# Starling1: Swarm Technology Demonstration

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## ABSTRACT

The Starling series of demonstration missions will test technologies required to achieve affordable, distributed spacecraft ("swarm") missions that: are scalable to at least 100 spacecraft for applications that include synchronized multipoint measurements; involve closely coordinated ensembles of two or more spacecraft operating as a single unit for interferometric, synthetic aperture, or similar sensor architectures; or use autonomous or semi-autonomous operation of multiple spacecraft functioning as a unit to achieve science or other mission objectives with low-cost small spacecraft.

Starling1 will focus on developing technologies that enable scalability and deep space application. The mission goals include the demonstration of a Mobile Ad-hoc NETwork (MANET) through an in-space communication experiment and vision based relative navigation through the Starling Formation-flying Optical eXperiment (StarFOX).

## WHY DEVELOP SWARM TECHNOLOGY?

A swarm is a free-flying distributed system. Distributed systems in space can allow greater spatial coverage, fractionation, or modularization and have the advantage of reducing cost for maintainability, scalability, flexibility, and responsiveness when compared to monolithic systems.[1,2,3] Distributed systems can support exploration concepts that involve multiple robotic assets working in tandem with astronauts and science missions that require large sensor networks, such as a reconfigurable large aperture.[4] Also, these technologies do not have to be destination specific. If developed with the right goal in mind, distributed system technology can be tested in low Earth orbit and be applicable at any interplanetary destination, including the Moon or Mars. Deep space extensibility is especially valuable as the National Aeronautics and Space Administration (NASA) focuses on expanding an infrastructure of commercial and government assets to establish the Deep Space Gateway to support a system of landers, habitats, and robotic missions in cislunar space and eventually Mars.[5,6]

Managing a larger number of distributed systems introduces operational challenges, especially if current operation paradigms are maintained and humans remain in the decision-making process. Increasing the autonomy of communication network setup, data distribution, and relative navigation can reduce the operational burden of using these distributed systems. The 2015 NASA Technology Roadmap explains the need for adaptive networks and relative navigation in more detail.[7]

In Technical Area 5.3.2, the roadmap states that "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 Technical Area description concludes that "These technologies will allow networks to automatically adjust in size and data paths as they become increasingly complex."

Regarding relative navigation, Technical Area 5.4.4 of the roadmap states that "The ability to perform multiplatform relative navigation (such as determine relative position, relative velocity, and relative attitude or pose) directly supports cooperative and collaborative space platform operations." Onboard relative navigation can reduce the risks associated with time delays from ground commands. "Capable relative navigation sensors will offer a level of safety and reliability that will be crucial to future missions."

Swarm systems have several potential applications. Communication and navigation technologies that increase autonomy will enable greater use of swarm systems for exploration and science applications by reducing the operational challenges. Strategic visions like the Deep Space Gateway could be facilitated or extended in capability with the use of distributed autonomous system for communication or research.

## STATE OF THE ART

### *State of the Art: Crosslink Communication*

Crosslink communication has a long history in spaceflight. The Apollo program, developed in the 1960s, used crosslink communication between the astronauts and the Lunar Module (LM), and between the LM and orbiting Command/Service Module.[8] The Tracking and Data Relay Satellite (TDRS) System has been in operation since the 1980s for support of the Space Shuttle and now International Space Station, among other programs.[9] For science missions, crosslink communication is most notably an enabling technology for data relays for Mars rover missions. Mars orbiting relay satellites support rover science operations by allowing for higher data throughput than a direct-to-Earth communication and have supported mission–critical entry, descent, and landing activities by relaying real time data to Earth when direct communication is not available, such as with the Mars Exploration Rovers (MER) in 2004 and Curiosity Rover in 2012.[10,11,12]

Commercially, space-to-space communication services are now possible through multiple systems including Globalstar[13], Iridium[14], and Orbcomm[15]. These organizations sell simplex (one-way) and duplex (two-way) communication devices that allow spacecraft to relay information to or from the ground. Much like systems used for manned spaceflight, these data networks operate with a fixed topology and typically serve as a one-step relay to and from the ground.

The PTScientists (German) led Mission to the Moon aims to launch in 2019. This mission, in partnership with Vodafone Germany, will attempt to establish the Moon's first 4G network, connecting two Audi lunar rovers to a base station in the Autonomous Landing and Navigation Module (ALINA). Nokia Bell Labs will create the space-grade Ultra Compact Network radio that will weigh up to a kilogram.[16] The use of 4G technology for exploration pushes the envelope for in-space networking but will rely on a centralized infrastructure that cannot be replicated on smaller robotic missions and is susceptible to single faults.

Small crosslink radios are relevant to the long-term technology goals because they can be packaged into more systems and enable large swarms through a single launch. In the SmallSat and CubeSat field, multiple missions have attempted or successfully performed crosslink communication between two spacecraft. PRISMA (2010 launch)[17], FASTRAC (2010)[18], VELOX (2014)[19], CanX-4/5 (2014)[20], Nodes (2016), OCSD (2017)[21], and GOMX-4 (2018)[22] have all operated in space. A few others such as CPOD (late 2018) and Proba-3 (late 2020)[23] plan to operate in the near future. These two-spacecraft missions cannot demonstrate dynamic routing of crosslink packets since they cannot test multiple routing paths between nodes or experience transmit collisions from two spacecraft on one receiver.

The selection of SmallSat or CubeSat missions with three or more crosslinking spacecraft is limited. The Chinese Tianwang-1 mission, also known as TW-1, was launched in 2015 and operated three CubeSats that used Portuguese Gamalink radios and a CubeSat Space Protocol (CSP). The crosslink architecture relied on time synchronization and is the only known mission which claims to demonstrate an ad-hoc network.[24] Although functional, time synchronization relies on a common timing reference within the network when the Global Positioning System (GPS) is not available, such as in deep space. If the timing reference is lost, a new reference must be established.

The 3 Diamonds mission, launched in 2017, is a three-spacecraft pathfinder project for a 200-spacecraft Sky and Space (SAS) system that is scheduled to launch in 2020. 3 diamonds and SAS are funded by Sky and Space Global (British) and use Gomspace (Danish) buses and crosslink radios. Although the final flight network will use hundreds of spacecraft, the concept of operations only requires three spacecraft to communicate together at one time.[25]

The Isreali Adelis-SAMSON mission plans to use crosslink communication between three spacecraft to share GPS data and perform autonomous cluster flight later this year (2018).[26] The communication technology will not attempt to demonstrate dynamic routing, scalability, or large data transfer over the crosslinks. From available information, it does not appear that data will be relayed over crosslink (multi-hop).

Very few missions have attempted communication with more than three CubeSats in a dynamic manor. A few years ago, NASA's Edison Demonstration of Smallsat Networks (EDSN) mission developed a communication architecture for eight 1.5U CubeSats. The system relied on scheduled communication windows and a star network topology. The mission allowed a hub ("Captain") to collect swarm telemetry and then transmit the data to the ground at the next available opportunity. The hub role rotated to a different spacecraft after about a day. As a result, the communication topology was not fixed and varied on a pre-defined time interval in order to increase robustness to spacecraft losses.[27] These scheduled activities required synchronization through a GPS time reference.

Despite robustness to loss of multiple spacecraft, the entire EDSN system was lost due to a failed launch in 2015.[28] Two engineering units from EDSN were upgraded and later flew from the International Space Station in 2016 as part of the Nodes project. The Nodes design extended the EDSN capability by allowing for dynamic reconfiguration of the network. The two spacecraft exchanged health information to determine who should relay data to the ground.[29]

The EDSN and Nodes method of communication was effective but not efficient. The architecture was limited in the ability to detect a missing spacecraft and dynamically adjust, did not support multiple-hop (two or more consecutive crosslink) communications for downlink, and was prone to packet loss (roughly 1/3 of packets transmitted were received).[30]

### *State of the Art: Ad-Hoc Communication*

On the ground, the growing use of mobile phones, laptops, and the recent expansion into the grander "Internet of Things" have created a growing community interest in developing Mobile Ad-hoc NETwork (MANET) protocols. These MANET protocols aim to establish peer-to-peer, self-configuring, and infrastructure-less networks that allow for dynamic topologies. To work, each communication device must serve as a router if needed.

MANET Routing protocols can be grouped in four categories, Table-driven, On-demand, Hybrid, and Hierarchical. The general characteristics of the categories are summarized here.[31]

Table-driven (proactive)

- Each node maintains one or more tables of routing information
- Each node works to update its table(s)
- Cons: Large routing data overhead and relatively slow reaction to restructures/failures

On-Demand (reactive)

- Routes are created when needed
- Employs on-demand route discovery
- Cons: Routes exist only while needed and are recreated each time, which can cause delays

Hybrid

- Uses a mixture of proactive and reactive techniques
- Nearby routes are managed proactively, more distant routes are set up reactively
- Cons: Little expected benefit in dynamic and homogeneous systems like swarms

Hierarchical

- Choice of proactive or reactive routing depends on the hierarchic level in which the node resides
- Routing is initially established with some proactively prescribed routes and then serves the demand from additionally activated nodes through reactive flooding
- Relative advantage of this scheme depends on the depth of nesting
- Con: Little expected benefit in dynamic and homogeneous systems like swarms

As part of the Starling1 effort, a survey was performed of MANET protocols in development. Table 1 shows the protocols organized by category. The protocols have varying degrees of use, but none of these protocols have been demonstrated in space and little is known about how well they can perform on available flight-proven crosslink processors and radios.

**Table 1: MANET Routing Protocols by Category**

| Proactive | Reactive | Hybrid | Hierarchical |
|---|---|---|---|
| Optimized Link Routing Protocol (OLSR) | Associativity-based Routing (ABR) | Zone Routing Protocol (ZRP) | Cluster-based Routing Protocol (CBRP) |
| Better Approach to Mobile Ad hoc Networking (BATMAN) | Ad hoc On-Demand Distance Vector (AODV) | Zone-based Hierarchical Link State (ZHLS) | Fisheye State Routing Protocol (FSR) |
| Destination Sequence Distance Vector (DSDV) | Flow State in the Dynamic Source Routing | DREAM | Order One Network Protocol (OONP) |
| Babel | Dynamic Source Routing | | |

### *State of the Art: Swarm Navigation*

By 2016, at least 8 large-satellite and 14 SmallSat missions had performed proximity operations between at least two spacecraft. A majority of these missions involved ground operations and multiple sensors that included GPS.[32] To support human exploration and deep space application, solutions that require GPS receivers are not ideal because a GPS equivalent service is not available. Starling1 also desires a simplified sensor suite that can be used on non-cooperative objects to reduce volume, cost, and technical risk.

Through NASA, the CubeSat Proximity Operations Demonstration (CPOD) project will demonstrate rendezvous, proximity operations and docking using two 3U CubeSats. To provide the relative orbit knowledge needed for docking, the two spacecraft will use an inter-satellite link to share data, such as GPS, and for ranging. The Rendezvous, Proximity Operations (RPO) Payload will contain visible and infrared imagers, a docking sensor, and an optical target aid.[33]

The Optical Communications and Sensor Demonstration (OCSD) mission uses a GPS receiver and a proximity camera to find and point toward a target spacecraft. A laser rangefinder is then used to determine distance.[34]

Canadian Advanced Nanospace eXperiments 4 and 5 (CanX-4 and CanX-5) use carrier-phase differential GPS techniques to obtain relative orbit measurements accurate to centimeter-levels in position.[35] Although this is one of the most accurate relative navigation solutions for SmallSats,[32] it does depend on GPS.

A few missions, such as Adelis-SAMSON and Shiver will attempt close-range formation flying between three or more spacecraft in the near future. Shiver, a Starling1 partner project managed by the Air Force Research Laboratory (AFRL), will attempt to perform autonomous station keeping between four 12U spacecraft systems. GPS receivers will be used for orbit knowledge and the ground system will distribute the orbit telemetry among the four spacecraft systems.

The Advanced Rendezvous using GPS and Optical Navigation (ARGON) experiment on the Prototype Research Instruments and Space Mission technology Advancement (PRISMA) mission was one of the first missions to attempt vision-based relative navigation with a non-cooperative target.[36] In April 2012, ARGON used angles-only measurements and a hydrazine propulsion system to perform a ground-based rendezvous of two SmallSats from 30km to 3km.

The Autonomous Vision Approach Navigation and Target Identification (AVANTI) experiment on the Bi-spectral InfraRed Optical System (BIROS) mission improved the vision-only relative navigation capability.[37] In November 2016, a microsat and nanosat performed autonomous rendezvous from 10km to <100m using a cold-gas resistojet.[38]

Both ARGON and AVANTI used star-trackers and GPS receivers. The GPS receivers were used for determining the orbit of the observing spacecraft. The star-trackers were used to determine the orbit of the targets. The passive sensors allow the system to determine the relative orbit of non-cooperative objects.

Fundamental limitations of previous vision-based relative navigation experiments such as ARGON and AVANTI are: 1) the execution of frequent orbit control maneuvers to improve observability of angles-only navigation; 2) the use of a-priori information on the target object to initialize the navigation system; 3) the identification and association of a single target in the field of view of the optical sensor. All these limitations need to be addressed and overcome to support autonomous operation of a swarm.

## STARLING1 MISSION

Starling1 will fly four 12U spacecraft into a low Earth, polar orbit and demonstrate technologies for in-space communication networking and non-cooperative vision-based relative navigation. Starling1 will be the first known mission to attempt dynamic network routing with at least four spacecraft. It will also be the first mission to attempt vision-based relative navigation with more than one target object. The mission will characterize both experiments in order to facilitate future development or provide justification for continued use of the technology.

### *Project Goals*

The two goals of the project are to:

1. Provide a platform that supports swarm technology development
2. Develop technology that enables large scale, destination agnostic swarms

The first goal is to build a system that performs the functions that have been demonstrated on prior missions. The requirements associated with this goal are to interface with a launch vehicle, operate for a minimum of 3 months, conduct basic in-space peer-to-peer communication, determine orbital elements, and to perform maneuvers.

The second goal is to advance the state of the art for distributed space systems. For applicability to future, deep space missions, there is a desire to not rely on Earth-centric technologies, such as GPS. The requirements associated with this goal are to test peer-to-peer multi-hop communication, establish the network topology without ground command, perform radiometric ranging and estimate the relative orbit of a non-cooperative target using optical observables without a-priori information.

***Proposed Solution: System***

The Starling1 project is currently in Phase-A defining requirements and performing preliminary analyses. Mechanical and electrical designs are not complete, but the general concept and mission needs have been defined. The overall development is managed as a Research and Technology Project under NASA Procedural Requirement (NPR) 7120.8 and will aim to tolerate high levels of risk, even in comparison to Class D missions as defined under NPR 8705.4 (Risk Classification for NASA Payloads).

In order to meet mission goals and requirements, the system will use four flight spacecraft for in-space communication and optical navigation. To minimize the initial dispersion of the swarm, the project will work with the launch vehicle provider to constrain the direction of deployment. Ideally, the deployment will be normal to the velocity vector where the effects of variation in dispenser ejection velocity are minimized.

***Proposed Solution: Swarm Communication***

The in-space communication will use existing CubeSat radios, augment them with carrier-sense capability for collision detection and avoidance, and implement an ad-hoc networking protocol to establish routing paths. The ability to perform carrier-sense will allow the system to operate without requiring time synchronization. Two patch antennas will be placed on opposite faces to provide near spherical coverage.

The Better Approach to Mobile Ad hoc Networking (BATMAN) protocol was chosen for further study based on availability, maturity, and ability to adapt and scale in an environment of limited network traffic and changing topology.

A community wireless network group in Berlin, Germany called “Freifunk” (Free Radio) is developing BATMAN as a replacement to the OLSR protocol that they currently use.[39] Most other wireless routing protocol implementations operate on Layer 3 of the Open Systems Interconnection (OSI) model, which means they exchange routing information by sending User Datagram Protocol (UDP) packets and make routing decisions by manipulating the kernel routing table. BATMAN operates entirely on OSI Layer 2 and avoids manipulation of Layer 3. BATMAN handles information routing and data traffic by encapsulating and forwarding all traffic until it reaches the destination, hence emulating a virtual network switch of all nodes participating. The overall advantage is that BATMAN can be implemented closer to the hardware and impacts fewer layers of the overall communication protocol when the network topology changes. This allows BATMAN to be network-layer (Layer 3) agnostic, to the point that a device can connect to the network with or without an Internet Protocol (IP) address.

In BATMAN, all nodes periodically broadcast packets, known as originator messages, to its neighbors. Each originator message consists of an originator address, sending node address, and a unique sequence number. Each neighbor changes the sending address to its own address and re-broadcasts the message. On receiving its own message, the originator does a bidirectional link check to verify that the detected link can be used in both directions. The sequence number is used to check the currency of the message. BATMAN is decentralized and does not maintain the full route to the destination. Each node along the route only maintains the information about the next link through which you can find the best route. This makes it suitable for spacecraft networks where resources are limited and routes may change frequently.

BATMAN, as the batman-adv kernel module, has been part of the official Linux kernel since release 2.6.33 in 2009 and has relatively high maturity for a protocol with available source code.[40] Through preliminary prototype testing using BeagleBone Blacks and WiFi radios, the BATMAN protocol demonstrated a sufficient ability to adapt to topology changes. These internal test results agree with other published finding.[41]

A comparison of performance between BATMAN, OLSR, and AODV shows that BATMAN provides good overall performance even as the number of nodes increases to 250 and as the number of hops required for a transfer increases to four. BATMAN was shown to require lower overhead than OLSR and operated with lower delay times.[42]

An extension of BATMAN has also demonstrated an ability to perform store-and-forward functions that are important to a Delay/Disruption Tolerant Network (DTN).[43] DTNs are appropriate for in space applications where line of site (such as with ground stations) are not always available or if crosslinks are temporarily lost. DTN and BATMAN store-and-forward functions are being assessed for applicability to Starling1 and future missions.

The BATMAN routing protocol will likely undergo modification in order to account for spaceflight hardware limitations, such as radio design and limited bandwidth and power. Routing table refresh rates may also have to be adjusted to accommodate for any oscillating orbital behavior of the network.

### *Proposed Solution: Swarm Navigation*

For relative orbit knowledge, an advanced optical navigation system called Angles-only Relative Trajectory Measurement System (ARTMS) is under development for Starling1. The system will use a commercial star tracker to provide images that can be processed autonomously onboard and post-facto on ground. ARTMS will process the images obtained by the observer spacecraft to detect multiple target spacecraft of the swarm against a background of known stars, create a centroid on the clusters of pixels, and determine the orbits of the target relative to the observer. The core algorithm makes use of an adaptive Unscented Kalman Filter (UKF) to estimate the relative orbital elements of the targets by processing sparse angle measurements and using coarsely known observer orbit and attitude data. In contrast to the state of the art, by accounting for orbital dynamics, ARTMS does not require the execution of dedicated observability maneuvers of the target spacecraft.

As part of the experiment, GPS data will be used on-ground to validate the angles-only navigation results but will not be required for estimating the orbit of the target spacecraft. To demonstrate deep-space applicability, Two-Line Elements (TLEs) will be uplinked from the ground to provide coarse knowledge of the observer orbit and initialize ARTMS on-board.

### *Extended Mission*

The scope of Starling1 is to create a platform and demonstrate new technology for crosslink communication and navigation. The integration of crosslink communication with navigation knowledge to perform autonomous coordinated flight has higher development risk and is only being considered as an extended mission, if the crosslink communication and navigation technology proves successful. This extended mission effort would be operated by the Distributed Satellite Autonomy (DSA) project, also based out of Ames Research Center and funded under NASA's Game Changing Development Program. The integration of a MANET protocol and ARTMS would allow for the first ever demonstration of distributed angles-only navigation across a space swarm with multiple observers and targets for synthetic stereoscopic vision.

Another option for an extended mission is to update the software, communication protocols, or configuration and performance tables in flight. OLSR and DTN protocols could be implemented for a direct comparison against BATMAN on identical hardware and in an identical environment.

## EXPECTED CHALLENGES

### *Challenges: Swarm Communication*

A uniformly spherical antenna coverage would eliminate pointing as a factor when determining network performance. However, additional antennas increase complexity, cost, and risk and isotropic radiators do not exist. A monopole ("whip") or dipole antenna can provide omnidirectional coverage and provide the largest view angles if the radiator can be separated from the spacecraft body. Monopole and dipole antennas on dispenser released CubeSats, such as Starling1, require some form of constraint and deployment. To maximize coverage with minimal complexity, two low-gain patch antennas will be located on opposite faces of the satellite. The orientation of the antennas will have to be accounted for when assessing the performance of the networking protocol.

Of the existing space-qualified radios, none have developed collision detection features that are common on terrestrial hardware, such as carrier-sense on IEEE 802.11 (WiFi) devices. In order to avoid transmit collisions without precise timing coordination, carrier-sense features need to be development for flight radios.

Although MANET protocols have operated on the ground with success, the space environment and cyclical drop-outs that can occur in space will present new challenges. Dynamic simulations will be built to test the BATMAN protocol before flight, but factors like beam pattern, radiation, and thermal noise on hardware will not be possible to model (under the current project budget). Additionally, porting the BATMAN protocol to a space-rated processor and radio may present unforeseen incompatibilities.

### *Challenges: Swarm Navigation*

The challenge of swarm orbit maintenance is common to the communication experiment and relative navigation experiment. In order to maintain the spacecraft within communication range and optical viewing range, at least three of the four spacecraft will need the ability to maneuver. Planning the maneuvers with orbit propagation uncertainties for all spacecraft means that maneuvers have to be well timed to minimize error and avoid collision. In addition, all executed maneuvers must be known by ARTMS for proper incorporation into a navigation solution.

Despite the simplicity of sensors for a purely optical navigation solution, there can still be a relatively high data volume. During commissioning, each spacecraft will have to store several images onboard and downlink them to the ground for processing. Once demonstrated to work, the data processing can continue onboard. The estimated orbit of the target can be sent to the ground and the ground can validate the results based on GPS data received from all spacecraft. Overall, special emphasis will be put on the ground validation effort since robustness of an angles-only navigation system is limited due to weak observability when no orbit control maneuvers are performed.

### *Current Gaps in Technology*

The data from the in-space demonstration of Starling1 will be used to characterize existing technology capability, but it will also be used to identify technology needs. Even at this early stage, it is already apparent that there is no existing s-band antenna system that can provide spherical coverage for CubeSats, flight-proven deep space CubeSat busses, or radiation tolerant radios that use state of the art terrestrial technology like 4G or IEEE 802.11. These technologies are not critical to Starling1 but might be desired on future projects in the Starling series of missions or required on future distributed systems for explorations.

## FUTURE WORK

The bus development and spacecraft integration and test will be performed in partnership with the Small Satellite Portfolio group at AFRL. AFRL's Shiver mission will use an identical bus to Starling1.

Currently the launch of Shiver and Starling1 is planned for late 2020. The expected launch will be from a Minotaur IV vehicle out of Vandenberg Air Force Base. Once officially manifested, launch interface discussions and launch integration plans will begin.

Autonomous operations and considerations will be coordinated with the DSA project which will potentially operate the four-spacecraft swarm after all Starling1 objectives are met.

## CONCLUSION

The long-term vision of human exploration will rely on distributed systems. Starling1 will take steps in developing new network communication and relative navigation capabilities that will enable scalable, autonomous operation of distributed systems.

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