Communications and Navigation for Distributed Small Spacecraft Beyond Low Earth Orbit (LEO)

Lead Center: GRC

Participating Center(s): ARC, GSFC, JPL

Scope Title:

End-to-End Deep Space Communications

Scope Description:

Develop enabling communications technologies for small spacecraft beyond LEO. These technologies will be required by spacecraft to conduct NASA lunar and deep space distributed spacecraft science missions. Innovations in communications technologies for distributed small spacecraft are essential to fulfill the envisioned science missions within the decadal surveys and contribute to the success of human exploration missions. To construct the lunar communications architecture [Ref. 11], it is appropriate to consider a hybrid approach of large and small satellite assets. Primary applications include data relay from lunar surface to surface, data relay to Earth, and navigational aids to surface and orbiting users. Distributing these capabilities across multiple small satellites may be necessary because of limited size, weight, and power (SWaP), but also to enhance coverage.

Technologies for specific lunar architecture are especially needed. For example, landers near the lunar South Pole may not have—and landers on the far side of the Moon will not have—direct line-of-sight to Earth-based ground stations and will need to send data through a relay satellite (or Gateway) to return data to Earth. Small surface systems (including rovers or astronauts on extravehicular activities (EVAs)) on the Moon will likely not have the necessary system resources to close a direct link to Earth. Human surface operations may require surface-to-surface over-the-horizon communications through an orbital relay. Deployment of sufficient traditional communications assets to maintain persistent global coverage of the lunar surface may be prohibitively expensive. Analogous to emerging LEO communications constellations, small spacecraft can operate as local relays in cislunar space.

Considerations of extension of the technologies and capabilities to the martian domain and other deep space applications are also solicited.

Interspacecraft networking is inherent to distributed mission and interoperable communications relay architectures. Enabling networking capabilities in small spacecraft requires low SWaP-C hardware for radio-frequency (RF) and optical cross links. While network protocols developed for interoperable communications relays may be
interchangeable with those for distributed missions, relay networks may not be scalable to very large scale sensor webs of small spacecraft. As such, addressing interspacecraft networking gaps may require investment in both hardware cross links and networking protocols that scale to hundreds of nodes, and require robustness for loss of nodes or as new nodes enter the network.

An end-to-end system needs to be considered for the application of small satellites for deep space missions as described in preceding paragraphs. Therefore, enabling technologies also include non-NASA ground services that keep the operations cost commensurate with the lower costs of the small satellites themselves. Automation of the ground services as well as the small satellite constellations are needed.

Communications solutions can operate in optical or various RF bands; however, considerations must be given to bandwidth, public and Government licensing, and compatibility with referenced candidate architectures.

**Expected TRL or TRL Range at completion of the Project:** 2 to 5  
**Primary Technology Taxonomy:**  
  - Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems  
  - Level 2: TX 05.2 Radio Frequency  
**Desired Deliverables of Phase I and Phase II:**  
- Prototype  
- Hardware  
- Software  

**Desired Deliverables Description:**  
Phase I: Identify and explore options for the deep space small-satellite missions, including ground services. Conduct trade analysis and simulations, define operating concepts, and provide justification for proposed multiple access techniques, frequency bands of operation, command and data handling, and networking solutions. Also identify, evaluate, and develop design for integrated communications payload(s) and one or more constituent technologies that enable distributed spacecraft operations in the relevant space environment beyond LEO. Integrated communications system solutions and constituent component deliverables should offer potential advantages over the state of the art, demonstrate technical feasibility, and show a path toward a hardware/software infusion into practice. Bench-level or laboratory-environment level demonstrations or simulations are desirable. The Phase I proposal should outline a path that shows how the technology can be developed into space-qualifiable and commercially available small-spacecraft communications payloads through Phase II efforts and beyond.

Phase II: Demonstration of communication technology via prototype or high-fidelity emulation. The relevant deep space environment parameters should be simulated as much as possible.

**State of the Art and Critical Gaps:**  
Small-spacecraft missions beyond Earth require compact, low-power, high-bandwidth radios for use on the Moon, Mars, the rest of the inner planets, around asteroids or other small bodies, and at other deep space destinations. The current state of the art is the Iris radio (0.5U, 1.2 kg, and 35 W) [Ref. 12] that has been operationally used at Mars, and there is no known affordable, readily available competitor. Future missions require systems that are lower SWaP-C, can operate in multiple bands (S, X, Ka-band, and optical), and can reach uplink and downlink speeds in excess of 20 Mbps. Spectral, modulation, information layer, and protocol compatibility with current technologies (Space Communications and Navigation (SCaN)); licensing and spectrum approval; and planned Government or commercial deep space communication architecture must all be considered.
Communications among spacecraft in a distributed spacecraft mission (DSM) configuration and between the DSM configuration and the Earth become more challenging beyond LEO distances. Collaborative configurations of widely distributed (10s to 100s of km apart) small spacecraft (180 kg or less) will operate far into the near-Earth region of space and beyond into deep space, further stressing the already limited communications capabilities of small spacecraft. Alternative operational approaches with associated enabling hardware and/or software will be needed with the following:

- **Uplinks (Earth-to-space) and downlinks (space-to-Earth):** Alternatives for coordinated command and control of the DSM configuration and individual small spacecraft from Earth as well as return of science and telemetry data to Earth. Each spacecraft cannot rely on its own dedicated Earth link, consuming valuable ground infrastructure and operators.

- **Integrated communications payload:** Hardware and software designs for the common and unique capabilities of each small spacecraft in the DSM configuration. Spacecraft communication SWaP-C should be reduced by at least 25% from a non-DSM spacecraft.

- **Small-spacecraft antennas:** Development of antennas optimized for either intersatellite or uplink/downlink communications are sought across a broad range of technologies including but not limited to deployable parabolic or planar arrays, active electronically steered arrays, novel antenna steering/positioning subsystems, and others suitable for use in high data rate transmission among small spacecraft over large distances. SWaP-C should be reduced from state of the art, such as the recent 6U CubeSat MarCO mission, which used a 0.2m$^2$ X-band reflectarray to achieve 29 dBic gain and 42% efficiency [Refs. 13, 14]. Operations compatible with NASA’s space communications infrastructure [Ref. 9] and Government exclusive or Government/non-Government-shared frequency spectrum allocations is required [Refs. 6, 7, 8].

- **Compatibility and interoperability with lunar communications and navigation architecture plans** [Refs. 1, 2, 3]. Application of the emerging lunar standards includes frequency allocations per link functionality, modulation, coding, and networking protocol standards. Ka-band frequencies and above are highly desired.

### Relevance / Science Traceability:

Several missions are being planned to conduct investigations/observations in the cislunar region and beyond. For example, Commercial Lunar Payload Services (CLPS); Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE); human exploration (Artemis) landing site and resource surveys; lunar communications and navigation infrastructure, including LunaNet, Mars communications relay, etc. Commercial and NASA small spacecraft, lunar surface assets, and manned vehicles in cislunar space and beyond will multiply within the decade. All of these missions will depend on small-spacecraft communications relays, time reference transmissions, and navigation capabilities.

### References:


[7] National Telecommunications and Information Administration Tables of Frequency Allocations:
Relative and Absolute Deep Space Navigation

Scope Description:

Develop enabling technologies for beyond low Earth orbit (LEO) relative and/or absolute position knowledge. This situational awareness allows for autonomous control of small spacecraft as well as determining and maintaining position within a swarm or constellation of small spacecraft. In addition, timing distribution solutions for the SmallSats are important. Earth-independent and Global Positioning System- (GPS-) independent navigation and timing are enabling capabilities required by spacecraft to conduct NASA lunar and deep space distributed spacecraft science missions. Innovations in navigation technologies for distributed small spacecraft are essential to fulfill the science missions envisioned within the decadal surveys and contribute to the success of human exploration missions.

Multiple small spacecraft operating in coordinated orbital geometries or performing relative stationkeeping can further expand human knowledge deeper into the universe by performing coordinated occultation, acting as virtual telescopes, and forming distributed apertures that would be prohibitively complex and expensive to launch into space as monolithic structures. Small-spacecraft formation flight can also enable swarm gravimetry, synchronized observation of transient phenomena, and proximity operations for inspection of other assets. Realizing these capabilities on affordable small spacecraft requires sensors and maneuvering systems that are low in mass, volume, power consumption, and cost.

Further expansion of small spacecraft use into deep space requires highly accurate position knowledge and precision timing that does not depend on GPS or other Earth-centric aids. Exploration mission operations that involve multiple-element distributed-mission architectures may involve 30 to 100 spacecraft, and the general expansion of the number of cislunar and deep space missions will stress or exceed current capacity of the Deep Space Network (DSN). Access to DSN ranging may not be available for multiple concurrent missions, may be blocked by terrain for surface operations, or may be limited by the radio capabilities of smaller missions. In concert with other available signals of opportunity and landed beacons, small spacecraft can provide relative ranging or triangulation to aid lunar navigation. Knowledge at the spacecraft of relative (between-spacecraft) situational
Awareness is needed for real-time stationkeeping/relative position control where required rapid reaction speeds preclude human-in-the-loop operation.

Future small-spacecraft missions will need to autonomously determine and transmit relative and absolute position as well as keep and exchange precise timing. These capabilities are required for small spacecraft to act as infrastructure for other missions and for distributed missions composed of small spacecraft beyond Earth. Navigation technologies and techniques may include inertial navigation combined with enhanced visual navigation capabilities (e.g., dual use of star-tracking instruments for relative navigation using surface features or other nearby spacecraft), x-ray emissions (from pulsars), and laser rangefinding to other spacecraft or surface landmarks. For use with small spacecraft, these systems must be compatible with the inherent size, weight, power, and cost (SWaP-C) constraints of the platforms.

Precise timekeeping and timing exchange is not only required for navigation but is fundamental to science data collection. Internetworked small spacecraft can help synchronize timing across multiple mission assets using an external timing source. Improvements in chip-scale atomic clocks that can be carried by the small spacecraft themselves can augment this capability to reduce the accumulation of errors over time or serve as the primary clock when other larger but more accurate reference sources are not available or feasible. The vast majority of current commercial interests and Government missions operate in near-Earth orbits. To date, both NASA and the commercial spaceflight industry have enjoyed strong investment in near-Earth situational awareness made possible by tracking and identification capabilities provided by the Department of Defense. As the number of cislunar missions grows and NASA encourages the development of the lunar service economy, similar investments in situational awareness capabilities in these new orbital regimes will be needed to help support NASA and commercial operations.

Primary applications include navigational aids to lunar surface and orbiting users. Distributing these capabilities across multiple SmallSats may be necessary because of limited SWaP, but also to enhance coverage. Technologies for specific lunar architecture are especially needed, but considerations of extension to the martian domain are also solicited. Navigation solutions for deep space distributed spacecraft missions (DSMs) may be addressed via hardware or software solutions or a combination thereof.

**Expected TRL or TRL Range at completion of the Project:** 2 to 5

**Primary Technology Taxonomy:**
- Level 1: TX 17 Guidance, Navigation, and Control (GN&C)
- Level 2: TX 17.2 Navigation Technologies

**Desired Deliverables of Phase I and Phase II:**

- Prototype
- Software
- Hardware

**Desired Deliverables Description:**

Phase I: Identify and explore options for the deep space navigation technology, conduct trade analysis and simulations, define operating concepts, and provide justification for proposed techniques, frequency bands of operation, command and data handling, and networking solutions. Also identify, evaluate, and develop design for integrated navigation payload(s) and one or more constituent technologies that enable distributed spacecraft operations in the relevant space environment beyond LEO. Integrated navigation system solutions and constituent component deliverables should offer potential advantages over the state of the art, demonstrate technical feasibility, and show a path toward a hardware/software infusion into practice. Bench-level or laboratory-environment-level demonstrations or simulations are desirable. The Phase I proposal should outline a path that shows how the technology can be developed into space-qualifiable and commercially available small-spacecraft communications payloads through Phase II efforts and beyond.

Phase II: Demonstration of navigation technology via prototype or high-fidelity emulation. The relevant deep space
environment parameters should be simulated as much as possible.

State of the Art and Critical Gaps:

Science measurements of distributed satellite missions (DSMs) are based on temporal and spatially distributed measurements where position knowledge and control are fundamental to the science interpretation. Current space navigation technologies are not adequate when relative or absolute position knowledge of multiple spacecraft are involved. State of the art (SOA) for attitude is the Jet Propulsion Laboratory's ASTERIA (Arcsecond Space Telescope Enabling Research in Astrophysics) 6U CubeSat demonstrated pointing stability of 0.5 arcsec (0.1 microdeg) rms over 20 min using guide stars. For position knowledge, missions still primarily use ranging transponders relying on a two-way Earth link. Examples of SOA for this ranging are the Iris transponder and the Small Deep Space Transponder (SDST) [Ref. 13].

Global navigation satellite services like the United States' Global Positioning System (GPS) provide very limited services beyond Geostationary Earth Orbit distances, and no practical services in deep space. Autonomous navigation capabilities are fundamental to DSMs to ensure known topography of the configuration at the time of data acquisition. Control of the distributed configuration requires robust absolute and relative position knowledge of each spacecraft within the configuration and the ability to control spacecraft position and movement according to mission needs. Critical areas for advancement are:

- Long-term, high-accuracy attitude determination: In particular, low-SWaP absolute attitude determination using star trackers, etc., to achieve sub-arcsec accuracy.
- Optical navigation: Solutions are sought for visual-based systems that leverage advances in optical sensors (e.g., cameras, star trackers) to observe and track a target spacecraft and perform pose and relative position estimation. Opportunities for innovation include methods that do not require the execution of satellite maneuvers and/or the design of external satellite features that enhance observability. Innovations may be appropriate for only certain regimes, such as near, medium, or far range; however, this context should be described. Solutions for various lunar and deep space mission operations concepts are of interest.
- Other novel navigation methods: Stellar navigation aids, such as navigation via quasars, x-rays, and pulsars, may provide enabling capabilities in deep space. Surface-based navigation aids, such as systems detecting radio beacons or landmarks, are invited.
- Methods for autonomous position control are also of interest. Technologies that accomplish autonomous relative orbit control among the spacecraft are invited. Control may be accomplished as part of an integrated system that includes one or more of the measurement techniques described above. Of particular interest are autonomous control solutions that do not require operator commanding for individual spacecraft. That is, control solutions should accept as input swarm-level constraints and parameters and provide control for individual spacecraft. Opportunities for innovation include the application of optimization techniques that are feasible for small satellite platforms and do not assume particular orbit eccentricities. State-of-the-art in this area is the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE), the first spacecraft to attempt to navigate to and maintain a near-circular halo orbit around the Moon as a precursor for Gateway [Ref. 11]. NASA is also partnering with universities for use of surface-feature-based navigation and timing [Ref. 12].

NOTE: Small-spacecraft propulsion technologies are not included in this subtopic.

Relevance / Science Traceability:

Space communications and position knowledge and control are enabling capabilities required by spacecraft to conduct all NASA missions. The concept of distributed spacecraft missions (DSMs) involves the use of multiple spacecraft to achieve one or more science mission goals.

Several missions are being planned to conduct investigations/observations in the cislunar region and beyond. For example, CLPS; human exploration (Artemis) landing site and resource surveys; and lunar communication and navigation infrastructure, including LunaNet, Mars communications relay, etc. All of these missions will benefit from improved communications and navigation capabilities.

References:


