Emerald: A Low-Cost Spacecraft Mission for Validating Formation Flying Technologies

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Abstract - Spacecraft formation flying is a proposed technology with vast performance implications ranging from enhanced mission capabilities to radical reductions in operations cost. To explore this concept and to enable its realization, Stanford University and Santa Clara University have initiated development of a simple, low cost, two-satellite mission known as Emerald.

The Emerald mission has four primary goals. First, it will verify component-level technologies necessary for advanced formation flying missions. This will include the test of low-power Global Positioning System (GPS) receivers for position sensing, simple radio modems for inter-satellite communication, and experimental microthrusters for position control. Second, it will integrate the operation of these payloads in order to experiment with simple closed loop relative position control. Third, it will validate the formation flying concept by using coarse on-orbit relative position sensing and control to improve a scientific investigation of lightning-induced atmospheric phenomena. Fourth, it will extend low-cost satellite development techniques critical to fielding multi-spacecraft fleets.

The bus design for the Emerald spacecraft will be based on Stanford`s Satellite Quick Research Testbed (SQUIRT) microsatellite design. This consists of a 15 kilogram structure, a modular 12 inch tall by 18 inch diameter hexagonal configuration, a 68332-based flight processor, a single battery, solar panels, and simple attitude and thermal control. A Space Shuttle launch in 2001 has been tentatively selected for the launch of this mission. Emerald will be developed as part of the Defense Advanced Research Projects Agency (DARPA) and Air Force Office of Scientific Research (AFOSR) University Nanosatellite Program, an element of AFOSR's TechSat 21 Program.

This paper will discuss the Emerald mission objectives and approach, the conceptual design of the Emerald spacecraft, and the programmatic structure of this joint Stanford University – Santa Clara University project.

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1. INTRODUCTION

Spacecraft formation flying is a technology in which a mission is performed by a virtual spacecraft comprised of a distributed array of simple, low-cost, highly coordinated vehicles such as a formation of small satellites. This is a dramatic departure from current monolithic bus architectures. Many scientific, military, and commercial space applications may be able to benefit from using a formation flying strategy in order to perform distributed observations for surveillance, Synthetic Aperture Radar (SAR) earth mapping, magnetosphere sensing, interferometry, and a variety of other missions.

This approach represents a new systems architecture that provides many potential performance and operations advantages, such as [1]:

- Extensive, autonomous co-observing programs with minimal ground support,
- Increased separation (baseline) between instruments enabling orders of magnitude improvement in space-based interferometry, improved world coverage for remote sensing, and simultaneous target observation using a variety of sensors,
- Replacement of large complex spacecraft with a flexible architecture of simple microsatellites offering redundancy and graceful degradation.

- Emphasis on instrument development and operation by streamlining and reducing bus development costs through standardization and economies of scale.
- Rapid insertion of crucial systems allowing long lead-time instruments to join the fleet as available.

With these potential benefits, however, come a variety of challenges. These include:

- Performing high-accuracy relative position sensing given transmission effects and disturbances,
- Controlling relative spacecraft position to levels of precision ranging from tens of meters to less than a centimeter,
- Developing and implementing fleet-level mission processing strategies,
- Implementing robust inter-satellite communications links for exchanging constellation management data,
- Developing low cost design approaches such that multi-satellite constellations become a competitive option for some missions.

Recent successes in GPS-based sensors have demonstrated that Carrier-Phase Differential GPS (CDGPS) techniques can be used to autonomously track the relative position and attitude between several spacecraft [2, 3, 4, 5, 6, 7, 8, 9]. This sensing technology offers the potential to achieve significant reductions in the weight, power, and cost of spacecraft attitude and orbit determination systems; it also may lead to significant reductions in ground operations costs through enhanced vehicle autonomy. Together with position control devices and inter-satellite communication links, GPS-based could in theory be used to enable precisely controlled spacecraft formations

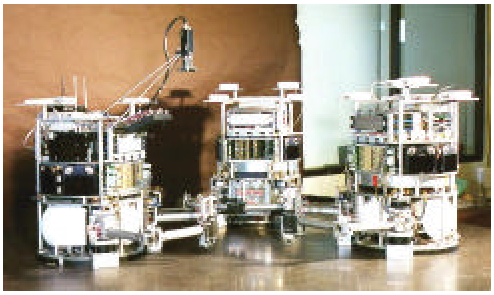
Since 1995, NASA's New Millennium Program (NMP) has been exploring formation flying technologies. The NMP EO-1 mission will attempt coarse formation flying (10-20 m) with the Landsat 7 spacecraft in order to validate the multi-spectral Landsat imager. However, because of time and budget constraints, no communication cross links will be possible for this experiment, resulting in a very limited demonstration. The NMP DS-3 mission will control multiple spacecraft to within a fraction of the wavelength of light (baselines of several kilometers) to perform optical stellar interferometry [10]. The autonomous operations planned for DS-3 control are also applicable to distributed SAR and Earth imaging missions. As part of the NMP technology development program, Stanford is developing a six spacecraft, six month mission called Orion that will demonstrate the full capabilities of formation flying [1]. Targeted launch for Orion is in 2002. Orion will demonstrate closed loop (sub-meter level sensing) station keeping and attitude control combined with the formation-level specification of maneuvers.

The Air Force Office of Scientific Research (AFOSR) is also sponsoring formation flying research in support of the Air Force Research Laboratory's revolutionary approach to performing space missions using large clusters of microsatellites [11]. In particular, AFOSR's TechSat 21 Program involves satellites flying in formation that operate cooperatively to perform a surveillance mission. One of the TechSat 21 initiatives, known as the University Nanosatellite Program (jointly sponsored by the Defense Advanced Research Projects Agency), involves the development of up to ten low-cost university spacecraft. These projects are intended to explore the military usefulness of nanosatellites; particular missions of interest include technology development experiments supporting formation flying, enhanced communications, miniaturized sensors, attitude control, maneuvering, docking, power collection, and end-of-life de-orbit. Selected universities in the Nanosatellite Program will be funded at a level of $100,000 to develop a spacecraft over a two-year period. In addition, a launch will be provided; currently, a Shuttle launch is being planned for early 2001.

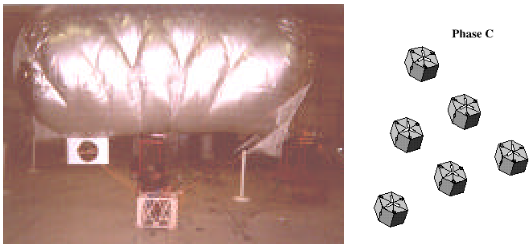
2. STANFORD'S FORMATION FLYING RESEARCH PROGRAM

Stanford University's Aerospace Robotics Laboratory (ARL) is a world leader in developing GPS-based formation flying systems. Shown in Figure 1, this includes work on the Orion project as well as several testbed systems.

One testbeds consists of 3 active free-flying robots that move on a 12 x 9 ft. granite table top [2, 3, 6, 12]. These air cushion vehicles simulate the zero-g dynamics of a spacecraft formation in a horizontal plane. Each vehicle has onboard computing and batteries, is propelled by compressed air thrusters, and communicates with the other vehicles via a wireless Ethernet.



(a) Granite Table Mobile Robots Performing Formation Flying in Two Dimensions



(b) Unmanned Aerial Blimp Capable of Formation Flying

(c) The Conceptual Orion Constellation

Figure 1. *ARL Formation Flying Systems*

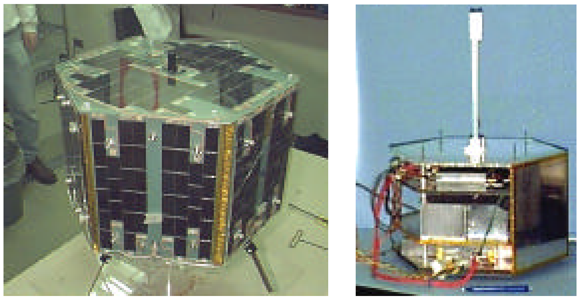
A second testbed demonstrates formation flight in three dimensions using lighter-than-air vehicles (blimps) [13]. This testbed will be used to demonstrate that various GPS errors, such as the circular polarization effect, can be modeled and eliminated from the measurement equations; these errors play a crucial role on-orbit because spacecraft can undergo more general 3D motions.

3. Spacecraft Design Programs at Stanford and Santa Clara University

In response to the University Nanosatellite Program, Stanford University and Santa Clara University have formed a team in order to propose the two-satellite Emerald mission.

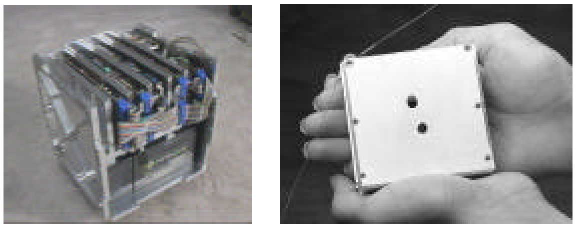
Both Stanford University's Space Systems Development Laboratory (SSDL) and the Santa Clara Remote Extreme Environment Mechanisms (SCREEM) Laboratory have successful, established programs in low-cost spacecraft design. Each has a small satellite program for producing low-cost, rapidly developed spacecraft for testing new technologies [14, 15]. Each program is structured such that students are responsible for managing and engineering the entire mission. In addition, each program relies on re-engineering commercial components not typically used for space applications. Professional oversight, industrial mentoring, and emphasis on verification testing are used to address the elevated risk inherent in these approaches.

SSDL's first two microsatellites, Sapphire and Opal, have each been developed for less than $50,000 cash. Sapphire is flight testing new micromachined sensors for the Jet Propulsion Laboratory [16]; Opal will be testing mothership/daughtership mission architectures for DARPA [17]. SCREEM's first two spacecraft projects include the Barnacle flight package for component testing [18] and a series of hockey-puck sized Artemis picosatellites that will be ejected as part of the SSDL Opal mission [19]. All of these spacecraft are currently targeted for launch in 1999. Figures 2 shows photographs of these spacecraft.



(a) SSDL's Sapphire Microsatellite

(b) SSDL's Opal Microsatellite



(c) SCREEM's Barnacle Microsatellite

(d) SCREEM's Artemis Picosatellite

Figure 2. *SSDL and SCREEM Spacecraft Projects*

4. The Emerald Mission

The Stanford – Santa Clara Emerald mission will further spacecraft formation flying research by attempting to meet four primary goals.

First, Emerald will serve as a low-cost, rapid prototyping testbed for component-level technologies crucial to the system level performance requirements of future formation flying missions. These component-level tests will include the following:

- Determining the accuracy and survivability of a low-cost, low-power GPS receiver,
- Evaluating the capability and robustness of an inter-satellite communications link based on local area network technology,
- Characterizing the performance of newly-developed microthrusters,
- Examining the value of very low-cost, low-performance, passive means of constellation position control such as tethers and drag panels.

Second, Emerald will use the aforementioned components to enable simple, closed-loop, on-orbit experimentation as the first step in Stanford's long-term program in spacecraft formation flying. As an example, the following experiments will be attempted:

- Communicate GPS receiver position data between the spacecraft via the inter-satellite communications link in order to perform on-orbit relative position determination.
- Use the microthrusters and drag panels to actuate very coarse on-orbit position control.

Third, Emerald will validate the formation flying concept by conducting a science experiment that can be enhanced through this technology. The science experiment consists of sampling lightning-induced Very Low Frequency (VLF) radio waves in order to study the ionosphere. Taking these measurements on physically distributed platforms with high accuracy relative position sensing and control contributes to the science that can be accomplished. This investigation is part of a broader small satellite-based ionospheric-science program being conducted by SSDL and the Stanford Space Telecommunications And Radioscience Laboratory (STARLAB) [20].

Fourth, it will extend and improve the low-cost satellite design, fabrication, and operation techniques that have been pioneered in the university and amateur satellite communities. These techniques represent an important step towards achieving low-cost, rapidly developed spacecraft for multi-satellite fleets. Many of the lessons learned in this field have already been incorporated into previous SSDL spacecraft; given available resources, additional enhancements to these designs will be made to further extend the capabilities of these space vehicles.

As depicted in Figure 3, the baseline mission configuration timeline is as follows:

- The two spacecraft will be stacked together and launched as a single object. During this first stage of operation, initial checkout, calibration and some limited component-level experimentation will occur. This stage of operation will last on the order of a two weeks.
- During the second stage of operation, the satellites will deploy into a tethered configuration on the order of tens of meters. During this stage, experimentation will include on-orbit relative position determination as well as simple closed loop relative position control using the drag panels and microthrusters. The tethered configuration will be maintained for several weeks to permit relative position experiments to occur without the fear of the vehicles drifting out of the range of their inter-satellite communications systems.
- 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. Upon ground command, the two halves of a mid-tether sub-satellite will separate such that the tether is split with an end weight on each end. This will result in rough gravity gradient stabilization for each satellite. The reaction wheel payload in each satellite will be oriented in order to control yaw; the drag panels may be used for wheel desaturation. When in communications range, relative positioning experiments will be performed. Once the formation decays, however, each vehicle will be operated independently in order to continue component-level experiments.

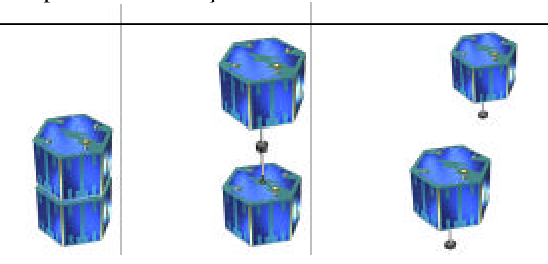

(a) Initial Deployment *(b) Tethered Operations* *(c) Separated Operations*

Figure 3. *Mission Configuration Timeline:*

5. THE EMERALD CONCEPTUAL DESIGN

In order to achieve this mission given the limited time and resources, the design of the Emerald satellites will be largely based on SSDL's heritage microsatellite design. This design has bus components capable of supporting the Emerald mission and has a flexible tray configuration allowing easy integration of new payloads. The 3-6 month Emerald mission will be operated using existing ground segment equipment available to SSDL.

Experimental Payloads

The primary payloads were selected to demonstrate the basics of autonomous on-orbit formation flying. These include: 1) sensor to determine the spacecraft position; 2) an inter-satellite communication system; and 3) actuators to control the relative spacecraft positions.

Position Sensing—For onboard orbit determination and relative navigation, a Stanford-modified Mitel 12-channel, 2 antenna GPS receiver will be flown on each spacecraft. Shown in Figure 4a, these receivers will be modified to operate in space, and they will also compute relative position (approximately 2-5 meter level accuracy in real-time) given the existence of an inter-satellite communication link. These receivers exist, and versions of them are used for ARL's other formation flying studies. As more advanced units are developed, they will be considered as replacements for the current units.

Inter-satellite Communication—In order to provide inter-satellite communication, several competing solutions are being considered:

- Adapting the commercially available, terrestrial 19.2 kbs wireless LAN radio modems currently used by ARL for other formation flying systems. One of these units is shown in Figure 4b.
- 900 MHz transceivers developed by UCLA and currently being adapted for space flight as part of the SSDL Opal mission.
- Enhancing an existing amateur radio system currently being used by SSDL.

Position Actuation—For position actuation, several solutions are being considered. Although all three of the following solutions will be targeted for incorporation into the Emerald mission, one or more may be abandoned given resource limitations:

- A simple tether or flexible boom will be used to 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 Johns Hopkins University Applied Physics Laboratory, a long-time proponent of drag-based position control, will assist with this payload.
- Advanced colloid microthrusters will be incorporated on the satellite. These thrusters, shown in Figure 4c, supply vectored thrust on the order of 0.11 mN, and have a specific impulse of approximately 1000 seconds. These components are being developed by Stanford's Plasma Dynamics Laboratory (PDL) [21]. In addition to providing orbital maneuvers, these components will also be evaluated for their ability to control attitude.

Science Validation—Each Emerald spacecraft will include a VLF receiving system for conducting new, compelling atmospheric science using a distributed satellite architecture that directly benefits from formation flying capabilities. VLF lightning discharges will be simultaneously received and sampled at 12kHz; the small differences between the received signals are of scientific interest and indicate ionospheric differences between the paths of each signal. The science instrumentation is being prototyped as part of the SCREEM Artemis project.; the Stanford STARLAB, a world leader in VLF-based atmospheric science, will provide technical guidance for this payload. The mission name, Emerald (Electromagnetic Radiation And Lightning Detection), refers to this science application.

Auxiliary Experiments—At the discretion of the mission team, auxiliary payloads may also be included on either of the Emerald mission satellites. Possibilities include:

- A component testbed for assessing the space environment performance of micromachined and commercial electronics.
- A low-cost, reaction wheel consisting of a commercial motor that has been re-engineered for space. A prototype of this component is shown in Figure 4d.
- A novel thermal control device that actively changes its optical properties in order to control temperature.

Payload Integration Approach—Without question, the attempt to incorporate all of these payloads is aggressive given the limits on spacecraft and programmatic resources. This is being addressed in a variety of ways. First, the Emerald mission will rely on existing, funded research programs in formation flying technologies. Second, it will depend on unpaid or externally funded students for nearly all developmental tasks. Third, it will utilize established mentoring and in-kind equipment and test facility contributions from the space industry. Fourth, it will use a schedule-driven management strategy for eliminating payloads that do not meet their development timelines.

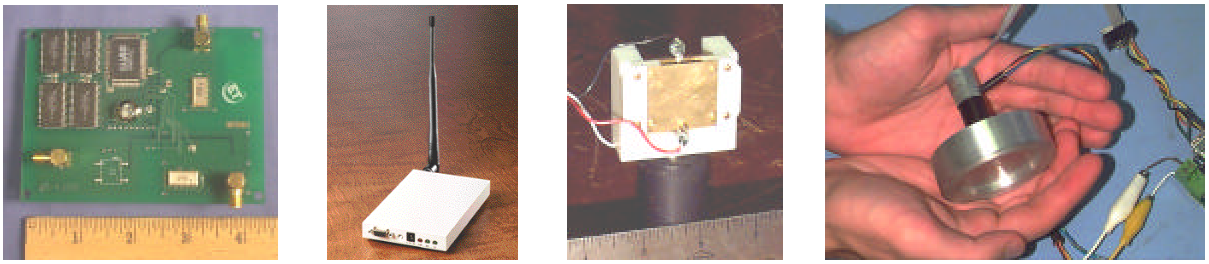
In addition to these approaches, a building block experimental strategy will be used to provide mission level robustness in the face of eliminated payloads and/or on-orbit failures. This approach will consist of first performing simple payload experiments in isolation in order to assess the space performance of individual components. Experiments requiring the use of multiple research payloads will then be accomplished in order to assess system level capabilities. As an example of this approach, the performance of the GPS receivers will first be tested individually. Next, they will communicate with each other via the inter-satellite communications payload in order to perform a relative positioning experiment. Then the position control devices will be added in order to achieve coarse relative position control. Designing the mission with this approach will ensure that valuable experiments may still be performed in case some payloads fail on orbit or are terminated due to developmental delays.

Satellite Bus Design

The Emerald buses will use SSDL’s 12-inch tall, 18-inch diameter hexagonal microsatellite configuration. This design employs a modular, stackable tray structure made of aluminum honeycomb. Figure 5 depicts assembled and exploded views of this configuration. Drag panels will be incorporated into this design by actuating two opposite side panels.

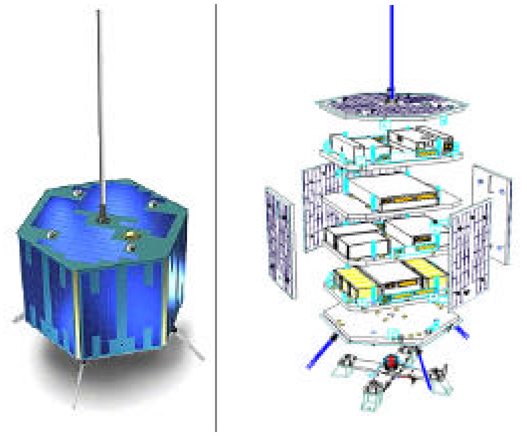
A radiation-tolerant Motorola 68332-based processor board, based on the Sapphire and Opal designs, will be used as the flight controller for both satellites. This processor has multiple serial ports, control lines, telemetry channels, and a proven student-developed operating system that includes an advanced expert system for automated platform control. Coarse attitude determination suitable to meet mission objectives, on the order of 5 degrees, will be provided with simple visible/infrared light sensors.

A 9.6 kbs packet communications system will be used. This will most likely be a variation of the Sapphire communications system depending on the communications frequencies selected for the University Nanosatellite Program. Previous SSDL and SCREEM microsatellites have used the 2-meter and 70-cm amateur frequency bands. The heritage power system consists of body mounted Silicon cell solar panels and a single NiCad battery. This system will provide 7 Watts of average power to components via a 5V regulated bus. Passive thermal control will be achieved through the use of insulation and thermal coatings. Figure 6 presents a basic satellite functional block diagram. Tables 1 and 2 provide preliminary mass and power budgets.



(a) 12-Channel GPS Receiver (b) Radio Modem (c) Colloid Microthruster (d) Re-engineered Reaction Wheel

Figure 4. *Various Emerald Mission Payloads*



(a) Assembled View (b) Exploded View.

Figure 5. *The Heritage Satellite Configuration*

Mission Operations

Stanford's SSDL has a well-established research program in space system operations. As part of this program, SSDL is developing a global operations system consisting of a network of amateur radio communication stations linked via the Internet. A centralized mission control complex provides conventional and advanced control capabilities for processing mission projects and maintaining system health [22]. This system is being baselined as the primary network for controlling the Emerald mission. If the objectives of the University Nanosatellite Program conflict with the use of amateur radio frequencies, other ground stations available to Stanford will be used. These include several installed antennae, including a 50 meter radio astronomy dish, as well as plans for future L-band and X-band communications stations.

6. EMERALD PROGRAM ORGANIZATION

Stanford and Santa Clara have demonstrated expertise in developing quality, low cost space systems capable of supporting advanced technology demonstrations. In addition, their previous collaboration on the OPAL/Artemis mission provides a strong foundation upon which to excel as a team. The Emerald team will include world-class researchers in formation flying technologies, experienced managers and systems engineers with outstanding records of leading student-based projects, and dozens of graduate and undergraduate engineering students capable of designing, fabricating, integrating, testing, and operating the spacecraft.

The Emerald mission development plan is to integrate Stanford and Santa Clara students into a single design team responsible for producing both spacecraft. This strategy will attempt to take advantage of potential economies of scale inherent in a unified, multi-product production activity. In addition, using component/subsystem teams composed of Stanford graduate students and Santa Clara undergraduate students will provide a logical hierarchy among the team and will ensure a consistent approach for the analysis, fabrication, and test of all subsystems.

Student Management Plan

Development of the Emerald spacecraft buses will be performed as part of established student programs at both Stanford and Santa Clara. Stanford offers several graduate courses in which students participate in the hands-on development of microspacecraft. Santa Clara involves its students through its senior design project program.

Together, these programs will provide a continuous integrated design team of approximately 50 students from all engineering disciplines in order to jointly develop the Emerald satellites. These students will be organized into payload and bus subsystem teams based on interest and capability. The payload teams will have the authority to work directly with the cognizant Principal Investigator. The bus teams will develop and produce the subsystems for both spacecraft buses; these will be nearly identical in most cases. A systems engineering team will manage requirements and interfaces, oversee trade studies and documentation, and control verification procedures.

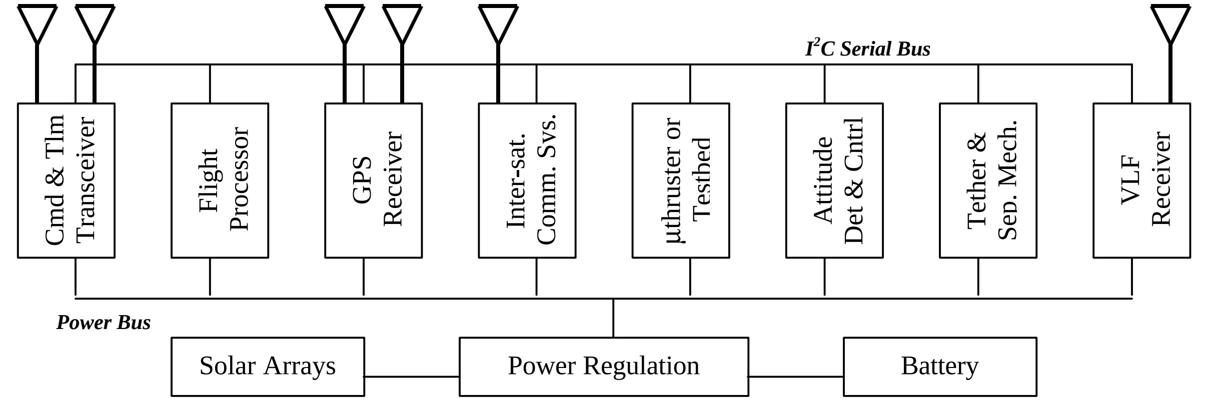


Figure 6. *Satellite Functional Block Diagram*

Table 1. *Preliminary Satellite Mass Budget*

Component/Subsystem	**Budgeted Mass (gm)**	**% of Total Mass**	**Basis for Estimate**
Payloads: - GPS system	250	1.67 %	Measured Prototype Mass
- Inter-satellite comm.	350	2.33 %	Measured Prototype Mass
- Reaction wheel	250	1.67 %	Measured Prototype Mass
- Tether/sub-satellite	2,000	13.33 %	Estimated
- Drag panel mechanisms	400	2.67 %	Estimated
- Microthruster OR testbed	500	3.33 %	Measured Prototype Mass
- VLF instrumentation	100	0.67%	Measured Prototype Mass
Structure	5,000	33.33 %	Mass of Heritage Design
Flight Processor	750	5.00 %	Mass of Heritage Design
Cmd & Tlm Transceiver	850	5.67 %	Mass of Heritage Design
Power	2,500	16.67 %	Mass of Heritage Design
Attitude Determination	300	2.00 %	Estimated
Margin	1,750	11.67 %	Reliance on Heritage & Prototypes
Total	**15,000**	**100.00 %**	

Table 2. *Preliminary Satellite Power Budget*

	Power Loads (Watts)			**Operational Modes**						
Component	**Stand-by**	**Active**	**Basis of Estimate**	**Stand-by**	**Telemetry Downlink**	**Relative Position Sensing**	**VLF Science**	**Reaction Wheel**	**Thrust Mode**	**Relative Position Control**
Payloads - GPS System	0.00	2.50	Proto-type	-	-	2.50	2.50	-	-	2.50
Intersatellite Comm. link	0.00	3.10	Proto-type	-	-	3.10	3.10	-	-	3.10
Reaction Wheel	0.00	2.84	Proto-type	-	-	-	-	2.85	2.85	2.85
µthruster or Testbed	0.00	1.00	Estimate	-	-	-	-	-	1.00	1.00
VLF Rcvr	0.00	0.50	Proto-type	-	-	-	0.50	-	-	-
Flight Processor	0.50	0.50	Heritage	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Cmd & Tlm Transceiver	1.10	9.10	Heritage	1.10	9.10	1.10	1.10	1.10	1.10	1.10
Attitude Determination	0.25	0.25	Estimate	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Tlm & Regulation	0.75	0.75	Heritage	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Mode Total With 15% Margin				**2.99**	**12.19**	**9.43**	**10.01**	**6.27**	**7.42**	**13.86**

Veteran students from previous spacecraft projects at both Stanford and Santa Clara will provide key leadership roles in managing the student team. These students will typically be Ph.D. students who will be co-investigators for Emerald's technology experiments as part of their dissertation research. Their participation will be funded through external research contracts.

Facilities

Both Stanford and Santa Clara have laboratory facilities for developing and operating the Emerald spacecraft. These include:

- Computer workstations at both schools for design modeling, simulation, and analysis
- Mechanical shops and development laboratories at both schools with appropriate instrumentation and supplies for fabricating and testing components and subsystems
- Dedicated space and equipment at both schools to support the integration and test of Emerald systems
- Limited environmental test equipment at Stanford to enable preliminary testing of components
- Donated and/or low cost access to extensive environmental test facilities at a number of aerospace companies in the Silicon Valley region

- Ground segment equipment at both schools for conducting operational system tests and for managing on-orbit operations of the spacecraft

The physical proximity of Stanford University and Santa Clara University will allow daily person-to-person interaction, the sharing of facilities, and an integrated development effort. Nevertheless, attention to and management of team communication and coordination is a paramount concern. To aid this, both schools will employ phone, fax, Internet, and videoconference communications. Web-based project documentation on existing workstations will permit distributed access and review of technical and managerial aspects of the project.

Systems Engineering Approach

The Stanford and Santa Clara spacecraft design programs specialize in the application of rational systems engineering approaches in order to develop quality, low-cost systems capable of meeting the needs of technology developers. These approaches include the following:

- Precise understanding and management of the technology validation requirements
- Formal, traceable flowdown of requirements to subsystems and components
- Generation and consideration of design alternatives based on system-level metrics
- Use and re-engineering of commercial components where appropriate
- Proactive application of robust project management techniques such as problem-tracking, rapid prototyping, proof-of-concept testing, interface management, and margin maintenance.
- Rigorous use of concurrent design principles to develop a simple system concept with acceptable performance that is also flexible, testable, and operable.
- Reliance on extensive testing and analyses in order to verify performance especially when risky and low-cost approaches are used
- Regular peer review of development activities by industry mentors

The execution of these tasks will be performed as a formal part of the Stanford and Santa Clara educational programs.

Schedule

The Emerald team will use a schedule-driven management strategy in order to scope technical complexity and payload integration. Significant schedule slips will be controlled by the removal of experiments from the mission as well as by the termination of subsystem enhancements.

Design and prototyping will occur through 6/99. Consistent with academic timing constraints, full-scale fabrication and integration occurs from 4/99-3/00. Environmental and operational testing will occur from 4/00-9/00. Three months are reserved as a margin.

7. CONCLUSIONS

The Stanford – Santa Clara Emerald mission will contribute to spacecraft formation flying technology research by demonstrating several critical sensing, communications, and actuation capabilities. Using a building-block experimental approach, the successful demonstration of individual technologies will lead to more advanced demonstrations aimed at verifying the capabilities of coarse control loops. Although simple in concept, this project serves as a valuable prototype for more advanced formation flying missions being developed by Stanford, AFOSR, and NASA.

University-developed spacecraft are a valuable alternative available to space system researchers. These vehicles serve as low-cost albeit risky platforms that may be used to rapidly verify the capabilities of advanced technology. In addition, such projects often lead to innovative design approaches, and they successfully promote the education of a new generation of aerospace engineers.

8. ACKNOWLEDGEMENTS

The authors wish to thank AFOSR and DARPA for their commitment to supporting university-based spacecraft development projects. Appreciation is also extended to NASA Goddard for their support of Stanford’s work in formation flying technology. In addition, the students in SSDL, ARL, and SCREEM are praised for their contributions to formulating the Emerald program and developing the heritage and prototype equipment upon which its design will be based. Finally, the insightful comments of this paper's technical reviewers have assisted in making this a stronger contribution. This work is being performed in partial satisfaction of graduate studies at Stanford University.

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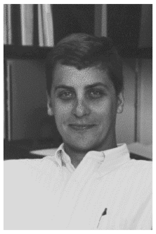

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