Microsatellite and Formation Flying Technologies on University Nanosatellites

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Abstract. The Air Force Office of Scientific Research, the Defense Advanced Research Projects Agency, NASA, and industry are jointly sponsoring the development and launch of 12 university nanosatellites. Through this project, the 10 selected universities will conduct innovative, low-cost experiments to explore the military usefulness of distributed satellite systems and micro and nanotechnologies in support of the Air Force Research Laboratory's TechSat 21 distributed radar aperture collaborative microsatellite constellation. Among the technologies to be explored are formation flying, enhanced communications, miniaturized sensors and bus technologies, attitude control, and distributed satellite capabilities. Launch is planned for late 2001. This paper provides some detailed information on the technologies and science objectives of each of the nanosatellites.

Program Overview

In 1998, the Air Force Office of Scientific Research and the Defense Advanced Research Projects Agency released a request for proposals seeking 10 universities to participate in a two-year program, the objective of which is to design, assemble, and fly nanosatellites. Selected universities are funded with grants of $100K over two years. This project, the University Nanosatellite Program, is a Special Topic of the Broad Agency Announcement on the Air Force Research Laboratory (AFRL) TechSat 21 Initiative. The TechSat 21 concept 'involves satellites flying in formation that operate cooperatively to perform a surveillance mission.'[1] Topics identified to support this concept are

- Formation and attitude control
- Micropropulsion
- Micro-Electro-Mechanical systems
- Enhanced communications
- Ionospheric effects
- Collective behavior of intelligent systems

AFRL/Space Vehicles Directorate is developing a deployment structure, securing a launch, and providing such advanced microsatellite hardware as high efficiency solar cells and micropropulsion units. NASA Goddard Space Flight Center has also teamed with the universities to provide approximately $1.2M in funding to demonstrate such formation flying technologies as advanced crosslink communication, navigation hardware, and flight control algorithms. Numerous industry partners are also supporting individual universities with hardware and design and testing services.

Delivery of the nanosatellites to AFRL is targeted for April 2001. AFRL will then integrate the satellites onto the deployment platform. The integrated payload will then be delivered to the launch vehicle integrator in June 2001 for launch on or after November 2001. Currently, a launch via the Shuttle Hitchhiker Experiment Launch System (SHELS) is planned. Further information on the program and presentations from the January 1999 kick-off meeting can be seen at the newly-remodeled Utah State University-hosted website, http://www.nanosat.usu.edu/.

Some universities are teamed together in groups of 2 or 3 to demonstrate formation flying and distributed systems technologies. Others are focused more on the miniaturization of bus and payload systems. The university teams and their projects are

- Emerald
  - Santa Clara University
  - Stanford University
- Ionospheric Observation Nanosatellite Formation
  - Utah State University (USUSat)
  - University of Washington (DawgStar)
  - Virginia Polytechnic Institute & State University (VTISMM)
- Boston University (Constellation Pathfinder)
- Carnegie Mellon University (Solar Blade Heliogyro Nanosatellite)
- Three Corner Sat Constellation
  - Arizona State University
  - University of Colorado at Boulder
  - New Mexico State University

Descriptions of these university programs follow. This paper updates the efforts summarized in Ref. 2.

EMERALD

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Satellites flying in formation is an evolving technology with vast scientific, military, and commercial potentials that range from enhanced mission performance to significant reductions in manufacturing and operations costs. As part of the University Nanosatellite Program, Stanford University and Santa Clara University are jointly developing Emerald, a low-cost, two-satellite mission for validating various formation flying technologies. The following describes some of the on-orbit demonstrations planned. More complete details are contained in Ref. 3.

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

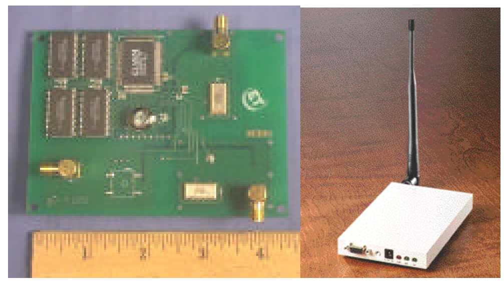
Advanced colloid microthrusters. To enable small scale position control, these thrusters can supply vectored thrust on the order of 0.11mN and have a specific impulse of approximately 1000s. Currently, microthrusters are planned to be incorporated on one of the Emerald spacecraft for attitude control as well as orbital maneuvers. These components are currently in development by Stanford's Plasma Dynamics Laboratory.

Radiation effects on microelectronics components. A testbed system to monitor component degradation in the space environment will be flown. Both single event and total dose effects on the performance of the microelectronics are to be characterized. The radiation environment will be monitored with dosimetry circuitry.

Intersatellite communications. Emerald plans to develop a simple intersatellite communication link from the commercially available 19.2kbs 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. A picture of the modem appears in Fig. 1 along with the Mitel GPS receiver and a colloid microthruster previously discussed.

Simple, passive position and/or attitude control device. Deployable panels on both spacecraft will allow predictable, low-performance drag control. Using these panels, control of the relative trajectories of the two satellites can be achieved.

VLF receiving systems. Both Emerald spacecraft will include receivers to record radio waves emitted by high altitude atmospheric phenomena associated with lightning. The experiment will help understand some of the fundamental happenings in Earth's ionosphere. The distributed sensing enabled by formation flying capabilities will enhance the scientific data and help validate the benefits of satellite formation flying. The receivers are based on an existing design developed at Stanford Space Telecommunications and Radioscience Laboratory. The mission name, Emerald (ElectroMagnEtic Radiation And Lightning Detection), refers to this experiment.



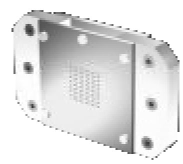


Figure 1. (Counter-clockwise from top right) ARL Radio Modem, Mitel GPS Receiver, Colloid Microthruster

These experiments will be built into a 14-inch tall, 16-inch diameter hexagonal bus adapted from heritage designs. The structure employs a modular, stackable tray structure made of aluminum honeycomb. Inside, command and data handling is provided by a SpaceQuest FCV-53 flight processor running the BekTek operating system. Both spacecraft to ground and intersatellite communications will be handled by a 9.6kbs packet communications system. The power system consists of body-mounted solar cell panels and a single multicell Ni-Cad battery. This system will provide 7W of average power to components via 5V and 12V regulated bus. Passive thermal control will be achieved through the use of insulation and thermal coatings. A magnetometer and simple visible/infrared light sensors will provide coarse attitude determination, on the order of 5°, while passive attitude control can be achieved with permanent magnets.

One of the most important upgrades to the heritage architecture is the shift to a serial command and data bus. As shown in Fig. 2, Emerald will use I^2C to connect all of the subsystems and experiments. This modular design simplifies integration and allows for stand-alone testing of components. It also allows the project to maintain a schedule driven design: If a payload fails to show enough progress at a quarterly

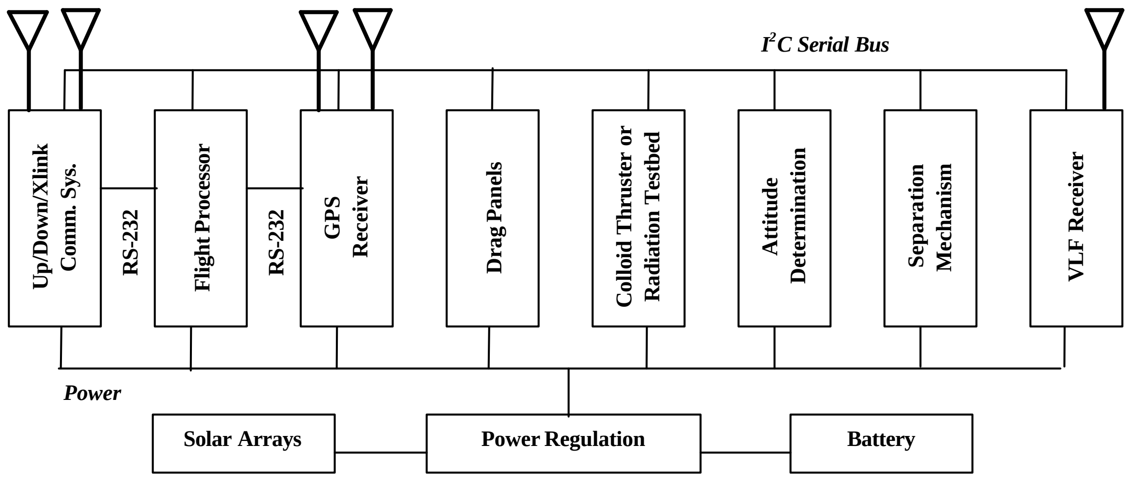
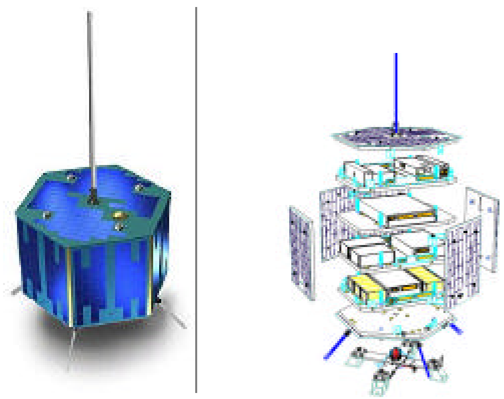


Figure 2. Emerald System Diagram

design review, it can be removed from the mission with minimal effect on the rest of the satellite.

The Emerald spacecraft, shown in Fig.3, will be stacked and connected to a baseplate which will be attached to the SHELS platform for launch from the space shuttle. Orion-1, a flight prototype for the planned 6-microsatellite Orion constellation under development by Stanford and NASA Goddard, is currently scheduled to be included on this same baseplate. After the baseplate is deployed from the shuttle, the Emerald stack and Orion-1 will be ejected in close proximity to minimize differences in orbital trajectories. After initial checkout, calibration, and some limited experimentation, the Emerald stack will separate to commence the distributed systems demonstrations. A possible joint mission with the Orion-1 spacecraft is targeted to explore the more complex, three-body autonomous formation flying problem.



(a) Assembled View *(b) Exploded View.*

Figure 3: Emerald Bus Configuration

IONOSPHERIC OBSERVATION NANOSATELLITE FORMATION (ION-F)

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Virginia Polytechnic Institute & State University: Christopher Hall (PI), Nathaniel Davis, Jaime DeLaRee, Wayne Scales, Warren Stutzman

Utah State University (USU), University of Washington (UW), and Virginia Polytechnic Institute (VT) are designing and developing a system of three spacecraft (Fig. 4) to investigate satellite coordination and management technologies and distributed ionospheric measurements. Advanced hardware for distributed space system to be demonstrated includes miniature pulsed plasma thrusters, gravity-gradient tether for attitude control, the GlobalStar constellation for telemetry, tracking, and command (TT&C), hydroxylammonium nitrate (HAN) based propulsion system, and enhanced intersatellite communication system, currently being developed by the Applied Physics Laboratory. In addition, an Internet-based operations center will be designed to enable each university to control its satellite from its own remote location and to share the two ground stations to be located at USU and VT. Industrial support from SDL, Primex Aerospace Company, BWX Technologies, EDO Barnes, GlobalStar Telecommunications, Orbital Sciences Corporation, Planetary Systems Corporation, Tethers Unlimited, and Honeywell has been identified, including funding for students, hardware, and satellite design support.

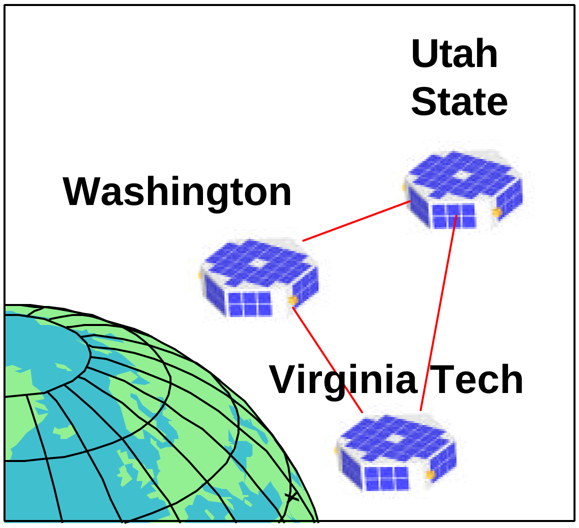

Figure 4: Ionospheric Observation Nanosatellites

Formation flying is a primary mission objective for ION-F. One important capability for formation control is a miniaturized propulsion system. UW has chosen to demonstrate the micro-pulsed-plasma thruster because of mass savings, simplicity, and the motivation of demonstrating electric propulsion.[4] A diagram of a pulsed plasma thruster is given in Fig. 5. Though their initial proposal did not include any propulsion capability, VT is currently considering the HAN-based propulsion system and is working with Primex Aerospace Company to determine the feasibility of implementing this system in their satellite design.[5] USU will attempt to use differential drag as a means to control relative position.

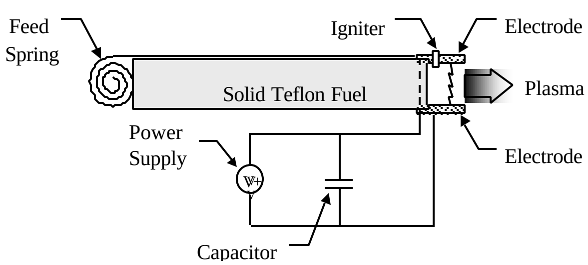

Figure 5: Basic Diagram of a Pulsed Plasma Thruster

With these capabilities in mind, the following activities are outlined as part of the ION-F formation flying mission:

- 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.
- Using the position control capabilities, three-satellite formationkeeping will be accomplished.
- More complex 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. The operations include maneuvering into a new formation and subsequent formation control.

The ION-F team plans further technology demonstrations. The following describes these on-orbit investigations:

Commercial LEO constellation for TT&C: VT is investigating the use of a GlobalStar telephone for TT&C. Based on preliminary analysis, findings conclude that a significant amount of data can be transmitted to the ground station.

Satellite Crosslinks: Collaborating with NASA Goddard and building on the past experiences of USU and the SDL, the ION-F team will demonstrate satellite crosslinks, exchanging relative GPS information and possibly attitude information.

Gravity-Gradient Tether: For simple, inexpensive attitude control, VT is incorporating a low-mass, 10m tether in their nanosatellite design. 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.

Ground Operations via Internet: The USU ground station will be used for ION-F, and another ground station at VT will be developed. In order to successfully coordinate the three satellites, an Internet-based ground station will be developed. This will allow coordination of experiments by the different universities as well as individual satellite control and data dissemination.

The science objective is the understanding of ionospheric density structures that can impose large amplitude and phase fluctuations on radio waves passing through the ionosphere. The ION-F constellation provides a unique opportunity to answer questions about ionospheric disturbances that cannot 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 orbital period must occur between the next observation. In general, the situation is even worse than this because only equatorial satellites have a good probability of measuring the same region twice due to the co-rotation of the ionosphere. This investigation contributes to the TechSat 21 mission by studying global ionospheric effects which affect the performance of space-based radars.

The ION-F team proposes using the nanosatellite constellation to make the first global multi-satellite electron density and multi-baseline RF-scintillation measurements in 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 ionosphere frequently shows density disturbances and fluctuations over a very large range of scale sizes (from hundreds of kilometers to centimeters) at all latitudes, longitudes, and nearly all altitudes. Ionospheric plasma density irregularities are associated with two-dimensional turbulent processes driven by both low latitude tidal neutral winds and high latitude current systems. One task is to determine the global distribution of plasma structure in both the quiet and disturbed ionosphere. Such measurements would provide essential information for the understanding of ionospheric effects on communications, navigation, and GPS systems and for the development and validation of realistic predictive global ionospheric models. These observations are related to the priority measurements set up the by the National Space Weather Program.

One of two possible instruments will be deployed on each of the satellites in the constellation, either a plasma frequency probe from which an absolute electron density can be determined or an electron saturation current probe which can measure relative electron density variations. The electron saturation current probe is based on the DC response of a plasma to an applied potential on a probe. The plasma frequency probe technique is based on the AC response of the probe. The instrument to be selected will be based on the resources available on the spacecraft, but in general, these instruments will be small, low-power, and have low impact on their host satellites.

The scintillation measurements will be extracted from the GPS receivers that are part of the orbit determination system on the spacecraft. The 1575MHz signal from the GPS satellites originate at 20,000 km over the Earth and must travel through the ionosphere, line of site, to the location of the nanosatellites at approximately 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 spacecraft.

The basic satellite structure is hexagonal with an approximately 18” diameter and varying heights. This configuration can be modified as needed to meet the specific launch environment conditions. The structure will consist of two aluminum isogrid hexagonal plates and six end covers. One of these plates will serve as the mounting baseplate for the spacecraft. The power subsystem will be a typical solar cell/battery design using high grade commercial industry NiCd battery technology. The entire spacecraft will be covered with solar cells, with the exception of the areas designated for the sensors. The navigation subsystem will consist of the GPS antenna, GPS receiver, and relative position software.

CONSTELLATION PATHFINDER

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Charles Stark Draper Laboratory: N. Dennehy, D. Sargent, M. Socha

The objective of the Constellation Pathfinder program is to demonstrate the feasibility of fabricating and launching three 1kg satellites that are capable of collecting and returning quality scientific and engineering data for several months. The particular nanosatellite proposed for use is based on one developed over the past two years through a NASA-supported study called the Magnetospheric Mapping Mission 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. A simplification of our current conceptual design is planned. With launch provided by the shuttle, the magnetometer will be measuring larger and therefore easier to measure fields in the ionosphere. Also, the lower altitude reduces RF communication requirements as does relaxation of the required data transmission rate, 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.

The nanosatellite configuration and functional block diagrams are shown schematically in Fig. 6. The outer hexagonal surface consists of power-providing solar cells mounted on a structural frame. The satellite electronics including batteries will be concentrated in the center, with radiation protection provided by means of a 40-mil aluminum box. The RF antenna is attached to the electronics box. A three-axis fluxgate magnetometer which is able to measure magnetic fields within an accuracy of 1% will be flown. The magnetometer is body-mounted with its location chosen to minimize contamination by spacecraft magnetic fields. The sun sensor looks radially outward and will be used to determine the phase of rotation. In conjunction with the magnetometer, it will determine the direction of the spin axis. Satellite spin will maintain the orientation of both the antenna and the solar cells within 30° of the ecliptic plane assuming that the shuttle orientation can be selected at the time of release to be in this range.

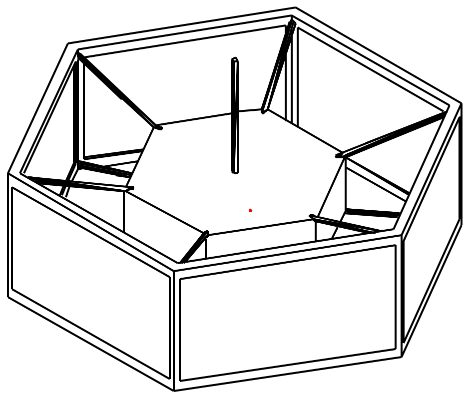

Figure 6. Constellation Pathfinder nanosatellite Circuitry will be near the center and magnetometer will be internal if adequate magnetic cleanliness can be achieved.

As compared to typical satellite designs this mission is particularly stringent in terms of requiring low mass and low power. In view of the large numbers of satellites eventually involved, the design must address manufacturability — simplicity of fabrication, assembly, and calibration. On the other hand, the large number of satellites also reduces the reliability requirements. Failure of a few satellites simply reduces the number of data points, but it does not lead to mission failure. Ref. 6 contains a much more detailed overview and discussion of this mission.

SOLAR BLADE HELIOGYRO NANOSATELLITE

Carnegie Mellon University
Richard Blomquist, William Whittaker (PI)

Solar sail concepts have existed for decades, but their implementation has been elusive and none have flown. The primary difficulty has been the need for great surface area relative to mass. Traditional spacecraft designs with hundreds of kilograms of mass led to kilometers of blade dimensions, which were impossible to rationalize, build, and fly. Nanosat technology drastically reduces mass and makes heliogyro design eminently practical and flyable. An artist's concept of the Solar Blade nanosatellite is depicted in Fig. 7.

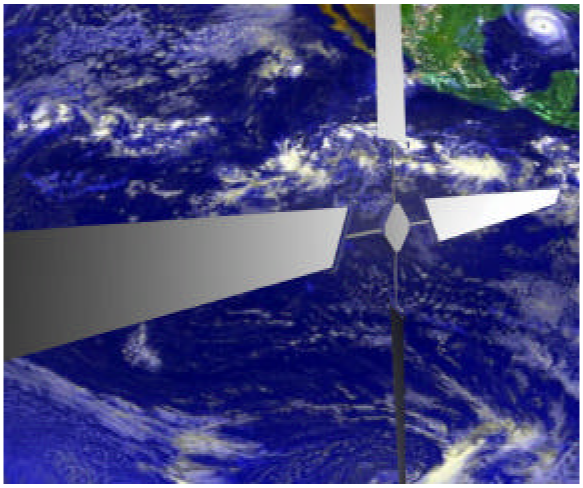

Figure 7. Solar Blade Heliogyro Nanosatellite

Carnegie Mellon proposes to develop and fly the first solar sail, a spacecraft which utilizes solar radiation pressure as its only means of propulsion and attitude control. The solar pressure will enable changes to altitude, attitude precession, spin rate and orbital position.

The Solar Blade Heliogyro Nanosatellite has the appearance of a Dutch windmill and employs control akin to a helicopter. 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 the size of a fire extinguisher.

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.

The Solar Blade Nanosatellite consists of a core containing the computer, communications system, and attitude determination hardware. Four bending struts emanate from the core and solar cells cover the top surface. The blades attach to the struts through individual actuators.

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.

Solar cells embedded on the flanges of the C-beam frame provide up to 28 Watts of power. The spacecraft computer, communication system, and station-keeping sensors at the center of the square connect to the frame through thin lenticular beams. Wiring between the solar cells and the other subsystems consists of thin-film flexible printed circuits.

THREE CORNER SAT CONSTELLATION (3∠Sat)

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University of Colorado Boulder: Elaine Hansen (PI), Anthony Colaprete, Dan Rodier

New Mexico State University: Stephan Horan (PI), Bobby Anderson

This project is a joint effort among Arizona State University (ASU), University of Colorado at Boulder (CU), and New Mexico State University (NMSU). Aptly named Three Corner Sat (3∠Sat), this constellation of three nearly identical nanosatellites will demonstrate stereo imaging, formation flying/cellular-phone communications, and innovative command and data handling. In addition, each university in the 3∠Sat constellation has the opportunity to fly an individual unique payload. Because of this team's heritage in space flight (CU's DATA-CHASER payload via Space Shuttle, August 1997), conventional satellite design (CU's Citizen Explorer via Delta, December 1999), and nanosatellite design (ASU's 6kg ASUSat1 via OSP Minotaur, September 1999), 3∠Sat will be ready for launch in late 2001.

There are a number of scientific and technical objectives for this mission. Fuller details are contained in Refs. 7–9, and a summary of each are is presented here.

Stereo Imaging. The 3∠Sat constellation has two primary science objective. The first goal is to stereo image small (<250m), highly dynamic (<1min) scenes including deep convective towers, atmospheric waves, and sand/dust storms. These stereo images will enable the computation of range to within 250m giving accurate data regarding the physical characteristics of the observed phenomena. The second objective is to conduct a global survey of cloud types, thickness, and altitudes which will contribute to climate modeling and prediction.

Stereo imaging from space has several advantages over conventional imaging, the most obvious being the ability to derive range data. This range data can be substantially more accurate than range data acquired by other more traditional means and also can cover a much greater area. Stereo imaging involves correspondence matching between an image pair and calculation of the resulting disparity. From the disparity, triangulation can be used to determine range data, and three-dimensional images and depth maps can be created. Accurate depth maps with range resolutions of about 250m enable the study of relatively small-scale, short-lived atmospheric events such as cumulus-cloud towers.

Zones of deep convection, in areas such as the Midwest, frequently create large cumulus towers that extend from the middle troposphere into the lower stratosphere. These zones of convection are frequently impassable to air traffic due to the highly unstable air. Radar, while able to warn aircraft of large convection cells, is unable to give accurate data as to their extent in altitude. Thus, air traffic is frequently diverted hundreds of miles regardless of the altitude extent of the convection cells. With better estimates of cloud heights, some air traffic may be able to traverse these convective boundaries by flying over areas of shallow convection.

Cloud heights are critical to our understanding of the Earth's climate and our ability to better model it. Because of their dynamic nature, both spatially and temporally, incorporating clouds and their effects into Global Circulation Models has been difficult. One key piece of data that is missing is the height and thickness of clouds at a global level. Using stereo imaging, the 3∠Sat team will measure the heights of clouds with a precision of less than 250m and make a statistical study of their type, height, and thickness.

In the last decade, studies have indicated that just as important as clouds, other aerosols, including mineral aerosols such as dust or sand, play an important role in Earth's climate system. Recent experiments have been undertaken or planned to understand the composition, structure, and distribution of mineral aerosols on both a local and global scale. Stereo imaging allows the statistical study of aerosol cloud structures, such as sand storms, and can provide information on the relationship between uplift efficiencies, boundary-layer thickness, and particle sizes with local environments.

As the time between traditional satellite images can be long, highly dynamic objects such as clouds and dust storms are currently stereo imaged in a way that makes the range data inaccurate. Stereo images from the GOES8 and GOES9 weather satellites have proven the effectiveness of using two satellites to view the same scene; however, these satellites can only view together for a few hours a day, and since they have relatively low image resolution, the range data is poor. For highly dynamic objects, several satellites with relatively good resolution need to image the same location at the same time. By using a formation of satellites, stereo images of small, highly-dynamic objects can be made, and from these stereo images, accurate range data may be calculated.

Formation Flying / Communications. To accomplish the science objectives, a "virtual formation" is proposed and will be demonstrated as part of the 3⅄Sat program. The virtual formation is a cooperative effort between satellites operating as a network where targeting and data acquisition are accomplished and results transmitted to the ground segment and to the other satellites via communications links without the need for strict physical proximity of the satellites. In this mode, the communications links carry the command and control data necessary to accomplish the mission regardless of the physical location of the satellites. For the mission to be accomplished, the locations of the satellites will need to be in range 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.

For accurate stereo imaging, 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 anticipated four-month lifetime of the mission. Given the initial spacing and lifetime, propulsive capability is not needed.

The baseline design of the mission incorporates the use of a commercial communications network in LEO which supplies the communications links as shown in Fig. 8. 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 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.

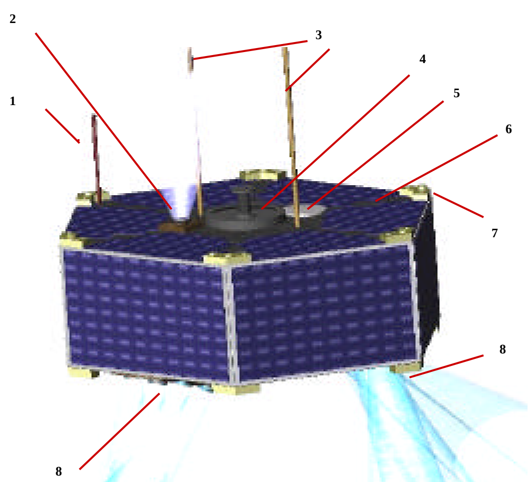
LEO satellites utilizing cellular telephone constellations is a new concept but one in which there is considerable interest in the government and private-sector space communities. This natural extension to the use of ground-based systems will be explored not only to demonstrate the utility of this mode 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.

Command and Data Handling (C&DH) System. The C&DH system for the 3⅄Sat constellation is designed as a distributed and simple system. As part of this distributed arrangement, 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.

University-Specific Experiment: ASU Micro-propulsion System. Micropropulsion systems can offer a wide variety of mission options, all relevant to formation flying: attitude control, stationkeeping, altitude raising, plane changes, and de-orbit. For its university-specific experiment, ASU is collaborating with AFRL and industry to design and fly a micropropulsion system. 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.

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. The mounting configuration within the launch vehicle will depend upon the launch vehicle and other satellites selected. The satellite will use gravity-gradient forces for stabilization with reasonable pointing accuracy, approximately +/– 5° for 500–700km orbits, depending on altitude.

All three satellites will be identical, except for a standard payload envelope where each university will have the option to fly its own unique experiment after the primary science objective has been met. The spacecraft structure will be low-cost and reliable. The exterior envelope of the structure is a six-sided disk structure consisting of tubular supports and machined end caps to hold the bulk of the loading (Fig. 9). The nanosatellites will be stacked for launch (Fig. 10). The design will feature a number of modular, removable trays, allowing for on-the-spot modifications without extra machining or irreversible processes. The design incorporates a common electrical bus that is easily accessible and durable. The material selection and component placement will eliminate the need for any extra shielding from EMI or radiation in space. The solar array panels will be mounted on thin aluminum sheets that mount to the exterior of the frame. All components will mount to aluminum honeycomb plates, which fasten to the main frame via slide-in interface brackets, and/or standard socket head cap screws. The batteries will be stored in the middle of the structure to avoid an unbalanced inertial configuration. These cells will be housed in an eccofoam/aluminum structure attached in a manner to stiffen the component panels from harsh vibration environments.



Primary exterior components shown:
1. Phone antenna
2. Star mapper (15^{O} FOV)
3. Parallel gravity gradient booms with tip masses
4. Integrated battery pack/release mechanism
5. GPS patch antenna
6. GaAs body mounted solar array (18% efficient)
7. Hard mounting points / lateral movement restraint
8. Four CMOS cameras (FOV 15^{O} single/54^{O} composite)

Figure 9. 3^Sat

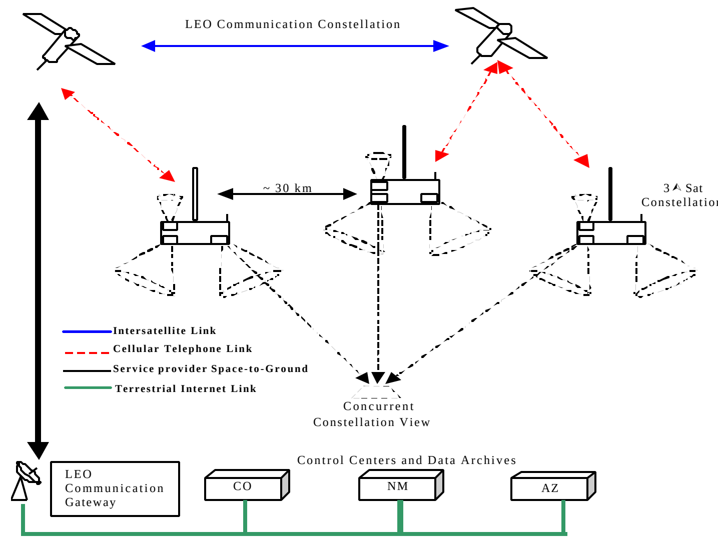


Figure 8. 3^Sat Constellation Overview

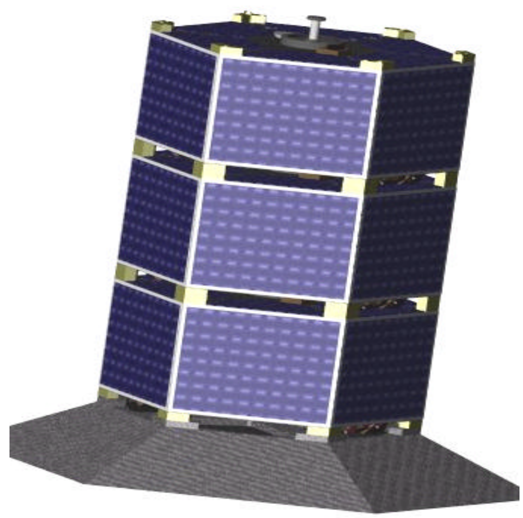


Figure 10. Launch Configuration

DEPLOYMENT STRUCTURE DESIGN

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Andrew Peffer, Jeff Ganley

The AFRL Space Vehicles Directorate will design, fabricate, and test a deployment structure to eject from the launch vehicle and deploy the 10 university nanosatellites. Two preliminary designs have been formulated to accommodate launch from an expendable launch vehicle as a secondary payload or from SHELS. SHELS, as depicted in Fig. 11, is a side bay ejection system under development that accommodates significantly greater weight and volume (180kg and 54” x 42.5” x 24”) than the typical hitchhiker canisters.

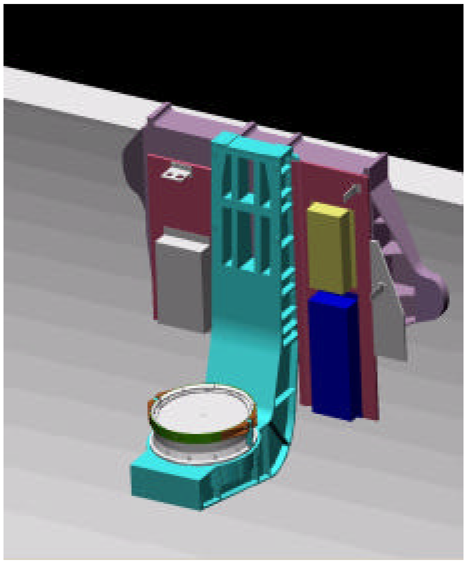

Figure 11. SHELS

The primary objective for the deployment structure is to 1) provide an interface to the shuttle SHELS system and 2) eject the nanosatellites following separation from the shuttle. It will not provide orientation, communication, or spin up capability, and the nanosat separations are executed via timer using battery power.

This project poses a unique problem with regard to the design of a deployment structure. Since each of the universities has unique configurations within volume and weight constraints, this increases design complexity for load transfer to the supporting structure and for arrangement within the launch vehicle. Preliminary design concepts (Figs. 12,13) for launching on 2 SHELS follow. Additionally, the universities have the option to pursue launches on the Pegasus or OSP Minotaur as secondary payloads.

Conclusion

The University Nanosatellite Program encompasses a broad range of technology demonstrations in the areas of miniature spacecraft subsystem components and formation flying. There are also numerous science measurements and experiments in such areas as GPS scintillation, solar wind, magnetic fields, and upper atmosphere ion density. These investigations are funded in support of the AFRL TechSat 21 program.

This program 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. If

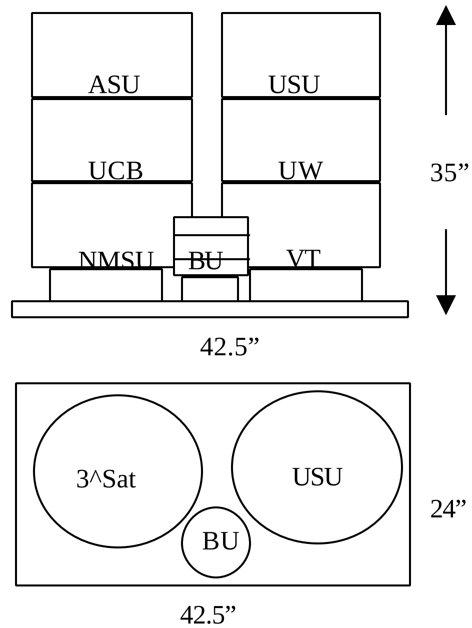

Figure 12. SHELS Payload A Configuration

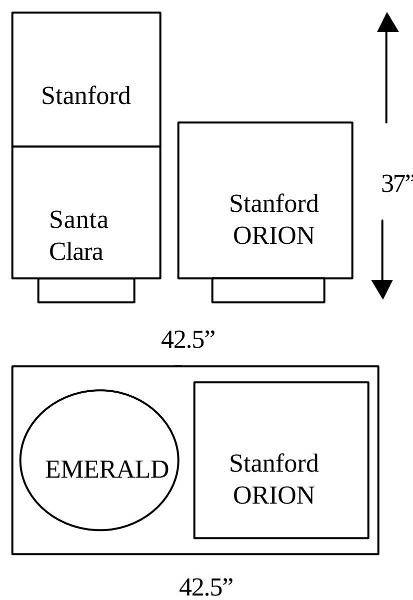

Figure 13. SHELS Payload B Configuration (Includes Stanford ORION Satellite funded by NASA Goddard)

these flight demonstrations are successful, it is very likely government sponsorship can be secured for follow-on launches of nanosatellites built by universities and other agencies.

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