Extending Beacon-Based Health Monitoring to Distributed Space Systems

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Abstract - Beacon-based health monitoring is a technology often noted for enabling drastic reductions in the cost of nominal telemetry monitoring. On board a spacecraft, software filters telemetry to derive a health assessment, and a periodic beacon broadcasts this assessment to the Earth. A network of low cost receiving stations receives the beacon signal and relays it to a central mission control center. At the mission control center, a suite of software responds according to the value of the health assessment; appropriate responses may include operator notification, automatic groundstation rescheduling to accommodate new health operations, and intelligent retrieval of appropriate operational documentation. Conceptually, this system acts as an automated mapping from spacecraft state to high-level operator response.

As part of its research programs in distributed space systems, Stanford University and Santa Clara University are extending the standard spacecraft beacon monitoring architecture for use in multi-satellite fleets. Two specific applications are currently being developed. First, a space segment level beacon is being developed as a single communication signal for updating the ground segment with fleet-level health data. Second, inter-satellite beacon broadcasts are being explored as a means of communicating fleet status among individual satellites and indicating operational mode changes in the event of anomalies.

This paper will present the beacon monitoring concept and ongoing validation results for single missions. In addition, the aforementioned extensions to distributed space systems will be described in detail. Finally, the incorporation of a distributed beacon system into the two-satellite Emerald spacecraft mission will be presented.

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1. INTRODUCTION

Multi-satellite systems such as the Defense Satellite Communications System (DSCS) communications system, the Geostationary Operational Environmental Satellite (GOES) weather satellite system, and the Global Positioning System (GPS) navigation system have been prevalent for more than a decade. These systems have proven the value of incorporating multiple spacecraft within their architectures in order to provide redundancy for, to increase the capacity of, and to extend availability of their mission services. In general, the design and control of the spacecraft within these systems are fairly conventional compared with single satellite systems. Each spacecraft is built as a full-scale, highly redundant, high cost vehicle. In addition, the command and control of the satellites within these systems is performed in parallel with ground-based human operators acting as the system-level coordinators.

Recent mission-driven demands are leading to a possible modification of this approach to multi-satellite systems in order to develop a new space system architecture option. The emerging vision is to field a tightly coupled, highly autonomous fleet of satellites. In addition to providing redundancy, increasing capacity, and extending availability, these systems would offer on-orbit flexibility, agility, reconfigurability, and graceful constitution/degradation. Their collective intelligence would permit the collaborative provision and fusion of mission services. Although not required, this vision often postulates the use of relatively small spacecraft with the hypothesis being that a fleet of precisely controlled small spacecraft can provide more value than a single, conventional, monolithic satellite. The use of numerous small spacecraft raises the additional potential benefit of achieving economies of scale in the development of the space segment.

While still notional in many respects, this vision generally attempts to exploit advances in system control techniques in order to gain orders of magnitude performance increases in service value, cost, and timeliness. Typical examples of the types of advanced control techniques required for achieving this vision include:

- Precision guidance services such as relative on-orbit positioning/attitude determination and control.

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- Robust health management services capable of efficient anomaly detection and fleet-level response.
- Efficient fleet processing services capable of intelligently responding to goal-level directives, reacting to interesting events, and extracting mission-specific products.

A variety of research programs are actively targeting these technology areas in support of the stated vision of distributed space systems. This includes work ranging from formation flying initiatives sponsored by the AFOSR Techsat 21 program to the artificial intelligence spacecraft control techniques developed by the NASA New Millennium Program.

2. BEACON MONITORING [1]

One specific technology with potential applicability to distributed space systems is beacon-based health monitoring. In development both at the NASA Jet Propulsion Laboratory as well as at Stanford University, beacon-based health monitoring specifically targets on-orbit anomaly detection and notification as a means of improving the cost-effectiveness of space missions.

Conventional Spacecraft Health Monitoring

The conventional method of detecting spacecraft anomalies is very costly. Tens of highly trained personnel per spacecraft are typically required in order to perform periodic, around-the-clock, real-time monitoring of spacecraft telemetry. These operators generally compare telemetry to predetermined limits in order to become aware of the existence of an anomaly; operator expertise and understanding of trends and operational modes provide an additional and more robust knowledge base upon which to assess spacecraft health. Apart from personnel requirements, the communications and network resources required to establish and conduct the spacecraft-to-operator link can be extensive, especially in large-scale space systems such as NASA's Deep Space Network (DSN) and the Air Force Satellite Control Network.

Automation of Health Monitoring

Historically, ground-based automation of the telemetry filtering process has been the primary strategy for improving the nominal monitoring of spacecraft. Although a variety of automated reasoning techniques have been applied, the most common approach has been the use of expert systems. When the automated telemetry detection program encounters an out-of-limits condition, operators are notified of these occurrences through mechanisms such as visual color or display changes, audio alarms, and paging systems. One of the most successful examples of this is at the University of California at Berkeley's Center for Extreme Ultraviolet Astronomy (CEA). In 1995, CEA introduced a control center-based expert system for monitoring payload telemetry from NASA's Extreme Ultra-Violet Explorer (EUVE) spacecraft. Over a two-year period, this monitoring system and its automated paging capability allowed CEA to reduce console operator manning levels from around-the-clock staffing to a single shift. This was performed while also expanding the scope of this monitoring from just the science payload to the entire spacecraft. This capability enabled a four year extension of the original 3.5 year EUVE mission by saving an estimated $600,000 of operations cost during this time [2, 3].

The Beacon Monitoring Concept

Beacon monitoring concept extends automated telemetry filtering by providing a low-cost and timely operator notification link when the filtering software is migrated to the spacecraft. The baseline beacon monitoring architecture is depicted in Figure 1.

In this configuration, the software telemetry filter continues to evaluate satellite health and to detect possible anomalies, but this software is now deployed on the spacecraft. The results of this process are compiled into a single health assessment message. This message, composed of only a few bits of information, typically specifies little more than an anomaly's existence, type, and/or severity. Accordingly, the health assessment message is equivalent to the alert information passed to an on-call operator in the ground-based automated telemetry filtering strategy.

As the health assessment message is continually produced on-board the spacecraft, it is periodically broadcast to the ground as a beacon signal. This can be accomplished by leveraging existing communications equipment used for mission data, spacecraft telemetry, and/or tracking beacon broadcasts; alternatively, a simple, dedicated beacon transmitter can be added to the spacecraft. The broadcast itself generally consists of simple carrier pulsing or tone modulation to represent the health assessment message's bit sequence. This broadcast strategy enables the use of low cost transmission systems and easily supports low bit rate broadcasts that may be necessary for low power and/or long distance communications.

A network of receiving stations is used to receive the broadcast health assessment message and to relay it to the spacecraft's mission control center. This network can be composed of existing space system stations, a new set of dedicated beacon receiving stations, and/or a commercially available communications system. Low cost network design and operations are promoted since spacecraft communications are receive-only, bit rates are slow, message decoding is simple, and processing functions are easily automated. Given a visibility schedule, the receiving network attempts to acquire and decode the spacecraft's health beacon. The received health assessment message is then forwarded to the mission control center using the station's conventional communications link. The station may also forward additional system health information pertaining to conditions such as the inability to acquire a scheduled beacon signal or a receiving station malfunction.

Upon reception of the health assessment message, an automated system at the mission control center initiates appropriate action based on the contents of the message. This includes logging the message and notifying the on-call operator in the event of an anomalous message. The response system may also automatically initiate preplanned anomaly response activities such as displaying appropriate operational and engineering documentation, scheduling high priority anomaly management contacts with the spacecraft, and re-planning the production of mission products that are affected by the anomalous conditions.

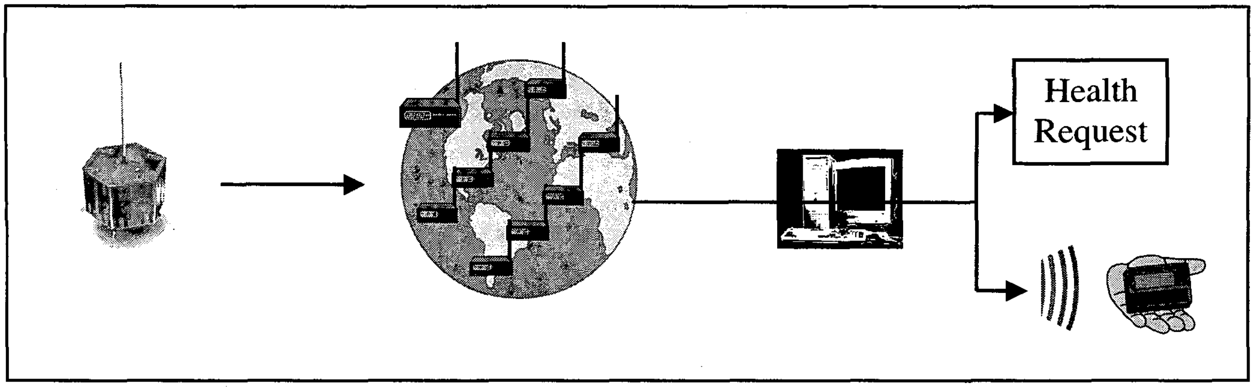


Figure 1. The Beacon Monitoring Architecture: An on-board health agent analyzes telemetry and derives a very high-level health assessment consisting of only a few bits of information. This message is periodically broadcast to the ground where it is received by a low-cost receive-only network of groundstations. The groundstations relay the health message to a centralized mission control center which initiates appropriate response actions. In the event of a vehicle anomaly, these actions might include scheduling new health contacts with the satellite and paging an on-call engineer.

Beacon Monitoring Implementations and Results

The beacon monitoring strategy has been studied by and is being developed for a variety of spacecraft operating within several space operations networks as a means of conducting cost-effective nominal spacecraft monitoring. Proposed implementations vary according to spacecraft mission attributes and cost drivers within the specific networks.

The first known full-scale study for implementing a beacon monitoring system was for the heterogeneous fleet of spacecraft operated by the Department of Defense through the AFSCN [4]. Known as Lifeline, this system used about 300 bits to periodically relay both health and position data. Although endorsed by a number of researchers [5], Lifeline received no further funding from the Air Force due to concerns over operations and maintenance costs.

NASA interest in beacon monitoring emerged at the Jet Propulsion Laboratory (JPL) in both the research and flight projects communities. Considered an enabling technology for future missions to Pluto and Europa, the NASA vision of beacon monitoring relies on a probe's highly autonomous flight software for producing a coarse two-bit health estimate [6, 7]. In February 1999, the technology for this concept was verified during the flight of the Deep Space 1 (DS-1) probe [8]. During this experiment, the DS-1 transponder broadcast a set of 1000-second non-coherent tones every hour. A 26-meter DSN test antenna at the DSN Goldstone site automatically relayed this signal to the beacon experiment team at JPL via the secure NASA Science Internet. E-mail and pager connections initiated appropriate action with the DS-1 operations team and the DSN scheduler.

Beacon monitoring for low-cost LEO university/amateur-built satellites was first proposed in 1995 both as a means of lowering small satellite lifecycle costs and as a way to inexpensively verify and validate the beacon monitoring strategy for more complex spacecraft missions [9]. Through a joint effort between Stanford University and JPL, beacon monitoring has been implemented for Stanford's first two microspacecraft, Sapphire and Opal. Both satellites filter telemetry and periodically broadcast a two-bit health assessment message. A low-cost, automated, receive-only groundstation has been developed for installation at sites throughout the world [10]. These stations relay the received health message to the Stanford mission control complex via the Internet; mission control automatically pages an on-call operator and initiates a high-priority request for future health analysis contacts.

The Stanford beacon operations system will commence on-orbit operations in 2000; Opal is manifested for launch in late 1999, and Sapphire has been targeted for a late 2000 launch. In preparation, significant ground-based testing has been used to verify and validate the Stanford beacon operations system. In particular, numerous controlled, double-blind, end-to-end experiments have been run with Sapphire in a simulated orbit. These experiments have compared the performance of a conventional operations approach to that of beacon operations for a series of real, injected satellite anomalies as well as several unplanned anomalies. Holding cost relatively the same, the experimental results repeatedly show that timeliness is drastically improved and confidence for beacon operators is strictly greater than or equal to that of conventional operators [11]; these system-level performance metrics may be traded against each other in order to reduce cost.

Conceptual View of Single Satellite Beacon Monitoring

Work in developing and assessing single satellite beacon monitoring systems has led to several conceptual observations concerning the role and value of the architecture. Related to applications to distributed space systems, two particular points are prominent.

First, the ability to convey very high level operational data between elements in the overall mission architecture can produce considerable value. Missions that don't provide this as part of their nominal mission may therefore benefit by the addition of such a service. Excellent candidates for this include deep space probes during their cruise phase, ultra-low cost university-based missions, and satellites in a dwell phase (i.e. redundant vehicles, spacecraft awaiting service/science activities, etc.). Even though a significant level of resolution and detail may be absent, the simple and periodic exchange of a few bits of data relating status, operational modes, and/or intentions is enough to coordinate a great deal of system activity.

Second, the ability to provide this service at a very low cost results in making beacon architectures competitively attractive. The use of low data-rate communications, simple receive-only ground stations, commercial or Internet-based ground communications networks, and automated notification/rescheduling are critical elements in achieving the low-cost criteria.

3. MULTI-SATELLITE BEACON MONITORING

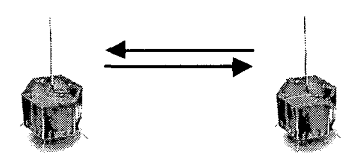
In considering the applicability of beacon technology to multi-satellite systems, it is instructive to apply the conceptual lessons of single-satellite beacon monitoring. Namely, multi-satellite space systems should be analyzed in order to identify low-cost opportunities for periodically exchanging very high-level status data that can significantly enhance mission performance. Several such applications are easily imagined.

First, a satellite's beacon signal could be received and used by other satellites in the fleet in addition to having it be used by the ground segment. A number of beneficial uses for this information may exist. For example, the existence of a major anomaly that prevents payload operation on one satellite could be communicated to other spacecraft in the fleet. Without knowing any other details of the anomaly, the other satellites could intelligently react to this situation. For example, another satellite might perform the payload operations of the anomalous satellite thereby fulfilling the role of a redundant unit. Alternatively, if the fleet was performing a collaborative activity requiring all satellites, the fleet could conserve resources by canceling the activity.

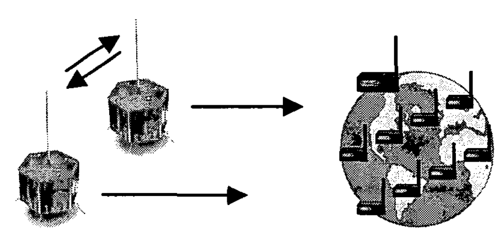
A second application of a distributed beacon system might involve using a space-to-ground beacon signal to represent the health or operational mode of the entire space segment. To achieve this, satellites would exchange health data, a fleet-level health message would be derived, and this message would be broadcast to the ground in order to trigger any necessary actions. Several design issues arise in considering how to implement this vision. These include, but are certainly not limited to, the following:

- <u>Locale of analysis and the exchange of health data</u>: This issue concerns where the health of a particular satellite should be computed and how this impacts the amount of exchanged data among spacecraft. In one extreme, each satellite could perform its own assessment and simply pass a high-level health message to each of the other spacecraft; this is equivalent to implementing inter-satellite beaconing, as described in the previous paragraph, as a component in an overall fleet-level beacon system. At the opposite extreme, raw telemetry could be exchanged among satellites, with each spacecraft assessing the health of all other satellites in the fleet. The first choice limits computational and communications requirements; the second choice could allow for more robust analysis by allowing health assessment discrepancies to inform the diagnostic process.
- <u>Format of the fleet-level beacon message</u>: This issue concerns the amount and content of the aggregate beacon message. At one end of the spectrum, it could simply be a concatenation of each satellite-specific health message. For example, if each satellite had a two-bit health status, a 8-satellite network would use a 16-bit fleet-level beacon message. At the other end, it could be logical OR of each of these messages. So, for the same 8-satellite network, the fleet-level beacon message would only be two bits; an emergency condition on one satellite would cause the fleet-level message to indicate a fleet emergency. An interesting intermediate possibility might be to use a 5-bit message: 2-bits for the fleet-level status, and another three-bits to indicate the satellite with the highest priority for attention. Of course, many possible solutions to this issue exist; how to choose the appropriate fleet-level message format is a function of the aggregate-level activities that will be initiated on the ground in response to the message [1].
- <u>Number of broadcast satellites</u>: This choice concerns which satellites should participate in the beacon broadcast process. The choice could be only one spacecraft, every vehicle in the fleet, or some subset. Certainly, multiple vehicles provides a redundancy for the beacon function itself; this may or may not be justified depending on the cost of implementation and the timeliness in becoming aware of a beacon system malfunction (requiring a return to conventional fleet monitoring practices). In addition, the physical distribution of the fleet and its connectivity with the ground segment affects this design issue

Figure 2 compares single satellite beacon monitoring with several possible implementations of multi-satellite beacon monitoring.



(a) Inter-satellite beaconing: Each satellite periodically transmits its message to the other satellites in the fleet.



(b) Fleet-level beaconing: Satellites communicate status data among themselves. Then each satellite derives a fleet-level message and periodically broadcasts it to the ground.

Figure 2. Potential Beacon Architecture Implementations for Distributed Space Systems

Although the emphasis in this discussion has been on the exchange of health-related data, using a beacon message to convey a small amount of general status data (i.e. data unrelated to anomaly status) can also provide drastic improvements in overall system performance. For example, JPL has proposed broadcasting the amount of available science data memory on a deep space probe. This information can be used to gauge when a science data download should next be scheduled. Given that the use of Deep Space Network resources is an expensive element or probe operations, the intelligent scheduling of contacts provides significant measurable benefits to mission cost.

In addition to possibly incorporating such single spacecraft mode data into a fleet beacon, there may be a few key fleet-specific status points that may also prove beneficial when periodically broadcast. For example, a formation-flying mission may include a bit conveying the operational state of the on-orbit relative position control system. If, for instance, the on-orbit system is non-operational (due to an equipment failure, a poor inter-satellite communications link, a limited power condition, etc.), relaying this fact via the beacon message could trigger the invocation of automatic ground-based navigation functions.

4. EMERALD: A DISTRIBUTED BEACON MONITORING FLIGHT EXPERIMENT

In order to verify and validate to potential of distributed implementations of beacon monitoring, the implementation of such an architecture has been selected as one of several technology experiments for the two-satellite Emerald mission [12]. Emerald is a joint Stanford University – Santa Clara University mission which is funded by the Air Force Office of Scientific Research, the Defense Advanced Research Projects Agency, and the NASA Goddard Space Flight Center as part of the TechSat 21 University Nanosatellite Program (UNP). The Emerald satellites, as well as eight additional spacecraft that are part of the UNP, are targeted for a Space Shuttle SHELS launch in 2002.

The Emerald Experiments

The two Emerald satellites will support several experimental investigations:

- Component verification: Several components will be tested for their operation in the space environment. These include a modified 12-channel Mitel GPS receiver and a newly developed colloid microthruster. In addition, an electronics testbed system will support chip-level performance of transistors, memory chips, and a variety of other components.
- Formation flying: Precision, sub-meter relative position determination will be achieved on-orbit through the exchange of GPS data via an inter-satellite communications link. In addition, on-orbit navigation algorithms will compute position control directives. These will be used to control low-authority position control actuators consisting of drag panels and the experimental colloid microthrusters. The result will be coarse but predictable relative orbital motion. As an auxiliary navigation package, the AI Solutions FreeFlyer suite of software will be used on the ground in order to produce relative navigation control directives.
- Autonomous System Operations: An on-board expert system will execute model-derived analysis rules in order to provide robust anomaly management. In addition, an on-orbit intelligent execution system will provide intersatellite command synchronization and planning. This will enable fleet-level commanding (i.e. a single high-level command to the fleet will cause coordinated fleet activity) and opportunistic science (i.e. the satellites will be able to detect "interesting" science events and react by commencing coordinated science data collection activities). Finally, a distributed beacon system will be implemented as described in the next section of this paper.
- VLF Science: Distributed sensing of lightning-induced Very Low Frequency (VLF) radio emissions will support a variety of science studies relating to lightning and to the structure of the ionosphere.

The Emerald Distributed Beacon System

As part of the autonomous system operations experiment, Emerald will be used to evaluate beacon architectures for multi-satellite systems. Both inter-satellite beaconing and fleet-level beaconing will be tested.

Due to the limited on-board computational capability, each satellite will derive its own two-bit health assessment message in a manner similar to Sapphire [9]. These messages, defined in Table 1, will be relayed between satellites. Together, these functions complete the required intersatellite beaconing capability.

Operationally, the relative beaconing data will be used to inform Emerald's collaborative, opportunistic science processing algorithms. Specifically, the Emerald spacecraft will be put into periods of opportunistic science operations during which each satellite will attempt to sense "interesting" lightning activity. If either satellite detects such activity, it will coordinate with the other spacecraft such that they will simultaneously collect high data rate samples of the lightning-induced radio emissions. Periods of listening for interesting science events are resource intensive and may last as long as 30 minutes. During this time, inter-satellite beaconing will be used to verify that each satellite is still capable of performing science operations. If this is no longer true due to an anomaly or resource constraint then the beacon will inform the other satellite of the condition thereby allowing it to abort the period of opportunistic science.

Message	Meaning	Possible Conditions
0 0	Normal	- Activity as expected
0 1	Alert	- Limited resources prevent continuation of opportunistic science operations
1 0	Critical	- Anomaly requiring attention within 12 hours
1 1	Emergency	- Unexpected CPU reset - Major anomaly requiring immediate attention

Table 1. Emerald Beacon Message Format

For simplicity, the inter-satellite beacon messages will be used as the basis for constructing the fleet-level beacon message. Assuming that the spacecraft are within inter-satellite communications range, each satellite will concatenate its two-bit health status with that of the other spacecraft. In addition, a fifth bit indicating the operational status of on-orbit navigation control will be added. This bit will be used to automatically invoke the ground-based navigation control system when on-orbit control is inactive.

Technically, the components will be duplicate or very similar versions of the system's incorporated into SSDL's previous spacecraft, Sapphire and Opal:

- The on-board expert system will be functionally similar in order to allow the analysis of telemetry channels and the execution of system commands. Implementation of this system will be different, however, due to the use of a new commercial off-the-shelf flight processor and operating system. The current plan is to modify the open source CLIPS expert system and to implement it as an application program. Modifications will include steps to port the source code to the new operating system as well as to implement some of the advanced production rule system capabilities incorporated into the Sapphire system [13].
- The beacon transmission system is currently being designed. For space-to-ground beaconing, the basic strategies used by Sapphire and Opal will be employed although the specific tone control technique will ultimately be determined by the final choice of transmitter. For inter-satellite beaconing, the standard inter-satellite communications system is the baseline choice of conveying status data.
- The existing automated, receive-only groundstations developed for Sapphire and Opal will be used. The current use of Internet connections to support message transfer to the mission control complex will also remain the same.
- The existing mission control complex message processing, commercial on-call operator paging system, and automated contact rescheduling techniques will be used.

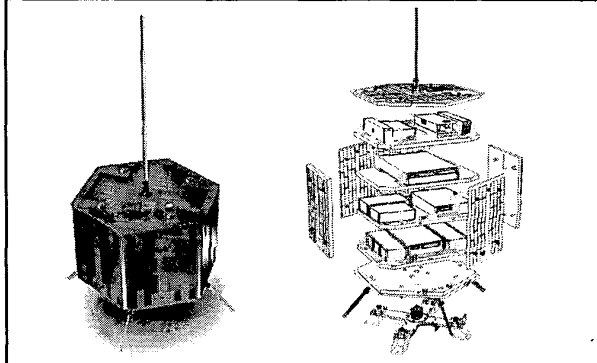
When operational, the system will be validated through a process of comparative evaluation. This will be done by simultaneously operating the mission with a conventional operations team and a distributed beacon operations team. As was done in validating the single satellite beacon architecture, these teams will work independently of each other. During this experiment, system-level validation metrics will be measured; these metrics will include cost (i.e. cost of infrastructure, cost of operational personnel, cost of bandwidth, etc.), timeliness (i.e. time to respond to anomalies, etc.), and value (i.e. confidence in system state of health, etc.).

The Emerald 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 Stanford University designs as well as on purchased space qualified components. The structural configuration consists of a 15 kilogram, 14-inch tall, 16-inch diameter hexagonal configuration employing a modular, stackable tray structure made of aluminum honeycomb. Drag panels will be incorporated into this design by actuating two opposite side panels. Figure 3 depicts assembled and exploded views of this configuration; figure 4 gives an artist's depiction of the two Emerald vehicles in orbit.

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, many of which will incorporate their own dedicated PICMicro processor, 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 Spectrolab 24% efficient solar cells which will be 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.



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

Figure 3. The Heritage Satellite Configuration

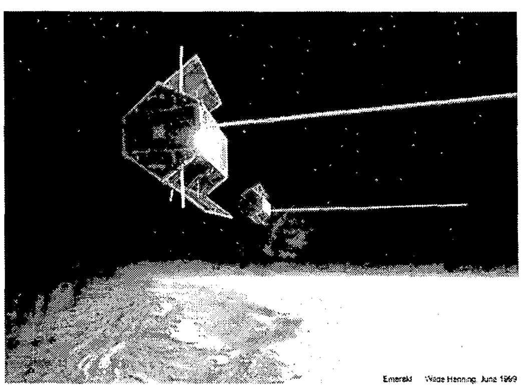


Figure 4. Emerald satellites in formation [Henning].

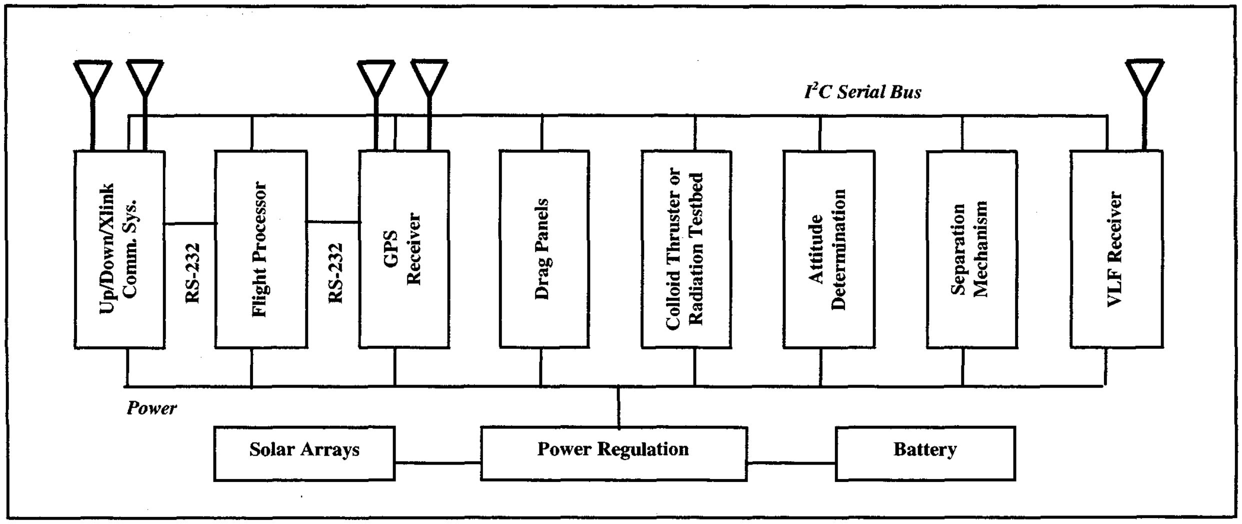


Figure 5. *The Emerald System Diagram*

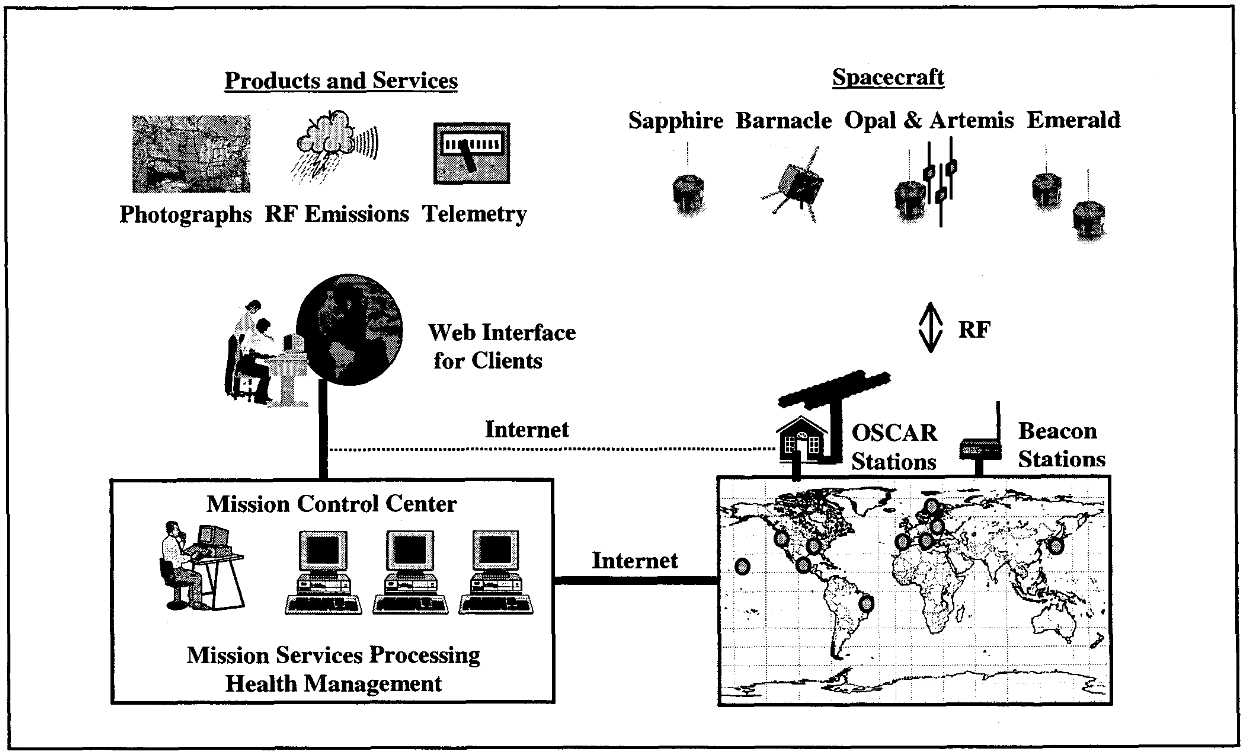


Figure 6. *The Mission Control Architecture*

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.

Emerald Mission Operations

Command and control of the Emerald spacecraft will be conducted through a global space operations network that is being established as part of Stanford's research program in space system operations [14]. 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. A web-based client interface provides simple and convenient conceptual level specification of desired services by principal investigators and the public. The overall mission architecture is pictured in Figure 6.

The Emerald Development Team

Stanford and Santa Clara have demonstrated expertise in developing quality, low cost space systems capable of supporting advanced technology demonstrations. Since 1994, Stanford has completed two complex microsatellites designed primarily by graduate students. Since 1998, Santa Clara has developed five very simple spacecraft designed primarily by undergraduate students. Fostered by their proximity and past collaborations, the development approach integrates Stanford and Santa Clara students into a single design team responsible for producing both spacecraft. Day-to-day team management is controlled by students. The team is organized into conventional subsystem development groups, and industry advisors and professors serve as mentors for technical and systems engineering aspects of the project.

5. Summary And Conclusions

For several years, beacon-based health monitoring has been identified as a strategy for reducing the cost of nominal monitoring for spacecraft. Recent experimental work with the NASA DS-1 and Stanford Sapphire microsatellite has demonstrated the viability of this technology and has quantitatively measured its benefits.

With considerable attention now being focused on highly automated satellite fleets, it is natural to consider the applicability of the beacon technology to distributed space systems. Potential applications include a single fleet-level beacon-based health signal as well as inter-satellite beaconing. The Stanford University – Santa Clara University two-satellite Emerald mission will incorporate such capabilities in order to verify fleet-level beacon technologies and to validate the performance of these architectures.

Although simple in concept, this project serves as a valuable prototype for developing distributed space system technologies for more complex missions. 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.

Acknowledgements

The authors wish to thank Prof. Robert Twiggs, Mr. Jay Wyatt, Mr. Gregg Swietek, Dr. Larry Capots, Mr. Mark Gersh, Dr. Pandu Nayak, and Mr. Mark Shirley for their feedback in the development of the technology discussed in this paper. In addition, the joint Stanford University – Santa Clara University Emerald student design team is acknowledged for its commitment to supporting the flight demonstration of the distributed beacon system. Finally, the insightful comments of this paper's technical reviewers have assisted in making this a stronger contribution.

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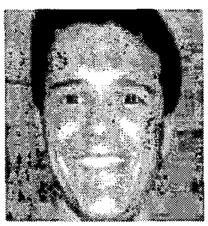

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