

GPS Micro Navigation and Communication System for Clusters of Micro and Nanosatellites

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Abstract. Formation flying will quickly revolutionize the way science, remote sensing and surveillance missions are performed in space, enabling a whole new range of applications for small satellites. Currently, there are numerous missions in the planning stages involving formation flying of a constellation of micro or nanosatellites. However, to truly achieve the goals of these formation-flying missions, an accurate means of relative ranging, determining time and position measurements, inter-satellite communications, and controlling the formation states is becoming critical.

Today, while there are very expensive products available for positioning and attitude determination, none of them are capable of meeting the precise positioning accuracy and attitude determination requirements of formation flying, let alone the mass and power restrictions of these tiny space vehicles.

This paper will address the needs of future formation flying missions by discussing a technology with integrated capabilities for communicating, relative ranging, and exchanging precise timing among spacecraft within the constellation. This system is being developed by integrating a Carrier Phase Differential GPS (CDGPS) navigation and attitude sensor with a low power, inexpensive, compact ranging and communications system. The result of this integration is a low-cost, robust, secure GPS micro navigation and communication system for micro and nanosatellite constellations.

Introduction

AeroAstro is developing an inter-satellite navigation, communications and ranging system to meet the needs of future micro and nanospacecraft missions. This system, named Star Ranger, will enable a variety of future formation-flying constellation missions.

Although formation-flying missions are continuing to become a more intriguing option for mission planners, an accurate means of determining relative range and position measurements, providing inter-satellite communications, and controlling the formation states (i.e., the relative attitude and

positions of the vehicles) is critical to meet mission goals. Currently, there are little or no options available to meet these mission requirements.

AeroAstro's Star Ranger technology addresses the needs of future formation flying missions by providing a system with integrated capabilities for communicating, relative ranging, and exchanging precise timing among spacecraft within the constellation. This Star Ranger system leverages existing technologies developed for use in power-efficient and lightweight communications technology.

Background

Since its inception, AeroAstro has been actively involved in developing a variety of low-cost technologies to exploit the use of space for scientific and commercial applications. In recent years, much of this development has been focused on components and technologies to be used on the AeroAstro Bitsy™ spacecraft kernel, a fundamental nanospacecraft core module which enables flexible, affordable missions.

Over the past few years, formation-flying missions have begun to gain appeal as mission designers began to recognize the benefits of combining multiple small assets to meet larger mission goals. This approach is typically more cost effective in the long term, due to the economies of scale enabled by large production runs of the small satellites, the adaptability of the system, and the ability to reduce launch costs through use of smaller secondary launch opportunities.

Through years of experience in the small satellite industry, AeroAstro recognized that there was a need for a variety of subsystems to support these new formation-flying missions. Star Ranger is just one of the low-cost components that AeroAstro is developing to meet the requirements of upcoming small multi-spacecraft missions.

The Bitsy spacecraft kernel and AeroAstro's Small Payload Orbit Transfer (SPORT) vehicle, which is an ideal delivery system for multiple spacecraft, are two other examples of technologies being developed for multi-spacecraft missions. In addition, AeroAstro is currently actively involved in the design of a highly integrated, power-efficient, X-Band telemetry transponder for nanospacecraft. This technology is baselined for the New Millennium ST-5 mission, the Nanosatellite Constellation Trailblazer. As it is inexpensive

and lightweight, it is ideal for missions requiring multiple small spacecraft.

Recently, the opportunity arose to develop the Star Ranger concept for flight on the Air Force Research Laboratory TechSat 21 demonstration mission. This development is allowing AeroAstro to leverage the technology and design concepts from ongoing communication development programs, the X-Band transponder development in particular. This AeroAstro experience will be combined with emerging RF component technology being developed for digital wireless communications, VSAT, and Direct Broadcast Entertainment. Use of this new, low-voltage technology will enable considerable reductions in complexity, mass, and cost needed for innovative yet low-cost communication and navigation products for these missions of the future.

Market Demand

As satellites continue to grow smaller, a whole new range of applications becomes feasible, formation flying missions in particular. Formation-flying spacecraft will revolutionize the way that science and surveillance missions are performed in space. Rather than using a single, large, expensive satellite to perform a given mission, many small, inexpensive satellites can be flown in a constellation more effectively. In the constellation configuration, significantly larger quantities of science data can be obtained, providing greater return on the overall investment.

In general, the concept of a constellation mission is to replace a large satellite with a "virtual satellite," a cluster of smaller satellites, typically flying in formation. In this configuration, each satellite has sufficient autonomy and collaborates effectively with its companion satellites in the cluster, but from

the users' standpoint, the cluster appears as one single satellite and sensor.

Through the deployment and management of clusters, constellations, or formations, the virtual satellite will be able to use multiple spacecraft to achieve an overall larger aperture, for monitoring low-power terrestrial sensors, for remote sensing, or for mapping the relationship between Earth and the sun. The distributed aperture provides increased angular resolution, greatly offsetting disadvantages of large clutter spread arising from each satellite's smaller aperture. Having many satellites in the cluster offsets the small signal to noise ratio of each satellite. By providing highly accurate angular information, the ambiguity in Doppler between "stationary" ground clutter and moving targets can be resolved.

Currently, there are numerous missions in the planning stages involving formation flying of a constellation of micro or nanosatellites. NASA is developing the Nanosatellite Constellation Trailblazer mission, designed to validate technologies for future nanosatellite constellation missions, such as the Magnetospheric Multi-Scale (MMS), Geospace Electrodynamics Constellation (GEC) and the Magnetosphere Constellation (MagCon) missions. The U.S. Air Force Research Laboratory is currently developing a demonstration for its future TechSat 21 mission. The TechSat 21 concept is a revolutionary approach to space-based surveillance systems, which will construct a cluster of small satellites orbiting in formation to create a distributed aperture.

These new missions will require integrated capabilities for communicating, relative ranging, and exchanging precise timing among spacecraft within the constellation to make them usable tools. In an optical application, the baseline of the sensor is an

important factor. In a radio application, both precise baseline and timing measurements are required to resolve phase, frequency, and time of arrival.

On the other hand, some missions will not need the precision of optical or radar interferometric measurements, but are likely to require the less precise ranging and communications capabilities over longer ranges. In these instances, it will be necessary to have knowledge of the distance or spacing between the constituent satellites and transfer information from one satellite to another in a multi-access method. These applications place significant burdens on metrics, circuit complexity, and power levels in order to achieve high-precision measurements over large ranges. While each of these missions has its own unique requirements, many of the basic needs are the same, permitting similar techniques to be used to achieve mission goals.

In order to enable future formation-flying missions, such as the ones described above, a number of key technologies need to be developed. First, a method of accurately determining range and relative position among the constellation's satellites is required in order to precisely control the formation states. Next, a way of enabling inter-satellite communications is needed to allow the transfer of engineering data among the spacecraft. Minimizing the dynamics of the formation is also critical to reduce the fuel necessary to maintain the formation.

Regardless of the specific requirements of a given mission, to achieve the goals of formation flying spacecraft, the inter-satellite ranging and communications system must be inexpensive, lightweight, and power-efficient.

As these needs become more apparent, inter-satellite ranging and communications is

becoming an area that is gaining interest in the government organizations that are responsible for these missions as well as commercial organizations, such as AeroAstro, who are interested in helping to make these micro and nanospacecraft constellations a reality.

Today, while there are very expensive products available for positioning and attitude determination, none of them are capable of meeting the precise positioning accuracy and attitude determination requirements of formation flying, let alone the mass and power restrictions of these tiny space vehicles. In order to efficiently deploy a constellation mission, the cost of each individual spacecraft needs to be kept low, or else total mission costs can spiral out of control. While some of the ranging products currently available might be acceptable for larger, more expensive satellites, they are prohibitive for nanosatellite constellations, in terms of both cost and mass.

The Solution: Star Ranger

AeroAstro is currently developing Star Ranger, a technology that will meet the inter-satellite ranging and communications needs of future formation flying missions. This work is being done through funding from the Air Force Research Laboratory, in anticipation of their TechSat 21 demonstration mission. Star Ranger development is leveraging work currently underway at AeroAstro on low-cost, lightweight communications components, baselined for flight on the ST-5 mission, as well as advances in commercial technologies such as wireless communications.

The goal of the Star Ranger effort is to develop a flexible system, capable of performing a number of different functions. It will provide capabilities for relative ranging to sub-centimeter accuracy, centimeter-level relative positioning, and attitude determination

to within 0.5°. It will also provide a duplex 128 kbps engineering data link between satellites to pass GPS differential correction information and to serve as an emergency uplink path through companion satellites to both communicate with or reboot the spacecraft Command and Data Handling (C&DH) system. Star Ranger will also exchange precise timing among the spacecraft in the constellation.

Design Features

There are a few key design features that enable Star Ranger to meet its requirements. Due to a requirement by AFRL to have a robust yet secure link between satellites, Star Ranger uses Ku-Band for its operation. It utilizes direct sequence spread spectrum (DSSS) for precise ranging. A two-PN code technique will be used for enabling multiple access among the three satellites within the formation. Bi-phase modulation (BPSK) will be used for modulating the engineering data link onto the PN code. Carrier-phase Differential GPS (CDGPS) has been chosen for the determination of relative position and attitude between the formation flying satellites.

The DSSS ranging system operates in the same manner as would a communications system based on the same technology. PN codes modulate the carrier while the engineering data is bi-phase modulated onto the PN code. The PN code of a spread spectrum signal is comprised of a series of chips, where each chip represents an equal and divisible portion of the total range, just as the marks on a ruler represent equal portions of the total measurement.

In the case of this ranging system, engineering data is sent as BPSK modulation on the PN code or baseband. Despite the fact that both

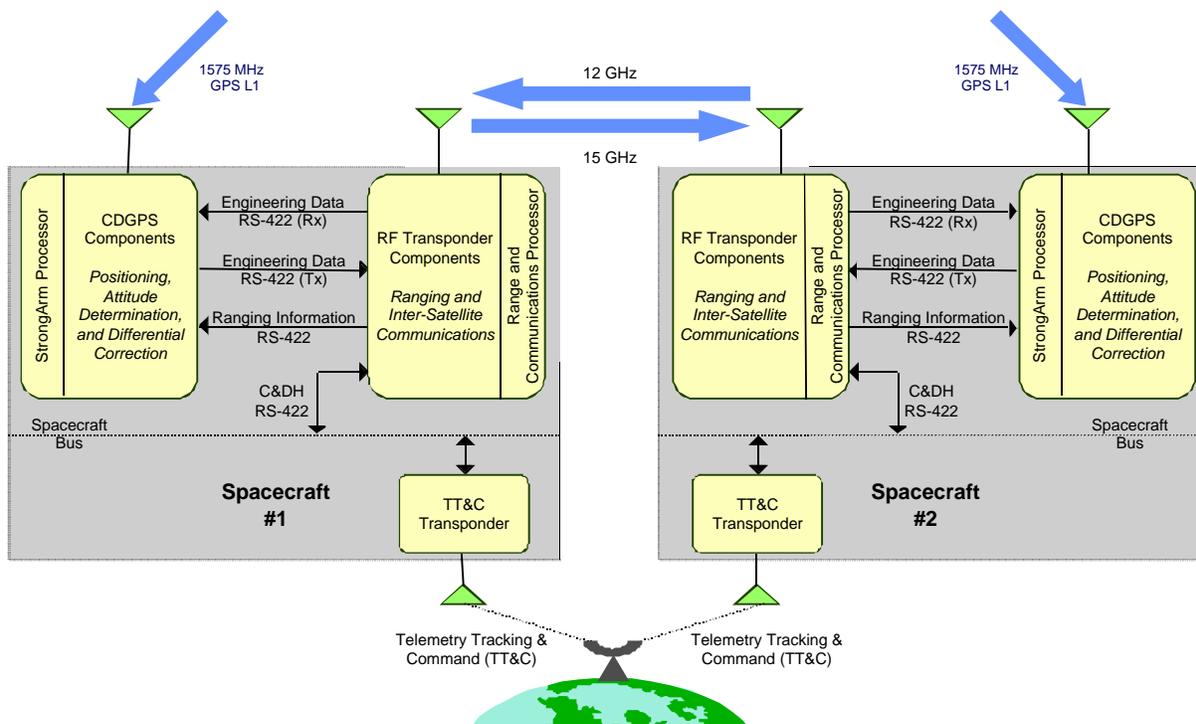


Figure 1. Star Ranger Conceptual Diagram

the ranging function and the transmission of engineering data share the PN code, they are completely unaffected by each other. In fact, in the Star Ranger system, ranging coefficients and GPS differential corrections are sent back and forth as engineering data between spacecraft, enhancing the operation and precision of the ranging, timing, and navigation functions.

AeroAstro has studied two basic techniques in the application of DSSS ranging that directly apply to ranging and communication between satellites at short and long distances. The first method is a simple, transmit and receive method, and the second is a slightly more complex method using a full duplex technique. For Star Ranger, AeroAstro has chosen the full duplex method, because it allows the transmitter and receiver to operate in a phase-coherent relationship. This permits precise timing to be continually passed between spacecraft without the necessity of

re-acquisition of the receiver's direct sequence signals each time a spacecraft switches between transmit and receive modes.

The use of a two-PN code technique was chosen to greatly accelerate the code acquisition, allowing each satellite to acquire ranging and communication signals rapidly from each other. The intent of the two-code system is to use a shorter acquisition code of 1023 chips in length, purely for initial acquisition purposes, rather than wait for the acquisition of a single long ranging code. The system will use the long code for precision tracking.

Star Ranger's modulator/demodulator generates both short and long PN codes for the transmitter and receiver correlation function. Modulation, or spreading of a DSSS signal, takes place, in this case, as a two-step function. First, each PN code is bi-phase modulated with the engineering data. Then,

the transmitter first local oscillator (LO) is mixed with each of the PN codes, and both PN codes are then modulated with the same engineering data simultaneously. This allows engineering data to be transferred between satellites on the short PN code even if the long code has not been acquired. Two streams of engineering data can also be sent separately using this method, one on the short PN code and one on the longer precise navigation code. While the system also lends itself to the application of QPSK modulation of the PN code, BPSK was chosen due to the reduced complexity in implementation. Either technique would double the engineering data throughput.

The receiving demodulator is slightly more complicated in that it must de-spread the spread spectrum signal and acquire the PN code in a correlating function. The bi-phase or BPSK engineering data is extracted from the incoming long and short PN codes. To determine range, the incoming long PN code is compared to the original transmitted PN code so that delay and phase for the range measurement can be determined.

AeroAstro has been exploring the application of multi-access, multi-node communications among the constituent spacecraft of a constellation. Multi-access is the ability of a number of transmitters to communicate with a number of receivers simultaneously on the same frequency. If the proper communication architecture is exploited, a satellite within a constellation should be able to communicate with any other satellite within a constellation.

In the particular application that Star Ranger is addressing, there is the need for all spacecraft to pass information among the constellation's satellites, consisting of ranging, positioning, and engineering data. One or more spacecraft must be able to transmit and receive, within the same bandwidth, simultaneously

communicating with specific spacecraft within the constellation.

In certain circumstances, there may also exist the need for one or more satellites to assume a major communication node role. This is a preferred state for simplification of communications of the constellation with Earth and necessary when a constellation is in a highly elliptical orbit and only a single spacecraft is close enough to the Earth to have a good communication link. In this configuration, one spacecraft within the constellation would assume control, as the primary node, for all communications between the constellation and the Earth, but each of the spacecraft would have the capability to act as the primary node.

The CDGPS used in Star Ranger is capable of relative positioning, using measurements from the NAVSTAR GPS constellation. CDGPS sensing techniques were chosen for Star Ranger because they provide very precise measures of the relative attitude and positions between vehicles in formation. To date, an accuracy of approximately 2 cm has been achieved through use of carrier-phase differential GPS. CDGPS data will also be used for attitude determination. In the present design, the CDGPS receiver has been combined with an embedded StrongARM processor, which is well suited to the low power and intensive computation requirements of formation flying spacecraft.

A second correlator and RF front-end ASIC have also been added, which share a common clock to aid in the synchronization necessary to make GPS differential carrier phase measurements between separate antenna inputs possible. By adding the second correlator, there has been a significant increase in the number of GPS satellites that can be tracked, a crucial factor in the performance and robustness of an on-orbit

GPS receiver. The two-RF correlator configuration used in the CDGPS also makes more efficient use of the already existing ARM60 processor onboard each GPS card.

Preliminary hardware testing and simulations indicate that the information required to initialize the onboard GPS receivers is relatively easy to obtain using the GPS constellation. Due to the expected natural motion of the TechSat 21 fleet of vehicles, upon which Star Ranger will be used, there will be numerous on-orbit, large-scale changes in the lines of sight to the GPS constellation. Recent analysis indicates that this relative motion of the vehicles within the formation can be compensated for by rapid dynamic resolution of the integers associated with the measurements between satellites through the very quick exchange of ranging and differential corrections transmitted over Star Ranger's data link. Better control of the formation's dynamics through quicker navigation updates will greatly reduce response time and fuel consumption of the satellites within the formation.

Star Ranger Capabilities

Specifications

Star Ranger is a highly capable, yet lightweight and inexpensive system. Based on the current design, a preliminary set of projected performance specifications has been developed. The ranging accuracy of Star Ranger is expected to be 1 cm or better, and the ultimate goal is set at 3 mm. Using CDGPS, it is expected that the relative attitude between spacecraft will be determinable to 0.5° or better. In addition, the overall relative position of each spacecraft with respect to each other will also be measurable to less than 1 cm, with a goal of 5 mm.

Star Ranger will be small and lightweight. Currently, the engineering model, including antennas, is projected to have a mass of less than 2 kg. As the design effort continues, an integrated approach to the higher frequency portion of Star Ranger is being explored. Presently, the design combines the front-end portion consisting of antenna, diplexer, LNA and up/down converter in a single assembly. This configuration was chosen to place the Ku-Band components close to the antenna to reduce the amount of loss between antenna and processing electronics. During this process, it is our intent to further reduce the overall mass during optimization of the engineering model.

Applicability to Future Missions

Star Ranger, or variations of the Star Ranger technology, will be capable of meeting the needs of a variety of constellation missions. While the specifications described above are those currently baselined for Star Ranger, the overall design concept will be flexible, allowing moderate changes in specification. For example, in some circumstances, a user might wish to trade off the high precision ranging accuracy for an increased range over which Star Ranger is operational. On another mission, where the use of GPS for angular determination might not be feasible, an alternate method using multiple antennas on each spacecraft might be an option.

The first mission for which Star Ranger will be utilized is the TechSat 21 mission. This mission is currently in the development stages, and AeroAstro has been working with the mission team to ensure that Star Ranger development is in line with mission requirements. As this development work is being funded by AFRL specifically for the TechSat 21 mission, the Star Ranger baseline specifications are aimed at meeting TechSat 21 requirements. However, the Star Ranger

design will remain flexible in order to permit it to be applicable to other missions.

The NASA Magnetospheric MultiScale mission, also currently under development, would be another ideal candidate for Star Ranger technology. While some of the mission requirements vary from that of TechSat 21, many of the same principles could be applied to MMS. In this particular application, the ranging precision requirements are a lot less stringent. However, the range over which the system must be operational is much greater.

MMS is just one of the missions in the NASA Sun-Earth Connections group. Two other missions, the Magnetospheric Constellation (MagCon) and the Geospace Electrodynamics Connections (GEC) missions, each of which are comprised of multiple spacecraft, would benefit from Star Ranger technology. The GEC mission profile is similar to the TechSat 21 mission, so it is likely Star Ranger could provide the capabilities required for inter-satellite ranging and communications on that mission. As with TechSat 21, the MagCon mission will be constrained in physical size (about the size of a large birthday cake), and therefore will have limited space for effective antennas. In addition, there will be extreme constraints on power consumption of the ranging and communication subsystem. A total integration of space-to-space communication and ranging with the space-to-Earth link is being considered for MagCon, due to these constraining factors. This is an option that AeroAstro is continuing to consider in the long-term Star Ranger development plan.

In order to truly exploit the capabilities of Star Ranger, future versions are likely to incorporate software that will enable high-level control of the microsatellite constellation

as a whole. The software, in conjunction with Star Ranger, would permit the mission controller to send a single command, which would then be distributed, as appropriate, to the various satellites in the constellation.

Conclusion

Through the development of low-mass, low-power, navigation sensors and the increasing popularity of smaller satellites, there will be new missions evolving in remote sensing requirements that require larger apertures in space in the form of optical and radio frequency applications. As the control of formation flying matures, the ability of applying interferometric principals for astronomical applications will follow as they have on Earth, as timing and processing techniques have matured.

At the present time, technology does exist for range and position measurement in space. However, onboard processing of interferometer data collected in space still remains power hungry, requiring large amounts of power to be collected in space, thereby reducing the possibilities of using small satellites for these applications. Opportunities do exist for serious applications that will require dynamic position and spatial measurements between satellites.

Star Ranger is already planned for use on TechSat 21 and is continuing to gain interest. Engineering models are in the process of being built for TechSat 21 metric testing. As the requirements are formalized for the TechSat 21 subsystem requirements, fabrication of flight models will begin. During the evaluation phase of the engineering models, AeroAstro is developing packaging techniques that will further reduce the mass and physical size of Star Ranger.