SSC99-VI-5

Emerald: An Experimental Mission in Robust Distributed Space Systems

Christopher Kitts[*,†], Freddy Pranajaya[*], Julie Townsend[*], and Robert Twiggs[*]

[*]Space Systems Development Laboratory, Stanford University
[†]Santa Clara Remote Extreme Environment Mechanisms Laboratory, Santa Clara University

Room 453, Durand Building
Space Systems Development Laboratory, Department of Aeronautics and Astronautics
Stanford University, Stanford, CA 94305-4035
Phone: 650-725-6794, Fax: 650-723-1685
kitts@leland.stanford.edu, freddyp@leland.stanford.edu, julieat@leland.stanford.edu,
btwiggs@leland.stanford.edu

Abstract. Distributed space systems are often cited as a means of enabling vast performance increases ranging from enhanced mission capabilities to radical reductions in operations cost. To explore this concept, Stanford University and Santa Clara University have initiated development of a simple, low cost, two-satellite mission known as Emerald. The Emerald mission has several on-orbit goals. First, it will verify an array of component-level technologies necessary for enabling highly capable and robust distributed space systems. Second, it will combine these technologies to experiment with simple closed loop relative positioning, distributed control, and autonomous operation. Third, it will validate the distributed space system concept by assessing how these capabilities improve a baseline scientific investigation involving lightning-induced atmospheric phenomena. The Emerald bus design is based on a heritage Stanford University design, a 15-kilogram, modular hexagonal vehicle relying heavily on commercial off-the-shelf components. Emerald is being funded through the AFOSR/DARPA University Nanosatellite Program, and a Space Shuttle launch in 2001 is being planned. This paper will discuss the Emerald team's programmatic and on-orbit objectives, the conceptual design of the Emerald spacecraft, and the development approach adopted by the university team.

Table of Contents

1. Introduction

Distributed space systems are multi-satellite system that work together in order to perform a unified mission. Such systems are an alternative to single monolithic satellite missions in which all on-orbit activities are performed on a single platform. Distributed space systems can range from global constellations offering extended service coverage to clusters of highly coordinated vehicles that perform distributed sensing.

While the former manifestation has proved successful for several communications, navigation, and remote sensing systems, the capabilities and value of the latter version are still largely unexplored. It has been postulated, however, that tightly coupled fleets demonstrating formation flying and autonomous operation capabilities will have a significant impact on many scientific, military, and commercial space applications for surveillance, synthetic aperture radar earth mapping, magnetosphere sensing, interferometry, and several other missions.

Highly coordinated fleets of spacecraft offer several potential performance advantages. These include the following[1]:

- Extensive, autonomous co-observing programs with minimal ground support,
- Increased observational baselines between instruments enabling revolutionary improvement in space-based interferometry, world coverage for remote sensing, and simultaneous target tracking,
- Replacement of large complex spacecraft with a flexible architecture of simple microsatellites that offers redundancy, reconfigurability, 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 the following[2]:

- 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 autonomously track the relative position and attitude between several spacecraft[3,4,5,6,7,8,9,10]. Together with position control devices and inter-satellite communication links, GPS-based could in theory be used to enable precisely controlled spacecraft formations. A variety of space missions to test this capability are currently in development. The NASA 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. The NASA 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[11]. In addition, Stanford is developing a six spacecraft, six month mission called Orion which will demonstrate closed loop (sub-meter level sensing) station keeping and attitude control combined with the formation-level specification of maneuvers[1].

Recent work in autonomous operations techniques has similarly demonstrated enhanced capabilities for precise and cost-effective system health management and mission services processing. These capabilities are crucial to managing clusters of coordinated spacecraft in an efficient manner. This work includes the development of advanced reasoning approaches such as model-based strategies as well as the judicious integration of these systems into mission operations systems. Specific highlights include the NASA DS-1 Remote Agent experiment and the beacon-based health monitoring systems developed by NASA and SSDL[12,13,14].

The Air Force Office of Scientific Research (AFOSR) is also sponsoring distributed space system research in support of the Air Force Research Laboratory's revolutionary approach to performing space missions using large clusters of microsatellites[15]. 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 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 are 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 late 2001.

The missions that compose the University Nanosatellite Program include the following: Constellation Pathfinder (Boston University), Solar Blade (Carnegie-Mellon University), 3 Corner Sat (Arizona State University, the University of Colorado, and New Mexico State University), ION-F (the University of Washington, Utah State University, and Virginia Tech), and Emerald (Stanford University and Santa Clara University).

2. The Stanford University – Santa Clara University Team

The Stanford University – Santa Clara University team has world-class experience in the development of low-cost university-class satellites as well as in the development of advanced spacecraft technology. Specific expertise contributing to the development of the Emerald mission is discussed here.

Low-Cost Satellite Design

Both Stanford's Space Systems Development Laboratory (SSDL) and the Santa Clara Remote Extreme Environment Mechanisms 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 and/or performing simple science missions[16,17]. 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. Between these two laboratories, several flight-ready spacecraft have been developed.

Since 1994, SSDL has developed two microsatellites, Sapphire and Opal, which are picture in Figures 1 and 2. Sapphire will flight test an array of new micromachined infrared sensors as well as a low cost satellite health assessment system for the Jet Propulsion Laboratory (JPL)[18]; in addition, it will offer basic photographic and communication services to the public. Sapphire is complete, but export licensing restrictions have prohibited launch planning. Opal will test a mothership/daughtership mission architecture for DARPA by housing and ejecting several sub-kilogram 'picosatellites'[19]. Opal will also characterize the operation of several commercial sensors for JPL and for the Stanford University's Gravity Probe-B mission. Opal is complete and is manifested for launch in September 1999 from Vandenburg Air Force Base on-board an Orbital Sciences Corporation OSP launch vehicle. Overall, the development of each of these spacecraft has required about 4.5 years of work, the participation around 75 graduate students, and a cash budget of approximately $50,000 for components.

Since 1998, Santa Clara University has developed five very simple satellites, two Barnacle project microsatellites and three Artemis project picosatellites, shown in Figures 3 and 4. The Barnacle vehicles will provide short duration component test for DARPA and JPL[20]. The sounding rocket version of Barnacle is manifested for launch in late 1999 on-board an amateur rocket as part of the international Cheap Access To Space (CATS) competition. The orbital version of Barnacle is also complete, but export licensing restrictions have prohibited launch planning. The three Artemis picosatellites will test the functionality of sub-kilogram spacecraft and will attempt to perform a simple distributed science

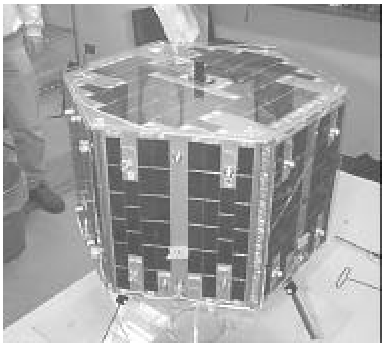


Figure 1. *SSDL's Sapphire Microsatellite*

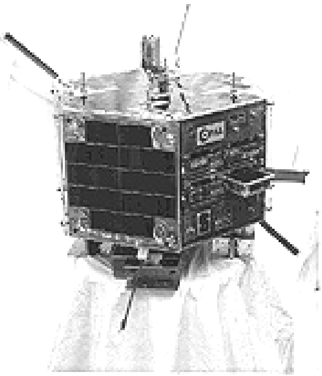


Figure 2. *The Stanford Opal Microsatellite*

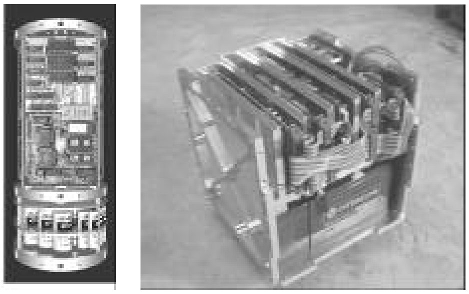


Figure 3. *The Santa Clara Barnacle Microsatellites*

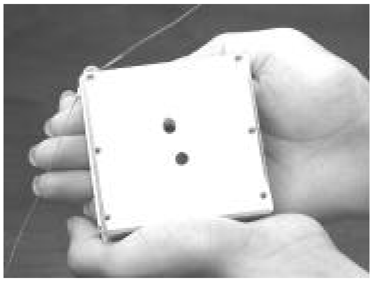


Figure 4. *One of Several Santa Clara Artemis Picosatellites*

experiment involving lightning-induced atmospheric phenomena[21]. These picosatellites will be ejected from the Stanford University Opal microsatellite after its launch in September 1999. Overall, the development of each of these projects has produced multiple spacecraft and has required about 11 months of work, the participation 7 undergraduate students, and a cash budget of approximately $10,000 for development equipment, components, and travel.

Advanced Spacecraft Technology

Stanford University serves as the principle advanced technology developer for the Emerald team. With respect to the mission theme of robust distributed space systems, the Aerospace Robotics Laboratory is providing expertise in GPS-based formation flying capabilities. In addition, the Space Systems Development Laboratory is guiding work in radiation testing, distributed computing architectures, and autonomous operations.

Formation Flying

Stanford University's Aerospace Robotics Laboratory (ARL) is a world leader in developing GPS-based formation flying systems. This work includes development of the Orion formation flying constellation as well as several formation flying testbed systems.

One testbed, shown in Figure 5, consists of 3 active free-flying robots that move on a 12 x 9 ft. granite table top[4,5,8]. 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.

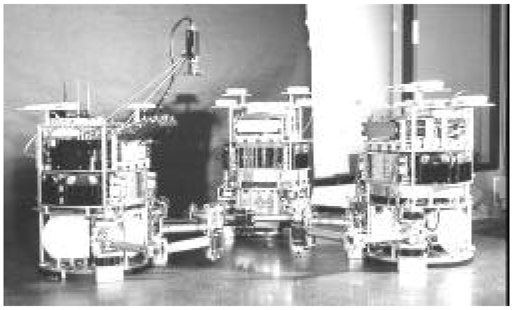


Figure 5. *ARL Formation Flying Robots*

A second testbed demonstrates formation flight in three dimensions using lighter-than-air vehicles (blimps). 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.

Radiation Testing

SSDL has initiated a new research program for characterizing how radiation affects new technologies in the space environment. This program includes the low cost, quick turn-around testing of components in space. As part of this work, a general purpose micro-electronics testbed is being designed for multiple space missions. The testbed will be able to functionally operate diverse microelectronics, to provide stimulus and measurement capabilities to characterize radiation-related failures, and to recover failed microelectronics when possible.

Distributed Computational Architectures

As part of several research and flight projects, SSDL has adopted a distributed computing architecture based on an array of simple PIC microprocessors connected to a centralized processor via an I^2C serial bus. This approach supports the migration of subsystem-related software and hardware control functionality from the primary flight computer to the subsystem. This has proved useful in simplifying subsystem interfaces and parallel subsystem development.

Autonomous Operations

SSDL has an active research program in the development of autonomous techniques for operating complete space systems. This work includes the development of new reasoning techniques, the exploitation of fundamental design models in these reasoning processes, and the incorporation of the resulting systems into spacecraft and their ground-based command and control networks. As part of this work, SSDL has led the development of a global microsatellite mission architecture consisting of several communications groundstations, amateur radio and Internet communications links, and a centralized mission control complex.

3. The Emerald Mission

The Stanford – Santa Clara Emerald mission will further understanding of robust distributed space systems in several ways. These include performing several flight experiments, providing general experimental services for auxiliary on-orbit investigations, and conducting a variety of developmental studies.

Flight Experiments

The Emerald mission is being designed to support several flight experiments.

Component Verification

The operation and performance of several specific components will be assessed.

The first of these is an array of COTS microelectronics components[22]. Developed through SSDL's radiation effects research program, a component testbed system will be used to monitor component degradation in the space environment. This system will characterize single event effects by continuously monitoring single event latch-ups and by periodically measuring single event upsets. Devices under test (DUTs) will be re-initialized and power cycled as needed. Total dose effects will be measured by assessing DUT functionality and by measuring supply currents and input/output voltages. The radiation environment will be monitored through dosimetry circuitry.

Second, a low-cost low-power GPS receiver developed by ARL will be tested. Shown in Figure 6, a modified Mitel 12-channel, 2 antenna GPS receiver will be flown on each spacecraft. These receivers exist, and versions of them are used for ARL's other formation flying studies.

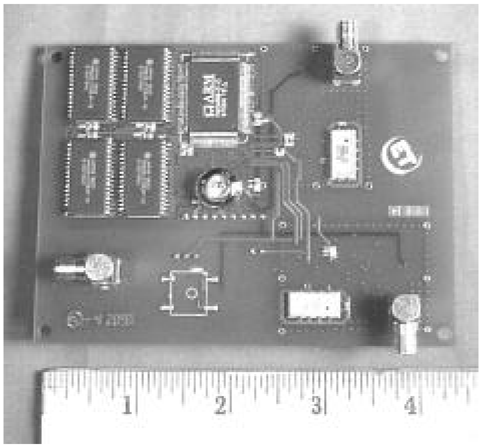


Figure 6. *The Modified Mitel GPS Receiver*

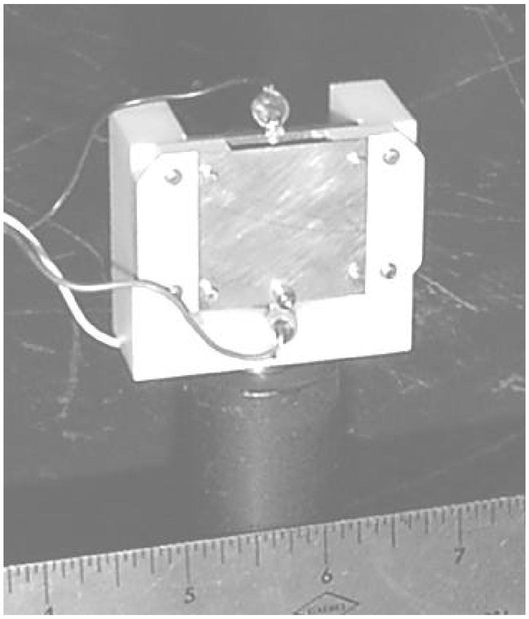


Figure 7. *Colloid Microthruster Prototype*

Third, advanced colloid microthrusters will be incorporated on one of the satellites. These thrusters, shown in Figure 7, 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)[23]. In addition to providing orbital maneuvers, these components will also be evaluated for their ability to control attitude.

Spacecraft Formation Flying

Given the proper operation of GPS receivers, coarse formation flying capabilities will be demonstrated by ARL researchers. Through the use of an inter-satellite communications link provided by the Emerald bus, the GPS receivers will exchange data and will compute relative position (approximately 2-5 meter level accuracy in real-time).

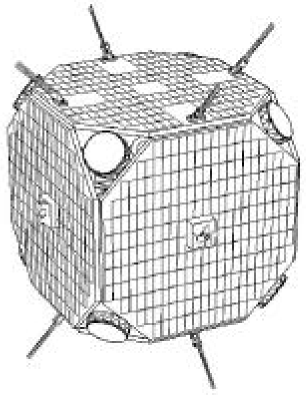


Figure 8. *The Orion Microsatellite*

With relative position determination established, relative position control will be attempted. First, a navigation control computation will be performed on-orbit. The resulting control directives will command a simple set of drag panels provided by the Emerald bus. These panels will increase the drag of one satellite thereby affecting the relative trajectories of the two satellites. Although the control authority of this system is limited, it is predictable and low-cost. As such, it is an appropriate technique for a mission of this type. As an option, the colloid microthrusters may also be used for position actuation at the conclusion of its component-level experiment.

An exciting joint flight opportunity, a formation flying demonstration with the Stanford University Orion-1 satellite is also targeted. Orion-1 is a flight prototype for the planned 6-satellite Orion constellation currently being developed by Stanford and the NASA Goddard Space Flight Center. Depicted in Figure 8, Orion-1 is a 50 kilogram 50 cm x 50 cm x 50 cm cube vehicle with 3-axis control, cold-gas thrusters, and a higher performance GPS receiver[1]. Compared to the navigation capability of the Emerald spacecraft, Orion is far more complex and capable thereby allowing it to fly in a tightly controlled manner with either or both of the Emerald satellites. This joint mission will elevate the relative position control issues involving Emerald from a 2-body autonomous rendezvous operation to a more interesting and complex 3-body autonomous formation flying problem.

Autonomous System Operations

The Emerald mission will provide several demonstrations of advanced and cost-effective autonomous operations techniques.

The Emerald vehicles will carry an enhanced version of the beacon-based health monitoring system that has been incorporated into the Sapphire and Opal spacecraft. A basic beacon-based health monitoring system is composed of an on-board software production rule system and a transmitter capable of broadcasting low data rate tones. This system determines and periodically broadcasts a very high level health status message. These broadcasts are received by a network of low-cost automated receiving stations developed by SSDL. The stations forward the health messages to a central mission control complex which automatically pages an on-call operator in the event of a vehicle anomaly. Initial experimentation has shown that this system is capable of drastically lowering the cost of nominal health monitoring[14]. The Emerald enhancements to this system will include a) the use of more robust model-based health assessment techniques, b) an inter-satellite beacon capability, and c) a single space segment level beacon broadcast to ground.

In addition, an on-orbit intelligent execution system is being developed for the VLF science payload. This system will provide synchronized control of the VLF systems on each Emerald satellite thereby allowing ‘space segment level control’ in which a single ground command initiates collaborative actions on both spacecraft. In addition, the ability to detect unplanned opportunistic VLF science events is being developed. This will allow the satellites to detect such events on their own and to subsequently coordinate data collection activities on their own. Additional capabilities involving on-orbit science data processing may also be explored.

Finally, an autonomous ground based navigation control system will be used to command satellite positioning when the on-orbit system is not functioning. This may occur do to component failures, power limitations, or because the vehicles are out of range of the intersatellite communications system. In the current design, the enhanced beacon system may be used to indicate the status of the on-orbit navigation system. Based on this information, the ground-based system will engage itself in order to compute and execute position control commands.

VLF Science

Each Emerald satellite will include a VLF receiving system for recording and analyzing VLF waves emitted by lightning. Developed by Santa Clara University and Stanford’s Space Telecommunications And Radioscience Laboratory (STARLAB), these receivers will support a variety of science studies relating to lightning and to the structure of the ionosphere[24]. The most compelling experiment involves distributed sensing by the VLF receivers on both Emerald vehicles. VLF lightning discharges will be simultaneously received and sampled at 12kHz; the small differences between the received signals are of scientific interest and indicate local ionospheric differences along the paths of each signal.

Formation flying technologies offer specific advantages in conducting this experiment. For example, tagging the received signals with accurate timing, absolute position, and relative position data provides great value to the science data. In addition, the possibility exists to actually command a sensing baseline over a territory of interest in order to optimize a particular study. Autonomous operation technologies also offer advantages such as supporting automated coordination of the vehicles and detecting unplanned science opportunities. For these reasons, this science mission is being used as a means of validating the distributed space system technology being verified through the other flight experiments. The mission name, Emerald (ElectroMagnEtic Radiation And Lightning Detection), refers to this science application.

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 order to provide funding and personnel. Second, it will also 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 is 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.

Auxiliary Investigations

Through the use of standard bus services being provided by the Emerald spacecraft, a variety of additional on-orbit investigations may be conducted. These are classified independently from the aforementioned flight experiments since these auxiliary investigations do not drive the required design and functionality of the satellites.

Possibly auxiliary investigations include:

- An assessment of the drag panel system as a position and/or attitude control actuator.
- An assessment of the inter-satellite communications system as a function of distance and environmental conditions.

- The use of GPS receivers and the inter-satellite communications system to study atmospheric phenomena.
- An extension, due to the impact of the drag panel system, to a previous study with the Sapphire and Opal microsatellites for using solar panel current data for computing attitude.
- Other investigations of interest that may be achieved through the use of command and telemetry services built into the baseline design.

Developmental Studies

During the process of developing the Emerald mission, several process-oriented studies will take place.

First, this project will naturally involve an exploration of general low-cost satellite design, fabrication, and operation techniques and approaches. Such techniques have been pioneered in the university and amateur satellite communities. Many of the lessons learned in this field have already been incorporated into previous Stanford and Santa Clara spacecraft; additional contributions to these methods will be made in order to extend the cost-effectiveness of the Emerald satellites.

Second, the project will explore the manner in which projects of this type are conducted in a university environment. Although both schools have performed such projects in the past, these methods will be formalized into an appropriate model for project-based integrative education and research activities. In addition, methods to support inter-school collaborations and distributed design teams will also be investigated.

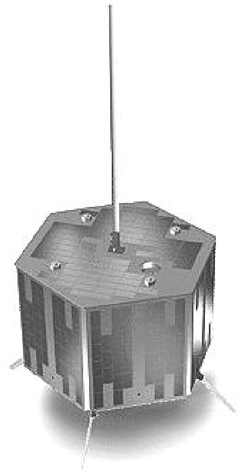
Third, the value of the PIC processor-based distributed computing architecture will be assessed. In particular, a qualitative evaluation of its contribution to simplified integration and development will be balanced with its monetary costs and any measured impact to reliability and robustness.

Fourth, an attempt will be made to develop a cost assessment for this program. In the past, rough approximations of cash outlays have been made for the Stanford microsatellites. For Santa Clara spacecraft, detailed accountings are available for purchased and donated component costs, programmatic costs such as travel, and an hourly assessment of personnel hours. For the Emerald project, the cost accounting will be more detailed and formalized; in addition, it will attempt to capture in-kind contributions for environmental testing, university services provided through overhead billing, and other total program costs.

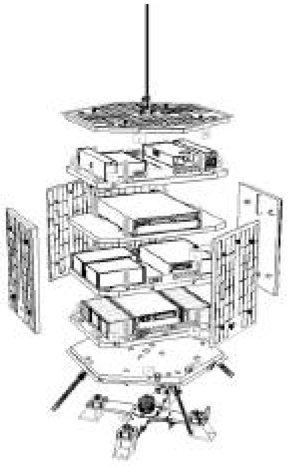
4. The Spacecraft Conceptual Design

In order to achieve this mission given the limited time and resources, the design of the Emerald satellites will be largely based on heritage SSDL designs as well as on purchased space qualified components.

The structural configuration for the Emerald vehicles will use SSDL's existing satellite bus design. This consists of a 15 kilogram, 14-inch tall, 16-inch diameter hexagonal configuration employing a modular, stackable tray structure made of aluminum honeycomb. Figure 9 depicts assembled and exploded views of this configuration. Drag panels will be incorporated into this design by actuating two opposite side panels.



(a) Assembled View



(b) Exploded View

Figure 9. *The Heritage Satellite Configuration*

For a flight computer, the Emerald satellites will use the commercially available SpaceQuest FCV-53 flight processor running the BekTek operating system. Together, this provides a radiation tolerant system with 1 MB RAM, a file system, and a schedulable command execution system. The processor will connect to most subsystems through the use of an I^2C serial bus.

A UHF, half-duplex, 9.6 kbs packet communications system will be used. This will include a SpaceQuest digital modem and a modified amateur radio transmitter and receiver. This system will be used for both inter-satellite communications as well as spacecraft to ground communications. A secondary VHF receiver may also be included for redundancy and to enhance the use of the satellites by amateur radio enthusiasts.

The power subsystem will include donated solar cells body mounted on each of the satellite's eight sides. A single multi-cell NiCad battery will be included, and regulated 5-volt and 12-volt power will be provided throughout the satellites. Coarse attitude determination on the order of +/- 5 degrees, suitable to meet mission objectives, will be provided with a magnetometer and simple visible/infrared light sensors. Passive attitude control is achieved through the use of permanent magnets. Passive thermal control will be achieved through the use of insulation and thermal coatings.

Payload components, discussed earlier in this paper, include the following: a GPS receiver on both satellites, VLF instrumentation on both satellites, a radiation testbed on one satellite, and a colloid microthruster on one satellite. Both satellites will include navigation and autonomy software.

Figure 10 shows a system-level diagram of the satellite components. Figure 11 gives an artist's depiction of the Emerald vehicles in orbit.

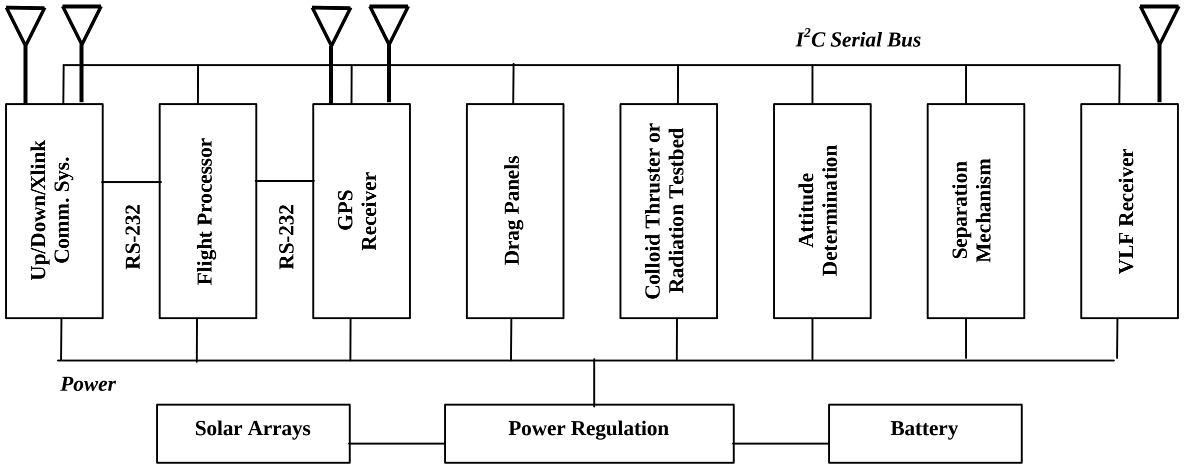


Figure 10. *The Emerald System Diagram*

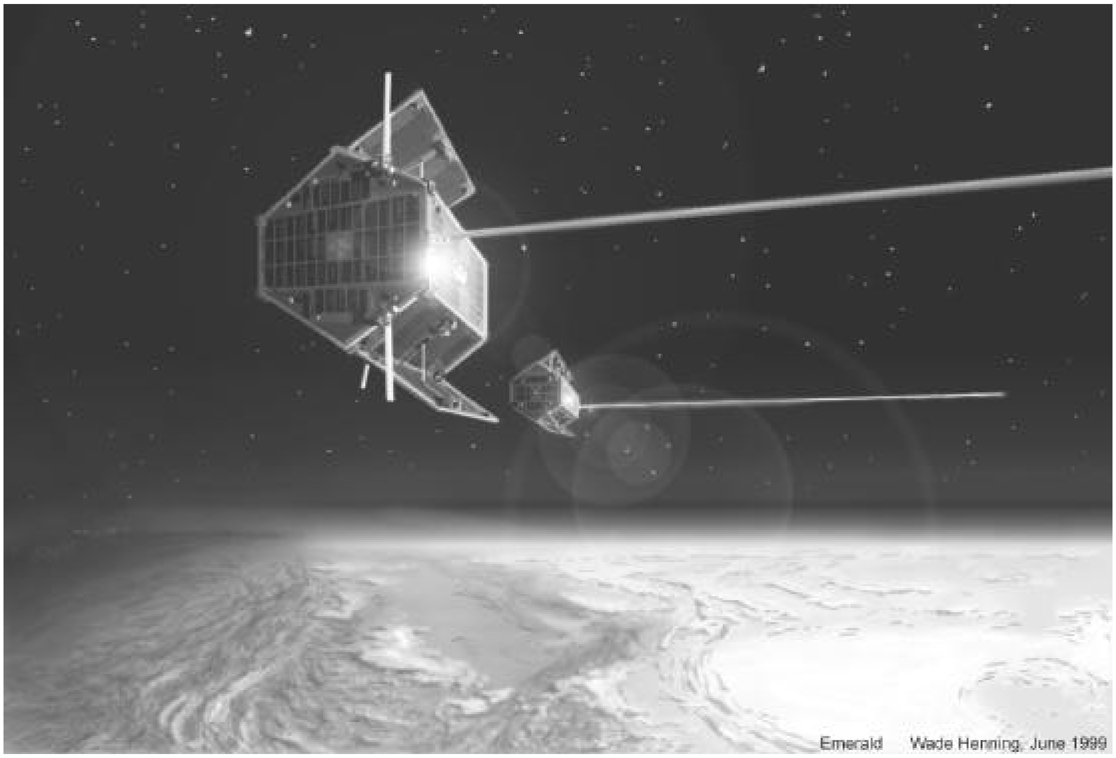


Figure 11. *Emerald satellites in formation [Henning].*

5. Emerald Mission Operations

The Emerald satellites will be launched from the Space Shuttle's SHELS launch platform with many of the other University Nanosatellite Program spacecraft. The current concept is for all satellites to be attached to a single baseplate which will be connected to the SHELS platform by a Marmon clamp. The Orion-1 microsatellite is currently being planned for inclusion on this baseplate as well. The Emerald satellites will be stacked, and the bottom Emerald vehicle will be attached to the baseplate.

When ready to deploy, the entire baseplate will separate from the Shuttle. After safe separation from the vicinity of the Shuttle, the various Nanosatellite Program spacecraft will be ejected at different times. The Emerald stack and the Orion-1 vehicle will be ejected in close proximity in order to minimize differences in orbital trajectories. Vehicle checkout and some initial flight experiments will be performed prior to separating the Emerald stack. When ready, the Emerald stack will separate and will commence its distributed flight demonstrations.

Command and control of the Emerald spacecraft will be conducted through a global space operations network that is being established as part of SSDL's research program in space system operations[25]. This system consists 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 services and maintaining system health. The overall mission architecture is pictured in Figure 12.

6. The 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.

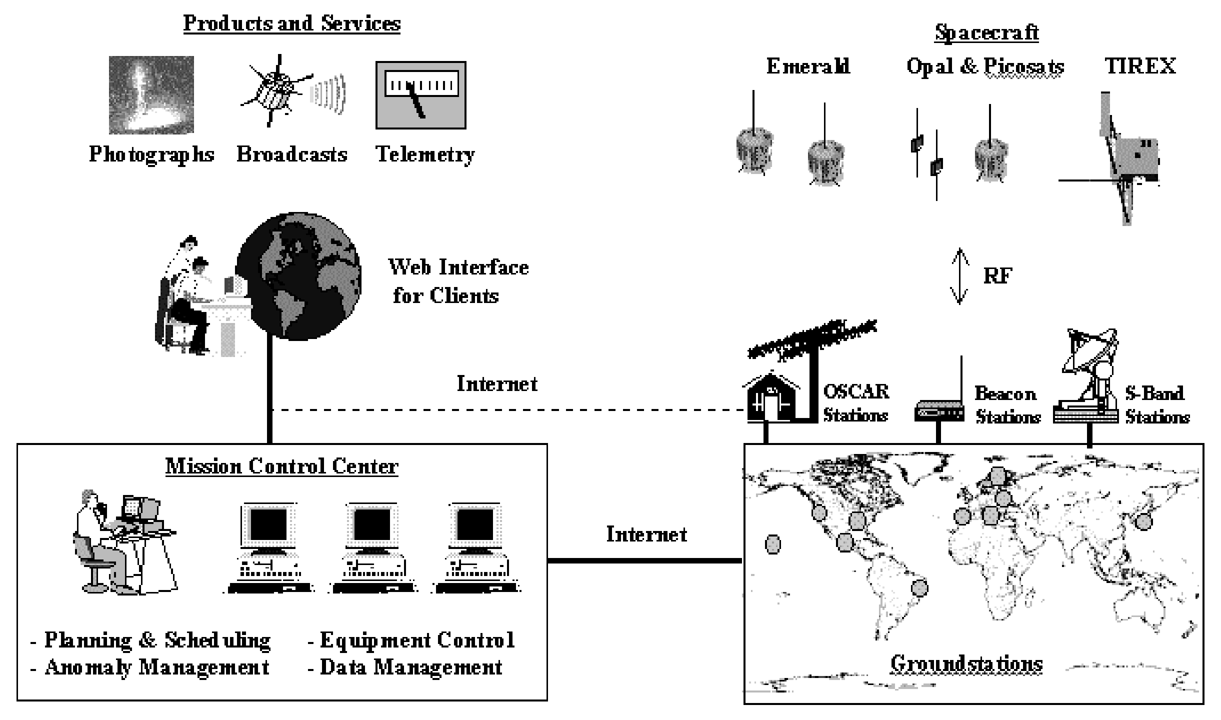


Figure 12. *The Mission Control Architecture*

Furthermore, the Emerald team includes world-class researchers in the required advanced spacecraft 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 team's development approach integrates Stanford and Santa Clara students into a single design team responsible for producing both spacecraft. This strategy attempts 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 provides a logical hierarchy among the team and ensures a consistent approach for the analysis, fabrication, and test of all subsystems.

Student Management Plan

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

Together, these programs provide a continuous integrated design team of approximately 40 students from all engineering disciplines in order to jointly develop the Emerald satellites. These students are organized into payload and bus subsystem teams based on interest and capability. The payload teams have the authority to work directly with the cognizant Principal Investigator. The bus teams develop and produce the subsystems for both spacecraft buses; these will be nearly identical in most cases. A systems engineering team manages requirements and interfaces, oversees trade studies and documentation, and controls verification procedures.

Veteran students from previous spacecraft projects at both Stanford and Santa Clara provide key leadership roles in managing the student team. These students are typically graduate students who are co-investigators for Emerald's technology experiments as part of their dissertation research. Their participation is 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 allows 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, the team employs phone, fax, Internet, and videoconference communications. Web-based project documentation on existing workstations permits 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 is performed as a formal part of the Stanford and Santa Clara educational programs.

Schedule

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

The overall development schedule is as follows. Design and prototyping occurs through 9/99. Consistent with academic timing constraints, full-scale fabrication and integration occurs from 9/99 through 6/00. Environmental and operational testing occurs from 6/00-12/00. Three months are reserved as a schedule margin.

7. Conclusions

The Stanford – Santa Clara Emerald mission will contribute to the understanding of distributed space systems. This will be achieved by verifying several component-level technologies, by combining these technologies to demonstrate enhanced control capabilities such as relative position control and autonomous science operations, and by validating these technologies by assessing their impact on a baseline science mission involving the study of lightning induced atmospheric phenomena. Although simple in concept, this project serves as a valuable prototype for more advanced formation flying missions being developed by Stanford, AFOSR, and NASA.

As is being demonstrated by the AFOSR/DARPA University Nanosatellite Program, university class 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 the distributed satellite control aspects of this project. In addition, the student team members at both Stanford University and Santa Clara University are praised for their dedication in the development of this mission.

References

[1] J. P. How, et. al., "ORION: A Low-Cost Demonstration of Formation Flying in Space Using GPS," In *AIAA/AAS Astrodynamics Conference*, August, 1998.

[2] C. Kitts, et. al., "Emerald: A Low-Cost Formation Flying Technology Validation Mission," In *Proceedings of the 1999 IEEE Aerospace Conference, Snowmass, CO*, March, 1999.

[3] F. Bauer, et. al., "Satellite formation flying using an innovative autonomous control system (AutoCon) environment," In *AIAA/AAS Astrodynamics Specialists Conference, New Orleans, LA*, August 1997.

[4] K. R. Zimmerman and R. H. Cannon Jr., "Experimental demonstration of GPS for rendezvous between two prototype space vehicles," In *Proceedings of the Institute of Navigation GPS-95 Conference, Palm Springs, CA*, September. 1995.

[5] J. C. Adams, et. al., "Technologies for spacecraft formation flying," In *Proceedings of the ION GPS-96 Conference, Kansas City, MO*, September, 1996.

[6] D. Folta, et. al., "Foundations of formation flying for mission to planet earth and new millennium," In *AIAA/AAS Astrodynamics Specialists Conference*, July 1996.

[7] J. Guinn and R. Boain, "Spacecraft autonomous formation flying earth orbiters using GPS," In *AIAA/AAS Astrodynamics Specialists Conference*, July 1996.

[8] T. Corazzini, et. al., "GPS sensing for spacecraft formation flying," In *Proceedings of the ION GPS-97 Conference, Kansas City, MO*, September, 1997.

[9] P. W. Binning, *Absolute and Relative Satellite to Satellite Navigation using GPS.* Dept. of Aerospace Engineering Sciences, University of Colorado, April 1997.

[10] K. Lau, et. al., "An innovative deep space application of GPS technology for formation flying spacecraft," In *Proceedings of the AIAA GNC Conference, San Diego, CA*, July 1996.

[11] M. Colavita, et. al., "The New Millennium Separated Spacecraft Interferometer," In *Proceedings of the Space Technology and Applications International Forum (STAIF-97), Albuquerque, NM*, 1997.

[12] D. Bernard, et. al., "Design of the Remote Agent Experiment for Spacecraft Autonomy", In *Proceedings of the 1999 IEEE Aerospace Conference, Snowmass, CO*, March, 1998.

[13] R. Sherwood, et. al., "Flight Software Implementation of the Beacon Monitor Experiment on the NASA New Millenium Deep Space 1 (DS-1) Mission," In *Proceedings of the Second International Symposium on Reducing the Cost of Spacecraft Ground Systems and Operations, Oxfordshire, United Kingdom*, July 1997.

[14] M. Swartwout, et. al., "Experiments in Automated Health Assessment and Notification for the SAPPHIRE Microsatellite", In *Proceedings of SpaceOps '98: The 5th International Symposium on Space Mission Operations and Ground Data Systems, Tokyo, Japan*, June , 1998.

[15] *AFOSR BAA on TechSat 21 (AFOSR BAA 98-6)*, Air Force Office of Scientific Research, 1998.

[16] C. Kitts and R. Twiggs, "The Satellite Quick Research Testbed (SQUIRT) Program", In *Proceedings of the 8th Annual AIAA/USU Conference on Small Satellites, Logan, Utah*, August 1994.

[17] C. Kitts and J. Ota, "The ParaSat Space Flight Program," pending publication in *Proceedings of the International Astronautical Federation Specialist Symposium: Novel Concepts for Smaller, Faster & Better Space Missions, Los Angeles, CA*, April 1999.

[18] R. Twiggs and M. Swartwout, "SAPPHIRE - Stanford's First Amateur Satellite", In *Proceedings of the 1998 AMSAT-NA Symposium, Vicksberg, MI*, October 1998.

[19] B. Engberg, et. al., "The OPAL Satellite Project: Continuing the Next Generation Small Satellite Development", In *Proceedings of the 9th Annual AIAA/USU Conference on Small Satellites*, September 1995.

[20] S. O'Boyle, et. al., "Smaller than Small, Faster than Fast, Cheaper than Cheap: The Barnacle Satellite Project,", In *Proceedings of the 12th Annual AIAA/USU Conference on Small Satellites*, September 1998.

[21] A. Valdez, et. al., "The Artemis Project: Picosatellites and the Feasibility of Faster, Better, Cheaper," in *Proceedings of the 1999 IEEE Aerospace Conference, Snowmass, CO*, March 1999.

[22] J. Cutler, "Merit: A Radiation Effects Testbed Program", Stanford University Research Report, May 1999.

[23] M. Cappelli and F. Pranajaya, "Colloid MicroThruster Research", Stanford University Research Report, July, 1997.

[24] C. Kitts, "A Small/Micro-/Pico-Satellite Program for Investigating

Thunderstorm-Related Atmospheric Phenomena", In *Proceedings of the 12th Annual AIAA/USU Conference on Small Satellites, Logan, Utah*, September, 1998.

[25] C. Kitts, "A Global Spacecraft Control Network for Spacecraft Autonomy Research," In *Proceedings of SpaceOps '96: The Fourth International Symposium on Space Mission Operations and Ground Data Systems, Munich Germany,* September 1996.