EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

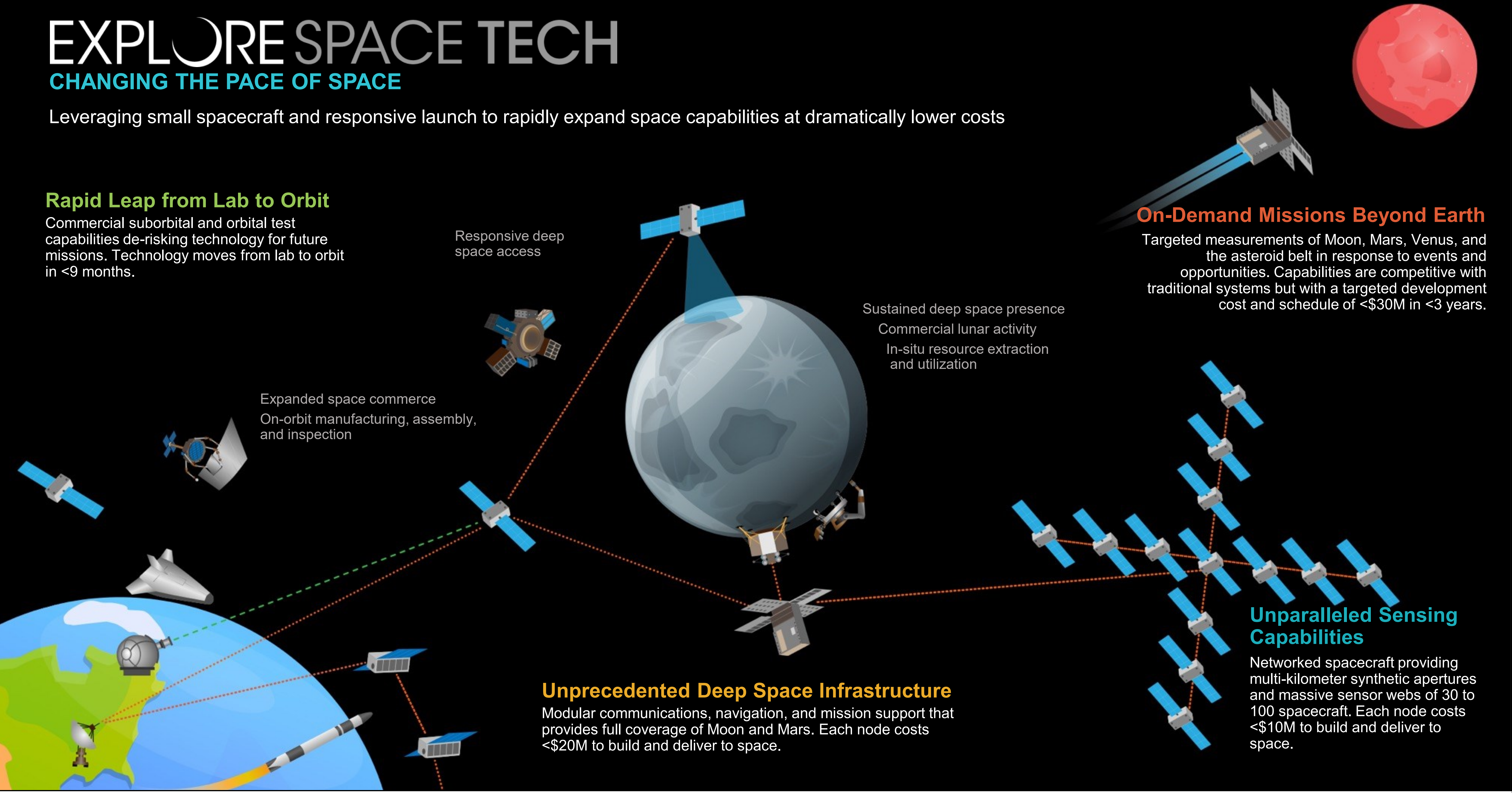
EXPLORE: Small Spacecraft Technologies
NASA Space Technology Mission Directorate

STMD welcomes feedback on this presentation. Please visit https://techport.nasa.gov/framework/feedback if you have any questions or comments regarding this presentation.

EXPLORE SPACE TECH

CHANGING THE PACE OF SPACE

Leveraging small spacecraft and responsive launch to rapidly expand space capabilities at dramatically lower costs



Rapid Leap from Lab to Orbit

Commercial suborbital and orbital test capabilities de-risking technology for future missions. Technology moves from lab to orbit in <9 months.

Responsive deep space access

Expanded space commerce

On-orbit manufacturing, assembly, and inspection

Sustained deep space presence

Commercial lunar activity

In-situ resource extraction and utilization

On-Demand Missions Beyond Earth

Targeted measurements of Moon, Mars, Venus, and the asteroid belt in response to events and opportunities. Capabilities are competitive with traditional systems but with a targeted development cost and schedule of <$30M in <3 years.

Unprecedented Deep Space Infrastructure

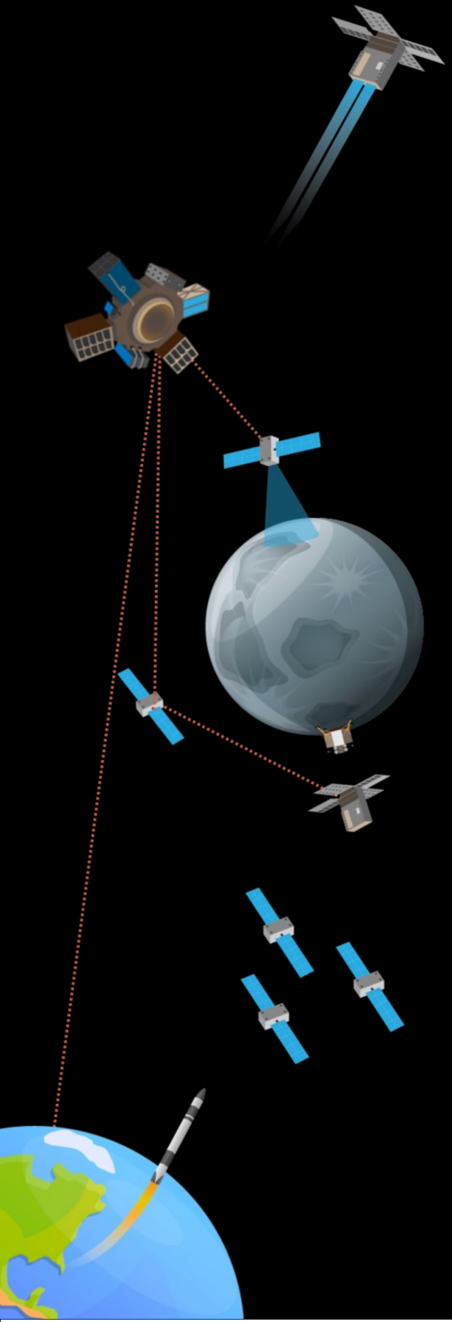
Modular communications, navigation, and mission support that provides full coverage of Moon and Mars. Each node costs <$20M to build and deliver to space.

Unparalleled Sensing Capabilities

Networked spacecraft providing multi-kilometer synthetic apertures and massive sensor webs of 30 to 100 spacecraft. Each node costs <$10M to build and deliver to space.

NOT ALL ACTIVITIES DEPICTED ARE CURRENTLY FUNDED OR APPROVED. DEPICTS “NOTIONAL FUTURE” TO GUIDE TECHNOLOGY VISION

CHANGING THE PACE OF SPACE: Envisioned Future For Small Spacecraft Technology



High dV Small Spacecraft Propulsion Systems

Low size, weight, power, and cost (SWaP-C) systems capable of imparting 2-5+ km/s change in velocity (dV) to microsatellites. Highly manufacturable and compatible with the deep space environment. ► Small missions to the Moon, Lagrange Points, NEOs and beyond as well as plane changes and more responsive missions in Earth orbit.

Deep Space Orbital Maneuvering Vehicles (OMVs)

OMVs capable of 10+ km/s dV and providing position, navigation, and timing (PNT) services and communications relay to deployed spacecraft or hosted payloads. Affordable and demonstrated in the deep space environment. ► Expansion of small risk-tolerant missions further beyond Earth and the ability to reach multiple destinations from a single launch.

In-Space Autonomy for Small Spacecraft and Distributed Systems

Significant (~75%) reduction in ground station aperture time for single small spacecraft missions. Increased in-space autonomy that allows 10’s of small spacecraft to operate as a single unit beyond Earth. ► Large distributed missions (e.g., heliophysics) and missions in Earth-orbiting or beyond that can react without ground stations in the loop.

Small Spacecraft Communications and PNT Services

Small spacecraft that can be deployed to the Moon and other deep space destinations to provide global PNT and communications relay infrastructure. ► Addresses future strain on terrestrially-based capabilities (e.g., tracking) caused by concurrent cislunar missions and global surface missions where direct communications with Earth is not feasible.

Interoperable Networking for Small Missions

Increased interoperability between government and commercial space networks. Operational interoperability protocols that help pair the NASA Delay Tolerant Networking (DTN) and LunaNet with the Hybrid Space Architecture. ► Ubiquitous communication between in-space assets, airborne systems, in-situ sensors, and ground assets as well as networking in cislunar space.

Small Spacecraft Proximity Operations and Abort Systems

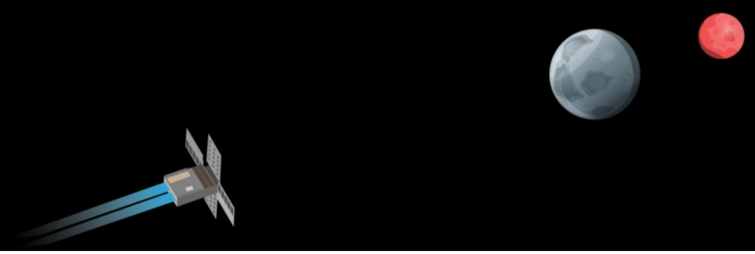
De-risked low size, weight, power and cost (SWaP-C) proximity sensors and reliable proximity abort systems. ► Reduced risk in use of small satellites in close proximity to high value assets (e.g., for servicing / inspection) and for small missions to natural targets like NEOs.

Responsive Access to Suborbital and Orbital Space

Additional suborbital vehicle performance and payload accommodations for technology testing (e.g., payloads hosted on recoverable orbital launch vehicle stages and hosted orbital payloads). ► Rapid advancement of capabilities requires frequent risk-tolerant opportunities to test and evaluate in an operational environment.

NOT ALL ACTIVITIES DEPICTED ARE CURRENTLY FUNDED OR APPROVED. DEPICTS “NOTIONAL FUTURE” TO GUIDE TECHNOLOGY VISION

High dV Small Spacecraft Propulsion Systems



Current State of the Art (2021)

Current demonstrated systems are typically able to provide 100’s of m/s of dV with experimental systems nearing 2 km/s dV at the nanosatellite scale.

Yost, B. and Weston, S. (ed.), “State-of-the-Art Small Spacecraft Technology”, NASA/TP-20210021263, October 2021

Envisioned Future

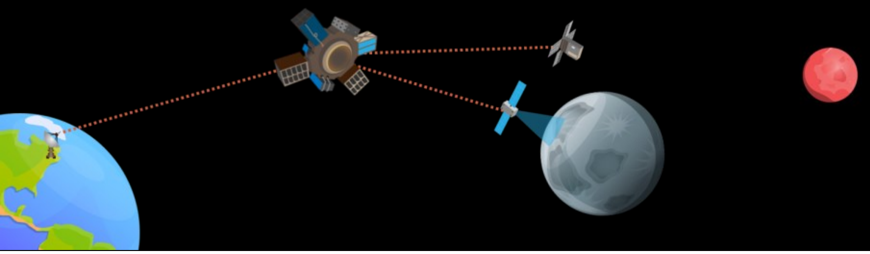
Low-SWaP-C systems capable of imparting 2-5+ km/s dV at the microsatellite scale. Highly manufacturable with repeatable performance and compatible with the deep space environment.

Enables small spacecraft missions to the Moon, Lagrange Points, Mars, Venus, and near-Earth objects (NEOs) as well as longer duration and more responsive missions in Earth orbit, including those at lower-altitude or requiring plane changes.

Small spacecraft represent cost-efficient mission options, but high dV implementation within SWaP-C constraints of small spacecraft is non-trivial.

- To achieve 5+ km/s dV, the propellant throughput / system life of nano- and microsatellite propulsion systems must be increased.
- Highly efficient propulsion (e.g., electric or dual mode) will be essential to meet volume and size constraints.
- Non-traditional propellants (e.g., “green”, metallic, water) may provide greater compatibility with lower cost launch opportunities
- Will require sufficient modification, testing, and analysis to ensure radiation tolerance and reliability for multiyear missions and deep space operation.
- Manufacturability and commonality between systems for different missions / applications will keep costs low and increase reliability.

Deep Space Orbital Maneuvering Vehicles (OMVs)



Current State of the Art (2021)

Orbital Maneuvering Vehicles (OMVs) have been demonstrated and used operationally in Earth orbit. Higher performance 5+ km/s dV capabilities in development with demonstrations anticipated in the near future.

Yost, B. and Weston, S. (ed.), “State-of-the-Art Small Spacecraft Technology”, NASA/TP-20210021263, October 2021

Tan, F. et al (ed), “NASA Access 2 Space Workshop: Summary Report: Increased Science Return through Rideshare”, NASA Doc. 20205006748, Laurel, MD, 31 August 2020

Envisioned Future

OMVs capable of 10+ km/s dV and that can provide position, navigation, and timing (PNT), communications relay, and other services to deployed spacecraft or hosted payloads. Affordable and demonstrated in the deep space environment.

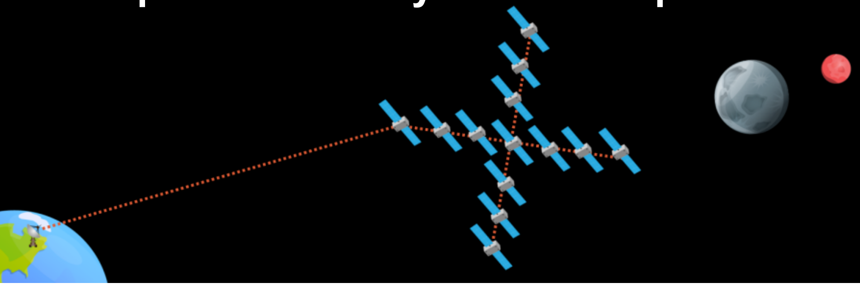
Enables expansion of small risk-tolerant missions further beyond Earth. Enables small missions to reach multiple destinations from a single launch, achieve multiple orbital plane changes or nontraditional orbits, and reach beyond the Moon, Mars, and Venus to asteroids in the main belt or other deep space objects.

OMVs allow small spacecraft to reach orbits less achievable with on-board propulsion, higher dV capability and PNT / communications relay can make OMVs uniquely enabling for cost-efficient missions.

- Emerging systems (e.g., small launch interplanetary transfer stages and GEO life extension systems) may require increased capabilities to achieve 10+ km/s dV
- Systems being demonstrated for Earth orbit applications (e.g., propulsive ESPA rings and other space tugs) may require modification and testing to de-risk them for multiyear missions and deep space operation.
- Adding PNT / communications relay to OMVs can significantly increase the operational capabilities of low-SWaP-C spacecraft for distributed (e.g., heliophysics) and multiple individual missions at deep space destinations.
- Interfaces for hosted scientific instruments and payloads can allow the OMV to also act as the primary spacecraft bus for a mission, reducing mission-specific developmental costs.

NOT ALL ACTIVITIES DESCRIBED ARE CURRENTLY FUNDED OR APPROVED. DEPICTS “NOTIONAL FUTURE” TO GUIDE TECHNOLOGY VISION

In-Space Autonomy for Small Spacecraft and Distributed Systems



Current State of the Art (2021)

Most current constellations use ground-based, semi-autonomous scheduling and orbital maintenance to decrease human-in-the-loop operations but still upload commands to each spacecraft individually. Newer systems move more autonomy onboard but still rely on updates from ground-based systems. DARPA's Blackjack and SDA's architecture seek to increase in-space autonomy.

Yost, B. and Weston, S. (ed.), "State-of-the-Art Small Spacecraft Technology", NASA/TP-20210021263, October 2021

Envisioned Future

Significant (circa 75%) reduction in ground station aperture time for single small spacecraft missions. Increased in-space autonomy that allows 10's of small spacecraft to operate as a single unit beyond Earth.

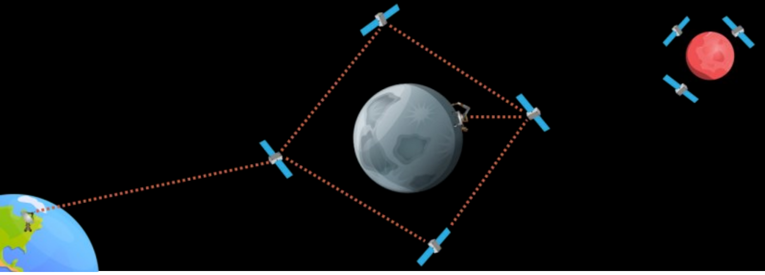
Enables large distributed missions such as sensor webs for heliophysics and advanced Earth-orbiting missions that can react without ground stations in the loop. Single-spacecraft autonomy can enable near-"lights out" operations for missions beyond Earth.

Small spacecraft are uniquely suited for large distributed missions, but operations are prohibitive without autonomy. In-space autonomy can also assist missions with communications limitations or that need to react to sensor data.

- Commercial software architectures and modules that are part of other USG / non-NASA distributed missions can be adapted for use by NASA missions and in environments operationally relevant for NASA.
- To enable multipoint measurements beyond Earth (e.g., heliophysics), 10s of spacecraft must be operated without saturating cross-link or ground-link bandwidth.
- Autonomous coordination allows small spacecraft to be configured in space as virtual telescopes and distributed apertures for investigation of Earth and the universe.
- Single-spacecraft autonomy can help addresses communications limitations and enable more robust situational awareness, fault recovery, and science data collection.
- Autonomous spacecraft can help enable responsible utilization of popular / congested orbits, providing benefits to commercial and USG users.
- Autonomy can also enable dynamic reconfiguration of assets for Earth observations

NOT ALL ACTIVITIES DESCRIBED ARE CURRENTLY FUNDED OR APPROVED. DEPICTS "NOTIONAL FUTURE" TO GUIDE TECHNOLOGY VISION

Small Spacecraft Communications and Position, Navigation, and Timing (PNT) Services



Current State of the Art (2021)

Space-based assets in Earth orbit currently provide global PNT and communications services for terrestrial activity and many small spacecraft in LEO. For lunar missions, PNT and communications are currently provided through large, terrestrially-based dishes such as those employed by NASA's Deep Space Network (DSN).

Envisioned Future

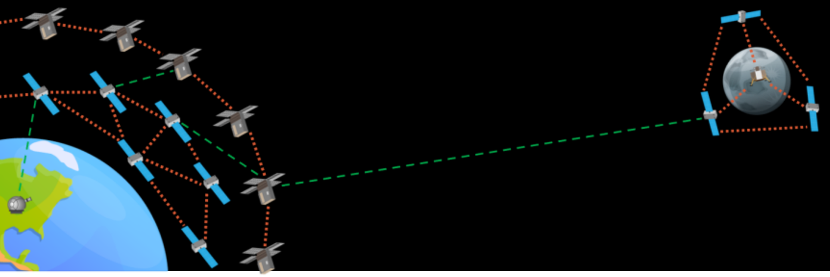
Small spacecraft that can be deployed to the Moon and deep space destinations to provide global lunar / comprehensive PNT and communications relay infrastructure.

Can help address the strain on current terrestrially-based capabilities - particularly tracking - from future cislunar and deep space missions. Offers options for cislunar and lunar surface missions where direct communications with Earth-based systems will not be available.

Low-SWaP-C deep space communications, navigation, and timing synchronization will be critical for missions beyond Earth. While use of Multiple Spacecraft Per Aperture (MSPA) capabilities will help DSN service a growing number of concurrent missions, peer-to-peer navigation (e.g., CAPSTONE) paired with DSN tracking or emerging capabilities for use of weak-signal multi-GNSS at the Moon (e.g., NavCube3-mini) can play a role.

- Low-SWaP-C solutions can allow multiple communications and PNT satellites to be deployed around the Moon or Mars from a single launch vehicle or OMV. Lunar relay architecture studies for global coverage have used a minimum of 3 to 5 satellites (some as many as 15). Studies on ideal Mars networks show a minimum of 5 or 6 satellites.
- Rapid and cost-effective deployment of infrastructure may be possible through adaptation of small spacecraft-based LEO/MEO commercial communications spacecraft and terrestrial telecom technology (e.g., 4G/5G cellular) to the cislunar environment.
- Optical cross-links and downlinks may provide very high-bandwidth alternatives to RF for in space elements and fixed ground stations.
- Low-SWaP-C PNT sources for deep space will also be needed for use on small spacecraft or on OMVs that can relay PNT information to small spacecraft.

Interoperable Networking for Small Missions



Current State of the Art (2021)

Delay Tolerant Networking (DTN) in use by NASA missions. Hybrid Space Architecture concept adopted by DoD and commercial companies as a "variable trust" network framework for rapid and secure data exchange across USG, international, and commercial space systems. NASA's Space Communications and Navigation Office developed draft operational interoperability standards for LunaNet.

Yost, B. and Weston, S. (ed.), "State-of-the-Art Small Spacecraft Technology", NASA/TP-20210021263, October 2021

NASA, "Draft LunaNet Interoperability Specification, LN-IS Baseline V001, 2 September 2021

Burleigh, S., "Interplanetary Overlay Network: An Implementation of the DTN Bundle Protocol", 4th IEEE Consumer Communications and Networking Conference, 11-13 January 2007

Moigne, J. and Cole, M., "Advanced Information Systems Technology (AIST) New Observing Strategies (NOS) Workshop Summary Report", NASA Doc. 20210010318, 26 February 2021

Envisioned Future

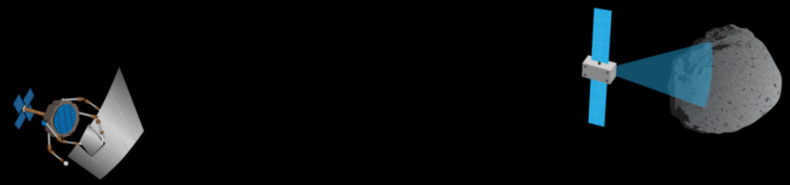
Increased interoperability between government and commercial space networks. Operational interoperability protocols that help pair the NASA LunaNet concept with the Hybrid Space Architecture and existing capabilities like DTN.

Enables ubiquitous communication between in-space assets, airborne systems, in-situ sensors, and ground assets. In cislunar space, will enable a network of surface and orbital nodes, low-SWaP-C relays, and more capable assets that can serve as hubs connecting to Earth-based communication networks.

Unification of interoperability approaches from NASA and the DoD can further ubiquitous networking and coordination across NASA, other USG, commercial, and international space assets.

- The Hybrid Space Architecture may help realize the dynamic coordination of assets from NASA and other organizations to optimize measurement acquisition for Earth observation across diverse capabilities.
- The LunaNet architecture resulted from efforts to leverage advances in small spacecraft technologies to update envisioned lunar communications architectures. NASA's SCaN Office has developed draft operational interoperability standards for LunaNet (https://go.nasa.gov/3ljMacw).

Small Spacecraft Proximity Operations and Abort Systems



Current State of the Art (2021)

Technology demonstrations at small spacecraft relevant scales have been conducted for on-orbit servicing and inspection with several more demonstrations upcoming.

Yost, B. and Weston, S. (ed.), “State-of-the-Art Small Spacecraft Technology”, NASA/TP-20210021263, October 2021

Envisioned Future

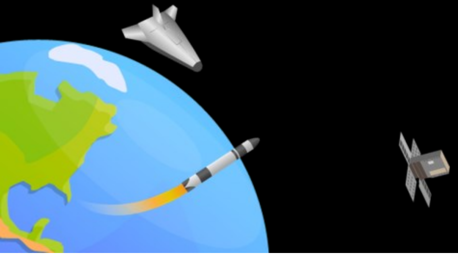
De-risked low-SWaP-C proximity sensors, software, and reliable proximity abort systems.

Needed to reduce risk in use of small satellites in close proximity to high value assets. These systems can also enable small missions to natural targets like NEOs or other missions requiring persistent formation flight.

Small spacecraft can be well suited to play roles in inspection, servicing, and other proximity operations with inhabited or high value assets as well as asteroids or other small bodies.

- Use of lower-cost risk-tolerant spacecraft in proximity to risk-intolerant assets is possible if the small spacecraft is equipped with a sufficiently robust proximity operations abort system that will reliably prevent a collision in the event of a fault or error.
- Low-SWaP-C onboard relative navigation systems for safe, autonomous, and persistent proximity / formation flight will be needed.
- Relative navigation sensors and proximity operations abort systems will need to be sufficiently demonstrated in operational relevant conditions.
- OMVs equipped with relative navigation / proximity operations abort systems can act as delivery (especially “last mile”) agents to high-value assets for servicing and resupply.

Responsive Access to Suborbital and Orbital Space



Current State of the Art (2021)

Commercial suborbital vehicles are currently providing valuable flight test capabilities for technologies relevant to exploration, discovery, and space commerce.

Envisioned Future

Additional vehicle performance and payload accommodations, including payloads hosted on recoverable orbital launch vehicle stages and greater access to orbital platforms for hosted technology testing.

Rapid advancement of capabilities requires frequent opportunities to test and evaluate new technology in an operational environment. Embracing "fly-fix-fly" and agile aerospace practices allows technologists to iterate through flights, and failures, to innovate at a pace impossible in a less risk-tolerant environment.

Advancement and additional access to commercial suborbital and LEO capabilities can further expand NASA use of rapid and lower cost commercial spaceflight for technology development and demonstration.

- Higher altitude suborbital flights, or the ability to host payloads on recoverable orbital rocket stages, could provide longer duration microgravity as well as access to speeds and heating conditions more relevant to planetary entry/reentry testing
- Routine and affordable hosting of small LEO payloads on orbital platforms can provide NASA-sponsored research rapid access to longer duration testing in relevant space environments.
- Through frequent low-cost access and increased capabilities – such as variable reduced gravity testing, high altitude balloon station keeping, and enhanced closed-loop EDL testing – commercial suborbital vehicles can continue to expand their role as a critical tool in the continuum of space technology flight testing.

NOT ALL ACTIVITIES DESCRIBED ARE CURRENTLY FUNDED OR APPROVED. DEPICTS "NOTIONAL FUTURE" TO GUIDE TECHNOLOGY VISION

Acronyms and Abbreviations

DTN	**Delay Tolerant Networking**
dV	**Delta-v**
EDL	**Entry, Descent, and Landing**
EELV	**Evolved Expendable Launch Vehicle**
ESPA	**EELV Secondary Payload Adapter**
GEO	**Geosynchronous Equatorial Orbit**
LEO	**Low Earth Orbit**
MEO	**Medium Earth Orbit**
MSPA	**Multiple Spacecraft Per Aperture**
NASA	**National Aeronautics and Space Administration**
NEO	**Near Earth Object**
OMV	**Orbital Maneuvering Vehicle**
PNT	**Position, Navigation, and Timing**
RF	**Radio Frequency**
SWaP-C	**Size, Weight, Power, and Cost**