University Nanosatellite Distributed Satellite Capabilities to Support TechSat 21

Dr. Kim Luu, AFRL, luuk@plk.af.mil, (505) 853-4134; Mr. Maurice Martin, AFRL; Dr. Mike Stallard, Aerospace Corp; Dr. Howard Schlossberg, AFOSR; Mr. Joe Mitola, DARPA; Dr. Dave Weidow, GSFC; Dr. Richard Blomquist, CMU; Dr. Mark Campbell, UW; Dr. Christopher Hall, VT; Elaine Hansen, CU; Dr. Stephen Horan, NMSU; Prof. Chris Kitts, Santa Clara Univ; Dr. Frank Redd, USU; Dr. Helen Reed, ASU; Dr. Harlan Spence, BU; Prof. Bob Twiggs, Stanford

ABSTRACT

A new way to perform space missions utilizes the concept of clusters of satellites that cooperate to perform the function of a larger, single satellite. Each smaller satellite communicates with the others and shares the processing, communications, and payload or mission functions. The required functionality is thus spread across the satellites in the cluster, the aggregate forming a "virtual satellite".

The Air Force Research Laboratory (AFRL) initiated the TechSat 21 program to explore the basic technologies required to enable such distributed satellite systems. For this purpose, Space Based Radar (SBR) was selected as a reference mission to help identify technology requirements and to allow an easy comparison to a conventional approach. A summary of the basic mission and the performance requirements is provided.

The satellite cluster approach to space missions requires science and technology advances in several key areas. Each of these challenges is described in some detail, with specific stressing requirements driven by the SBR reference mission. These TechSat 21 research and technology areas are being studied in a coordinated effort between several directorates within AFRL and the Air Force Office of Scientific Research.

In support of TechSat 21, the Air Force Office of Scientific Research and the Defense Advanced Research Projects Agency are jointly funding 10 universities with grants of $50k/year over two years to design and assemble 10–12 nanosatellites (approx 10kg each) for launch in November 2001. The universities are conducting creative low-cost space experiments to explore the military usefulness of nanosatellites in such areas as formation flying, enhanced communications, miniaturized sensors and thrusters, and attitude control. AFRL is developing a deployment structure and providing advanced microsatellite hardware, and NASA Goddard is providing advanced crosslink communication and navigation hardware and flight algorithms to demonstrate formation flying. Numerous industry partners are also supporting the universities with hardware, design expertise, and test facilities. Areas of particular interest to the TechSat 21 program include autonomous operation and simplified ground control of satellite clusters, intersatellite communications, distributed processing, and formation control. This paper summarizes both hardware and computational challenges that have been identified in both the TechSat 21 and the university nanosatellite programs for implementing operational satellite subsystems to accomplish these tasks.

INTRODUCTION

The availability of highly capable satellites with high performance per unit cost and/or weight, in particular the emerging nano and microsatellites, enables one to envision new concepts for space operations. One example is the use of a cluster of satellites in formation that work cooperatively to perform a mission. The required functionality is spread across the satellites in the cluster, the aggregate forming a "virtual satellite" (Ref. 1). The satellites maintain constant communication and monitor each other, so that they can maneuver and stay in formation by virtue of simple, low-effort cluster orbits (Refs. 2-5). The mission planning, sensor processing, health monitoring, and command functions are distributed among the members of the cluster.

One important application of these clusters is to synthesize large apertures. Since the satellites are not connected by structures, they can be separated over very large baselines that cannot be considered for monolithic apertures. This feature can be beneficial for such missions as space based radar, which typically requires large power-aperture products to achieve acceptable area coverage rates or large apertures for detection of slow moving targets in clutter. Another mission application is mobile or jam resistant communications, which benefit from narrow beamwidths and tailorable beam patterns associated with large apertures. Other applications, such as interferometric imaging or source detection/location, benefit from the large and tailorable baselines afforded by these distributed satellite systems (Ref. 6).

This system architecture is very adaptable. Since neither the geometry of the cluster or the number of satellites in the cluster is fixed, the cluster configuration can be changed to suit a mission need. The "growability" of these virtual satellites is attractive for high value, high cost missions. The system performance can be slowly increased over time with a phased deployment and/or tailored to meet evolving threats or world conditions. Furthermore, the deployment cost can be spread over a number of years, while still providing acceptable but ever increasing levels of performance. Optimization of the cluster geometry by modifying the baselines or shifting satellites between clusters can permit alternate missions to be performed or to adapt to a particular mission application (e.g., a new target characteristic or revisit time requirement).

Distributed satellite systems also promise a reduction in cost for several reasons, including the aforementioned capability for unlimited apertures and the adaptability inherent in this approach. A virtual satellite can be composed of many identical units, each of a manageable size for manufacturing and test. This enables economies of scale to be realized in the mass production of these satellites. The satellite mass is smaller, so that a launcher's capacity can be more fully utilized by launching several satellites. The small mass also permits piggyback launches, especially for replenishment of clusters.

REFERENCE MISSION AND DESIGN

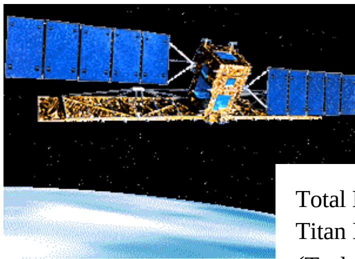
The TechSat 21 program was initiated by AFRL to develop and demonstrate the key enabling technologies for distributed satellite systems. To help focus the research in the TechSat 21 program and provide a basis of comparison for the idea of a virtual satellite, a reference mission was selected. The chosen mission stresses many of the operational and hardware technologies required for a distributed satellite system and is also of interest to the Air Force. A mission and system design developed by the Air Force Space Sensor Study Team (1995) and extended by the Space Based Radar Integrated Product Team (Ref. 7, 8) was selected for this purpose. This space system is designed to augment and enhance the Joint Surveillance Target Attack Radar System by providing theater detection and tracking of slow moving ground vehicles or Ground Moving Target Indication (GMTI). The space system is also required to perform radar imagery (Synthetic Aperture Radar, or SAR) and provide GMTI and SAR data to the continental US and the theater in a timely manner.

To meet these requirements, a system of 35 low altitude satellites (and 5 spares) each with a 6m x 22m phased array antenna was selected. The radar operates at 10GHz with 2000W average radiated power. Three channel displaced phase center antenna or space-time adaptive processing provides clutter suppression for slow target detection. The radar operates only over two theaters, which can be located anywhere in the world. The GMTI and SAR data are uplinked to geostationary relay satellites to a central distribution location or downlinked directly to theater mobile ground stations. The system is designed for 10 years of operations.

This basic design was evaluated by the Aerospace Corporation's Conceptual Design Center (CDC). The CDC provides a system level concurrent design capability using satellite subsystem experts and systems engineers. The CDC produces a system level design (launch, ground, and space segments) with detailed estimates of the characteristics of each element and subsystem and captures the interactions between them. In addition, the CDC computes the life cycle cost of the system. Two designs were developed (Ref. 9), one based on existing technology (freeze date 1996) and one based on advanced technology (freeze date 2003-5). A description of these satellite designs is provided in Figure 1. The satellite design based on existing technology is estimated to be 12,500 kg and requires a Titan IV for launch. The life cycle cost is estimated to be $26.8B (1997 dollars).

The advanced technology design exploits new developments in space power generation and storage, phased array antennas (Ref. 10), antenna structures, space-capable radiation-hardened processors, electric propulsion, and advanced electronics packaging which will be ready for insertion in the 2003-5 timeframe. This satellite design is estimated to be 4,400 kg and requires a Delta II for launch. The life cycle cost of this system is estimated to be $14.9B (1997 dollars).

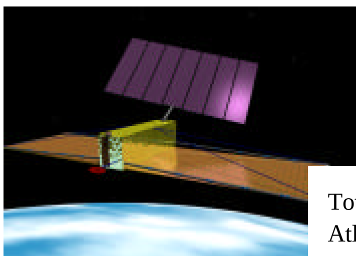
A conceptual system design for a virtual satellite approach to the reference radar mission was also developed by CDC to meet the requirements of the reference mission. A technology freeze date of 2005 was selected with a system initial operational capability of 2010 and a mission life of 10 years. Thirty-five clusters of eight satellites each (plus 40 spares) are employed in a highly inclined Walker constellation of 7 orbital planes at 800 km to provide global coverage with minimal outages. The data dissemination function relies on geosynchronous relay satellites assumed to exist in the mission timeframe. The overall system architecture is fairly conventional, with each cluster functioning as a single satellite. However, the virtual satellite and each satellite in the cluster are of an innovative design.



Total Mass 12,500 kg
Titan IV Launch vehicle
(Tech Freeze - 1996)

Current Technology Design

- Hardwired, Hard-Packaged T/R modules
- Truss-backup Antenna Structure
- GaAs Rigid Solar Array
- NiH_2 Batteries
- Composite Structure
- Chemical Propulsion



Total Mass 4,400 kg
Atlas II Launch vehicle
(Tech Freeze - 2003)

Advanced Technology Design

- Planar, High Density Packaged T/R Modules
- Tension-stiffened Antenna Structure
- High Efficiency GaAs Solar Array
- Flywheel Energy Storage
- Multi-Functional Structures
- Electric Propulsion

Figure 1. Monolithic Space Based Radar Designs

The estimated weight of the conceptual design, using technologies that will be available in 2005–2010, is less than 100kg. The total life cycle cost was estimated to be $8.3B (1998 dollars). These cost estimates are based on traditional costing models that are thought to be conservative for this small satellite size and large productions. Even with this conservatism, this approach is expected to cost about one-third that of a traditional approach.

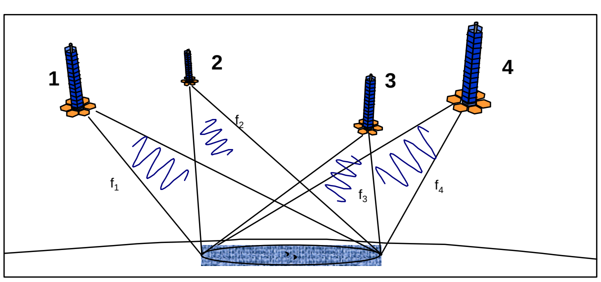


Figure 2. Sparse Array Operations Concept

ENABLING TECHNOLOGIES FOR DISTRIBUTED SATELLITE SYSTEMS

In this section, the key science and technology advancements needed to enable virtual satellites or distributed satellite systems are described. The following discussion uses the radar application to help illustrate and define the technology challenges. However, many of these are generic to other missions, especially radio-frequency missions such as communications or radiometry.

One challenge is to develop a sparse aperture approach for GMTI in which slow moving targets are to be detected against large ground clutter. This problem has historically required very large, high-power satellites and is seen as an extreme test of the concept of a virtual satellite. It is thought that the improved angular resolution, arising from the large effective aperture of a sparse array as illustrated in Fig. 2, has the potential to offset the many problems, such as grating lobes, that come from splitting a single large satellite into many smaller satellites. Four research projects are underway as part of the TechSat 21 program to explore this idea. Performance calculations based one approach show that the reference mission requirements can be met using 8 satellites in a cluster of roughly 250m in extent. Each satellite requires a $4m^2$ antenna, transmitting 200W average.

Further development of algorithms for acquiring and processing sparse aperture data is needed. These algorithms must be robust to cluster geometry and number of satellites in the cluster. Novel sparse sensing techniques require highly orthogonal signal structures, which can be achieved by using separate center frequencies or coded transmissions. These codes must have low auto-correlation and cross-correlation sidelobes. Algorithms are also required which are amenable to dynamic parallel processing, where the computational and memory resources of each satellite are optimally utilized. The TechSat 21 program is building a computational testbed to explore these issues using simulated environments, candidate architectures, and satellite hardware characteristics with the capability for some hardware-in-the-loop testing of processors and inter-satellite communications hardware.

To maintain an effective sparse aperture, the satellite cluster is required to accurately maintain a fixed spatial configuration. Solutions of the linearized orbital dynamical equations indicate that stable relative orbits can be found and are characterized by elliptical relative motion (Refs. 2, 3). Natural perturbations will introduce drifts in the orbits. However, since the satellites are in close proximity they experience nearly the same perturbing effects. The required delta-V to maintain these stable orbits is therefore very small, on the order of tens of m/s per year (Ref. 4). These solutions are critical to the idea of a cluster. If large propulsive capabilities were required to maintain the desired geometry, a cluster would not be viable. Fortunately, it is expected that this rich solution set will provide ample combination of spatial configurations that are suitable for the many applications. The optimization of these orbits for arbitrary applications is a critical area of on-going TechSat 21 research, in addition to the development of efficient collaborative control of the orbits, cluster reconfiguration maneuvering, collision and plume impingement avoidance, and cluster initiation.

Maintenance and control of these cluster configurations requires accurate position sensing and actuation (micro-propulsion). The radar application described above relies on position control within tens of meters and position knowledge to centimeters. Accurate three-dimensional relative positional sensing technologies including differential GPS, radio-frequency and laser ranging, and optical imaging techniques are key technologies for satellite clusters. The fine control of position requires small-impulse bit, high specific impulse propulsion systems. Electric propulsion technologies are most promising for this application, precisely because of their main drawback for other applications — low thrust. The challenge is to miniaturize these devices for application to this class of nano and microsatellites. Three research efforts are underway as part of the TechSat 21 program to explore micro-pulsed plasma thrusters, Micro-Electro-Mechanical Systems (MEMS) thrusters, and micro-Hall effect thrusters.

Virtual satellite concepts are significantly different from conventional satellites and require new distributed system design methodologies and design tools. The cluster geometry, allocation of resources, and inter-satellite coordination of information, all of which are dynamic and changeable, must be factored into the design approach. Tools that permit optimization of the satellite cluster performance and allocation of individual satellite capabilities are required. One powerful approach developed by Massachusetts Institite of Technology with AFRL is called Generalized Information Network Analysis which abstracts the distributed satellite system as an information network (Ref. 11). This allows rapid analysis of system architectures against meaningful performance metrics.

Microsatellite technologies which increase the capability of the satellites per unit mass, volume, and cost are essential to cluster concepts. These technologies for traditional satellite subsystems must be amenable to mass production, rapid integration, minimal hand assembly, and streamlined testing methods to permit rapid production and deployment at low cost. Some technologies in this area include MEMS, advanced electronics packaging such as high density interconnect, multi-functional structures, and thin-film photovoltaics. These and other microsatellite technologies are under development at AFRL and other government laboratories.

Another effect that requires consideration is the propagation delay and refraction caused by the ionosphere. Since very accurate timing of signal returns are required to resolve the angles of arrival in many applications, heterogeneity of the ionosphere on the scale of the cluster diameter may introduce significant errors. Turbulent structures in the ionosphere have been measured to scales of tens of kilometers, but there are currently no detailed data or models that can be used to evaluate these effects for the current concept. Furthermore, the radar detection will employ coherent signal processing techniques to increase signal gain by factors of 100–1000 or more. Such processing is extremely sensitive to fluctuations in phase that may reduce the anticipated gain dramatically. The effect of even small ionospheric phase fluctuations, negligible for space-based communication and navigation systems, will be amplified substantially by space based radar signal processing. Detailed models and in-situ monitoring could allow this effect to be compensated and are being explored as part of the TechSat 21 research.

UNIVERSITY NANOSATELLITE PROGRAM

The university nanosatellite program aims to develop and demonstrate many of the technical challenges related to nano and microsatellites and cluster architectures, as described in the previous section. There are 10 participating universities, and of these, 8 are working in collaborations of 2 or 3. The teams and their projects are:

Three Corner Sat Constellation (3⅄Sat)

- Arizona State University (ASU)
- University of Colorado at Boulder (CU)
- New Mexico State University (NMSU)

EMERALD

- Stanford University
- Santa Clara University

Ionospheric Observation Nanosat Formation (ION-F)

- Utah State University (USU)
- Virginia Polytechnic Institute and State Univ (VT)
- University of Washington (UW)

Constellation Pathfinder

- Boston University (BU)

Solar Blade Heliogyro Nanosatellite

- Carnegie Mellon University (CMU)

The universities are planning creative low-cost space experiments to explore the military usefulness of nanosatellites. In the following section, these experiments in areas such as simplified ground control of satellite clusters, distributed processing, formation and attitude control, intersatellite communications, miniaturized sensors and thrusters, and ionospheric effects causing propagation delay and refraction of signals. Fuller details on the university projects are found in Ref. 12.

TECHNOLOGY AND SCIENCE OBJECTIVES

Each university is developing one or more nanosatellites for launch in late 2001. Those universities or teams planning multiple spacecraft will address technology challenges associated with distributed satellite systems, and all face the difficulties of building capable spacecraft with masses on the order of 10kg.

Simplified ground control of satellite clusters and distributed processing: The 3⋀Sat team proposes to demonstrate innovative Command and Data Handling (C&DH) with their constellation of three identical nanosatellites. Figure 3 shows their satellites stacked in launch configuration. Designed as a distributed and simple system for C&DH, each satellite uses a satellite processor board that serves as its local controller, data interface, on-board memory, and processor. The three-satellite constellation can be controlled and managed by a processor on any of the three satellites via the communication links. The satellite processor can be responsible for supervising the operation of the three spacecraft and managing their resources. This supervision can be automatically accomplished within the constellation by the selected satellite processor which can initialize and distribute commands and which can monitor and react to science and engineering data from the three spacecraft.

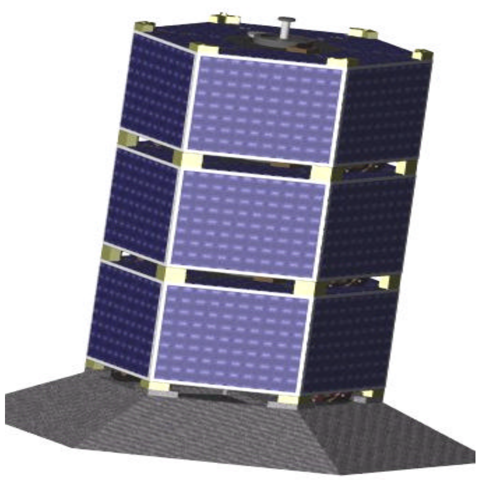


Figure 3. 3⋀Sat Satellites in Launch Configuration

For ground operations, the ION-F team will develop an Internet-based ground station in order to successfully coordinate the three satellites in their formation. The USU ground station will be used, and another ground station, most likely at VT, will be developed. The Internet will allow for coordination of experiments by the different universities as well as individual satellite control and data dissemination. VT is also investigating use of the GlobalStar LEO constellation for satellite telemetry, tracking and commanding of the satellite using commercial communications technology.

Formation and attitude control: NASA Goddard Space Flight Center is providing crosslink communication and navigation hardware and flight algorithms to demonstrate formation flying. Three teams, 3⋀Sat, EMERALD, and ION-F, address this critical technology with various formations and control schemes.

To accomplish the science objectives, a "virtual formation" is proposed and will be demonstrated as part of 3⋀Sat. The locations of the satellites will need to be "in range" for the mission to be accomplished and mutually known in order for each to support its portion of the mission, but physical proximity is not a requirement for the formation network. The 3⋀Sat constellation will consist of three satellites flying in a linear follow-formation with relatively constant separation from each other. The separation distance selected is based on altitude and camera field of view, with final determination based on the chosen launch vehicle. For stereo imaging, the primary science objective of 3⋀Sat, a nominal spacing of tens of kilometers between the satellites is required. With a controlled deployment to achieve this initial spacing, the satellites will remain within range for the suggested four-month lifetime of the mission. Therefore propulsive capability is not needed.

The EMERALD Mission is divided into three distinct stages that progress from a simple single satellite to two free flying satellites in a coarse formation. Using a building block experimental strategy, the research payloads first will be characterized in isolation. Then, they will be coordinated and combined to permit simple demonstrations of fundamental formation flying control functions such as relative position determination and position control.

- At release, the two spacecraft will be stacked together and will travel as a single object. This will allow initial checkout, calibration, and some limited experimentation.
- During the second stage of operation, the satellites will separate and a simple tether or flexible boom will uncoil, linking the two vehicles. This tethered stage will allow full formation flying experimentation including relative position determination and closed loop relative position control using the drag panels and microthrusters.

- During the final stage of operation, the tether will be cut in order to permit true two-body formation flying for a limited period of time. The tether will have a simple sub-satellite at its midpoint. Upon ground command, the two halves of the sub-satellite will separate. Each satellite will retain half of the tether and half of the sub-satellite, providing very rough gravity gradient stabilization. The full sequence is illustrated in Fig. 4.

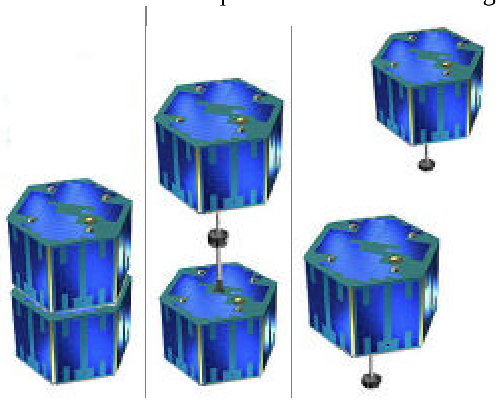


Figure 4. EMERALD Mission Sequence (Joined, Tethered, Formation Flying)

For onboard orbit determination and relative navigation, a Stanford-modified Mitel 12-channel GPS receiver will be flown on each spacecraft. This receiver can compute relative position to approximately 2–5m level accuracy in real-time using differential GPS techniques. They will be modified-for-space versions of the receivers currently in use by the Stanford Aerospace Robotic Laboratory's (ARL) other formation flying experiments.

Formation flying is a primary mission objective for ION-F. It is expected that each of the three satellites will have relative navigation capabilities. The team intends to fly their control and formation algorithms but are investigating additional collaboration with NASA Goddard and their partners. The following activities were outlined as part of the formation-flying mission of ION-F:

- After deployment of the three linked satellites, a checkout will occur of the subsystems, including GPS calibration, attitude determination, and possibly communications.
- After initial checkout and relative calibration, the satellites will separate. The satellites will deploy into a close leader-follower formation, and individual performance characterization and disturbance quantification will be performed.
- More complex two satellite formations will be examined such as side-by-side (same altitude but different inclination) and same ground track (NASA Goddard's "ideal" formation). The operations will include maneuvering into new formations and subsequent formationkeeping.
- Complex three-satellite formations will be attempted. Two examples include 1) maneuvering three satellites in a leader-follower formation to three satellites with the same ground track and 2) a rotating formation about an equidistant point.
- Formationkeeping using both position and attitude is proposed.
- Additional NASA Goddard collaboration and control algorithms can be accommodated.

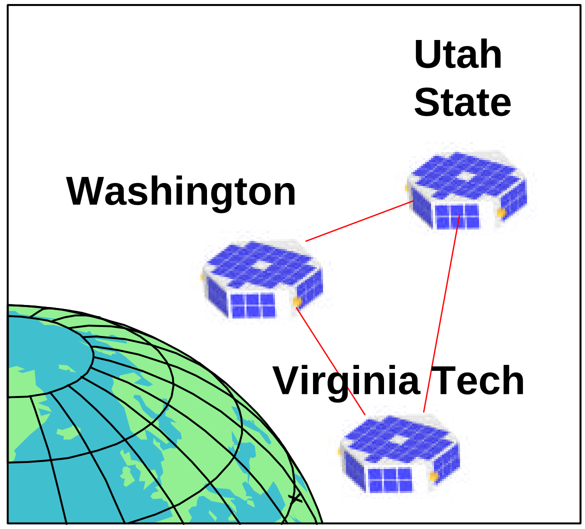


Figure 5: Ionospheric Observation Nanosatellites

Two systems are proposed for attitude control of the ION-F spacecraft. The first is through magnetic control. The objective here is to develop 3-axis attitude control given the very limited power and weight availability on a nanosatellite. ION-F will meet this challenge with an all-magnetic torquer system where permanent magnets on stepper motors are used instead of traditional torquer coils. The attitude determination will be achieved by a combination of Earth horizon and sun sensors, giving three-axis control to approximately two to three degrees. The second option is a tethered system. Adding a low-mass tether for gravity gradient stability will provide simple attitude control for the VT satellite. Nominally the tether will be a simple non-conducting ribbon. The spacecraft will also include a small digital camera for imaging the tether during deployment and during the eclipse exit period of the orbit. This will provide useful data on the flexible dynamics of tether systems.

Intersatellite communications: In order for a cluster to function as a virtual satellite and to simplify ground control, each member of the cluster must have means to communicate with the rest of the cluster. The three teams demonstrating formation flying and Constellation Pathfinder have addressed this challenge in their projects.

The design of the 3◭Sat mission utilizes a commercial communications network in Low Earth Orbit (LEO) which supplies the communications links. This will allow each satellite to be contacted via the LEO network regardless of the position of the satellite relative to the ground station – with predictable visibility outages. Because each satellite in the network will be visible to the LEO communications constellation, there will be the ability for satellites to perform their mission coordination without the need for visibility from the ground station or with each other. The LEO communications network knits together the virtual formation.

LEO satellites utilizing cellular telephone constellations is a new concept but one in which there is considerable interest in the government and private-sector space communities. This natural extension to the use of ground-based systems will be explored not only to demonstrate the utility of this mode of communications but also to act as an experiment to characterize the constellation itself and the limits on the operations. A technology goal of 3◭Sat is to perform the first steps in this characterization.

EMERALD plans to develop a simple intersatellite communication link from the commercially available19.2kbs wireless radio modems currently used by ARL for ground based formation flying systems. This will provide the real-time communication link necessary for differential GPS measurements.

Collaborating with NASA Goddard Space Flight Center and building on the past experiences of USU and the Space Dynamics Lab, the ION-F team will demonstrate satellite cross-links, exchanging relative GPS information and possibly attitude information. It is expected that each of the three satellites will have cross-communication links.

The Constellation Pathfinder program demonstrates the feasibility of fabricating and launching one to three, <1kg satellites that are capable of collecting and returning quality scientific and engineering data for one to four or more months. Despite the very small size of the spacecraft, demonstration of satellite-to-satellite communication may be possible.

Propulsion: Tight formation control and the ability to perform varying missions by changing the cluster geometry require propulsive capability. The university projects have planned a variety of propulsive methods that are suitable for nano and microtechnology.

Each university in the 3◭Sat constellation has the opportunity to fly an individual unique payload, should it desire to do so. ASU is collaborating with AFRL and industry to design and fly a micropropulsion system. Micropropulsion systems can offer a wide variety of mission options, all relevant to formation flying: attitude control, orbital drag make-up, altitude raising, plane changes, and de-orbit. The objective of ASU's research is to take a systems point of view and develop a safe and simple micropropulsion system for nanosatellites. In particular, the ASU satellite will demonstrate orbit raising and de-orbiting once the 3◭Sat virtual-formation/stereo-imaging mission is completed.

To enable small scale position control, EMERALD proposes to employ advanced colloid microthrusters which can supply vectored thrust on the order of 0.11mN and have a specific impulse of approximately 1000s. These components are currently in development by Stanford's Plasma Dynamics Laboratory. Other options include the passive position devices below:

- A simple tether or flexible boom will maintain the satellites within a given distance, on the order of tens of meters. This tether may be cut later in the mission in order to demonstrate advanced formation flying capabilities.
- Deployable panels on both spacecraft will allow simple, low performance drag control. During the tethered mission phase, these panels can be used to maintain tether tension as well as to attempt closer positioning.

The ION-F team is considering two versions of microthrusters that are currently in development. Primex Aerospace Company is working with UW to scale down the power requirements of their micro-pulsed plasma thrusters (μPPT). The UW nanosatellite will fly either the μPPT propulsion system or a cold gas system. Primex, Honeywell, and AFRL are working separately on MEMS-based thrusters such as micro-hydrazine. These will be flown on either the USU or VT nanosatellite if the maturity of the technology will allow it. The small modular nozzles allow many options as to microthruster size. Although development time will most likely require more than two years, the potential for nanosatellites is very high.

CMU proposes to develop and fly the first solar sail, the Solar Blade Heliogyro Nanosatellite, a spacecraft which utilizes solar radiation pressure as its only means of propulsion and attitude control. Solar pressure will enable changes to altitude, attitude precession, spin rate, and orbital position. The Solar Blade Nanosat has the appearance of a Dutch windmill, as shown in Figure 6, and employs control similar to helicopters. Four solar reflecting blades mount radially from a central spacecraft bus and actuate along their radial axis. The satellite uses collective and cyclic pitch of these solar blades relative to the sun's rays to control its attitude and thrust. The spacecraft weighs less than 5kg, and when stowed is a package approximately 0.5 m diameter by 1 m.

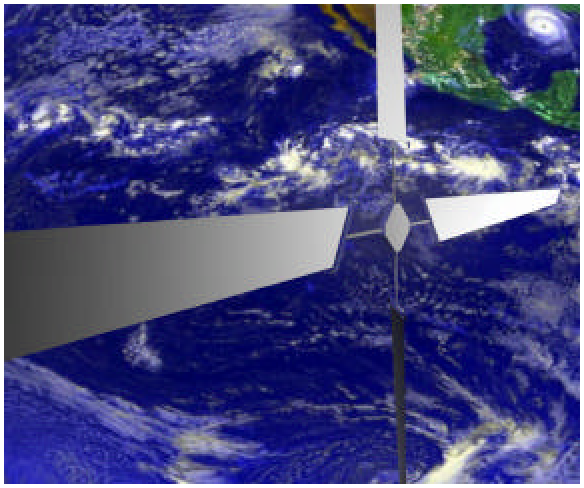


Figure 6. Solar Blade Heliogyro Nanosatellite

The satellite will demonstrate attitude precession, spin rate management, and orbital adjustments, after which it will spiral out past the orbit of the moon. For the Solar Blade Nanosat, plane change maneuvers will be most efficient when the sun is furthest out of the orbit plane. This increases the magnitude of the orbit-normal component of force that can be used for the plane change maneuver. Plane change maneuvers can also be conducted if the sun lies in the orbit plane by orienting the solar blades at an angle relative to the orbit plane, optimally 45°. Unlike eccentricity changes, which can be implemented throughout the orbit using a single solar blade orientation, plane change maneuvers must change polarity on opposite ends of the axis of plane rotation. This is not possible unless the sun is in the plane of the orbit since the solar blades cannot produce a positive orbit normal force if the sun is above the orbit plane. Therefore, in most situations, plane change maneuvers will be conducted over an orbital arc on one side of the orbit near the axis of desired orbit rotation. In addition to attitude and orbital maneuvering, the ultra-light spacecraft will communicate with the Earth, uplinking commands and relaying orbital and attitude information to ground stations.

Each blade of the Solar Blade is a 20m long by 1m wide aluminized Kapton sheet 8 microns thick. Edge reinforcing Kevlar and battens of 80 micron-thick Kapton provide added stiffness and resistance to tears. Small brushless motors rotate the blades.

Micro-electronics: EMERALD will support a couple of auxiliary payloads, including MERIT, the MicroElectronics Radiation In-flight Testbed, which will characterize the performance of advanced microprocessors, MEMS technologies, and other electronic components in the space environment. This payload is being developed as part of a separate Stanford Space System Development Laboratory research program in conjunction with Boeing, the Naval Research Laboratory, The Aerospace Corporation, Honeywell, UTMC, and the Laurence Berkeley Labs.

Science missions: Some of the space and outer atmospheric science experiments are of particular interest to TechSat 21 and other systems susceptible to ionospheric effects such as communication and navigation satellite systems.

The science objective of ION-F is the understanding of ionospheric density structures that can impose large amplitude and phase fluctuations on radio waves passing through the ionosphere. The constellation provides a unique opportunity to answer questions about ionospheric disturbances that can not be addressed any other way. A single satellite can only provided very limited information on the dimensions and evolutionary time scales of the ionospheric disturbances it flies through because a full orbit (90 minutes) must occur between the next observation. In general the situation is even worse than this because only truly zero inclination equatorial satellites have a good possibility of measuring the same region twice due to the co-rotation of the ionosphere with the Earth. This science investigation contributes to the TechSat 21 basic research mission of investigating global ionospheric effects which affect the performance of space based radars. It also addresses broader Air Force interests in ionospheric effects on navigation and communication links.

The ION-F team proposes to use the nanosat constellation to make the first global multi-satellite electron density measurements in the ionosphere. We also propose to make the first global multi-baseline RF-scintillation measurements of the ionosphere. The scintillation of GPS signals using receivers on each spacecraft will provide information about the scale sizes of disturbances between the nanosatellite constellation and the GPS transmitter. The scintillation measurements will be extracted from the GPS receivers and are part of the orbit determination system on the nanosats. The 1575MHz signal from the GPS satellites originate at 20,000km over the Earth and must travel through the ionosphere, line of site, to the location of the nanosats at 360km altitude. The signal will encounter regions of disturbed ionospheric plasma which will slightly increase or decrease the signal strength at the receivers. The size of these disturbed regions can be estimated by comparing signals measured over closely related propagation paths, such as between two nanosats.

The Constellation Pathfinder program proposes to use a particular satellite design as shown in Figure 7 that is based on one developed over the past two years through a NASA-supported study called the Magnetospheric Mapping Mission (MMM) at Boston University. That study objective has been to assess the feasibility of placing hundreds of satellites equipped with magnetometers, into orbits extending into the tail of the magnetosphere, thereby obtaining a much more detailed three-dimensional picture of dynamic phenomena in geospace than has been possible previously. The Constellation Pathfinder proposal will take the first pathfinding step toward such an ultimate implementation. The shuttle LEO orbit provides several simplifications of the current conceptual design: the magnetic field is larger and therefore easier to measure, the lower altitude reduces power requirements for RF communication, and the natural radiation environment will be much lower. The hardware demonstration of building and flying such a satellite, or small suite of satellites, will provide a proof of principle that will be helpful in many scientific and strategic applications where a fleet of coordinated small satellites is required.

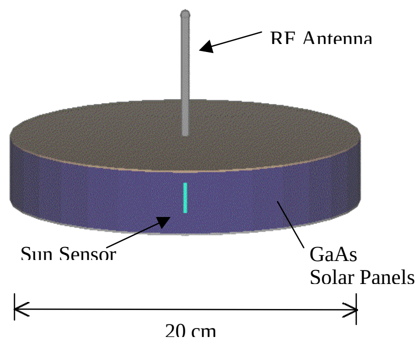


Figure 7: Constellation Pathfinder Satellite

CONCLUSION

The University Nanosatellite Program is a low-cost approach to explore cutting-edge technology for the TechSat 21 program. It has the potential to provide significant payoff for very modest funding by DoD and NASA given the broad university resources being applied and support by industry partners. The program harnesses the creativity originating from academia and provides a unique, hands-on space experience for undergraduate and graduate space design and engineering students. The program is also a shining example for cooperation between many entities among educational institutions, government agencies, and industrial corporations and on different levels. These university projects will draw together teams of students in the various engineering departments, just as the TechSat 21 program is a cooperative effort between the Office of Scientific Research, Space Vehicles, Sensors, and Propulsion Directorates. If the initial nanosatellite flight demonstrations are successful, it is very likely that government sponsorship can be secured for follow-on launches.

REFERENCES

1. Canavan, G., D. Thompson, and I. Bekey, “Distributed Space Systems,” in *New World Vistas, Air and Space Power for the 21st Century*, United States Air Force, 1996.
2. Janson, S.W. and H. Helvajian, “Batch Fabricated Microthrusters: Initial Results,” Proceedings of the 32nd AIAA / ASME / SAE / ASEE Joint Propulsion Conference, 1-3 July 1996, Lake Buena Vista, FL, AIAA paper 96-2988.
3. Kong, E., R. Sedwick, and D. Miller, “Exploiting Micropropulsion and Orbital Dynamics for Aperture Synthesis Using Distributed Satellite Systems,” AIAA Defense and Civil Space Programs Conference and Exhibit, Huntsville, AL, 28-30 October 1998, AIAA paper 98-5289.
4. C. Sabol, R. Burns, and C. McLaughlin, “Formation Flying Design and Evolution,” AAS/AIAA Spaceflight Mechanics Meeting, Breckenridge, CO, 7-10 February 1999, AAS paper 99-121.
5. Pollard, J.E., C.C. Chao, and S.W. Janson, “Dynamics and Control of Cluster Orbits for Distributed Space Missions,” AAS/AIAA Spaceflight Mechanics Meeting, Breckenridge, CO, 7-10 February 1999, AAS paper 99-126.
6. Das, A. and R. Cobb, “TechSat 21 - Space Missions Using Collaborating Constellations of Satellites,” Proceeding of the 12th Annual AIAA/USU Conference on Small Satellites, Logan, UT, 31 August-3 September 1998.
7. Jones-King, Y., J. Garnham, R. Blackledge, B. Preiss, F. Jonas, and F. Sherrod, “Space Based Radar for the Next Century (U),” NATO SET Panel Report, October 1998.
8. Garnham, J.W. and M.T. Tuley, “Space Based Radar Technology Trade Analysis,” IEEE Aerospace Conference, Breckenridge CO, March 1996.
9. Dawdy, A., “SPEAR-X Conceptual Design Center Final Report,” Aerospace Corporation Technical Operating Report 97(1206)-1, 14 July 1997.
10. Adler, A., M. Mikulas, J. Hedgepeth, J. Garnham, and M. Stallard, “Novel Phased Array Antenna Structure Design,” IEEE Aerospace Conference, Aspen, CO, March 1998.
11. Shaw, G.B., “The Generalized Information Network Analysis Methodology for Distributed Satellite Systems,” PhD Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, October 1998.
12. Martin, M. et al., “University Nanosatellite Program,” IAF Symposium, Redondo Beach, CA, 19-21 April 1999.