AIAA-99-4654

EXPERIMENTS IN DISTRIBUTED MICROSATELLITE SPACE SYSTEMS

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

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

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. Funded through the AFOSR/DARPA University Nanosatellite Program, the Emerald mission will involve several studies involving the design and operation of distributed space systems. First, "low-level" inter-satellite navigation techniques will be explored. Second, "high-level" multi-satellite health and payload operations will be demonstrated. Third, system validation will be attempted 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. This paper will discuss the Emerald mission's focus on distributed space system technologies as well as the design of the two spacecraft and the distributed ground segment.

TABLE OF CONTENTS

1. INTRODUCTION

Distributed space systems consist of multi-satellite fleets and their ground segments and are used to provide a unified space-based service. These systems can embody a multitude of forms and may be applied to achieve a variety of objectives:

- Providing Redundancy: Satellites with identical functionality can be used to provide redundancy in the case of failures.
- Increasing Capacity: Satellites with similar functionality can be used to increase the system's capacity and throughput for a given service area
- Extending Availability: Similar satellites can be physically distributed in order to increase the spatial coverage of and/or to extend the temporal availability over a region of interest
- Achieving Fusion: Similar satellites with overlapping service regions can generate products that are fused in order to produce enhanced products such as stereo or super-resolved images.
- Incorporating Specialization: Satellites may perform specialized tasks in order to act as distinct functional subsystems that take part in multiple real-time control loops within the overall space system. This may consist of distributed portions of the system's payload instrumentation such flying portions of an optical system on distributed platforms in order to achieve large observational baselines; this architecture has been proposed for the NASA Deep Space-3 mission. Specialization may also involve broader 'satellite bus' support functions such as using a set of vehicles within the fleet to provide local navigation beacons for use by satellites within the fleet. Finally, specialization may extend to system command and control by supplementing groundstations with on-orbit communication relays or even providing typical mission control services from an on-orbit platform.

Current navigation, communication, and observation constellations have shown the value of a distributed fleet for providing a unified mission service. The "fleet operation" of these missions, however, is often nothing more than controlling conventionally designed satellites in a parallel manner with little to no coordination apart from managing orbital stations. While effective for current applications, far more technically advanced versions of distributed space systems are being proposed as a means of providing enhanced mission services.

The developing vision of revolutionary distributed space systems typically cites the desire to field a tightly coupled, highly autonomous group of satellites that provide on-orbit flexibility, redundancy, reconfigurability, and graceful degradation. This vision often includes the following technical elements:

- Guidance and navigation services such as relative positioning and attitude determination and control.
- Fleet-level mission service provision allowing the specification of high-level goals and providing inter-satellite planning, synchronization, and execution capabilities.
- Advanced health management services capable of efficient anomaly detection and fleet-level reconfiguration.

Overall, these types of capabilities are cited as a means of enabling new types of space missions as well as increasing the cost-effectiveness of many existing missions. In addition, the use of numerous smaller and simpler spacecraft provides a variety of economic and logistical benefits. For instance, it is possible to standardize the use of bus components and to therefore reduce costs through economies of scale. Distinct physical portions of the system can foster collaborative development among dispersed organizations. On-orbit, the fleet has built-in redundancy, the ability to be reconfigured, and the quality of graceful degradation. And finally, long lead-time components and new technologies can join the fleet as available.

While the benefits of distributed space systems are compelling, a number of challenges arise in their implementation. These include achieving high-accuracy relative position sensing, providing efficient low-thrust propulsion, implementing robust inter-satellite communications links, developing fleet-level collaboration techniques, and developing low-cost design approaches.

Many research and flight programs exist to address these challenges. With respect to navigation, a variety of GPS-based techniques are being explored.[1,2,3,4,5,6,7,8] 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.[9] 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.[10]

Recent work in autonomous operations techniques has similarly demonstrated enhanced capabilities for precise and cost-effective system health management and mission services processing. 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.[11,12,13]

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.[14] 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. As part of this program, the joint Stanford University – Santa Clara University Emerald mission is focusing on advanced distributed space system technologies with the hope of verifying and validating aspects of this exciting vision.

2. THE STANFORD UNIVERSITY – SANTA CLARA UNIVERSITY TEAM

The Stanford University – Santa Clara University team has world-class experience in the design of low-cost university-class satellites, the engineering of advanced spacecraft technology, and the development of compelling, low-cost science missions.

Low-Cost Satellite Design

Both Stanford's Space Systems Development Laboratory (SSDL) and the Santa Clara Remote Extreme Environment Mechanisms Laboratory (SCREEM) 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.[15,16] For each of these programs, students completely manage and engineer the development of the spacecraft. Since 1994, Stanford University has produced two microsatellites, Sapphire and Opal. Similarly, since 1998 Santa Clara University has produced five very simple microspacecraft as part of its Barnacle and Artemis projects. It is worth noting that these two programs have previously worked together on the development of one particular distributed space system architecture, that of a mothership (the 20 kilogram Opal microsatellite) which ejects a cluster of very simple science craft (three sub-kilogram Artemis picosatellites).

Advanced Spacecraft Technology

The Emerald team holds world-class expertise in the technical issues inherent in exploring advanced distributed space systems.

The Stanford Aerospace Robotics Laboratory (ARL) is providing expertise in GPS-based formation flying. ARL has developed highly capable GPS receiving systems and has implemented formation flying capabilities in several mobile robot testbed systems [2]. In addition, ARL is leading the development of the aforementioned 6-satellite Orion formation flying mission.

The Stanford Plasma Dynamics Laboratory (PDL) is contributing its expertise in propulsion systems. PDL has vast experience in the development of a wide variety of low-thrust thrusters.

SSDL and SCREEM are providing expertise in advanced autonomous techniques for operating complete space systems. Previous work in this field 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 both spacecraft and ground systems. As part of this work, a global space operations system for controlling the Emerald satellites is being developed. This system consists of several communications groundstations throughout the world, amateur radio and Internet communications links, and a centralized mission control complex.[17]

Distributed Science

SCREEM and Stanford's Space Telecommunications and Radioscience Laboratory (STARLAB) are providing expertise and heritage equipment for Emerald's baseline science mission. These laboratories have teamed previously in the development of the Artemis mission which is using picosatellites to monitor lightning-induced Very Low Frequency (VLF) radio waves in a distributed manner.[18] Emerald will be performing a similar scientific investigation and will fly an enhanced version of the Artemis VLF receiver.

3. THE EMERALD MISSION

The Stanford – Santa Clara Emerald mission will further understanding of distributed space systems in several ways. These include experiments relating to "low-level" navigation, "high-level" health and payload processing, and the performance of a distributed science mission.

Navigation

Experiments relating to inter-satellite navigation include the checkout of specific component-level technologies, the demonstration of on-orbit relative position control, and the flexible use of ground-based control.

Component Verification. The operation and performance of several navigation-related components will be assessed.

First, a low-cost low-power GPS receiver developed by ARL will be tested. Shown in Figure 1, 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.

Second, advanced colloid microthrusters will be incorporated on one of the satellites. These thrusters, shown in Figure 2, 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).[19] In addition to providing orbital maneuvers, these components will also be evaluated for their ability to control attitude.

On-orbit Relative Position Control. 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).

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 3, 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.[10] 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.

Ground Segment Relative Position Control. 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, an enhanced beacon system (described later) 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.

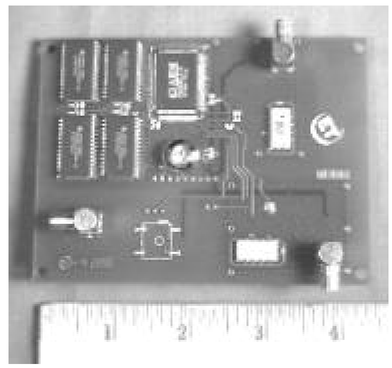


Figure 1. *The Modified Mitel GPS Receiver*

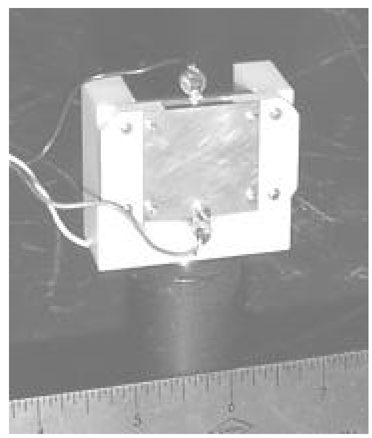


Figure 2. *Colloid Microthruster Prototype*

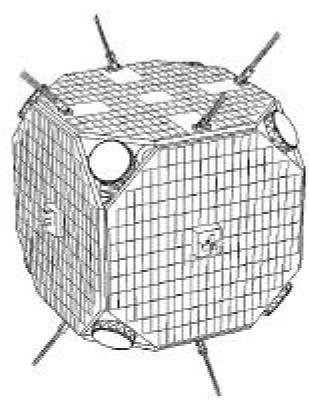


Figure 3. *The Orion Microsatellite*

Health and Payload Processing

The Emerald mission will provide several demonstrations of advanced and cost-effective health and payload processing techniques.

First, 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[13]. 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 science payload. This system will provide synchronized control of the science 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 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.

As a related experiment in satellite development and operation, the Emerald vehicles are being designed with simple but capable PIC microprocessors into most subsystems. The PICs connect to the main flight computer through an I^2C serial bus. Developers have hypothesized that this approach will make the development process more efficient by supporting a simple and easily defined wiring interface, by migrating subsystem software responsibilities to the subsystem development teams, and by enabling comprehensive subsystem-level test. These potential benefits will be assessed and weighed against any drawbacks that occur due to cost, power, mass, and radiation tolerance. Furthermore, the satellite's computing architecture will allow commands to be sent directly to a specific component, bypassing the main flight computer. This capability will be used to support several demonstrations of distributed control.

Distributed Science

Each Emerald satellite will include a VLF receiving system for recording and analyzing VLF waves emitted by lightning. Developed by SCREEM and STARLAB, these receivers will support a variety of science studies relating to lightning and to the structure of the ionosphere[20]. 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.

Distributed space system 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. Furthermore, advanced "high level" operations technologies 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.

4. SPACECRAFT CONCEPTUAL DESIGN [21]

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 4 depicts assembled and exploded views of this configuration. Drag panels will be incorporated into this design by actuating two opposite side panels.

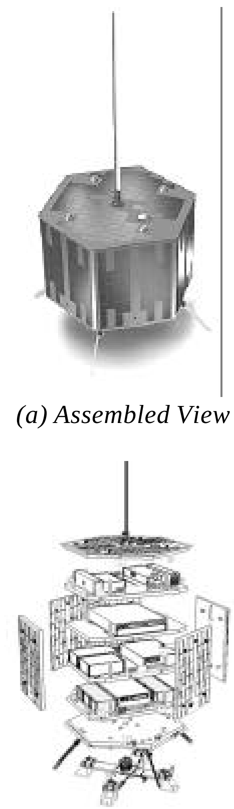
For a flight computer, the Emerald satellites will use the commercially available SpaceQuest FCV-53 flight processor running the BekTek operating system. Together, this provides a radiation tolerant system with 1 MB RAM, a file system, and a schedulable command execution system. The processor will connect to PIC microprocessors in 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.

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 5 shows a system-level diagram of the satellite components. Figure 6 gives an artist's depiction of the Emerald vehicles in orbit.



(a) Assembled View

(b) Exploded View

Figure 4. The Heritage Satellite Configuration

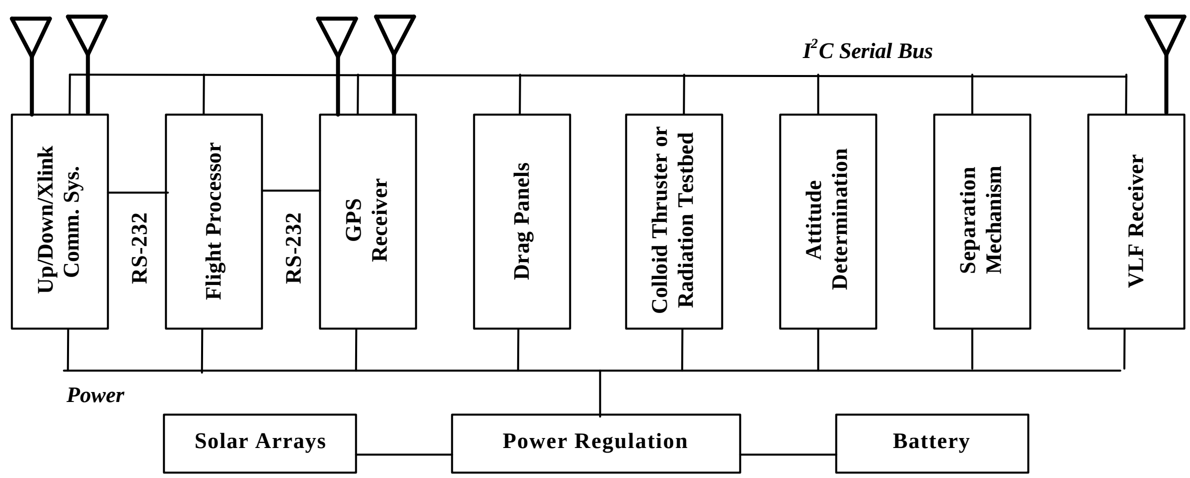


Figure 5. *The Emerald System Diagram*

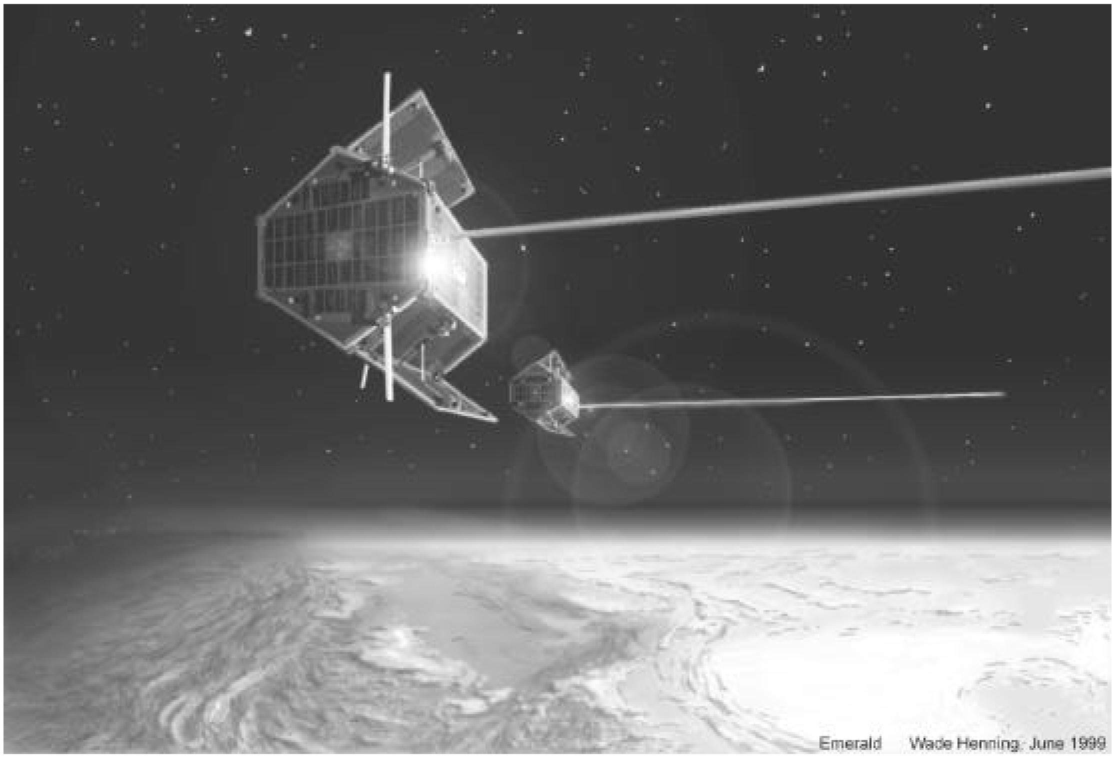


Figure 6. *Emerald satellites in formation [Henning].*

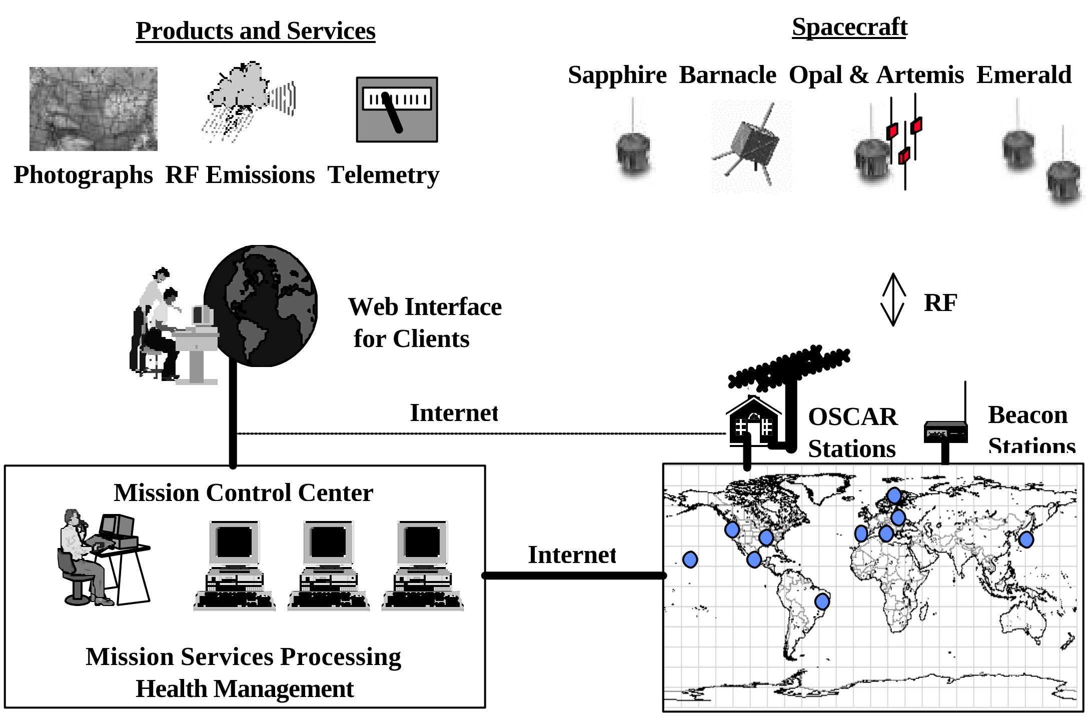


Figure 7. *The Mission Control Architecture*

5. MISSION OPERATIONS ARCHITECTURE

The Emerald satellites will be launched from the Space Shuttle's SHELS launch platform with many of the other University Nanosatellite Program spacecraft. 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[17]. 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 7.

6. DEVELOPMENT APPROACH

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. In both programs, students follow formal systems engineering processes in order to develop capable, low cost designs with an acceptable amount of risk. 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.

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; it also ensures a consistent approach for the analysis, fabrication, and test of all subsystems. Students are organized into payload and bus subsystem teams based on interest and capability. 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.

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.

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.

Payload Integration Approach

Without question, the Emerald mission 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 the aforementioned 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.

7. CONCLUSIONS

The Stanford – Santa Clara Emerald mission will contribute to the understanding of distributed space systems. This will be achieved by conducting a variety of experiments in relative satellite navigation, in high-level health management and payload processing, and in distributed science. 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 Goddard Space Flight Center for its support of the distributed satellite control aspects of this project. In addition, Ames Research Center, the Jet Propulsion Laboratory, and the Lockheed-Martin Advanced Technology Center are thanked for their support of the autonomous operations aspects of this research program. Finally, 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] 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.

[2] 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.

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

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

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

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

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

[8] 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.

[9] 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.

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

[11] 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.

[12] 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.

[13] 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.

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

[15] 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.

[16] 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.

[17] 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.

[18] 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.

[19] M. Cappelli and F. Pranajaya, “Colloid MicroThruster Research”, Stanford University Research Report, July, 1997.

[20] 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.

[21] 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.