value:
Spectral efficiency: 10*log (1 + SNR) b/s/Hz

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015 - 2021	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.2 Radio Frequency Communications
5.2.2 Power-Efficient Technologies

5.2.2.1 Traveling Wave Tube Amplifiers (TWTAs)

TECHNOLOGY

Technology Description: Vacuum electronics-based helical traveling-wave tube amplifier.

Technology Challenge: Availability of materials, precision manufacturing, and assembling of parts are challenges.

Technology State of the Art: Ka-band TWTA with higher output power, higher efficiency, and reduced mass.

Parameter, Value:

TWTA output power: 400 W at Ka-band.

TRL 3

Technology Performance Goal: Improve the TWTA efficiency and reduce the mass.

Parameter, Value:

Target efficiency is 70% to 75% and target reduction in mass by 1 kilogram (approximately a 20% reduction in mass)

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Space-qualified high-efficiency radio frequency (RF) power amplifiers (PAs).

Capability Description: Provide RF PAs that operate at NASA's communications frequencies, provide output power scalable to the mission need, high power overall efficiency, and low mass.

Capability State of the Art: TWTAs are flying on the following missions: Mars Reconnaissance Orbiter (MRO), Kepler, Lunar Reconnaissance Orbiter (LRO), etc.

Parameter, Value:

MRO:100 watts, efficiency 55% at X-band;

Kepler: 35 watts, 40% efficiency at Ka-Band;

LRO: 40 watts, 40% efficiency at K-band

Capability Performance Goal: TWTA to provide RF power for deep-space missions, with improved efficiency and reduced mass.

Parameter, Value:

TWTA output power in the range of 35 to 200 watts;

Example, TWTA output power: 200 W or higher and efficiency of 70% at Ka-band, and mass 3.5 kilograms or less

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Europa	Enabling	--	2022*	2019	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.2 Radio Frequency Communications
5.2.2 Power-Efficient Technologies

5.2.2.2 Solid-State Power Amplifiers (SSPAs)

TECHNOLOGY

Technology Description: GaAs and GaN high electron mobility transistor (HEMT) and monolithic microwave integrated circuit (MMIC) technology based SSPAs.

Technology Challenge: Electrical properties of semiconductor epitaxial layers, transistor reliability, thermal reliability, radiation hardness, packaging, and manufacturing are challenges.

Technology State of the Art: Ka-Band SSPA with higher output power, higher overall efficiency and reduced mass.

Parameter, Value:

SSPA output power: 20 to 40 watts at Ka-band

TRL 2

Technology Performance Goal: To improve the SSPA overall efficiency and reliability and also to reduce the mass.

Parameter, Value:

Target efficiency is 35% to 40% and target reduction in mass by 0.5 kilograms (approximately a 25% to 50% reduction in mass)

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Space-qualified high-efficiency radio frequency (RF) power amplifiers (PAs).

Capability Description: Provide RF PAs that operate at NASA's communications frequencies, provide output power scalable to the mission need, high power, added efficiency, and low mass.

Capability State of the Art: SSPAs are flying on the following missions: Deep-Space One, Solar Dynamic Observatory, and Juno.

Parameter, Value:

Deep-Space One: 2.7 watts, efficiency 15% at Ka-band.

Solar Dynamic Observatory: 2.5 watts, efficiency 14% at Ka-band.

Juno: 2.5 watts at Ka-band carrier only, for gravity science

Capability Performance Goal: SSPA to provide RF power for near-Earth and deep-space missions, with improved overall efficiency and reduced mass.

Parameter, Value:

SSPA output power of 10 watts for near-Earth and 40 watts for deep-space missions;

Efficiency of 35% or higher at Ka-band;

Mass including modulator, digital control circuits, and interface board: 1.0 kilograms or less for a 10 watt amplifier and 2.0 kilograms or less for a 40 watt amplifier

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Precision and All-Weather Temperature and Humidity (PATH)	Enhancing	--	2024*	2019	4 years
Earth Systematic Missions: Climate Absolute Radiance and Refractivity Observatory (CLARREO)	Enhancing	--	2021*	2016	4 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.2 Radio Frequency Communications
5.2.3 Propagation

5.2.3.1 Low-Earth Orbit (LEO) Ka-Band Propagation Studies

TECHNOLOGY

Technology Description: Studies of Ka-band propagation as they apply to low-Earth orbiting satellites for system design margins.

Technology Challenge: Many fast tracking ground stations (e.g., 1 meter-class antenna) need to be installed at various Earth locations to obtain enough passes for meaningful, long term beacon data for a low-Earth orbit (LEO) spacecraft beacon. Requires Ka-band beacon on LEO payload.

Technology State of the Art: LEO propagation studies are limited to short passes, and often during non-meaningful times of the day, resulting in lack of statistically significant data.

Parameter, Value:
Total known cumulative ground station data collected for LEO propagation is approximately 30 days for a specific site.

TRL
6

Technology Performance Goal: Characterize enough events to separate atmospheric and orbital dynamics effects to obtain statistically significant models for the design of high reliability LEO communications systems.

Parameter, Value:
Total cumulative ground station data collection for LEO propagation should be one-year minimum for a specific site.

TRL
9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Need to develop understanding of LEO propagation parameters which currently are lacking.

Capability Description: Characterizing propagation effects at Ka-band on LEO paths through the atmosphere provides the capability to design high reliability Earth-space LEO communications systems.

Capability State of the Art: Currently, geosynchronous Earth orbit (GEO) propagation statistics at Ka-band are used to predict atmospheric effects for LEO systems.

Parameter, Value:
Total cumulative ground station data collected for LEO propagation is approximately 30 days for a specific site.

Capability Performance Goal: Characterize enough events to separate atmospheric and orbital dynamics effects to obtain statistically significant models for the design of high reliability LEO communications systems.

Parameter, Value:
Station-years of data: 1 year minimum.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Earth Systematic Missions: Lidar Surface Topography (LIST)	Enhancing	--	2024*	2019	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.2 Radio Frequency Communications
5.2.5 Earth Launch and Re–entry Communications

5.2.5.1 Mitigation of Reentry Plasma Effects

TECHNOLOGY

Technology Description: Maintain radio frequency (RF) communications to re-entering vehicles during one of the most critical portions of an exploration mission.

Technology Challenge: Implement a conformal antenna within a variable magnetic field to create RF 'windows' in the reentry plasma.

Technology State of the Art: Electrophilic injection into flow field and aerodynamic shaping.

Parameter, Value:
No dynamic control over implementation during reentry.

TRL 4

Technology Performance Goal: Eliminate the RF blackout phenomena induced by the reentry plasma by a dynamic and high control fidelity implementaton process.

Parameter, Value:
Maintain communications and navigation of a re-entering vehicle throughout the entire and general dynamic reentry environment.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Space-qualified robust RF blackout mitigation methodology for vehicle reentry.

Capability Description: Provide RF blackout mitigation methodology that operates at NASA's communications and global positioning system (GPS) frequencies, and minimize implementation overhead through low mass and large conversion efficiency to create and adjust magnetic field.

Capability State of the Art: No benchmark has been established.

Parameter, Value:
No benchmark has been established.

Capability Performance Goal: Completely eliminate reentry induced RF blackout.

Parameter, Value:
Maintain RF communicatios throught entire mission lifetime.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	4 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	4 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	4 years

5.2 Radio Frequency Communications
5.2.6 Antennas

5.2.6.1 Deployable Antennas

TECHNOLOGY

Technology Description: ≥ 5 meter diameter deployable mesh or shape memory polymer microwave reflectors.

Technology Challenge: Needs flight demonstration to reduce risk.

Technology State of the Art: Ka-band deployable mesh reflectors in development; Ka-band shape memory polymer antennas in development, but lagging mesh technology.

Parameter, Value:	TRL
60% efficiency at Ka-band for a 5 meter mesh reflector	5

Technology Performance Goal: Surface accuracy to enable Ka-band operation and reliable deployment and shape accuracy.

Parameter, Value:	TRL
Diameter: > 5 meter; Efficiency: > 60%; Aerial density: < 1 kg/m^2	3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Space-qualified deployable antennas.

Capability Description: 5 to 20 meter class lightweight and highly efficient deployable antennas capable of operation at Ka-band and higher frequencies.

Capability State of the Art: Large deployable antennas for geostationary satellite commercial communications are well established at and below Ku-band; 4.75 meter radial rib mesh reflector was used on Galileo mission (suffered deployment anomaly); 14 meter inflatable membrane antenna experiment is on satellite Spartan-207.

Parameter, Value:

12 meter L-band, 5 meter Ku-band;

60% efficiency at and below Ku-band

Capability Performance Goal: High reliability, low mass, and large aperture capable of Ka-band operation.

Parameter, Value:

Efficiency: > 60%;

Aerial density: < 1 kg/m^2

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	2 years
Discovery: Discovery 14	Enhancing	--	2023	2020	2 years

5.2 Radio Frequency Communications
5.2.6 Antennas

5.2.6.2 Phased Array Antennas

TECHNOLOGY

Technology Description: Electronic beam steering.

Technology Challenge: ~30% efficient monolithic microwave integrated circuits (MMICs); leverage commercial applications and economy of scale to reduce cost; novel architectures to alleviate thermal management issues (e.g., reflect arrays).

Technology State of the Art: Large format phased arrays available for aeronautical applications.

Parameter, Value:

Aeronautical phased array antenna: Transmit 29.5 – 31.0 GHz Receive 19.7 – 21.2 GHz effective isotropic radiated power

(EIRP) @ boresight: 49.6 dBW EIRP @ 65 deg: 45.6 dBW gain-to-noise-temperature (G/T) @ boresight: 8.3 dBi/K G/T @ 65 deg: 41 dBi/K

TRL 4

Technology Performance Goal: High cost (> $1,000/element) and low efficiency (10 to 15%) hinders insertion of phased array technology into NASA missions. Also, poor efficiency causes thermal management problems.

Parameter, Value:

Array Efficiency: > 20%;

Cost down to < $100 per element

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Space-qualified large aperture phased array antennas.

Capability Description: Vibration-free beam steering/no moving parts, multiple independent beams/multiple access, adaptive beam profile/adaptive nulling, graceful degradation, and essentially instantaneous beam slewing/repositioning.

Capability State of the Art: Earth Observing-1 (EO-1) X-Band Array and Messenger X-Band Array. Phased array antenna installed on the Orion Multi-Purpose Crew Vehicle. Commercial Ka-Band Transmit Array.

Parameter, Value:

EO-1 X-Band Array; 64 elements; 105 Mb/s 22 dBW EIRP @ 60 deg; 8.225 GHz Size: 33 cm x 30 cm x 7 cm;

Messenger X-Band Array: 8 slotted waveguide elements; 8.432 GHz Scan Range: ±45 deg one-dimension;

Ka-band Transmit Array: 1,500 elements, 24 simultaneous beams dual-pole operation 20 μs beam hopping rate 3 arrays in orbit

Capability Performance Goal: Higher efficiency and lower cost.

Parameter, Value:

Array Efficiency: > 20%;

Cost down to < $100 per element

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Gravitational Wave Surveyor Mission	Enhancing	--	2035*	2035	5 years
Strategic Missions: CMB Polarization Surveyor Mission	Enhancing	--	2035*	2035	5 years
Strategic Missions: Far Infrared Surveyor Mission	Enhancing	--	2035*	2035	5 years
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enhancing	--	2035*	2030	5 years
Strategic Missions: X-ray Surveyor Mission	Enhancing	--	2035*	2030	5 years
Strategic Missions: Exoplanet Direct Imaging Mission	Enhancing	--	2030*	2025	5 years
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enhancing	--	2024*	2020	5 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Earth Systematic Missions: Three-Dimensional Tropospheric Winds from Space-based Lidar (3D Winds)	Enhancing	--	2030*	2025	5 years
Solar Terrestrial Probes: Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)	Enhancing	--	2025	2021	5 years
Solar Terrestrial Probes: Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI)	Enhancing	--	2032	2030	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.2 Radio Frequency Communications
5.2.6 Antennas

5.2.6.3 Atmospheric Phase Compensation for Uplink Arrays at Ka-Band

TECHNOLOGY

Technology Description: Compensation of atmospheric turbulence effects to maximize transmit power of ground based arrays.

Technology Challenge: Minimum detectable phase necessary for Ka-band compensation versus X-band compensation 4 times higher. Deep-space missions may require non-active form of atmospheric phase sensing.

Technology State of the Art: Atmospheric phase compensation has been demonstrated in real-time at X-band with a downlink signal present, but not yet at Ka-band and not without an active downlink signal.

Parameter, Value:
Operational frequency: 8.4 GHz

TRL 6

Technology Performance Goal: Achieve real-time phase compensation at Ka-band to allow for next generation uplink array communications systems.

Parameter, Value:
Operational frequency: 32 GHz

TRL 3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Need to develop this capability to operate at Ka-band.

Capability Description: Systems that can detect and compensate in real-time the effects of atmospheric turbulence on transmit signals from ground-based arrays at Ka-band.

Capability State of the Art: Real-time atmospheric phase compensation using downlink signals has been successfully demonstrated at X-band frequencies.

Parameter, Value:
Operational frequency: 8.4 GHz

Capability Performance Goal: Achieve real-time phase compensation at Ka-band to allow for next generation uplink array communications systems.

Parameter, Value:
Operational frequency: 32 GHz

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enabling	--	2024*	2020	3 years
Earth Systematic Missions: Snow and Cold Land Processes (SCLP)	Enabling	--	2024*	2019	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.2 Radio Frequency Communications
5.2.6 Antennas

5.2.6.4 Small-Satellite Distributed Multiple Input Multiple Output (MIMO)

TECHNOLOGY

Technology Description: Distributed communications architecture based on deployment of MIMO antenna arrays on multiple small satellites.

Technology Challenge: Frequency and time synchronization of multiple satellite transceivers. Data distribution and cooperation among multiple distributed nodes. Ability to accurately estimate channel state in presence of significant orbital dynamics and latency due to range.

Technology State of the Art: Distributed MIMO systems deployed in some terrestrial long term evolution cell phone networks. Multiple base stations cooperate to perform MIMO beamforming to multiple mobile users simultaneously. Mobile users do not cooperate on transmission.

Parameter, Value: Current performance parameters based on reliance on optical point-to-point systems for all high-data-rate communications at long ranges.

TRL: 1

Technology Performance Goal: Demonstrate multiple Gb/s MIMO space-to-ground link from at least geosynchronous Earth orbit (GEO). Demonstrate stable channel tracking and node synchronization for both frequency and time across network. Demonstrate significant cost reduction over point-to-point equivalent capability.

Parameter, Value: Synchronization of distributed satellite nodes to less than reciprocal bandwidth in time and 0.1% in frequency. Real-time channel tracking.

TRL: 2

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low-cost, reliable, high-data-rate local area networks in deep-space communications.

Capability Description: Low-cost, energy-efficient, scalable, fault-tolerant, high-data-rate communications support for single-hop and planetary relay communications over cislunar and greater ranges.

Capability State of the Art: High-data-rate communications currently provided with point-to-point radio frequency (RF) links using high-power amplifiers and high-gain dish antennas on satellite and very large dish antennas at ground station. High data rates are typically dependent on zero redundancy deployable reflectors and tight surface tolerances. Full capability usually has to be deployed at one time.

Parameter, Value:
Very high cost and relatively low energy efficiency for high-data-rate communications. Single-point of failure at either end of link. Difficulty with pointing tolerances. Difficult to scale current systems for different applications.

Capability Performance Goal: High data-rate communications provided by a constellation of small satellites with low-power amplifiers and small antennas. Performance degrades gracefully. Data rate and antenna size scale easily for mission-specific applications. Incremental development, deployment, and evaluation are possible.

Parameter, Value:
20 Gb/s from 1 A.U. and 3 Tb/s from low-Earth orbit (LEO);

Reduction of 75% in transponder mass;

80% reduction in life cycle costs from current levels;

Retain 80% performance with one complete element failure at either end of link

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years

5.2 Radio Frequency Communications
5.2.6 Antennas

5.2.6.5 Conformal, Low-Mass Antenna Systems

TECHNOLOGY

Technology Description: Conformal, low mass antenna systems.

Technology Challenge: Space-qualified materials, designs, and techniques for creating conformal, low mass antenna systems that may have a time-varying aperture shape.

Technology State of the Art: Single element and multi-element antennas created from flexible circuits and e-textile antennas.

Parameter, Value:	TRL
Mass reduction: ~2x Throughput performance: ~2x	6

Technology Performance Goal: Antenna elements constructed with less volumetric and mass impact to the surrounding systems; enabling higher performance antenna systems to be fielded.

Parameter, Value:	TRL
Mass reduction: ~10x Throughput performance: ~10x	3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: To develop lower-mass antenna systems that more easily integrate into flight systems.

Capability Description: Antennas with an aperture surface that more easily integrates with the surrounding flight system. These systems may be textile or flexible in nature, e.g., multi-layer-insulation, spacesuits, or inflatable structures. These structures may have time-varying surface shape properties.

Capability State of the Art: Conventional antenna systems manufactured to match the shape of the surrounding system. This may be done through either the antenna elements themselves conforming to the antenna platform shape or the radome matching the surrounding system shape.

Parameter, Value:

Mass: 1 to 20 lbm;

Data throughput: 1 to 50 Mb/s

Capability Performance Goal: Ability to create antennas that have a reduced volumetric and mass footprint to the flight system, enabling possibly larger apertures to be used as a result, and may employ techniques to automatically correct for the effects of a possibly time-varying aperture shape.

Parameter, Value:

Mass: 0.1 to 1 lbm;

Data throughput: 10 Mb/s to 1 Gb/s

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015 - 2021	3 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years

5.2 Radio Frequency Communications
5.2.6 Antennas

5.2.6.6 Antenna Array Architecture Enablers

TECHNOLOGY

Technology Description: Radio frequency (RF) components, beamformers, and algorithms for enabling antenna arrays.

Technology Challenge: Space-qualified antenna arrays and related technologies continue to be one of the most expensive space systems to develop in terms of both resources and time, yet the architecture and implementation of these systems is typically the enabling component for particular applications in communications and navigation. Advances in several areas will enable significantly more capable antenna systems to be fielded including: lower cost, ideally commodity RF hardware to enable larger antennas; space-qualified array architectures and components that enable multiple-user access and adaptive digital beamforming and null steering; algorithms for improving the performance of multiple-input multiple-output (MIMO) and other multi-antenna communications and navigation systems; and techniques to conduct in-situ characterization and calibration of multi-antenna systems.

Technology State of the Art: MIMO systems, digital beamformed arrays, conventional phased arrays, and multiple aperture combining for received arrays.

Parameter, Value:
Implementation and integration cost reduction: ~2x;
Throughput performance: ~2x

TRL
6

Technology Performance Goal: Order of magnitude increase in data throughput and order of magnitude reduction in development and integration costs.

Parameter, Value:
Implementation and integration cost reduction: ~10x;
Throughput performance: ~10x

TRL
3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Game-changing advances in component technologies that enable significant advances in achievable antenna array performance and enable alternate, higher-performance architectures to be used. Multiple antenna aperture combining.

Capability Description: To develop higher-performance antenna systems in terms of lower cost implementations, higher efficiency designs, correct manufacturing errors, and leverage algorithms that make more efficient use of a single or multiple antenna apertures employed by flight systems.

Capability State of the Art: MIMO systems, digital beamformed arrays, conventional phased arrays, and multiple aperture combining for received arrays. Some S-band and C-band commodity array systems.

Parameter, Value:
Integration and Custom Development Cost: $10 million (M) to $100 M;
Data throughput: 2 to 500 Mb/s

Capability Performance Goal: Order of magnitude reduction in implementation and integration costs, increased data throughput, greater efficiency of designs via improved components, architectures, and characterization and calibration techniques. Commoditize antenna array systems up through Ka-band

Parameter, Value:
Integration and Development Cost: < $1 M to $10 M;
Data throughput: 100 Mb/s to 10 Gb/s

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years

5.3 Internetworking
5.3.1 Disruption-Tolerant Networking

5.3.1.1 Disruption Tolerant Networking (DTN) Basic Services

TECHNOLOGY

Technology Description: Algorithms and software or firmware implementations of basic DTN services, such as Licklider Transport Protocol and Bundle Protocol.

Technology Challenge: High-speed, flight-qualified processors/field-programmable gate arrays (FPGAs). High-speed and high-volume, flight-qualified memory.

Technology State of the Art: DTN protocols were uploaded and demonstrated on the Deep Impact and Earth Observing-1 (EO-1) Missions.

Parameter, Value:

Deep Impact: 160 kb/s;

EO-1: 4 kb/s, 7 MB storage

TRL 7

Technology Performance Goal: Flight-qualified software/firmware and platforms to achieve networked communications service benefits to flight platforms.

Parameter, Value:

Flight platform: flight-qualified hardware (not internal to the International Space Station, or ISS);

Data rate: 300 Mb/s deep-space / 10 Gb/s near-Earth;

Data storage: > 14 TB

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Robust networking.

Capability Description: Provides networked communications in environments with long delay and/or disrupted links.

Capability State of the Art: DTN services are being implemented for operational use on the ISS.

Parameter, Value:

Flight platform: commercial-off-the-shelf (COTS) laptop;

Data rate: 70 Mb/s;

Data storage: up to 150 GB

Capability Performance Goal: Flight-qualified software/firmware and platforms to achieve networked communications service benefits to flight platforms.

Parameter, Value:

Flight platform: flight qualified hardware (not internal to ISS);

Data rate: 300 Mb/s Deep-space / 10 Gb/s near-Earth;

Data storage: > 14 TB

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 Years
Into the Solar System: DRM 5 Asteroid Redirect — Crewed in DRO	Enhancing	2022	2022	2015 - 2021	3 Years

5.3 Internetworking
5.3.2 Adaptive Network Topology

5.3.2.1 Ad Hoc and Mesh Networking of Mobile Elements

TECHNOLOGY

Technology Description: Algorithms for establishment of ad hoc and mesh networks for coordinated communications among mobile elements.

Technology Challenge: Establishment of networks under space application constraints (speed of light delays, data rate asymmetry, etc.) is a challenge.

Technology State of the Art: ISS onboard wireless local area network (802.11n).

Parameter, Value:
Number of users: few;
Data rate: up to 63 Mb/s;
Coverage: local

TRL 9

Technology Performance Goal: Ad hoc establishment of high data rate interconnectivity between many individual nodes.

Parameter, Value:
Number of users: many 10s;
Data rate: Gb/s aggregate;
Coverage: wide area

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Robust networks for mobile user elements.

Capability Description: Provides unplanned coordinate timing, position, and spacing within the operational needs of human and robotic missions by mobile elements.

Capability State of the Art: Any International Space Station examples (Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES) or Wireless).

Parameter, Value:
Number of users: few;
Data rate: up to 63 Mb/s;
Coverage: local

Capability Performance Goal: Ad hoc establishment of high data rate interconnectivity between many individual nodes.

Parameter, Value:
Number of users: many 10s;
Data rate: up to 10 Gb/s aggregate;
Coverage: wide area

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	4 years

5.3 Internetworking
5.3.2 Adaptive Network Topology

5.3.2.2 Disruption Tolerant Networking Routing

TECHNOLOGY

Technology Description: Adaptive routing in disruptive networks to enable discovery of resources and adapt to failures to form routes expanding connectivity coverage and increasing end-to-end capacity and latency performance.

Technology Challenge: Conceiving routing algorithms suitable for the space mission environment (delays, disruption, mission design constraints).

Technology State of the Art: Contact graph routing (CGR) accounts for predictable dynamics but not for unpredicted events. CGR does adapt to variations in offered traffic, but not to unplanned communications capabilities.

Parameter, Value:	TRL
Unpredicted events and capability: not able to handle in real-time	2

Technology Performance Goal: Convergence time to determine successful routes.

Parameter, Value:	TRL
Determined by mission need. Unpredicted events and capability: able to handle in real-time	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Adaptive routing algorithms.

Capability Description: Adaptive routing in disruptive networks – discovery of resources and adapt to failures to form routes expanding connectivity coverage and increasing end-to-end capacity and latency performance.

Capability State of the Art: Capability does not exist.

Parameter, Value:
Improved resource utilization (storage, power, availability) and reachability (ability to reach endpoint due to contact discovery).

Capability Performance Goal: Enable 20+ node networks of power constrained or link constrained elements. Ability to provide reliable data transfer with unplanned outages and possible additions of networked nodes.

Parameter, Value:
20 nodes, low power, adaptive

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	4 years

5.3 Internetworking
5.3.2 Adaptive Network Topology

5.3.2.3 Disruption Tolerant Networking Quality of Service

TECHNOLOGY

Technology Description: Extensions of differentiated services.

Technology Challenge: Conceiving quality of service (QoS) algorithms suitable for the space mission environment.

Technology State of the Art: Basic marking of traffic class exists, but protocols for QoS handling are very limited.

Parameter, Value: Simple node based queuing.

TRL 2

Technology Performance Goal: Network-level process for capturing distinct characterization among traffic types.

Parameter, Value: Determined by mission need.

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Quality of service algorithms.

Capability Description: Methods to distinguish traffic according to timeliness, importance, and robustness, and queueing and routing protocols maximizing performance based on QoS metrics.

Capability State of the Art: Simple, strict priority assignment and data handling.

Parameter, Value:
QoS maps to fixed levels of priority; aggregate service level performance measure of throughput, latency by requirement for each class.

Capability Performance Goal: Guarantees critical information return during degraded or otherwise constrained mission scenarios.

Parameter, Value:
3+ classes of data having different service level requirements.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	4 years

5.4 Position, Navigation, and Timing
5.4.1 Timekeeping and Time Distribution

5.4.1.1 Trapped Mercury Ion Clock (DSAC)

TECHNOLOGY

Technology Description: High-stability clock based upon microwave interrogation of high-Q mercury trapped ion "filter."

Technology Challenge: Trap tube fabricability and lamp lifetime are challenges as well as miniaturization of electronics.

Technology State of the Art: Being developed for 1 year flight demonstration with local quartz ultra-stable oscillator (USO)—Deep Space Atomic Clock (DSAC).

Parameter, Value:	TRL
DSAC demo ~16 liters, ~16 kg, 1.5×10^{-13} short term, $<3 \times 10^{-15}$ stability floor.	6

Technology Performance Goal: Reduce size and mass. Increase operational lifetime.

Parameter, Value:	TRL
<5 liter, <10 kg, same performance for near term deep space navigation application. Various size, weight, and power (SWaP) stability performance trades for other infusion scenarios.	7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Stable, reliable, and long life space clocks.

Capability Description: Provide space-qualified high frequency stability at long time intervals. Technology can be operated with traditional quartz USO or other advanced local oscillators (LO's) (e.g. photonic/comb based LO's).

Capability State of the Art: Laboratory and ground clocks at frequency stability floor level of $2\text{-}3 \times 10^{-16}$. Short term stability $< 10^{-14}$ demonstrated with advanced LO's.

Parameter, Value:

Laboratory based standards operating in a metrology laboratory environment.

Capability Performance Goal: Long-term stability of 10^{-15} for near-term NASA infusion with a quartz LO. Order of magnitude SWaP, short, and long term stabilities possible for other applications.

Parameter, Value:

Deployable in deep space spacecraft, liter size, kg mass.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Europa	Enhancing	--	2022*	2019	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.4 Position, Navigation, and Timing
5.4.1 Timekeeping and Time Distribution

5.4.1.2 Trapped Ion Optical Clocks

TECHNOLOGY

Technology Description: High-stability clock based upon optical interrogation of high-Q trapped ytterbium ion "filter."

Technology Challenge: Miniaturization of trap tube, laser stabilization, and optical comb is a challenge.

Technology State of the Art: Laboratory feasibility demonstration.

Parameter, Value:	TRL
Laboratory room-sized and high power	2

Technology Performance Goal: Reduce size while improving stability performance.

Parameter, Value:	TRL
Liters: 2; Kilograms: 2; Same performance	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Space clocks.

Capability Description: Provide space-qualified, high-stability, and high-accuracy frequency standards both at short term and long term, and both radio frequency (RF) and optical signals.

Capability State of the Art: Laboratory demonstration—not space.

Parameter, Value:
10^{-17} stability floor, 1×10^{-15} better short-term stability.

Capability Performance Goal: Short term 1×10^{-14}, with 10^{-16} stability floor in space.

Parameter, Value:
Deployable in deep-space spacecraft, < 10 liter size, < 10 kilogram mass.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	5 years

5.4 Position, Navigation, and Timing
5.4.1 Timekeeping and Time Distribution

5.4.1.3 Cold Atom Lattice Optical Clocks

TECHNOLOGY

Technology Description: High-stability clock based upon holding cold atoms in a dipole lattice trap during optical interrogation.

Technology Challenge: Laser robustness, comb robustness, and system integration are challenges.

Technology State of the Art	TRL	Technology Performance Goal	TRL
Technology State of the Art: Laboratory demonstrations. **Parameter, Value:** Short term 1×10^{-16}, with 10^{-18} stability floor	3	**Technology Performance Goal:** Reduce size and mass, and mature base technologies. **Parameter, Value:** Cubic meter, 100 kilogram mass	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Space clocks.

Capability Description: Provide space-qualified, high-stability, and high accuracy frequency standards both at short-term and long-term, and both radio frequency (RF) and optical signals.

Capability State of the Art	Capability Performance Goal
Capability State of the Art: Laboratory demonstration. **Parameter, Value:** 10^{-18} stability floor, 10^{17} accuracy	**Capability Performance Goal:** Short term 1×10^{-16}, with 10^{-18} stability floor. **Parameter, Value:** Deployable on the International Space Station

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enabling	--	2020	2017	3 years
Planetary Flagship: Europa	Enabling	--	2022*	2019	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.4 Position, Navigation, and Timing
5.4.2 Onboard Auto Navigation and Maneuver

5.4.2.1 Low-Thrust Trajectory Optimization in a Multi-Body Dynamical Environment

TECHNOLOGY

Technology Description: Algorithms and software for efficient preliminary and high-fidelity design and optimization of low-thrust trajectories in a multi-body dynamical environment.

Technology Challenge: Low-Thrust trajectory design is complex with a very large design space. It is difficult to efficiently search that design space to determine optimal low-thrust trajectories, especially in multi-body dynamical regimes.

Technology State of the Art: Exploration of a portion of the preliminary design space can be done with a very labor intensive process. Furthermore, high fidelity optimization is slow and limited to a very narrow range of solutions based on the preliminary design efforts.

Parameter, Value:
1x

TRL
2

Technology Performance Goal: 100x improvement in exploration efficiency of mission trajectory design options.

Parameter, Value:
100x improvement in mission trajectory design options.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced mission design: low-thrust trajectory optimization.

Capability Description: Improved low-thrust algorithms and software will significantly enhance overall mission capability, enabling future missions to compute multi-revolution spiral trajectories, exploit multi-body dynamics, and fully investigate the wide range of design options. This is useful for planetary orbiter missions, outer planet tour design, and libration point mission design, among others.

Capability State of the Art: Currrent capabilities are not designed to compute multi-revolution spiral trajectories in a full dynamical model, nor can it exploit multi-body dynamics, which are indispensible for studies in moon and outer planet tours as well as libration point missions.

Parameter, Value:
Limited investigation of multi-body and other complex trajectories

Capability Performance Goal: Significantly enhance low-thrust trajectory design capability by allowing designers to enforce new mission critical constraints while optimizing alternative objectives . Enable design of more ambitious low-thrust missions. Reduce computation time. Increase efficiency of searching broad design space. Vastly reduce computation time.

Parameter, Value:
100x improvement in mission trajectory design options

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	2 years
Discovery: Discovery 14	Enhancing	--	2023	2020	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	2 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	2 years
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.4 Position, Navigation, and Timing
5.4.2 Onboard Auto Navigation and Maneuver

5.4.2.2 Fault-Resistant, High Performance Navigation Architectures

TECHNOLOGY

Technology Description: Fault-resistant, high-performance navigation architectures using advanced dissimilar sensor navigation failure detection, isolation, and recovery (FDIR) for error detection from robust, high-performing sensors.

Technology Challenge: Developing high-performing navigation systems that use all types of sensors in real-time is a challenge.

Technology State of the Art: Need to use all available sensors, including sensors with high bandwidth and large amounts of data.

Parameter, Value: | **TRL**

Need the ability to take sensors off-line autonomously or bring them on-line when certain conditions are met. This can be considered advanced FDIR. | 6

Technology Performance Goal: Use of high bandwidth sensors in real-time onboard navigation systems.

Parameter, Value: | **TRL**

Real-time high-bandwidth navigation systems. | 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Autonomous navigation architectures.

Capability Description: Provides navigation system performance independent of communications with the ground.

Capability State of the Art: Need to use all available sensors, including sensors with high bandwidth and large amounts of data.

Parameter, Value:

Architectures are either single or double rate group (inertial measurement unit and other sensors).

Capability Performance Goal: Use of high bandwidth sensors in real-time onboard navigation systems.

Parameter, Value:

Real-time high-bandwidth navigation systems.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.4 Position, Navigation, and Timing
5.4.2 Onboard Auto Navigation and Maneuver

5.4.2.3 Onboard Trajectory Planning and Optimization Algorithms

TECHNOLOGY

Technology Description: Neural net trajectory planning; genetic algorithm-based trajectory planning.

Technology Challenge: Robust real-time trajectory optimization on a flight computer is a challenge.

Technology State of the Art: Current trajectory optimization/planning algorithms are unwieldy and are not configured for use on flight computers; this function is done on the ground.

Parameter, Value:
Since this is done on the ground with powerful computers, the time to perform the mission planning is small. It needs to work on a target flight processor and generate feasible mission plans and converge within 60 seconds.

TRL
2

Technology Performance Goal: Demonstrate trajectory optimization software on a flight computer.

Parameter, Value:
Optimized trajectory that meets constraints and converges in less than 60 seconds.

TRL
7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Autonomous planning and optimization algorithms.

Capability Description: Plan and optimize trajectories onboard during loss of communications with the ground.

Capability State of the Art: This technology is not currently available for use on flight computers.

Parameter, Value:
Currently done on the ground; Jet Propulsion Laboratory developed Autonav but it had limited capability.

Capability Performance Goal: Demonstrate trajectory optimization software on a target flight computer.

Parameter, Value:
Optimized trajectory (delta-V, constraints satisfied).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	4 years
Discovery: Later Discovery Program	Enabling	--	2026	2023	3 years

5.4 Position, Navigation, and Timing
5.4.2 Onboard Auto Navigation and Maneuver

5.4.2.4 Advanced Onboard Navigation Algorithms

TECHNOLOGY

Technology Description: Gaussian mixture model-based estimation; mulitple-model estimation, sigma point Kalman filters, cauchy-based filters.

Technology Challenge: Large state filters require significant computational resources.

Technology State of the Art: Current technology is either extended Kalman filter (EKF)- or Linear Kalman Filter (LKF)-based.

Parameter, Value:
Current technology is EKF- or LKF-based. Need Multiple Model Filters and Gaussian Mixture Models Filters that work on current processors. Currently, there are no such filter architectures available.

TRL
6

Technology Performance Goal: Filters that are not exclusively based on linear system theory and are capable of handling a large number of non-linear states. Examples of these types of filters include: advanced Gaussian mixture models-filters, mutiple-model filters, sigma point Kalman filter (SPKF), and nonlinear filters.

Parameter, Value:
Large-state (> 20 states) nonlinear filters

TRL
7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Nonlinear estimation for navigation.

Capability Description: No capability.

Capability State of the Art: Current, technology is either EKF- or LKF-based.

Parameter, Value:
Few-state (< 20) EKF and LKF.

Capability Performance Goal: Advanced EKF, multiplicative extended Kalman filter, SPKF, and nonlinear filters.

Parameter, Value:
Large-state nonlinear filters.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	2 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.4 Position, Navigation, and Timing
5.4.2 Onboard Auto Navigation and Maneuver

5.4.2.5 Onboard Real-Time Mission Re-Sequencing

TECHNOLOGY

Technology Description: Onboard maneuver planning and sequencing algorithms.

Technology Challenge: Real-time planning and sequencing on a flight computer using a real-time operating system is a challenge.

Technology State of the Art: In case of loss of communications with the ground, Orion has designed specialized trans-Earth injection (TEI), lunar orbit insertion algorithms.

Parameter, Value:	**TRL**
Orion currently has the ability to retarget midcourse maneuvers autonomously and operate on stored sequence; it can't re-sequence autonomously.	5

Technology Performance Goal: Robust onboard planning and sequencing.

Parameter, Value:	**TRL**
Real-time onboard planning and sequencing on a flight computer with a real-time operating system.	7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Autonomous crew return.

Capability Description: Plans and executes maneuver targeting algorithms onboard during loss of communications with the ground.

Capability State of the Art: Current technology relies on the ground to perform maneuver planning and execution.

Parameter, Value:

No current capability. Need to re-sequence activities to achieve the objective of returning crew to Earth.

Capability Performance Goal: Robust onboard planning and sequencing.

Parameter, Value:

Real-time onboard planning and sequencing on a flight computer with a real-time operating system.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	2 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.4 Position, Navigation, and Timing
5.4.2 Onboard Auto Navigation and Maneuver

5.4.2.6 Autonomous Outer Planet Tour Navigation

TECHNOLOGY

Technology Description: Techniques and algorithms for estimating and controlling spacecraft trajectories in outer planet satellite tours, based on data derived and computations performed onboard.

Technology Challenge: In-situ navigation measurements need to be identified and efficient techniques for processing them onboard need to be developed.

Technology State of the Art: Academic papers exist on this topic.

Parameter, Value: Position accuracy (value varies) — **TRL** 2

Technology Performance Goal: Validation using Cassini (or similar) navigation configuration.

Parameter, Value: Position accuracy (value varies) — **TRL** 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Autonomous outer planet tour navigation.

Capability Description: Algorithms and sensors that allow outer planet tour navigation to be performed onboard in autonomous fashion.

Capability State of the Art: Navigation is ground-based.

Parameter, Value:
10 kilometer flyby altitude uncertainty

Capability Performance Goal: Elimination of round-trip light time delay; increased accuracy of flight path estimation and control; reduced reliance on Deep-Space Network (DSN) tracking before and during critical operations.

Parameter, Value:
100 meter flyby altitude uncertainty

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	3 years

5.4 Position, Navigation, and Timing
5.4.2 Onboard Auto Navigation and Maneuver

5.4.2.7 Advanced Deep-Space Trajectory Design Techniques

TECHNOLOGY

Technology Description: Advanced deep-space trajectory design techniques.

Technology Challenge: Future missions may be enabled or benefit from new trajectory types that are more complicated and/or involve more complicated environments.

Technology State of the Art: Current software tools can find and optimize sequences of high-energy transfers; and given an initial design can optimize lower energy trajectories and low-thrust trajectories.

Parameter, Value:

Simulation runtime: days per simulation

TRL: 6

Technology Performance Goal: Highly accurate and efficient trajectory design techniques for deep-space missions involving continuous low-thrust propulsion; multi-body gravitational interactions; multiple vehicles; or travel in close proximity to small bodies with irregular gravitational fields.

Parameter, Value:

Simulation runtime: minutes per simulation

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: New efficient general software tools for designing new types of trajectories.

Capability Description: New software tools for designing planetary mission trajectories for each of the following trajectory types: multiple encounter tours, flight in close proximity to small bodies, multiple spacecraft, low-energy transfers, and continuous low thrust.

Capability State of the Art: Capabilities exist at some level, but lack speed and fidelity.

Parameter, Value:

Multiple parameters, such as, number of encounters, number of bodies, proximity, etc., as well as execution speed—currently days to weeks

Capability Performance Goal: Faster, more accurate trajectory generation.

Parameter, Value:

Multiple parameters, such as, number of encounters, number of bodies, proximity, etc., as well as execution speed—hours desired

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years

5.4 Position, Navigation, and Timing
5.4.2 Onboard Auto Navigation and Maneuver

5.4.2.8 Deep-Space Positioning System (DPS)

TECHNOLOGY

Technology Description: A compact, low-mass, low-power hardware and software system capable of performing deep-space autonomous navigation for robotic and human missions virtually anywhere in the solar system.

Technology Challenge: Challenges include developing high-sensitivity optical and radiometric measurements with robust autonomous navigation algorithms in a reusable low size, weight, and power (SWaP) package for deep-space navigation.

Technology State of the Art: Individual optical and radiometric sensors with custom interfaces to flight avionics.

Parameter, Value:	TRL
Custom hardware and software interfaces between sensors and avionics	9

Technology Performance Goal: High-performance, low-SWaP, reusable system with low recurring and operations costs.

Parameter, Value:	TRL
< 10 kilograms, < 30 Watts, < 30 x 30 x 30 centimeters; Simple position and delta-V vector interface to flight avionics; Navigation operations cost reductions ~50%	7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Provide the equivalent of global positioning system (GPS) throughout the solar system, to enable missions that cannot be done with ground-in-the-loop and provide robust, safe return for human deep-space missions.

Capability Description: Single flight unit that produces kilometer-level onboard orbit determination and targeting (absolute and target relative) anywhere in the solar system without ground-in-the-loop.

Capability State of the Art: Autonomous navigation demonstrations on Stardust and Deep Impact missions.

Parameter, Value:

Kilometer-level onboard orbit determination for small body flyby and impact missions

Capability Performance Goal: Autonomous navigation combining optical and radiometric measurements to provide onboard position determination and targeting anywhere in the solar system.

Parameter, Value:

Kilometer-level onboard orbit determination and targeting anywhere in the solar system

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015 - 2021	2 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	2 years

5.4 Position, Navigation and Timing
5.4.2 Onboard Auto Navigation and Maneuver

5.4.2.9 High Rate Spacecraft Guidance, Navigation, and Control (GN&C)

TECHNOLOGY

Technology Description: A highly capable spacecraft GN&C system capable of accurately controlling a spacecraft during rendezvous phase with an uncooperative target with high relative velocities.

Technology Challenge: Develop a GN&C system that can efficiently guide, navigate, and control spacecraft motion in all phases of flight, especially high relative motion proximity operations.

Technology State of the Art: Proximity operations today support a SOA of ~0.24 degrees per second relative motion between vehicles.

Parameter, Value:

In order to support the high relative velocity rendezvous and proximity operations necessary for some missions, it is necessary for the GN&C to refresh at a rate of at least 50 Hz.

TRL: 2

Technology Performance Goal: A need exists to improve, by up to two orders of magnitude, the characterization and navigation capabilities of the GN&C to 25 degrees per second without compromising accuracy.

Parameter, Value:

Existing SOA is limited to extremely slow approach rates and low relative motion. Limited by refresh rates of onboard computing and capabilities of the GN&C and supporting sensors.

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Improved relative motion sensor technology, improved onboard computing capability, improved vehicle attitude and position control effectors, and improved algorithms for operations of the GN&C system.

CAPABILITY

Needed Capability: An accurate and efficient GN&C system capability of extremely accurate attitude and position maneuvers at high rates for modern, nimble spacecraft.

Capability Description: Provide rendezvous targeting and proximity operations navigation information for an uncooperative and high relative motion target to the GN&C system of a spacecraft.

Capability State of the Art: Recently flown sensors, capable of only the proximity operations portion of the mission, have had refresh rates of ~15 Hz.

Parameter, Value:

0.24 degrees per second relative motion

Capability Performance Goal: The required GN&C system must be capable of operating in all phases of flight, including rendezvous, navigation, and proximity operations. The update rate must be at least 50 Hz.

Parameter, Value:

25 degrees per second relative motion

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015 - 2021	2 years

5.4 Position, Navigation, and Timing
5.4.3 Sensors and Vision Processing Systems

5.4.3.1 Improved Deep Space Network (DSN) Radiometric Data

TECHNOLOGY

Technology Description: Improvement of deep-space tracking systems and calibrations to yield more accurate, robust, and timely Doppler, ranging, and interferometric tracking data.

Technology Challenge: Equipment and atmospheric/ionospheric/tropospheric calibration.

Technology State of the Art: Current DSN radiometrics.

Parameter, Value:

2 to 10 millimeters per second for Doppler data, 2 to 10 meters for range data, and 2 nrad for delta-differential one-way ranging (DOR) data.

TRL: 6

Technology Performance Goal: Improved radiometric tracking.

Parameter, Value:

1 millimeter per second for Doppler data, 1 meter for range data, and 1 nrad for delta-DOR data.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Improved DSN radio metric data.

Capability Description: One-way and two-way DSN radio metric tracking data of higher accuracy, after calibration.

Capability State of the Art: Two-way Doppler and range data are obtained by DSN tracking of planetary spacecraft; delta-DOR data are sometimes collected and processed.

Parameter, Value:

2 to 10 millimeters per second for Doppler data, 2 to 10 meters for range data, and 2 nrad for delta-DOR data.

Capability Performance Goal: Increased tracking data accuracy, allowing more accurate flight path estimation and control and reduced operations workforce.

Parameter, Value:

1 millimeter per second for Doppler data, 1 meter for range data, and 1 nrad for delta-DOR data.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years

5.4 Position, Navigation, and Timing
5.4.3 Sensors and Vision Processing Systems

5.4.3.2 Optimetric Data for Navigation

TECHNOLOGY

Technology Description: Data types derived from an optical communications signal that are analogous to or improve upon tracking techniques using communications signals' microwave frequencies.

Technology Challenge: Synchronous time measurements in an asynchronous receiver pulse position modulation (PPM).

Technology State of the Art: Laboratory demonstration.

Parameter, Value: Range accuracy of 30 centimeters

TRL 2

Technology Performance Goal: Ranging accuracy with space qualifiable system.

Parameter, Value: Range accuracy of 30 centimeters or better

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Optimetric data for navigation.

Capability Description: Metric tracking data at optical frequencies for deep-space missions, analogous to radio metric tracking data.

Capability State of the Art: Two-way Doppler and range data and delta- differential one-way ranging (DOR) data are obtained by Deep Space Network (DSN) tracking of planetary spacecraft at radio frequencies.

Parameter, Value: 1 to 5 meter radio frequency ranging

Capability Performance Goal: Increased tracking data accuracy at substantially higher transmission frequencies.

Parameter, Value: Range accuracy of 30 centimeters or better

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years

5.4 Position, Navigation, and Timing
5.4.3 Sensors and Vision Processing Systems

5.4.3.3 Miniature, High-Accuracy, Multi-Function Star Tracker

TECHNOLOGY

Technology Description: Celestial attitude and orbital object detection sensor.

Technology Challenge: Production of next generation imager and real-time celestial navigation processing is a challenge.

Technology State of the Art: Commercial inertial compass algorithms.

Parameter, Value: 14 bits intensity, 1280 x 1280 resolution

TRL: 2

Technology Performance Goal: High accuracy, low size, weight, and power (SWaP).

Parameter, Value: 2 arcsec attitude accuracy, < 1 kilogram, < 500 cm^3, < Magnitude 9 orbital object brightness

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced complementary metal-oxide-semiconductor (CMOS) star tracker that can track orbital objects, beacons, or illuminated retro-reflectors.

Capability Description: Next generation CMOS imagers and high performance radiation-tolerant field-programmable gate arrays (FPGAs) enable compact, accurate star trackers to track and rendezvous with orbital debris or spacecraft on a CubeSat budget and SWaP.

Capability State of the Art: Star trackers are larger and heavier than majority of CubeSats or Class D Experiment Quality and reliability.

Parameter, Value: Custom charge-coupled devide or obsolete CMOS imager with older processors; simple star algorithms: 0.1 degree accuracy, 1 Hz.

Capability Performance Goal: Miniature star tracker to fit in CubeSats.

Parameter, Value:
Accuracy: < 0.01 degree;
Volume: 200 cm^3

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	2 years
Discovery: Discovery 14	Enhancing	--	2023	2020	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	2 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	2 years
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.4 Position, Navigation, and Timing
5.4.3 Sensors and Vision Processing Systems

5.4.3.4 Fast Light Optical Gyroscopes for Precision Inertial Navigation

TECHNOLOGY

Technology Description: Enhanced-performance optical gyroscopes.

Technology Challenge: Integration of optical bench breadboard into a dead-band-free diode pumped alkali ring laser gyroscope flight unit is a challenge.

Technology State of the Art: Current gyroscopes exhibit higher drift rates without self-alignment or external updates.

Parameter, Value:
Compact, accurate, and stable laser diode and a passive cavity gyroscope with temperature controlled atomic vapor cell.

TRL 3

Technology Performance Goal: High accuracy, low size, weight, and power (SWaP).

Parameter, Value:
< 0.005 degrees per hour

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-accuracy optical gyroscopes.

Capability Description: Compact frequency-stable laser diode combine with atomic vapor cell can increase the angular rate sensitivity of a ring laser gyro by a scale factor of S = 85.

Capability State of the Art: Various micro-electrical mechanical system (MEMS) and fiber optic gyroscopes do not have the sensitivity or lack of moving parts.

Parameter, Value:
0.5 degrees per hour

Capability Performance Goal: Integrated passive cavity or active cavity (ring gyro modules).

Parameter, Value:
Low size, weight, and power module that operates in typical space environments with breadboard performance levels.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	2 years
Discovery: Discovery 14	Enhancing	--	2023	2020	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface mission (DRA 5.0)	Enhancing	2033	--	2027	2 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	2 years
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.4 Position, Navigation, and Timing
5.4.4 Relative and Proximity Navigation

5.4.4.1 Optical-Navigation-Grade Cameras

TECHNOLOGY

Technology Description: Optical-navigation-grade cameras that can be used as sensors for onboard autonomous navigation.

Technology Challenge: Challenges include developing large-pixel cameras with global shutters tolerant to radiation.

Technology State of the Art: Advanced cameras and light detection and ranging (LIDAR).

Parameter, Value: Current optical navigation cameras are rolling shutters. Need high-resolution (> 10 MP) cameras with global shutters.

TRL: 5

Technology Performance Goal: Large detectors with global shutters.

Parameter, Value: 10 MP cameras with global shutters.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced sensors for onboard autonomous navigation.

Capability Description: Provides advanced relative and absolute navigation sensors.

Capability State of the Art: Camera-based optical navigation and LIDAR (flash and scanning).

Parameter, Value: Optical cameras: 5 to 10 MP

Capability Performance Goal: Large detectors with global shutters.

Parameter, Value: Global shutters with 10 MP cameras

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.4 Position, Navigation, and Timing
5.4.4 Relative and Proximity Navigation

5.4.4.2 High-Resolution Infrared Cameras

TECHNOLOGY

Technology Description: High-resolution infrared (IR) cameras that can be used as sensors for onboard autonomous navigation.

Technology Challenge: Achieving higher resolution is a challenge.

Technology State of the Art: Advanced visible cameras and light detection and ranging (LIDAR).

Parameter, Value: Current IR cameras are low resolution.

TRL 4

Technology Performance Goal: Advanced IR cameras.

Parameter, Value: Need IR cameras > 5 MP

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced sensors for onboard autonomous navigation.

Capability Description: Provides advanced relative and absolute navigation sensors.

Capability State of the Art: Camera-based optical navigation and LIDAR (flash and scanning).

Parameter, Value: 0.3 to 1 MP

Capability Performance Goal: Non-cryogenic, high-resolution digital IR cameras.

Parameter, Value: > 5 MP, uncooled

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.4 Position, Navigation, and Timing
5.4.4 Relative and Proximity Navigation

5.4.4.3 Flash Light Detection and Ranging (LIDAR), Scanning LIDARs

TECHNOLOGY

Technology Description: Rendezvous LIDARs and landing LIDARs.

Technology Challenge: Need to improve per-pixel range and accuracy; increase size of scan; and enable high dynamic range of detector/ readout integrated circuit (ROIC) assembly.

Technology State of the Art: Numerous commercial and government applications, but no NASA space experience.

Parameter, Value:

Commercial scanners: < 2 kilometers, 10 to 100 minute scan.

TRL 3

Technology Performance Goal: Photon sensitive detector and ROIC.

Parameter, Value:

Range of operation: 20 kilometers to < 1 meter;

Range accuracy: < 1 centimeter, 1 to 2 second scan

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: LIDARs for relative navigation.

Capability Description: The mecury cadmium telluride detector and associated ROIC; InGaAs detector scanning LIDARs with highly accurate range.

Capability State of the Art: Commercial Sensor:

Range of operation: 1.5 kilometer to < 1 meter,

Range accuracy: < 0.5 meters

Parameter, Value:

1.5 kilometer, not eye-safe

Capability Performance Goal: 512 x 512 detector and ROIC

Parameter, Value:

Range of operation: 20 kilometer to < 1 meter;

Range accuracy: < 1 centimeter

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.4 Position, Navigation, and Timing
5.4.4 Relative and Proximity Navigation

5.4.4.4 High Performance Light Detection and Ranging (LIDAR)

TECHNOLOGY

Technology Description: Improved performance in LIDARs as sensors for onboard autonomous navigation.

Technology Challenge: Flash LIDARs with large field of view (FOV) and good performance at long and short ranges. Commercial Flash LIDAR.

Technology State of the Art	TRL	Technology Performance Goal	TRL
Technology State of the Art: Advanced cameras and LIDARs.		**Technology Performance Goal:** Large FOV, commercial Flash LIDAR.	
Parameter, Value: LIDARs (scanning and flash) (128 x 128 and 256 x 256)	5	**Parameter, Value:** > 512 x 512 pixel flash LIDARs	7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced sensors for onboard autonomous navigation.

Capability Description: Provides advanced relative and absolute navigation sensors.

Capability State of the Art	Capability Performance Goal
Capability State of the Art: Camera-based optical navigation and LIDAR (flash and scanning).	**Capability Performance Goal:** Large FOV, long range. The commercial sensor is a technology that needs development; has potential for increased sensitivity (dynamic range), increased range accuracy, and longer range of operation.
Parameter, Value: LIDARs (scanning and flash) (128 x 128 and 256 x 256)	**Parameter, Value:** > 512 x 512 pixel flash LIDARs

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.4 Position, Navigation, and Timing
5.4.5 Autonomous Precision Formation Flying

5.4.5.1 Rapid Trajectory Design Near Small Bodies

TECHNOLOGY

Technology Description: Prototype software and algorithmic framework to support rapid exploration of transfer options near small bodies and close-proximity operations of small body missions.

Technology Challenge: Although some initial research has been performed to show the feasibility of this technique, work needs to be done to develop the techniques and algorithms necessary for application to a wide variety of asteroid transfer algorithms. This mid-Technology Readiness Level technology was conceived from the astrodynamics discipline.

Technology State of the Art: Manual process

Parameter, Value:
Manual process

TRL: 2

Technology Performance Goal: Trajectory computation time decreased from days to minutes.

Parameter, Value:
50x improvement in trajectory performance;
Ability to compute onboard

TRL: 2

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Algorithms for flight and ground use to enable rapid trajectory design near small bodies.

Capability Description: Recent interest in missions to small bodies has demonstrated the need for techniques to quickly design trajectories for close-proximity operations around the body. Such a capability would allow a rapid evaluation of the trade-offs between different proposed mission scenarios and enable a more thorough search of the design space. This capability will improve the overall quality of mission proposals by providing additional opportunities for science and reducing the required propellant. Once such a mission is in flight, it will allow quick redesigns for changing mission requirements.

Capability State of the Art: The design of trajectories around asteroids is often a lengthy and customized process that relies heavily on the mission designer's intuition. The process is currently long and involved, and tailored to a particular situation. Design pre-launch or re-design post-launch are done manually with substantial turn-around time.

Parameter, Value:
Manual process

Capability Performance Goal: The techniques are mission enhancing in that they will enable quicker computations of desired transfers. They are potentially mission enabling in that trajectory options that might otherwise not be considered may be found and analyzed using these techniques. In each case, the savings in terms of design time are significant. Automation based on these techniques would result in significant cost savings.

Parameter, Value:
50x improvement in trajectory performance;
Ability to compute onboard

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	2 years

5.4 Position, Navigation, and Timing
5.4.5 Autonomous Precision Formation Flying

5.4.5.2 Embedded Software Defined Radio (SDR), Antenna, and Protocol

TECHNOLOGY

Technology Description: SDR for bearing measurements to automated rendezvous and docking (AR&D) targets and to natural quasar and planetary radio frequency (RF) sources for navigation and timing.

Technology Challenge: Embedded protocol and antenna configurations to provide bearing accuracy for deep-space navigation and AR&D are challenges.

Technology State of the Art: Other government agency docking system uses a dedicated RF system with various gimbaled antennas.

Parameter, Value:
There are over 1,000 RF-emitting pulsars in mapped locations and receive frequency agile SDR concepts and units.

TRL: 4

Technology Performance Goal: Hard mounted segmented antenna and receiver to measure direction to quasars, and beacons for navigation.

Parameter, Value:
Flight demonstration of bearing measurement using fixed segmented antenna and embedded protocol in communications SDR.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: SDR systems with embedded rendezvous and quasar navigation.

Capability Description: Differential phase detection from fixed multi-element antenna enable angular bearing measurements to AR&D targets or bearings to quasars and other planetary emitters for navigation references.

Capability State of the Art: Various dedicated RF systems used for rendezvous for decades using differential signal strength measurements from gimbaled parabolic antennas.

Parameter, Value:
100s of kilometers range;
High size;
Weight;
Size;
Power

Capability Performance Goal: Embedded capability for multi-element receive antenna and embedded format protocol for direction and range within space-to-space communications.

Parameter, Value:
Low size, weight, and power module that operates in typical space environments with minimal addition to baseline spacecraft communications.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	2 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.4 Position, Navigation, and Timing
5.4.6 Autonomous Approach and Landing

5.4.6.1 Primitive Body/Lunar Proximity Operations and Pinpoint Landing

TECHNOLOGY

Technology Description: Techniques and algorithms for estimating and controlling spacecraft trajectories in proximity to the Moon or small bodies (including pinpoint landing scenarios), based on data derived and computations performed onboard.

Technology Challenge: More complex trajectory environments coupled with more stringent requirements.

Technology State of the Art: Deep Impact human-in-the-loop with limited real-time onboard processing.

Parameter, Value:
Processing: mixed human-in-the-loop and onboard

TRL 4

Technology Performance Goal: Elimination of round-trip light time delay; increased accuracy of flight path estimation and control.

Parameter, Value:
Processing: autonomous

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: New software tools for designing and optimizing primitive body/lunar proximity operations and pinpoint landing.

Capability Description: Algorithms and sensors that allow primitive body/lunar proximity operations and pinpoint landing to be performed in autonomous fashion.

Capability State of the Art: Deep Impact human-in-the-loop with limited real-time onboard processing.

Parameter, Value: Processing: mixed human-in-the-loop and onboard

Capability Performance Goal: Elimination of round-trip light time delay; increased accuracy of flight path estimation and control.

Parameter, Value:
Processing: autonomous

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years

5.4 Position, Navigation, and Timing
5.4.6 Autonomous Approach and Landing

5.4.6.2 Multi-Altitude Terrain Recognition Navigation (TRN) Sensor System

TECHNOLOGY

Technology Description: Imager, altimeter, and image processor.

Technology Challenge: Space-qualified dynamic range camera and altimeter with robust TRN algorithms for various descent profiles

Technology State of the Art: 1/3 to 2 MP cameras with simple altimeter and onboard TRN algorithms.

Parameter, Value:
Landing uncertainty of > 100 meters

TRL 4

Technology Performance Goal: Guided descent to precision landing in rugged terrain.

Parameter, Value:
Landing uncertainty circles of 100 meters

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Precision lander guidance based on Mars Reconnaissance Orbiter and Lunar Reconnaissance Orbiter terrain maps.

Capability Description: To guide a lander into the extreme terrains of Martian canyons and lunar polar craters requires adaptation and validation of cruise missile TRN for Mars and lunar missions.

Capability State of the Art: Using terrain maps from overhead images, terrestrial TRN systems fly at near-constant height and require limited image and map scalling.

Parameter, Value:
Terminal accuracy of systems is smaller than a "barn door."

Capability Performance Goal: Descending from tens of kilometers at 45 degrees to vertical descent angles and varying illumination, landing circles of hundreds of meters.

Parameter, Value:
Landing circles of hundreds of meters without mapped obstacles and varying illumination.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.5 Integrated Technologies
5.5.1 Radio Systems

5.5.1.1 Intelligent, Multipurpose Software Defined Radio (SDR)

TECHNOLOGY

Technology Description: Software-based communications and navigation functions in a reprogrammable signal processing platform that senses and adapts to link and system conditions to efficiently increase data transfer and reduce user burden.

Technology Challenge: Limited radio resources/power consumption and intermittent links make awareness of the communications system difficult. Need to develop power efficient platforms with cognitive applications and identify parameters to sense and determine how improvement is measured.

Technology State of the Art: Cognitive radios that negotiate spectrum use with other radios and learn system behavior.

Parameter, Value:
Data rate: 800 to 1,500 Mb/s;
Flexibility: programmable on-orbit;
Learned behavior: new

TRL 3

Technology Performance Goal: Develop platforms and applications (cognitive engines) that learn behavior to optimize data transfer.

Parameter, Value:
Reduce platform and system resource use

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Self-aware/cognitive radio.

Capability Description: Radios that automatically optimize their link characteristics and resources based on perceived conditions or learned behavior.

Capability State of the Art: Radio platform and applications are reprogrammable on the Space Communications and Navigation (SCaN) Testbed SDRs on the International Space Station. Adaptive (Prox-1) links used with Mars Reconnaissance Orbiter to surface rovers.

Parameter, Value:
Fully reprogrammable on-orbit (data rates of 400 Mb/s at Ka-Band). For global positioning system (GPS) applications, better than 20 meter accuracy.

Capability Performance Goal: Self reconfiguration and intelligent network management. Adaptive/cognitive modulation, coding, and data management to maximize data throughput.

Parameter, Value:
1.5 Gb/s at Ka-band, on-orbit, software-based real-time GPS orbit determination to < 10 meters

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2017	2 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	2 years
Discovery: Discovery 13	Enhancing	--	2020	2017	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.5 Integrated Technologies
5.5.2 Ultra Wideband

5.5.2.1 Ultra-Wideband Impulse Radio

TECHNOLOGY

Technology Description: Ultra-wideband impulse radio for real-time location estimation, time synchronization, and data transport.

Technology Challenge: Having different systems for tracking, time synchronization, and data transport are costly and place undue burden on a spacecraft's size, weight, and power (SWaP). Need to incorporate and integrate these functions into a single system.

Technology State of the Art: Multiple different systems to provide tracking, data communications, and time synchronization. Examples include spread-spectrum radiometrics, satellite navigation systems, and continuous-wave communications systems.

Parameter, Value: Multi-Mb/s communications, centimeter-level location accuracy, and nano-second temporal synchronization.

TRL 3

Technology Performance Goal: Low-cost and SWaP system that can provide high-data-rate communications, high-precision real-time location estimation, and high-precision time synchronization for proximity applications.

Parameter, Value: Multi-Mb/s communications, centimeter-level location accuracy, and nano-second temporal synchronization.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ultra-wideband radio.

Capability Description: Low cost, size, weight, and power system that can provide high-data-rate communications, high-precision real-time location estimation, and high-precision time synchronization for proximity applications, such as formation flying of small satellites, distributed cooperative beamforming and multiple input multiple output (MIMO) communications using small satellite constellations, surface operations in global positioning system (GPS)-deprived environments, and intra-vehicular activity (IVA) and extravehicular activity (EVA) asset tracking and telemetry transport.

Capability State of the Art: Multiple sensors, systems provide capability.

Parameter, Value: Multi-Mb/s communications, centimeter-level location accuracy, and nano-second temporal synchronization.

Capability Performance Goal: Integrated system that provides time synchronization, position location, and data transport.

Parameter, Value: Multi-Mb/s communications, centimeter-level location accuracy, and nano-second temporal synchronization.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

5.5 Integrated Technologies
5.5.3 Cognitive Networks

5.5.3.1 Automated Intelligent Networked Systems

TECHNOLOGY

Technology Description: Develop a system in which each communications node on the network is dynamically aware of the state and configuration of the other nodes to autonomously optimize their operational parameters in response to changes in user needs or environmental conditions.

Technology Challenge: Challenges include mission operations culture changes and trust in automation.

Technology State of the Art: Biologically-inspired network architectures and emulation networks have been developed and are currently being studied at the university level.

Parameter, Value:

Currently, elements of this technology are being used by commercial entities for advertising and improving system performance.

TRL: 2

Technology Performance Goal: Fully-autonomous, self-healing, adaptive, intelligent systems in operational space and ground networks.

Parameter, Value:

Reduction in system operator interaction and intervention time (cost); reduction in system processing power.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Intelligent systems and biologically-inspired algorithms.

Capability Description: Achieve optimal communications system performance while autonomously responding to dynamic changes in user needs, system security, and environmental conditions.

Capability State of the Art: Modern network systems routinely utilize rules-based algorithms to optimize system performance. Automated intelligent systems have a learning component.

Parameter, Value:

Index of autonomous functioning of the network topology;

SOA: rules based, extremely limited autonomy

Capability Performance Goal: Ability of all space and ground network nodes to be dynamically aware, self-healing, and able to autonomously act to achieve mission goals and optimize overall system performance in nominal and off-nominal conditions.

Parameter, Value:

Reduction in system operator interaction and intervention time (cost);

Reduction in system processing power

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015 - 2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

5.5 Integrated Technologies
5.5.6 Radiofrequency and Optical Hybrid Technologies

5.5.6.1 Large Aperture Combined Radio Frequency (RF)/ Optical Apertures

TECHNOLOGY

Technology Description: Develop required technology to enable ground-based large combined optical and RF apertures to utilize large infrastructure development by NASA and reduce operating costs.

Technology Challenge: Developing combined optical and RF apertures and developing optical aperture to approach 8 meters are challenges.

Technology State of the Art: Two optical panels on 34-meter antenna.

Parameter, Value: 30 centimeter optical panels — **TRL** 2

Technology Performance Goal: Minimal degradation on up to 8-meter optical telescope integrated into a 34-meter antenna.

Parameter, Value: 8 meter total aperture size — **TRL** 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Large aperture optical ground terminal for deep-space optical communications.

Capability Description: 8 meter or larger.

Capability State of the Art: Current optical communications ground apertures are in the 1 to 3 meter diameter all-optical class.

Parameter, Value: 1 to 3 meter diameter

Capability Performance Goal: Combined RF-optical aperture with ~34 meter RF aperture and > 5 meter optical aperture.

Parameter, Value: > 5 meter (ideally 8 to 10 meters) diameter optical on a 34 meter RF

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	5 years

5.6 Revolutionary Concepts
5.6.1 X-Ray Navigation

5.6.1.1 X-Ray Navigation (XNAV)

TECHNOLOGY

Technology Description: Pulsed X-ray signals from millisecond pulsars (MSPs) enable a global positioning system (GPS)-like absolute position determination to support autonomous navigation throughout the solar system and beyond.

Technology Challenge: Reduce volume and pointing constraints.

Technology State of the Art: Scalable end-to-end software and hardware-in-the-loop simulation using a modulated X-ray source (MXS) have demonstrated feasibility in high and low dynamics envrionments.

Parameter, Value:

Simulations in low-Earth orbit (LEO) with NICER sized detector show < 10 kilometer with 2 weeks of observations; interplanetary cruise show < 10 kilometer with 1/56th size NICER detector

TRL 6

Technology Performance Goal: First demonstration of real-time, onboard X-ray pulsar based navigation using the Neutron Star Interior Composition Explorer (NICER) X-ray timing instrument.

Parameter, Value:

< 10 kilometer, worst direction, with 2 weeks of valid measurements from NICER on the International Space Station.

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Onboard autonomous spacecraft navigation.

Capability Description: Autonomously determine spacecraft position anywhere in the solar system.

Capability State of the Art: Radio frequencyoptical systems with direct line-of-site, e.g., GPS and Deep Space Network (DSN).

Parameter, Value:

Tens of centimeter range;

Tens of nrad

Capability Performance Goal: Use of pulsed X-ray emitting millisecond pulsars distributed throughout the galaxy for navigation.

Parameter, Value:

Performance dependent on effective detector area, and observation/integration time, < 10 kilometer with high dynamics (e.g., LEO), and 100s of meters with low-dynamics (e.g., interplanetary cruise).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	3 years
Discovery: Discovery 13	Enabling	--	2020	2017	3 years
Discovery: Discovery 14	Enabling	--	2023	2020	3 years

5.6 Revolutionary Concepts
5.6.2 X-Ray Communications

5.6.2.1 X-Ray Communications (XCOM)

TECHNOLOGY

Technology Description: Exploit extremely low beam divergence of X-rays to provide high-rate, deep-space, low transmit power, highly physically secure data links, and enable new penetrating communication capabilities.

Technology Challenge: Platform isolation and achieving pointing accuracy (quasi-static: < 10 mrad, and dynamic: tens of mrad) are challenges.

Technology State of the Art: Flight-qualified modulated X-ray source (MXS) for Gravity and Extreme Magnetism Small Explorer. Bench-top testbed demonstrates feasibility.

Parameter, Value:	TRL
100s kb/s in short range ground laboratory tests	4

Technology Performance Goal: Space demonstration over 100 kilometer using Neutron Star Interior Composition Explorer (NICER) X-ray timing instrument as receiver with MXS/optic combination as transmitter (telemetry rate limited by NICER). After NICER demonstration, develop advanced receiver to demonstrate Gb/s communications capability.

Parameter, Value:	TRL
100s kb/s	7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Deep-space communications; reentry communications.

Capability Description: Communications constraint mitigation for deep-space, Gbits/W. Assured communications through harsh environments (e.g., hypersonic plasma shroud) and secure space-to-space links.

Capability State of the Art: Inter-satellite/relay links in Earth orbit.

Parameter, Value:
Gb/s at geosynchronous Earth orbit (GEO) (Laser Communications Relay Demonstration)

Capability Performance Goal: > 10 Gb/s per watt of transmitter power

Parameter, Value:
Multi-Gb/s at GEO

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Later Discovery Program	Enabling	--	2032	2029	9 years

5.6 Revolutionary Concepts
5.6.3 Neutrino-Based Navigation and Tracking

5.6.3.1 Neutrino-Based Navigation and Tracking Technologies

TECHNOLOGY

Technology Description: Neutrino sources as navigation beacons enable navigation and tracking directly through normal matter.

Technology Challenge: Developing new concepts for efficiently generating and detecting neutrinos is a challenge.

Technology State of the Art: Neutrino detectors are able to determine angle of arrival (AoA) and differentiate between types of neutrinos. AoA to known sources can be used for attitude and position knowledge.

Parameter, Value:	**TRL**
Extraterrestrial neutrino detection rate: ~10 neutrinos per year	3

Technology Performance Goal: The size and power consumption of neutrino detectors need to be significantly reduced for practical in-space navigation application.

Parameter, Value:	**TRL**
Suitcase-sized neutrino detectors; << 100 W power consumption	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Spacecraft navigation and tracking using Earth-based or natural sources of neutrinos. Unobstructed line-of-sight not needed.

Capability Description: Provides ability to determine position and attitude of spacecraft anywhere in the universe, including submerged spacecraft.

Capability State of the Art: Radio frequency (RF) systems are used for navigation and tracking when direct line-of-sight exists to system's fiducial nodes (e.g., Transit, Deep Space Network, global positioning system,Tracking and Data Relay Satellite System).

Parameter, Value:

Position fixing capabilities deriving from angular estimates of sources. Current neutrino observatories provide angular accuracy ~10 to 20 mrad.

Capability Performance Goal: Use of natural and man-made neutrino sources for navigation.

Parameter, Value:

Performance depends on detector performance. Current neutrino detectors are massive (~10^9 kilograms) and have very low rates of detection, but have fairly high accuracy in estimating AoA. Hence, mass reduction, or any other breakthrough in neutrino detection mechanisms, is the primary goal.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Later Discovery Program	Enabling	--	2032	2029	9 years

5.6 Revolutionary Concepts
5.6.4 Quantum Key Distribution

5.6.4.1 Entangled Photon Sources

TECHNOLOGY

Technology Description: Creation of entangled photons by backward quasi-phase matched interaction in waveguide.

Technology Challenge: Waveguide manufacture requires micromachining with very low tolerance (sub-micron).

Technology State of the Art: Development of waveguide source prototype.

Parameter, Value: Unknown

TRL 3

Technology Performance Goal: Improve the entangled photon generation rate.

Parameter, Value: Target rate is 107 Hz/mW/nm

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Source for quantum key distribution.

Capability Description: Provide entangled photons at high rate to enable quantum key distribution enabling secure communications.

Capability State of the Art: Conventional entangled photon sources from nonlinear crystals have low generation rates.

Parameter, Value: 2,100 Hz/mW/nm

Capability Performance Goal: High rate of entangled photon generation.

Parameter, Value: 107 Hz/mW/nm

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Push	Enhancing	--	--	--	5 years

5.6 Revolutionary Concepts
5.6.4 Quantum Key Distribution

5.6.4.2 Waveguide Single Photon Source

TECHNOLOGY

Technology Description: Single photon waveguide source for quantum key distribution.

Technology Challenge: Efficiency improvement in waveguide source needs to be demonstrated and accurate pointing needed.

Technology State of the Art	TRL	Technology Performance Goal	TRL
Technology State of the Art: In laboratory development. **Parameter, Value:** Unknown	3	**Technology Performance Goal:** Improve the quantum key distribution rate. **Parameter, Value:** Target rate is 10 kb/s	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Unconditionally secure free space communications.

Capability Description: Provide secure key at increased data rate.

Capability State of the Art	Capability Performance Goal
Capability State of the Art: Conventional quantum key distribution uses attenuated diode or nonlinear crystal sources. **Parameter, Value:** 250 bits per second over 143 kilometers	**Capability Performance Goal:** High rate of quantum key distribution. **Parameter, Value:** 10 kb/s from ground to the International Space Station

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Push	Enhancing	--	--	--	5 years

5.6 Revolutionary Concepts
5.6.5 Quantum Communications

5.6.5.1 Quantum Communications

TECHNOLOGY

Technology Description: Quantum communications to utilize linkage across space of entangled photons for improved data rates.

Technology Challenge: High-flux single photon sources, as well as entangled photon sources, need significant development in order to enable long-range communications at a significant data rate for interplanetary communications.

Technology State of the Art: Demonstrations of entangled photon transmission has been done, but not over interplanetary distances.

Parameter, Value: 250 bits per second over 144 kilometers

TRL: 3

Technology Performance Goal: Demonstrate high interplanetary data rates.

Parameter, Value: Target rate is 60 Mb/s

TRL: 5

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Need to increase interplanetary communications data rates.

Capability Description: Utilize entangled photons in quantum techniques such as superdense coding, teleportation, and quantum illumination to increase interplanetary communications data rates.

Capability State of the Art: Conventional radio frequency deep-space communications.

Parameter, Value: 6 Mbit per second from Earth-Mars (Mars Reconnaissance Orbiter's antenna can beam data to Earth at a rate of up to 6 Mb/s)

Capability Performance Goal: High interplanetary data rate.

Parameter, Value: 60 Mb/s

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	13 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	13 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	13 years

5.6 Revolutionary Concepts
5.6.6 Superconducting Quantum Interference Filter Microwave Amplifier

5.6.6.1 Superconducting Quantum Interference Filter (SQIF) Microwave Amplifier

TECHNOLOGY

Technology Description: Superconducting Quantum Interference Devices (SQUIDs) permit the detection of magnetic fields as small as 10^{-15} Tesla. An integrated array of (NxN) SQUIDs of incommensurate area forms a SQIF demonstrating a noise temperature that is inversely proportional to the square root of N.

Technology Challenge: Very low inductance superconducting loops, high critical current, integrated flux concentrator, and yield over large chip size are challenges.

Technology State of the Art: Niobium SQIFs 2-dimensional arrays consisting of hundreds of series and parallel Josephson junction SQUID loops.

Parameter, Value: Prototype X-band SQIFs demonstrated at > 30 dB gain

TRL: 3

Technology Performance Goal: Quantum limited noise performance.

Parameter, Value: 1.5 K noise temperature at Ka-band

TRL: 2

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Quantum limited microwave receivers.

Capability Description: Provide low noise front-end for space communications—ground or flight.

Capability State of the Art: Basic SQIF theory developed around 2000. Prototype devices demonstrated at ~100 MHz.

Parameter, Value: Current 20 K, 0.1 µm high electron-mobility transistor (HEMT) low noise amplifier noise temperature is about 15 K at Ka-band.

Capability Performance Goal: Achieve quantum limited noise performance.

Parameter, Value: 10x improvement in sensitivity/noise temperature

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Push	Enhancing	--	--	--	5 years

5.6 Revolutionary Concepts
5.6.7 Reconfigurable Large Apertures

5.6.7.1 Reconfigurable Large Aperture Technologies

TECHNOLOGY

Technology Description: Large, space-based apertures formed from smaller apertures on multiple spacecraft that have the ability to quickly respond to changing needs.

Technology Challenge: Requires advances in guidance, navigation, and control (GN&C); semiconductor processors; computing architectures; advanced materials; power and propulsion; miniaturized communications components; ad hoc or wireless network protocols; and cognitive swarm operations.

Technology State of the Art: Other government agency seeks to demonstrate the feasibility and benefits of a satellite architecture wherein the functionality of a traditional “monolithic” spacecraft is delivered by a cluster of wirelessly-interconnected modules.

Parameter, Value:	TRL
Cluster Flight Application core flight software fully tested	4

Technology Performance Goal: Demonstrate station keeping, satellite/module ingress and egress, collision avoidance, and scatter/re-gather maneuvers.

Parameter, Value:	TRL
Formation flying flight demonstration with at least 6 month experiment duration	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Reconfigurable, cooperative satellite modules with autonomous/cognitive navigation.

Capability Description: Cluster concept includes electronic beam steering, reduced antenna mass, higher antenna efficiency, lower power density in the transmit system components (e.g., alleviate thermal problems and dangers of high-voltage breakdown), spatial power combining, reduced pointing loss, and a fail-soft capability.

Capability State of the Art: Ground systems only (e.g., Square Kilometer Array on the drawing board).

Parameter, Value:

Synchronized apertures;

Wide band single feeds covering frequencies from 500 MHz to 11 GHz

Capability Performance Goal: Space-based multiple reflector/satellite cluster system demonstrating intensive real-time signal processing.

Parameter, Value:

Ka-band lightweight antenna arrays capable of relative navigation and cluster coordination

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Gravitational Wave Surveyor Mission	Enhancing	--	2035*	2035	5 years
Strategic Missions: CMB Polarization Surveyor Mission	Enhancing	--	2035*	2035	5 years
Strategic Missions: Far Infrared Surveyor Mission	Enhancing	--	2035*	2035	5 years
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enhancing	--	2035*	2030	5 years
Strategic Missions: X-ray Surveyor Mission	Enhancing	--	2035*	2030	5 years
Strategic Missions: Exoplanet Direct Imaging Mission	Enhancing	--	2030*	2025	5 years
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enhancing	--	2024*	2020	5 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years
Earth Systematic Missions: Three-Dimensional Tropospheric Winds from Space-based Lidar (3D Winds)	Enhancing	--	2030*	2025	5 years
Solar Terrestrial Probes: Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)	Enhancing	--	2025	2021	5 years
Solar Terrestrial Probes: Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI)	Enhancing	--	2032	2030	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.7 Orbital Debris Tracking and Characterization
5.7.1 Tracking Technologies

5.7.1.1 High-Power Wideband X-Band Klystron

TECHNOLOGY

Technology Description: High-power wideband X-band klystron.

Technology Challenge: Developing a 500 kW X-band klystron with a 120 MHz bandwidth.

Technology State of the Art: 400 kW X-band klystron with a 40 MHz bandwidth.

Parameter, Value:
Power: 400 kW;
Bandwidth: 40 MHz

TRL 6

Technology Performance Goal: 500 kW X-band klystron with a 120 MHz bandwidth.

Parameter, Value:
Power: 500 kW;
Bandwidth: 120 MHz

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Improved tracking of orbital debris.

Capability Description: Provide improved tracking of orbital debris.

Capability State of the Art: 400 kW X-band klystron with a 40 MHz bandwidth.

Parameter, Value:
Power: 400 kW;
Bandwidth: 40 MHz

Capability Performance Goal: 500 kW X-band klystron with a 120 MHz bandwidth.

Parameter, Value:
Power: 500 kW;
Bandwidth: 120 MHz

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Gravitational Wave Surveyor Mission	Enhancing	--	2035*	2035	2 years
Strategic Missions: CMB Polarization Surveyor Mission	Enhancing	--	2035*	2035	2 years
Strategic Missions: Far Infrared Surveyor Mission	Enhancing	--	2035*	2035	2 years
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enhancing	--	2035*	2030	2 years
Strategic Missions: X-ray Surveyor Mission	Enhancing	--	2035*	2030	2 years
Strategic Missions: Exoplanet Direct Imaging Mission	Enhancing	--	2030*	2025	2 years
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enhancing	--	2024*	2020	2 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	2 years
Earth Systematic Missions: Geostationary Coastal and Air Pollution Events (GEO-CAPE)	Enhancing	--	2024*	2019	2 years
Earth Systematic Missions: Lidar Surface Topography (LIST)	Enhancing	--	2024*	2019	2 years
Earth Systematic Missions: Precision and All-Weather Temperature and Humidity (PATH)	Enhancing	--	2024*	2019	2 years
Earth Systematic Missions: Gravity Recovery and Climate Experiment (GRACE)-II	Enhancing	--	2024*	2019	2 years
Earth Systematic Missions: Snow and Cold Land Processes (SCLP)	Enhancing	--	2024*	2019	2 years
Earth Systematic Missions: Global Atmosphere Composition Mission (GACM)	Enhancing	--	2024*	2019	2 years
Earth Systematic Missions: Three-Dimensional Tropospheric Winds from Space-based Lidar (3D Winds)	Enhancing	--	2030*	2025	2 years
Solar Terrestrial Probes: Interstellar Mapping and Acceleration Probe (IMAP)	Enhancing	--	2022	2019	2 years
Solar Terrestrial Probes: Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)	Enhancing	--	2025	2021	2 years
Solar Terrestrial Probes: Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI)	Enhancing	--	2032	2030	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.7 Orbital Debris Tracking and Characterization
5.7.1 Tracking Technologies

5.7.1.2 Ka-Band Objects Observation and Monitoring

TECHNOLOGY

Technology Description: A ground-based phased array of widely separated antennas operating in the Ka-band that can provide both high range and spatial resolution.

Technology Challenge: Developing an antenna array with significant effective isotropic radiated power (EIRP) and G/T that also has a lower lifecycle cost that monolithc approaches is a challenge.

Technology State of the Art: 3-element array.

Parameter, Value:	TRL
3-element array of 12 meter antennas	5

Technology Performance Goal: 100-element array of 12-meter antennas with 100 kW amplifiers.

Parameter, Value:	TRL
100-element array of 12-meter antennas with 100 kW amplifiers	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Improved tracking of orbital debris.

Capability Description: Provide improved tacking of orbital debris.

Capability State of the Art: Goldstone Solar System Radar.

Parameter, Value:

70 meter antenna: 400 kW, 40 MHz bandwidth

Capability Performance Goal: 100-element array.

Parameter, Value:

100-element array of 12-meter antennas with 100 kW amplifiers

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Strategic Missions: Gravitational Wave Surveyor Mission	Enhancing	--	2035*	2035	2 years
Strategic Missions: CMB Polarization Surveyor Mission	Enhancing	--	2035*	2035	2 years
Strategic Missions: Far Infrared Surveyor Mission	Enhancing	--	2035*	2035	2 years
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enhancing	--	2035*	2030	2 years
Strategic Missions: X-ray Surveyor Mission	Enhancing	--	2035*	2030	2 years
Strategic Missions: Exoplanet Direct Imaging Mission	Enhancing	--	2030*	2025	2 years
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enhancing	--	2024*	2020	2 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	2 years
Earth Systematic Missions: Geostationary Coastal and Air Pollution Events (GEO-CAPE)	Enhancing	--	2024*	2019	2 years
Earth Systematic Missions: Lidar Surface Topography (LIST)	Enhancing	--	2024*	2019	2 years
Earth Systematic Missions: Precision and All-Weather Temperature and Humidity (PATH)	Enhancing	--	2024*	2019	2 years
Earth Systematic Missions: Gravity Recovery and Climate Experiment (GRACE)-II	Enhancing	--	2024*	2019	2 years
Earth Systematic Missions: Snow and Cold Land Processes (SCLP)	Enhancing	--	2024*	2019	2 years
Earth Systematic Missions: Global Atmosphere Composition Mission (GACM)	Enhancing	--	2024*	2019	2 years
Earth Systematic Missions: Three-Dimensional Tropospheric Winds from Space-based Lidar (3D Winds)	Enhancing	--	2030*	2025	2 years
Solar Terrestrial Probes: Interstellar Mapping and Acceleration Probe (IMAP)	Enhancing	--	2022	2019	2 years
Solar Terrestrial Probes: Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)	Enhancing	--	2025	2021	2 years
Solar Terrestrial Probes: Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI)	Enhancing	--	2032	2030	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

5.7 Orbital Debris Tracking and Characterization
5.7.2 Characterization Technologies

5.7.2.1 Improved Modeling

TECHNOLOGY

Technology Description: Improved modeling of orbital debris characteristics, such as orbits, size, and density.

Technology Challenge: Developing models and algorithms to fuse input from multiple sensors and radar systems. Reducing the size of the tracked debris increases the debris population size, which requires increased computational requriements on the model user.

Technology State of the Art: Orbital Debris Engineering Model (ORDEM) 3.0 and low-Earth orbit (LEO-)to-geosynchronous Earth orbit (GEO) Environment Debris (LEGEND) model.

Parameter, Value: Tracks debris larger than 10 cm in LEO and 1 m in GEO. Statistical modeling for smaller debris.

TRL: 6

Technology Performance Goal: Orbital debris modeling software with ability to handle more and smaller debris.

Parameter, Value: Track debris smaller than 10 cm in LEO and smaller than 1 m in GEO.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Improved modeling of orbital debris characteristics.

Capability Description: Provide improved modeling of orbital debris characteristics, such as orbits, size, and density.

Capability State of the Art: ORDEM 3.0 and LEGEND.

Parameter, Value: Tracks debris larger than 10 cm in LEO and 1 m in GEO.

Capability Performance Goal: Ability to identify areas of higher and lower density of small orbital debris.

Parameter, Value: Track debris smaller than 10 cm in LEO and smaller than 1 m in GEO.

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Strategic Missions: Gravitational Wave Surveyor Mission	Enhancing	--	2035*	2035	2 years
Strategic Missions: CMB Polarization Surveyor Mission	Enhancing	--	2035*	2035	2 years
Strategic Missions: Far Infrared Surveyor Mission	Enhancing	--	2035*	2035	2 years
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enhancing	--	2035*	2030	2 years
Strategic Missions: X-ray Surveyor Mission	Enhancing	--	2035*	2030	2 years
Strategic Missions: Exoplanet Direct Imaging Mission	Enhancing	--	2030*	2025	2 years
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enhancing	--	2024*	2020	2 years
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	2 years
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Earth Systematic Missions: Lidar Surface Topography (LIST)	Enhancing	--	2024*	2019	2 years
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Earth Systematic Missions: Snow and Cold Land Processes (SCLP)	Enhancing	--	2024*	2019	2 years
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Solar Terrestrial Probes: Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)	Enhancing	--	2025	2021	2 years
Solar Terrestrial Probes: Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI)	Enhancing	--	2032	2030	2 years

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