Three Corner Sat Constellation – Arizona State University: Management; Electrical Power System; Structures, Mechanisms, Thermal, and Radiation; Attitude / Orbit Determination and Control; ASU Micropropulsion Experiment; and Integration

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Abstract. Part of the AFOSR/DARPA/NASA GSFC University Nanosatellite Program, 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), our proposed constellation of three identical nanosatellites will demonstrate stereo imaging, virtual formation operations, cellular-phone communications, and innovative command and data handling. In addition, each University has the opportunity to fly an individual unique payload should it desire. With our 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 6 kg ASUSat1 via OSP Minotaur, September 1999), our constellation will be ready for launch in late 2001. This paper describes ASU's functional areas of responsibility towards meeting the 3⮝Sat mission objectives: overall Project Management; Electrical Power System; Structures, Mechanisms, Thermal, and Radiation; Attitude / Orbit Determination and Control; ASU Micropropulsion experiment; and Integration. The companion papers by our consortium partners describe their respective areas of responsibility: CU – Command & Data Handling, Distributed Operations, Stereoscopic Imaging, Science Operations, and Spacecraft Operations; and NMSU - Communications, LEO Telecomm Services, Intersatellite Communications, and Ground Stations and Network.

Introduction

This paper will begin by providing a brief overview of the initial opportunity that was presented which resulted in formation of the Three Corner Sat (3▲Sat) project. We'll then give a detail of the 3▲Sat Mission Goals. (This and the previous section are somewhat common to all three papers). We'll then discuss in further detail those functional areas for which Arizona State University (ASU) has undertaken primary responsibility: Project Management; Electrical Power System; Structures, Mechanisms, Thermal, and Radiation; Attitude / Orbit Determination and Control; ASU Micropropulsion experiment; and Integration.

Overview

3▲Sat is a constellation of satellites to be built by Arizona State University, University of Colorado at Boulder (CU), and New Mexico State University (NMSU). A proposal requesting Air Force Office of Scientific Research / Defense Advanced Research Projects Agency funding for this project was submitted under the University Nanosatellite Program, a Special Topic of the Broad Agency Announcement on the Air Force Research Lab (AFRL) TechSat 21 Initiative. The TechSat 21 concept 'involves satellites flying in formation that operate cooperatively to perform a surveillance mission'. Five basic areas of research were identified to support this concept, as follows:

- ♦ Micro-Propulsion
- ♦ Sparse Aperture Radar
- ♦ Micro-Electro-Mechanical Systems
- ♦ Ionospheric Effects
- ♦ Collective Behavior of Intelligent Systems

The University Nanosatellite Program is funding ten university 'research projects centered on the design and demonstration of nanosatellites', defined as sizes from 1 – 10 kg. The awards are 'for universities to design, assemble, and conduct on-orbit experiments for these satellites.'

Mission Goals

The 3▲Sat consortium will perform research and development of technologies supporting the TechSat 21 concept, and specifically the University Nanosatellite Program special topic, by the design, construction, and operation of a three-satellite constellation. Student education will be emphasized by involvement in all aspects of the project.

Stereo Imaging

The primary science objective of the 3▲Sat constellation is to stereo image small (< 100 meter), highly dynamic (< 1 minute) scenes including deep convective towers, atmospheric waves, and sand/dust storms. These stereo images will enable the computation of range to within 100 meters giving accurate data regarding the shape, thickness and height of the observed phenomena. This is described in detail in Hansen et al.[1]

Virtual Formation Operations

To accomplish the science objectives, a 'virtual formation' is proposed and will be demonstrated as part of our 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 stereo imaging, a nominal spacing of tens of kilometers between the satellites is sufficient. 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. Further detail is provided in Horan et al.[2]

Communications

The design of the 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. Further detail is provided in Horan et al.[2]

Command and Data Handling (C&DH) System

The C&DH 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. Further detail is provided in Hansen et al.[1]

ASU Micropropulsion Experiment

Micropropulsion systems can offer a wide variety of mission options, all relevant to formation flying: attitude control, station keeping, 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 systems requirements are discussed below in a later section.

Management and Schedule

Student Management

The 3⅄Sat project is student-managed with faculty oversight. Students participate from the initial concept, through the design and development, and will participate through flight, ground operations, and data collection. Students come from varied backgrounds in engineering, science, and business and from all levels of experience (principally undergraduate). They participate as interns/fellows, volunteers, or receive course credit. The students receive significant industry advisement.

Team Formation

The 3⅄Sat Mission includes both a flight segment (the spacecraft) and a ground segment (everything else). The flight segment consists of two parts of the spacecraft, the 'spacecraft bus' and any 'payloads', as well as a third part we'll call 'integration', covering such issues as interface control, integration, and testing. The ground segment consists of the ground stations used to communicate with the satellites; the mission operations, such as science operations and spacecraft operations; education and public outreach; and general project management.

In outline form, and adding subsystems for the spacecraft bus and specific payloads, so far we have (bolded items will be explained subsequently):

1) Flight Segment
    a) Spacecraft Bus
        i) **Electrical Power System (EPS)**
        ii) **Communications (Comm)**
        iii) **Command and Data Handling (C&DH)**
        iv) **Structures, Mechanisms, Thermal, and Radiation (SMTR)**
        v) **Attitude / Orbit Determination and Control (AODC)**
    b) Payloads
        i) **Stereoscopic Imaging**
        ii) LEO Telecomm Services (Comm)
        iii) Intersatellite Communications (Comm)
        iv) Distributed Operations (C&DH)
        v) Generic payload envelope
            (1) ASU – Micropropulsion experiment (AODC)
    c) **Integration** (interface control, cabling, integration, testing)
2) Ground Segment
    a) **Ground Stations and Network**
    b) Mission Operations
        i) **Science Operations**
        ii) **Spacecraft Operations**
    c) **Education and Public Outreach (E&PO)**
    d) **Management**

For functional areas of responsibility, we'll take the bolded items from above and place them on the same hierarchical level and (for lack of a better label) call them 'subsystems'. Some of our payloads are experimental bus-type components, so they will be placed under the appropriate bus subsystem. (When considering bus vs. payload functions, we'll require that any payload faults have zero impact on bus functionality.) Now our outline, with lead universities and points of contact, looks like Table 1:

Table 1. 3⮝Sat Functional Areas of Responsibility, with Points of Contact.

Subsystem / Functional Area of Responsibility	Lead University	Point of Contact
1) EPS	ASU	Assi Friedman
2) Comm a) P/L: LEO Telecomm Services b) P/L: Intersatellite Communications	NMSU	Steve Horan Steve Horan Steve Horan
3) C&DH a) P/L: Distributed Operations	CU	Elaine Hansen Sam Siewert
4) SMTR	ASU	Brian Underhill
5) AODC a) P/L: ASU – Micropropulsion	ASU	Brian Underhill Joyce Wong
6) P/L: Stereoscopic Imaging	CU	Tony Colaprete
7) Integration	ASU	Brian Underhill
8) Ground Stations and Network	NMSU	Steve Horan
9) Science Operations	CU	Tony Colaprete
10) Spacecraft Operations	CU	Elaine Hansen
11) E&PO	All	Helen Reed, Elaine Hansen, Steve Horan
12) Management	ASU	Brian Underhill

This table lists each functional area of responsibility (subsystem) with an identified lead university and point of contact. This does not mean that students at each school can participate **only** on the subsystems for which their school has leadership responsibility. In fact we encourage students at each university to participate in any and all areas for which they have an interest. We only ask that these students coordinate their efforts through the lead. The idea here is that we do not let the distant locations of each of the schools preclude participation on a particular subsystem. Student participation on any team requires coordination through the leadership, independent of whether or not that lead is at the student's school or one of the partner schools.

Next we will address formation of personnel groups into teams. Initially it might appear that we should have a team of people for each subsystem. However, with 12 subsystems, this would be far too many teams and therefore too many meetings, especially considering the limited number of people available. Our current model is that just a few teams are formed, and each team has defined subsystem responsibilities. Many of our subsystems possess a natural grouping around student disciplines. Teams formed using this model would consist of the appropriate student personnel, and hold meetings with agenda items covering just those students' areas of responsibility. This challenge of coordinating the necessary subsystem efforts, across three distant locations, with a limited number of personnel resources, is a significant one indeed. Hopefully, this grouping of teams and subsystem responsibilities will result in successful completion of the project needs with an efficient utilization of the available personnel resources.

Table 2 follows, showing these personnel teams across the top, the subsystems on the left, and each team's level of responsibility in the table cells. Levels of responsibility are:

1) **Primary** – this team has ultimate responsibility to ensure that the subsystem is completed adequately. This team will do the majority of work involved toward meeting these ends. This team will also define those tasks to be accomplished by any supporting teams, and will be responsible for monitoring those tasks.
2) Support – this team has a significant amount of responsibility for successful development of this subsystem, though not the primary responsibility. They will provide input to the primary team, but will ultimately receive their required tasks for this subsystem from the primary team.
3) *Minimal* – this team as a minimum needs to stay apprised of this subsystem's progress. This team may also have more involvement than receiving progress updates, but it won't be to the same level as 'support'.

Table 2. 3⮝Sat Personnel Teams

Personnel Team ->		Electronics	Software	Structures	Systems
~discipline ->		EE	CS/CSE	ME/AE	all
<u>Subsystem</u>	<u>Univ</u>				
EPS	ASU	**primary**	support	support	support
Comm P/L: LEO Telecomm Services P/L: Intersatellite Communications	NMSU	**primary**	support	support	support
C&DH P/L: Distributed Operations	CU	support	**primary**	*minimal*	support
SMTR	ASU	support	*minimal*	**primary**	support
AODC P/L: ASU-Micropropulsion	ASU	support	support	**primary**	support
P/L: Stereoscopic Imaging	CU	support	support	support	**primary**
Integration	ASU	support	support	support	**primary**
Ground Stations and Network	NMSU	support	support	*minimal*	**primary**
Science Operations	CU	*minimal*	support	*minimal*	**primary**
Spacecraft Operations	CU	*minimal*	support	*minimal*	**primary**
E&PO	All	*minimal*	*minimal*	*minimal*	**primary**
Management	ASU	*minimal*	*minimal*	*minimal*	**primary**

Using this model then, each school will have (at most) its own Electronics, Software, Structures, and Systems team leaders - to coordinate the efforts of its local students (maximum of four teams). This should provide for a minimum of teams and therefore meetings and management structure, full coverage of necessary subsystem efforts, and plenty of opportunity for students to gain knowledge and exposure to those areas that interest them.

Meetings and Reports

An organized meeting structure ensures communication between subsystems and members. A weekly telecon meeting is held and all members of the project are required to "attend".

Subsystem leaders "meet" weekly to lay out milestones. Subsystem leads are then responsible for assembling their groups to delegate tasks and to write the weekly report. Each subsystem has a separate one-hour meeting (telecon) once a week to discuss tasks within their group and help each other out.

Reports are a major part of the program. Reports, due every week, are compiled and emailed out to all team members before each weekly meeting. These are used as a progress indicator to evaluate individual performance. Information is maintained on a website.

Project Schedule

Milestone	**Date**
Project Start	January 1999
System Requirements Review	August 1999
Technical Interchange Meetings	(every 2 months)
Preliminary Design Review	October 1999
Critical Design Review	March 2000
Build	March-August 2000
Integration and Test	Fall 2000
Environmental Test	November 2000
Qualification Readiness Review	December 2000
Flight Readiness Review	February 2001
Launch-Vehicle Integration	April 2001
Launch	late 2001

Systems Engineering Approach

Integration and Testing

The reliability of the structure will be tested using simplified models, followed by extensive finite-element modeling. A developmental structure will be used for integration testing, along with static, shock and vibration loading tests. This structure will be followed by a qualification unit, which will be assembled identically to flight. The assembled structure will be qualified at 120% of expected shock and vibration levels of the launch environment. Five final structures will be built: three for flight and two as backup units. The structure will be relatively inexpensive so more structures may be made for general testing and integration purposes.

Trade Studies

Several of the components that will be selected for 3◭Sat will be flown in space for the first time on this mission. Nanosatellites are still in the experimental stages, so there are few manufacturers of nanosatellite components. To ensure that the components selected will survive the space environment, studies will be performed. The main characteristics by which components will be judged are weight, power, and cost. These are common constraints for space missions, but they are non-negotiable requirements in a nanosatellite mission. This strict budget leads to new and creative ways to do the same tasks that larger satellites do. For specific mission needs, where the technology does not yet exist to perform the needed task, it is important to incorporate the ground station as a mission partner to fill this gap.

Quality Assurance Approach

Measures will be taken to ensure that proper quality is met, timelines are kept, and data are preserved. To ensure quality in design and manufacturing, all students will be trained in the use of the software packages and machining techniques. Material selection will pass all NASA outgassing requirements and launch vehicle safety requirements. Project leaders will ensure that all members are aware of any timeline issues, and that students who meet or exceed those schedules will be rewarded.

Student-run projects need to enforce documentation, yet keep it to a minimum to ensure that students have time to do the engineering work. It is essential to have a documentation system that is reliable yet not cumbersome. Most documentation will come in the form of reports that will be compiled and stored electronically. Reports will consist of weekly reports of general progress, project reports documenting design details and issues, and final semester reports summarizing progress during the term. The other documentation will include standard review packages. These documents are updated by the individual team members, and are reviewed by the systems leaders and external advisors. Documentation will be accessible through ftp by all three schools. Documentation, platform, and drawing standards have all been set, allowing for full compatibility among the schools. Regular telecons will be held among all three schools to ensure that all team members are aware of the general team progress and issues.

Risk Mitigation and Technology Dependence

Two mission critical areas are security and redundancy. Any satellite in orbit is susceptible to hackers. It is important that a proper security system is implemented to avoid losing control of the spacecraft. An unauthorized user repeatedly calling the satellite, or calling the satellite and hacking the system, could occur and possibly jeopardize the mission. The first is an occurrence that anyone with a phone could do, so it will be critical that a number blocking device be installed on each phone, which will only allow calls from authorized operators. A backup system will also be in place utilizing an encryption scheme that only allows authorized users into the system.

The only systems that will be considered for redundancies are the cell phone, power-on device, main computer and deployment signal. These are the main systems that could not endure a single failure without the entire mission being jeopardized. Though there are other systems that are mission critical, many of them could handle a small failure without being knocked off line, or are just too expensive or heavy to have backups.

Electrical Power System

The design of a power system for a nanosatellite is no small challenge. Since the only energy source available is solar, the effective solar-array area becomes the most critical factor in determining available power for the satellite. With the small surface area available to the nanosatellite, available power is very limited. Another problem in a nanosatellite is that many of the payloads and experiments require surface area for sensors, probes, and antennas. This requirement makes the area available to the solar array even smaller.

The small size of the nanosatellite usually makes the effort of employing a deployable or tracking array too difficult to be efficient due to the complex mechanics, added weight, and possible obstructions of the experiments themselves. These limitations almost always leave a body-mounted array as the only viable solution.

Another severe problem with solar-array design is the large semiconductor-to-solar-cell technology ratio. Semiconductor-component technology is currently growing at a larger rate than solar-cell technology. As a result, more payloads can be integrated into the design. With more payloads, more power is needed for required scheduled operations. Current growth of solar-cell technology is not fast enough to provide the higher-efficiency cells required to power all of the added payloads. Present commercially available solar cells have an efficiency of about 24% - almost the limit for current GaAs technology.

Keeping these limitations in mind, the 3⮝Sat satellites will attempt to maximize the overall efficiency of the power system using the following strategy. The basic configuration for the solar array will be body-mounted arrays on all six sides plus an additional array on the top bulkhead. The array surface area will be the maximum permissible size while taking into account the needs of the experiments. Such a configuration will guarantee that electricity is always generated while the satellite is in the sun's view.

In addition to the body-mounted array the team is looking into an option of a deployable (but not steerable) array. Such a concept would include folding panels that deploy from the side panels and effectively double the surface area of the side panels. Such an approach is very attractive for the power budget, but will be considered only after the requirements of all the payloads have been met.

Available commercial solar cells vary largely in efficiency, durability, and price. The University Nanosatellite Program has been offered a donation of triple-junction GaAs cells made by SpectroLab. These cells are adevertised to have an efficiency of 24%.

Due to the varying illumination conditions on the solar array the operating conditions also change. In order to extract the maximum available power, Peak Power Tracker (PPT) units will be employed. On the 3⮝Sat satellites, several PPTs will be used to maximize power transfer to the bus.

A robust battery pack is another design challenge in space use. In orbits with eclipses, battery packs are a must for whole-orbit operation. The battery pack is also needed to regulate and stabilize the satellite's power bus. Space-rated batteries are expensive and difficult to obtain. The 3⮝Sat team will follow the heritage of ASUSat1 by qualifying commercial cells for space use. Since operation during an entire orbit constitutes a battery cycle, vigilant charge and discharge management is necessary for proper battery maintenance. In order to simplify the design of the power system and save hardware, charge will be regulated using payload scheduling. Instead of introducing shunt systems to prevent overcharge, payloads will be used to divert excess power from the battery pack. Scheduling will be used in a similar way to control the discharge depth of the battery.

The power system will provide three voltages to the satellite modules. The first is an unregulated bus voltage. This voltage will essentially be the battery voltage and will be used by the modules to generate voltages needed only by that module. The remaining two voltages will be regulated supplies. This will be implemented using high-efficiency DC/DC converters. Current design is to use the typical bus voltages of 5V and 3.3V.

In addition to the energy conversion and storage functions, the power system will also have a control node on the satellite's data bus. This node will provide the status of the power system to the other modules. Such information will include solar-array voltage and temperature; battery capacity, mode, and temperature; PPT and DC/DC converters status; and power-consumption status. Such information gathered by the power system itself will enable the other modules to get quick updates of power-system status, taking the data-processing task off of the individual modules.

The main motivation leading the design of the power system is to design a high-efficiency independent system that will provide the necessary power to sustain a meaningful operation profile. Furthermore, the power system will provide accurate reports of its status to the other modules for operation consideration. The team will implement proven design concepts, incorporating the latest technologies where beneficial.

Structures, Mechanisms, Thermal, and Radiation

Our team collectively brings many "lessons learned" that are directly applicable to 3⮝Sat. As an example, our ASUSat1 nanosatellite project has provided extensive trade studies and lessons on structural elements.[3] We gained experience in the areas of drawing standards, machining capabilities, and solid modeling applicable to the design of structures and mechanisms. Ground-system software tools have been successfully demonstrated on CU's DATA-CHASER Mission, an attached payload on the Shuttle in August 1997. Updated versions of these tools for execution both on the ground and on-board are now being developed for use on CU's Citizen Explorer Mission, scheduled for launch in December 1999. All three universities have significant experience in mission design from these various programs.

With regards to the spacecraft bus, we strive for the design to be lightweight, simple (minimal high-risk deployables and appendages), robust, and practical, and one that could be scaled for almost any launch vehicle and able to accommodate most payload options. These potentially affect a mission in areas such as power production, communications ability and so forth, but greatly increase reliability and reduce risk and cost.

In our vision, designs should have the following characteristics and be adaptable to a variety of tasks and functions:

Modular:

- Allows change up until the last minute
- Capable of multiple missions and payloads
- Easy to size for any launch environment
- Easy to assemble
- Easy to disassemble
- Integrated multi-use mechanisms, structures and components
- Requires minimal work to gain access to any component

Systemic:

- Built in radiation and EMI shielding
- Fully grounded chassis and planes
- Has an easy to manage cable routing scheme
- High thermal conductivity for quick temperature transfer

Practical:

- Inexpensive and simple
- Most exotic material is aluminum honeycomb, which is very common
- Multiple hard points to which handles can be attached for handling
- Uses standard parts with only small repetitive machining requirements

All too common in the space business is change, change after there are supposed to be no more changes. With this in mind, the main asset of a design should be its adaptability to change. For example, if a component grows and needs more volume, the structure should be easily adjustable in all directions. If the worst case happens and the payload changes, after hole patterns are already drilled, then replacing a single part of the structure is inexpensive. This can be compared to other structures that would have to be completely redesigned and/or rebuilt in either instance. This same paradigm of adaptability applies to software and mission changes as well.

Another goal of the design should be to minimize the number and variety of stock materials and different parts and components. Parts that are standard or designed from common materials, require minimal and easy machining, and are identical whenever practical. Multifunctional parts are also preferred; e.g. a battery pack can serve as a structural member. This will minimize costs and other manufacturing issues.

The spacecraft bus designs suggested below are by far not the only possibilities, nor are they necessarily the best at this point, but they do feature characteristics which we feel cover many of the areas of concern. The suggested bus shape of the structure was chosen to be a six-sided right extruded polygon with flat bulkheads on the top and bottom of the bus. Six was chosen based on maximum power generation and modularity. Two different versions are provided here:

The first is based on a frame of thin-walled aluminum tubing with main component panels that slide into the frame. For the main support for the panels and the structure itself, the battery pack is inserted down the center of the structure. At final assembly the outer panels (e.g. solar panels) can be mounted on each of the six sides, and bolted into the brackets (Figure 1, next page).

Proposed satellite assembly

Assembled proposed satellite

Figure 1. One Proposed Structural Concept

The second structural concept (Figure 2) allows for more payload volume and access to the centerline of the satellite, a key consideration for micropropulsion experiments. The main component panels are placed towards the perimeter of the satellite volume. At final assembly the outer panels (e.g solar panels) slide in as the outer structure.

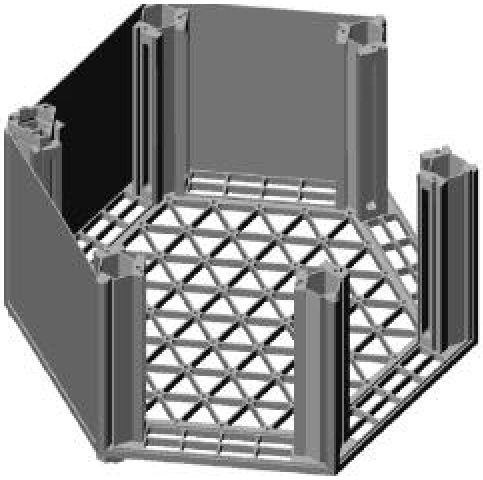
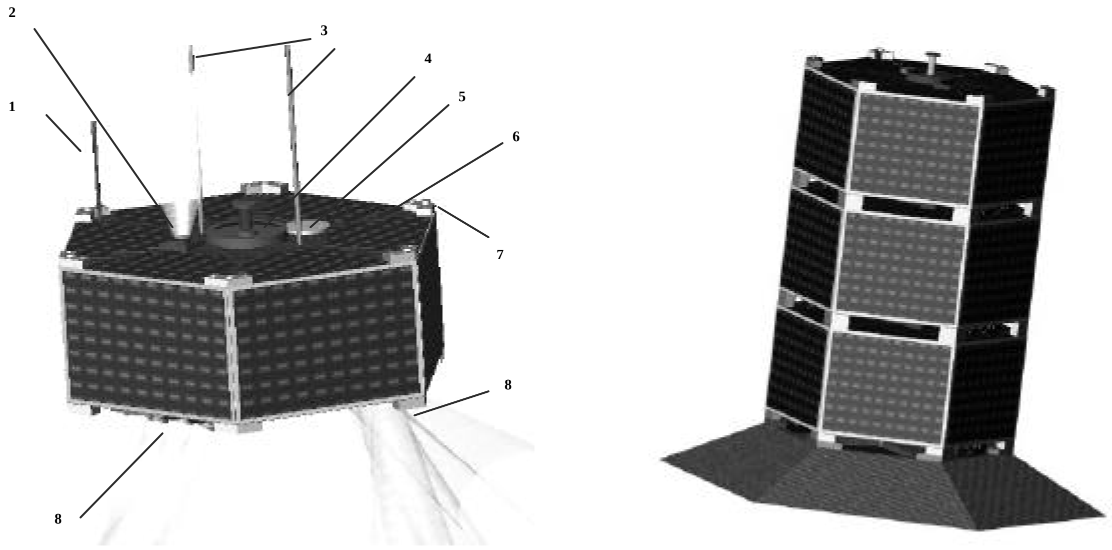


Figure 2. Another Proposed Structural Concept

A schematic of the integrated spacecraft including a representation of the three of them stacked in the launch vehicle is shown in Figure 3. The projected constraints include a maximum total mass of 10 kg and volume of 0.03 m^3. Each satellite will consist of body-mounted solar arrays that should give us a maximum average illuminated area of 0.22 m^2, with an estimated in-Sun average of about 0.16 m^2. This translates to 33 watts of power based on 18%-efficiency cells. For attitude control, the ASU students have developed an innovative, passive, gravity-gradient fluid damper which, coupled with a parallel-gravity-gradient-boom configuration, can yield a reasonable (+/- 5 degrees) pointing accuracy for a 500-700 km altitude orbit. If the lower-altitude NASA Space Shuttle is the designated vehicle, we shall make the appropriate design modifications (see next section).



Flying Configuration

Launch Configuration

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)

Primary interior components not shown:
1. Boom Deployment Mechanism
2. C&DH Electronics
3. Power Control Board
4. Cell Phone
5. GPS Receiver
6. Paraffin Actuated Pin-Pullers
7. Structural Supports, Tubes and Panels
8. Camera Boards With Micro Controllers

Figure 3. Spacecraft Overview

Attitude / Orbit Determination and Control

This 3⅄Sat subsystem covers both attitude determination and control considerations (traditional ADCS) and orbit determination and control considerations (i.e. Guidance and Navigation).

The 3⅄Sat project incorporates two parallel design paths: one at a high LEO orbit (550 – 1000 km) where gravity-gradient effects can be used for primary stabilization, and the other for a shuttle-altitude orbit (300 – 400 km) where gravity-gradient stabilization is not a viable option.

The original 3⅄Sat design was for the higher altitude where we plan to use a multitude of fixed imaging lenses aboard each spacecraft and a gravity-gradient boom as the sole means of attitude stabilization. Then utilizing an accurate and dynamic attitude determination via a star-tracker and the inherent slight wobbling of a gravity-gradient stabilized platform, accurate image targeting would be accomplished.

At the lower shuttle altitudes, gravity-gradient effects are overwhelmed by upper atmosphere disturbances. For this design path, we are reviewing a number of design options for attitude control / image targeting, including steerable lenses, an aero-boom, and traditional active control components such as magnetic torquers, momentum/reaction wheels, and even control moment gyros. Of course the small design envelopes permitted on nanosatellites contributes greatly to the design challenge of utilizing these components, which in turn will require serious trade consideration and perhaps development of very innovative solutions.

At the bus level, orbital considerations will not employ any means of orbit control, only orbit determination. This will be accomplished on-board each spacecraft using the latest available small-scale GPS technology. Although not utilized at a bus level, the generic payload envelope aboard each spacecraft is available for micropropulsion experiments. One such experiment to be flown on the ASU satellite is discussed next.

ASU Micropropulsion Experiment

ASU is collaborating with AFRL personnel to flight test a micropropulsion system on a university satellite. After satisfying the four-month on-orbit demonstration as part of the 3⌃Sat constellation, the ASU spacecraft (ASUSat2) will extend its mission lifetime by performing an orbit-raising operation.[4] A micropropulsion system will be required to execute this maneuver with the aid of an adequate attitude sensing / control system. Depending on the mass and shape of the satellite, it will be raised to at least 550km, where it can support an orbit lifetime of no less than 2 years. Ideally, upon the completion of the second mission lifetime, the satellite would perform a de-orbit maneuver to eject itself from LEO. This operation, of course, would depend on the status of the battery. If the battery should indicate signs of failure before reaching the 2-year lifetime on the destination orbit, one option is to perform the de-orbit before the end of the second mission. On that account, it would still allow the micropropulsion system to demonstrate its functionality—orbit-raising and de-orbit—without being hindered by power limitations. The objectives of these orbit transfer maneuvers are to facilitate data collection to demonstrate and validate micropropulsion technologies.

Two micropropulsion systems are being considered to demonstrate unique technology on ASUSat2 within the pre-launch time frame. They are the free molecule micro-resistojet (FMMR) with water propellant, described in detail by Ketsdever, et al[5], and a cold-gas (CG) micronozzle thruster that uses nitrogen for fuel. Compared to other micropropulsion systems being developed in the industry, such as variations of the ion thruster, the FMMR and CG micronozzle are better candidates for ASUSat2. Although these two systems do not produce very high Δv as compared to some systems (e.g. Hall thruster), their mass and power requirements are a much better match for the ASUSat2 constraints. In addition, the maturity of the technology places these two systems ahead of the others for the two-year pre-launch time frame. Nevertheless, we welcome any other ideas and possibilities that may improve our ASU-specific micropropulsion experiment.

After a preliminary study, the FMMR offers several additional benefits over the CG micronozzle from a systems standpoint. It is less prone to catastrophic plugging, the feed system mass and valving requirements are minimized, and the micro-machined structure is compact, lightweight and robust in construction. In fact, the entire FMMR system mass will be approximately 4 kg including propellant. The estimated power requirement is about 20W. On the other hand, the CG micronozzle has several apparent disadvantages from a systems point of view. It will require high-pressure feed lines, pressure regulation, and strict propellant filtering due to the concern of catastrophic plugging of the nozzle throat. The total system mass of the CG micronozzle is about 5 kg including propellant, and the power requirement is between 10 and 30 W. Nevertheless, unlike the FMMR, the CG technology has been previously demonstrated in space.[4]

The above calculations are based on a worst-case scenario in which ASUSat2 is released at 250 km. With a higher altitude insertion, smaller micropropulsion-system requirements for mass, volume, and power will be available. Moreover, trading on-orbit lifetime for smaller resource usage provides another possibility. For example, ASUSat2 could be on-orbit for one year instead of two, thus relaxing the altitude-raising requirement. These are some system trades that will be considered over the next six months of design. However, the team feels that the numbers are encouraging and suggest success of the FMMR as a candidate for microspacecraft propulsion. Nevertheless, it is recognized that although the FMMR appears to be a more attractive micropropulsion system for ASUSat2, it still requires some additional development to make it a flight ready system. An innovatively customized CG micronozzle system will be developed in parallel to ensure a micropropulsion system is ready for the launch of ASUSat2. Moreover, to reiterate, we are also open to investigating other systems for this application.

Integration

Any experienced engineer can appreciate that integration is one of the most challenging aspects of system design. It marks the point where all the know-how from all the disciplines comes together and testing begins on a system level, rather then component level. The 3⌃Sat project adds a number of unique aspects to this already challenging task.

Each member school is located an appreciable distance from the others, bringing a significant challenge to any teamwork efforts. A choice needed to be made regarding how team responsibilities would be divided, considering such things as the distance between locales and the short timeline to delivery. The first option considered was that each school could build its own satellite, and that the constellation would come together only as the delivery date was approached. However, with the short timeline involved, it was felt that none of the schools would have the resources available required to design, build and test its own complete and unique satellite, and have the three successfully work together as a constellation.

Instead the consortium chose to have each school focus on specific subsystems, particularly those for which it has some previous experience. Each school would then design, build and test a particular subsystem to be used on each of the three spacecraft. This would assure the desired consistency among the platforms, and not unduly burden each of the schools' resources.

However, this option does retain a very real integration challenge – but not one that occurs just prior to delivery. Instead the integration difficulties would occur much earlier in the project development, at the subsystem integration level.

To address this aspect of systems integration, a new concept had to be introduced, a concept we're calling 'remote integration'. This concept first requires that a modular architecture is employed, an architecture that we had already decided to use to address the issues incurred with three distinct production partners (independent of the distance issue). Then, with the availability of the internet as a communications medium, the schools will design and build 'internet bridges' that will enable each school to connect its modules to a local bus just as if they were all connected to the satellite's internal communications bus. The great advantage of this approach is that for the first stages of integration, the units will be tested remotely. Once the basic functionality has been established the units will be shipped to the integration facility where final integration will take place.

Conclusions

3▲Sat is a student-run project under the AFOSR/DARPA/NASA GSFC University Nanosatellite Program. Three universities are teamed together to build a constellation of three nanosatellites that demonstrates stereo imaging, formation flying, cellular-phone communications, and innovative command and data handling. Launch is expected in late 2001. This paper describes ASU's functional areas of responsibility towards meeting the 3▲Sat mission objectives: overall Project Management; the Electrical Power System; Structures, Mechanisms, Thermal, and Radiation; Attitude / Orbit Determination and Control; the ASU Micropropulsion experiment; and Integration. The companion paper "Three Corner Sat Constellation – University of Colorado, Boulder: Command & Data Handling, Distributed Operations, Stereoscopic Imaging, Science Operations, and Spacecraft Operations," by Hansen et al., describes CU's functional areas of responsibility towards meeting the objectives, while the paper "Three Corner Sat Constellation – New Mexico State University: Communications, LEO Telecommunications Services, Intersatellite Communications, and Ground Stations and Network", by Horan et al., describes NMSU's functional areas of responsibility.

Sponsors

AFOSR/DARPA/NASA GSFC, NASA Space Grant College and Fellowship Program, Lockheed Martin Management & Data Systems - Reconnaissance Systems, Honeywell Space Systems, Lockheed Martin Astronautics, Motorola, AFRL Edwards AFB, Cogitec, Space Quest, Microchip, Ball Aerospace, Spectro Lab, and JPL.

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