A Small/Micro-/Pico- Satellite Program for Investigating Thunderstorm-Related Atmospheric Phenomena

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Abstract: A low cost, multi-satellite program for conducting novel atmospheric science is described. The program exploits simple visual and radio frequency sensing in order to investigate atmospheric phenomena induced by thunderstorms. The science instrumentation is supported by a variety of standalone and collaborative small, micro-, and picosatellite vehicles in order to meet the program's science requirements while also exploring a spectrum of small satellite approaches for conducting meaningful science. This multi-mission program is being developed jointly by student design teams at Stanford University and Santa Clara University.

TABLE OF CONTENTS

1. INTRODUCTION

Stanford University's Space Systems Development Laboratory (SSDL) is dedicated to providing world class education and research in all aspects of space system design, fabrication, test, and operation. The primary vehicle for achieving this goal is the rapid, low-cost development of small satellites that are completely managed and engineered by students [1]. As an educational project, the simplicity of these satellites affords graduate students a unique opportunity to understand the operation of a complete system; furthermore, the speed of these projects allow students to experience a complete mission lifecycle from conception to on-orbit operation. From the research and development perspective, these platforms can be used to support a variety of low power, mass, and volume payloads in a low-cost albeit high risk space mission. Several SSDL graduate students are using microspacecraft-based experiments in support of their dissertation work.

SSDL's primary spacecraft fabrication enterprise is the SQUIRT program [2]. The general design guidelines for SQUIRT-class vehicles include a 25 pound bus mass, a 12 inch tall by 18 inch diameter modular hexagonal structure, a cash equipment budget of $50,000, heavy reliance on re-engineered commercial equipment, a 12 month limit on orbital life, and the use of amateur radio communications. SSDL's eventual goal is to establish an educational and laboratory infrastructure to support the production of a fully capable SQUIRT satellite on a yearly basis. The first SQUIRT spacecraft is SAPPHIRE, shown in Figure 1, which will characterize a MEMS infrared sensor, perform Earth photography, and broadcast data and synthesized voice messages [3]. SAPPHIRE is flight ready and is being investigated for a flight opportunity in 1999. The second SQUIRT spacecraft is OPAL, which will mechanically eject several daughter spacecraft in addition to characterizing several commercial sensors [4]. OPAL is in its final year of development and is being prepared for a launch opportunity in September of 1999.

This approach to engineering education has generated widespread interest in universities throughout the world. Accordingly, SSDL has assisted several institutions in initiating their own satellite engineering program. The most rewarding of these efforts has been the establishment of the Santa Clara Remote Extreme Environment Mechanisms (SCREEM) laboratory at Santa Clara University. Together, SSDL and SCREEM have initiated the ParaSat space flight program as a means of extending the SQUIRT program's educational benefits to undergraduate institutions with limited resources [5]. The general design guidelines for ParaSat-class vehicles are similar to those of the SQUIRT program with the following exceptions: orbital lifetimes may be on the order of days or weeks, cash equipment budgets are limited to about $5,000, limited or no functionality for several subsystems is permitted, and permanent attachment to spacecraft and/or rocket stages is considered acceptable. The first ParaSat spacecraft is Barnacle, shown in Figure 2, which will characterize commercial accelerometers and test a simple radiation tolerant processing system during a sounding rocket mission in late 1998 [6]. An orbital flight opportunity for a duplicate Barnacle vehicle is also being considered.

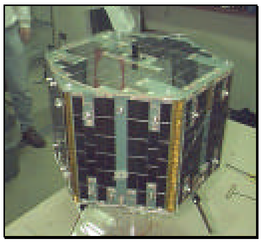


Figure 1: *The Sapphire Microsatellite*

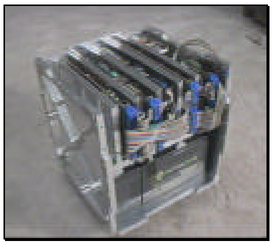


Figure 2: *The Barnacle Microsatellite*

These accomplishments have prompted a desire to extend the programmatic goals of the next generation of spacecraft being developed by both SSDL and SCREEM. These extensions include supporting novel scientific research, exploring a range of small satellite strategies for conducting missions, and broadening the educational benefits of these projects.

2. PROGRAM GOALS

To meet the extended programmatic goals for the next generation of SSDL and SCREEM spacecraft, a variety of science missions and architectures were considered. These options were evaluated based on science value, laboratory expertise, student interest, teaming relationships, available funding, and launch opportunities. As a result, a multi-satellite program for investigating thunderstorm-related atmospheric phenomena was selected.

2.1 Science Goals

Thunderstorms and their associated lightning are commonly experienced events in many regions throughout the world. For several decades, thunderstorms have been known to play an important electrodynamic role on a global scale:

- More than 2000 thunderstorms are active at any time with an average of 100 lightning strikes per second [7]. Figure 3 displays a three month global flash density measurement.
- Lightning leads to intense electromagnetic pulses (EMP) of ~20 GW power [8] and can transfer several hundred coulombs of charge to the ground in several milliseconds [9]. Figure 4 shows a damaging lightning strike.
- Thunderstorms act as charge generators that maintain >5x10^5 Coulombs of charge against atmospheric conduction losses [10].

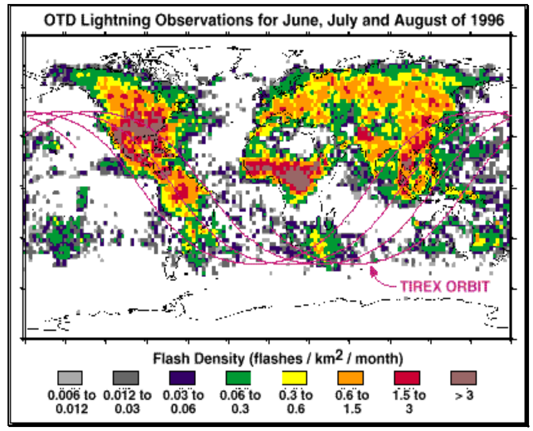


Figure 3: *Measured global lightning flash density [Courtesy H. Christian, NASA MSFC].*

Figure 4: *Lightning Strikes a City Skyline.*

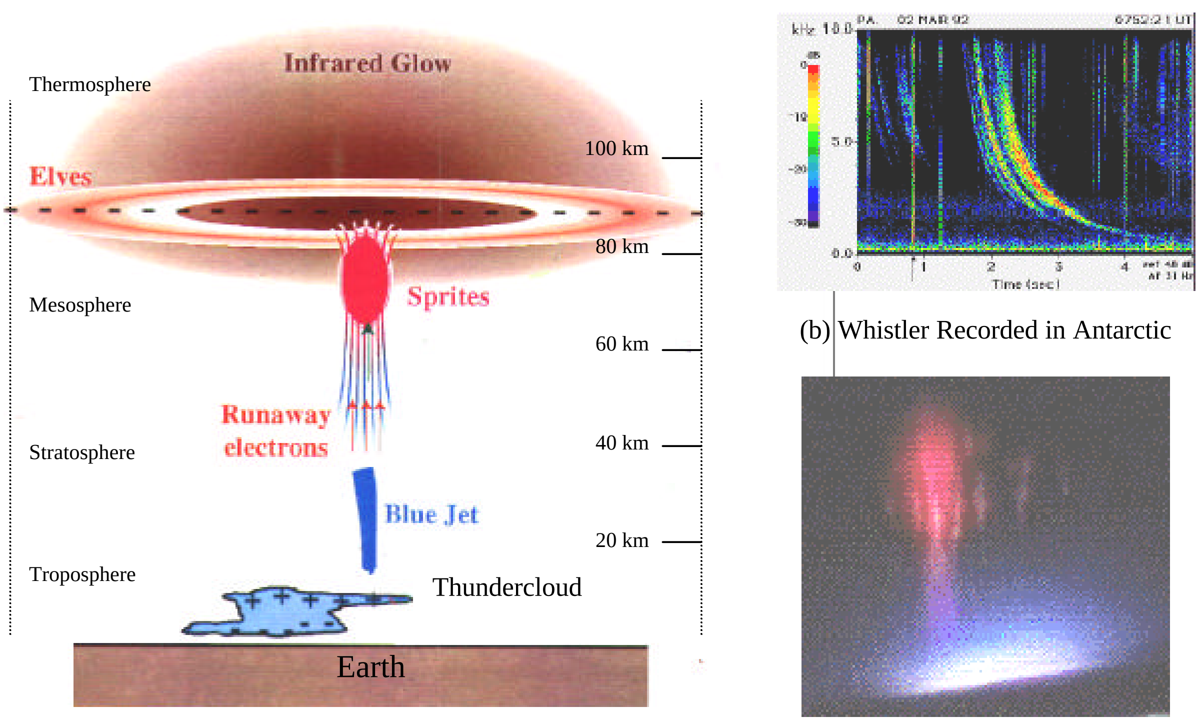
The practical effects of this activity are widespread [11]. Each year, lightning kills or injures hundreds of people, starts thousands of fires, and causes millions of dollars of property damage. Communications are disrupted, power lines are crippled, and electrical systems are damaged by surges. Lightning has even affected spacecraft launches where it has caused the temporarily disabling of Apollo 12 in 1969, the destruction of a Navy communication satellite in 1987, and the premature launch of several sounding rockets also in 1987. Furthermore, lightning is a strong indicator of weather attributes such as atmospheric convection, water growth rates, and the release of latent heat.

During only the past five years, vast experimental evidence has demonstrated the strong electrodynamic coupling that exists between thunderstorms and a variety of related atmospheric phenomena. Shown in Figure 5, these include [12]:

- Blue Jets: Rapidly ascending (~100 km/sec), highly collimated, primarily blue beams of luminosity that rise from the tops of thunderclouds and extend to ~50 km.
- Red Sprites: Red luminous glows lasting up to tens of ms and extend from ~50-90 km.
- Elves: Lightning-induced flashes lasting ~1 ms, at an altitude of ~80-100 km, and with a lateral extent of >300 km.
- Infrared Glow: Persistent infrared (4.3 µm) glow at altitudes of 70-130 km. and with a lateral extent of >300 km. Believed to be caused by excited CO_2 which derives its energy from N_2 which, in turn, is excited by electrons accelerated by a thunderstorm's electric field.
- VLF Events: Subionospheric VLF signal changes occurring simultaneously (within 20 ms) with lightning discharges.
- Whistlers: VLF signals captured by the Earth's magnetic field and directed to the polar regions; the audible signal produced by a VLF receiver sounds like a low whistle.

These phenomena have been theoretically explained with electron heating models based on lightning EMP [13], large quasi-electrostatic thundercloud fields [14], and runaway electron processes [15]. Clearly, however, far more experimental data is needed to mature these conceptualizations and to provide insight into the relationships among the phenomena, their statistical attributes, and their long duration global morphology. In addition to simply enhancing scientific knowledge, this understanding holds a key to a variety of practical applications such as weather prediction, robust communications, electronic protection, and golfer safety.

The scientific goal of the new multi-satellite SSDL/SCREEM spacecraft program is to provide measurements and observations of quantities related to these phenomena. This will be done in conjunction with primary principal investigators from Stanford's STARLAB, an electrical engineering laboratory with world class expertise in this scientific field. The specific scientific questions and the manner in which they will be addressed are shown as Questions 1-6 in Table 1.



(b) Whistler Recorded in Antarctic

(a) Jets, Sprites, Elves, and Infrared Glow Above Thundercloud

(c) Image of a Red Sprite

Figure 5: *Thunderstorm-related Atmospheric Phenomena*

2.2 Small Satellite Technology Goals

Previous SSDL/SCREEM spacecraft projects have established a loose benchmark concerning the performance of student teams in developing simple spacecraft. For example, SAPPHIRE consumed resources roughly equivalent to $45,000 paid in cash for equipment and 12 full time equivalent engineers; Barnacle has been developed with $2,000 paid in cash for equipment and 2.5 full time equivalent engineers. By incorporating lessons learned, leveraging components from previous projects, and

	Question	Approach	Mission	Closure
Q1:	Do thunderstorms produce quasi-steady mesospheric infrared glow?	- Scan Earth limb 4.3 micron CO2 emission - Collect Earth limb images above thunderstorms	TIREX	- Correlate limb images with measured CO2 emissions - Correlate space/ground weather observations with CO2 emissions
Q2:	Are sprites, jets, and elves associated with mesospheric infrared emissions above thunderstorms?	- Scan Earth limb 4.3 micron CO2 emission - Collect Earth limb and ground based images above thunderstorms	TIREX	- Correlate space/ground imagery with CO2 emissions - Compare observations with theoretical transfer models
Q3:	How are the mesospheric and lower ionospheric regions affected by upward electrodynamic coupling of electrostatic thunderclouds?	- Scan Earth limb 4.3 micron CO2 emission - Collect Earth limb images above thunderstorms	TIREX	- Determine distribution, rates, and spatial extent of infrared glow - Compare observations with theoretical transfer models
Q4:	What types of thunderstorms produce sprites, jets, and elves?	- Collect Earth limb and ground based images above thunderstorms	TIREX	- Determine rates of sprites, jets, and elves in different regions - Correlate space/ground weather observations with limb imagery
Q5:	Can thunderstorm location and intensity be determined and/or enhanced through space-based VLF monitoring?	- Receive VLF impulses	TIREX EMERALD PEARL	- Correlate VLF signal attributes with ground weather observations
Q6:	Can the wavelength of thunderstorm-induced VLF signals be determined via instantaneous sensing in space?	- Concurrently receive VLF impulses on separate platforms	EMERALD PEARL	- Correlate VLF signals and platform position data to compute wavelength - Compare wavelength estimate with ground based estimates
Q7:	What resources are required to perform various academic microsatellite mission?	- Collect detailed measures of resource expenditures during development and operation	TIREX EMERALD PEARL	- Summarize consumption estimates - Correlate with data from similar academic projects to develop model
Q8:	What are the competitive effects (cost, time, performance, etc.) of various management/technology approaches?	- Measure resource consumption differences as a function of isolated, small scale innovations	EMERALD PEARL	- Compare consumption data for each innovation to assess trades
Q9:	How can aggressive, secondary technology demonstration missions be supported with minimum risk and maximum benefit to the primary mission?	- Develop policy for selecting, integrating, and canceling secondary missions - Track cost/benefit impacts of secondary payloads on primary mission	TIREX EMERALD PEARL	- Develop impact model based on primary/secondary mission attributes - Compare cost/benefits of secondary payloads with baseline - Adapt selection/integration policy
Q10:	For a given science theme, what are the limitations of scope and performance for varying sizes (small, micro-, pico-) of spacecraft?	- Track mission design decisions - Measure performance of equivalent functions for each mission	TIREX EMERALD PEARL	- Compare scope and functional performance for each mission - Compare other competitive metrics
Q11:	For a given science theme, what are the limitations of scope and performance for various mission architectures (single, collaborative, mother/daughter)?	- Track mission design decisions - Measure performance of equivalent functions for each mission	TIREX EMERALD PEARL	- Compare scope and functional performance for each mission - Compare other competitive metrics
Q12:	How can the educational benefits of microsatellite projects be extended to vocational/secondary students?	- Apply proven development techniques to establish new, less complex educational projects - Track student interest and performance metrics	TIREX	- Compare cost/benefits of these projects with baseline approaches - Adapt educational program as necessary
Q13:	How can science education be incorporated into existing microsatellite-based engineering projects?	- Apply proven development techniques to integrate a science education program - Track student interest and performance metrics	TIREX EMERALD PEARL	- Compare cost/benefits of this combined approach with baseline approaches - Adapt educational program as necessary

Table 1: *Programmatic questions and approaches*

capturing economies of scale related to multi-satellite production, however, a goal of the new multi-satellite project is to achieve significant improvements in cost, development time, and quality/reliability.

SAPPHIRE, OPAL, and Barnacle all supported technology demonstration missions. Although the new program will have a science focus, an additional goal will be to flight test even more aggressive small satellite technologies on-board these spacecraft. Furthermore, a comparative evaluation of the effects of spacecraft size, number, and processing architecture are also a goal of this program.

These goals will be achieved through evaluation of Questions 7-11 listed in Table 1.

2.3 Education Goals

The graduate level SQUIRT program has repeatedly demonstrated the value of conducting hands-on, real-world, team-based satellite development projects; benefits include the ability of students to understand the complete system and to experience all phases of a mission lifecycle. The Barnacle project was a successful first attempt at reformulating this experience for undergraduate students.

The additional educational goals for the new SSDL/SCREEM satellite program involve introducing even less advanced students to these experiences as well as incorporating a science component into the educational program. These goals are represented by Questions 12-13 in Table 1.

3. SATELLITE SYSTEMS

To achieve the stated programmatic goals, this program will include the development of several university satellite missions. These include 1) a single small satellite mission known as TIREX, 2) a collaborative, two microsatellite mission known as EMERALD, and 3) a concurrent, two picosatellite mission known as PEARL. This section presents a summary of each satellite project; Table 2 compares basic parameters for these missions.

Mission	TIREX	EMERALD	PEARL
# Satellites	1	2	2
# Design Teams	1	2	1
# Students/Team	50	10	7
Mission Life	6-12 months	3 months	0.1 month
Cost/Satellite	$13 Million	$100,000	$2,500
Satellite Mass	150 kg	10 kg	0.5 kg
Satellite Size	420,000 cm^3	50,000 cm^3	200 cm^3
Satellite Power	220 W	8 W	0.5 W
Data/Day/Satellite	800 MB	1.5 MB	0.2 MB
Development Time	32 months	24 months	12 months

Table 2: *Comparison of Mission Parameters.*

3.1 TIREX

The TIREX (Thunderstorm Infrared Radiation Explorer) mission consists of a single, 150 kg small satellite, shown in Figure 6a, being developed as a contender for the NASA University Explorer Program [12]. The spacecraft will be developed for $13 million, will have a 6-12 month mission life, and will be launched in 2001 on the Space Shuttle into a 51.6° inclination, 450 km circular orbit.

TIREX will conduct the first global survey of CO_2 4.3μm infrared emission from 50-110 km altitude in order to quantify the thunderstorm-atmospheric electrodynamic coupling that produces the persistent infrared glow above thunderstorms. In addition, it will record lightning discharges and their associated high altitude optical emissions (sprites, jets, and elves) over high thunderstorm activity regions where real-time downlink capability will exist. These measurements will support determination of the underlying physical coupling mechanisms as well as the occurrence rate, spatial extent, and global effects of the phenomena.

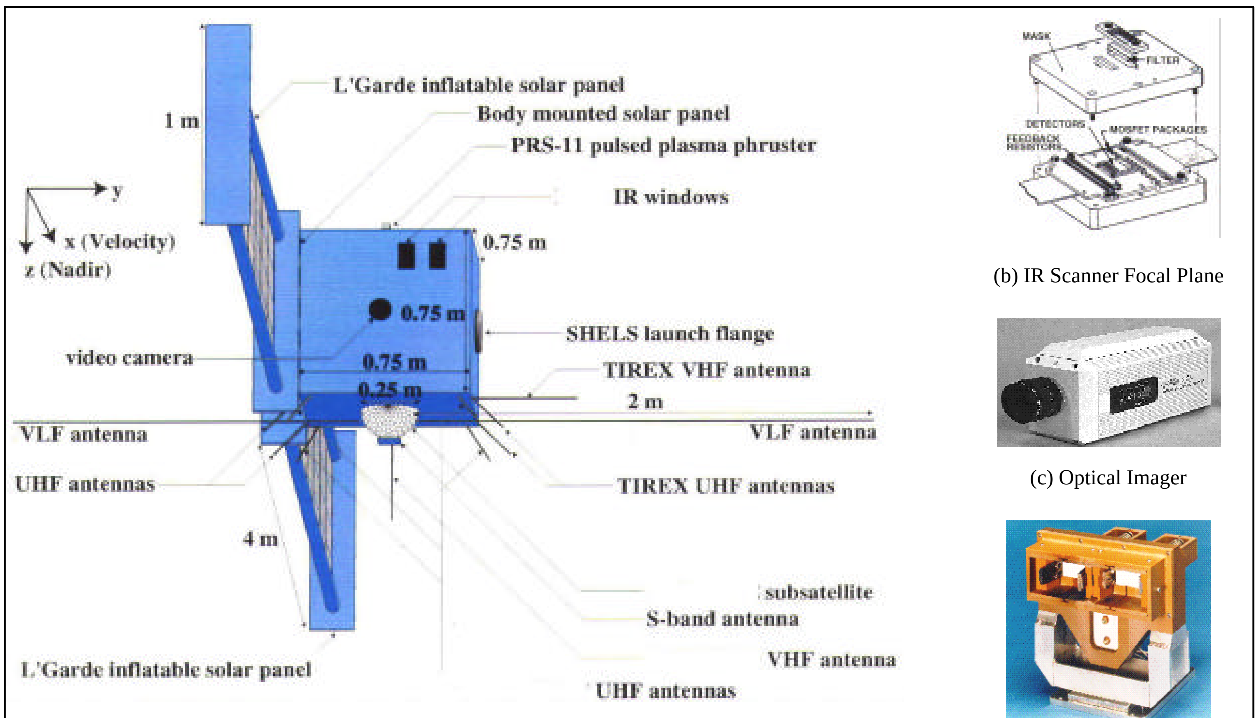
TIREX instrumentation includes a limb IR sensor and an optical imager. The custom, cryocooled IR sensor uses a wide-field OH sensor to locate the Earth's OH layer (typically at the approximate height of infrared glow regions) and provide steering mirror commands to properly position a narrow-field IR sensor's FOV. The IR sensor's focal plane assembly design is shown in Figure 6b. The optical imager, shown in Figure 6c, provides real-time night imaging of the infrared glow, sprites, jets, and elves. The imager is a modified, commercial, intensified camera with a 20° x 13° FOV and providing ~1 km pixel resolution. Compression is used to accommodate a ~1 Mbit/sec S-band downlink.

The TIREX bus consists of modular, 0.75 m cube structure with two Primex pulsed plasma thrusters, shown in Figure 6d, for altitude raising and orbit maintenance. Momentum wheels and torque coils are used to achieve 0.5° 3-axis attitude control; attitude determination is provided by the science instrumentation, a magnetometer, an Earth sensor, and a GPS receiver. The GPS receiver will also provide on-board position and timing data. An unspecified, Power PC class processor will be used with 2-4 GB of data storage capacity and a multi-tasking operating system supplied by Goddard Space Flight Center. The power subsystem consists of two 1x4 meter L'Garde inflatable solar panels providing 270 Watts at BOL, Ni-Cad batteries, and a 28 Volt bus. A 1 Mbit/sec S-band communications system supports science data download; a 9600 baud UHF/VHF system is used for spacecraft command and control. Cryogenic radiation and a variety of standard active/passive measures will be used for thermal control.

TIREX also supports a largely stand-alone student payload in support of the program's educational objectives. This package consists of a VLF receiver and antenna for detecting the impulsive radio waves generated by thunderstorms. These signals will be rebroadcast via FM amateur radio to student and public investigators on the ground. With knowledge of satellite position, these broadcasts can be used to study thunderstorm intensity and location. This subsystem will draw power from TIREX on an as-available basis, use a separate 9600 baud command and telemetry link, and be controlled by an advanced version of the Barnacle low cost processor. Mounted on the Earth-facing side of TIREX, the exterior of this payload will be covered with small, highly polished mirrors to support ground-based visual tracking similar to that proposed by the Starshine project [16]. This payload will be completely managed, engineered, and operated by students from SSDL, SCREEM, and the associated vocational and secondary schools. This hands-on activity will be supported by an aggressive classroom and Internet based educational program addressing both the science and engineering issues raised by the project. This simple mission will naturally introduce the more complex issues being addressed by TIREX and which will be a subject of a public education series sponsored by STARLAB.

TIREX is complementary to other missions such as TRMM, TIMED, MSX, CIRRIS, UARS, and NIMBUS 7; none of these missions were specifically designed for high performance observation of a thunderstorm's infrared glow.

Referring to Table 1, TIREX specifically addresses programmatic questions 1-5, 7, and 9-13.



(a) Spacecraft Configuration

(b) IR Scanner Focal Plane

(c) Optical Imager

(d) Pulsed Plasma Thruster

Figure 6: *The TIREX Mission.*

3.2 EMERALD

The EMERALD (Electromagnetic Radiation and Lightning Detection) mission consists of two 10 kg. SQUIRT class microsatellites with a three month mission life that are being developed in preparation for the DARPA/AFOSR University Satellite Research Initiative. The spacecraft will be developed for $200,000 within two years by a joint SSDL/SCREEM student team; the satellites will be launched together from the Space Shuttle.

Like the TIREX student payload, each microsatellite will house a VLF receiver and antennae in order to acquire the impulsive radio waves generated by thunderstorms. For the baseline science processing shown in Figure 7b, these signals will be time-tagged and rebroadcast via FM amateur radio; with knowledge of satellite position, these broadcasts can be used to study thunderstorm intensity and location. Furthermore, the combined broadcasts can be analyzed to estimate VLF wavelength.

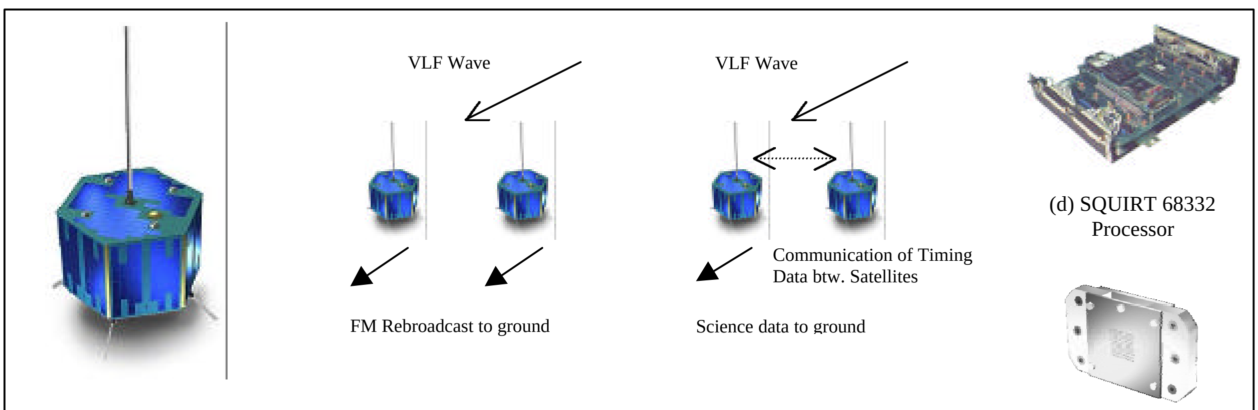
Shown in Figure 7c, several advanced science processing levels are being considered. These levels take advantage of capabilities offered by possible secondary, technology demonstration payloads:

- Using on-board GPS data for tagging the signals with precision location information.
- Using a satellite cross-link to support relative GPS-based position estimation.
- Using microthrusters, shown in Figure 7e, to relative satellite positioning.
- On-board digitizing, storing, and processing of VLF signals to derive peak wavelength times.
- Combining crosslink and on-board processing in order to compute VLF wavelength on-orbit.

The EMERALD buses will be nearly identical and will use many of the subsystem components developed for previous SQUIRT vehicles. As shown in Figure 7a, each microsatellite will be packaged in the 12 inch tall, 16 inch diameter hexagonal structure. Constructed of ¼ inch aluminum honeycomb, the modular tray configuration allows convenient arrangement of subsystem components and rapid assembly. The communications system will be composed of a reengineered, commercially available, amateur radio Mode J transceiver and terminal node controller. Eight body mounted silicon cell solar panels will provide over seven watts of average power. A single Ni-Cad or Lithium Ion battery will provide energy storage.

The standard SQUIRT 68332-based processor, shown in Figure 7d, will be modified to increase its radiation tolerance by adding latch-up protection and EDAC circuitry. SAPPHIRE's Chatterbox flight software will be adapted for use; this software includes an advanced, persistence-based expert system for reactive health management and mission products processing [17]. Attitude control will be achieved either through SAPPHIRE's magnetic/solar pressure spin scheme or through a more advanced gravity-gradient/momentum wheel combination. Sun and Earth sensors will permit on-board attitude determination. Passive thermal control will be achieved through the use of coatings and insulation.

EMERALD will also support several non-science-related secondary missions. These include testing MEMS components, advanced power subsystems, and several autonomous operations technologies. Referring to Table 1, EMERALD specifically addresses programmatic questions 5-11 and 13.



(a) SQUIRT Configuration | (b) Baseline Science Processing Configurations | (c) Advanced Science Processing Configuration | (e) Colloidal Microthruster

Figure 7: *The EMERALD Mission*

3.3 PEARL

The PEARL (Picosatellite Ejection and Reception of Lightning) missions consists of two 0.5 kg. ParaSat class picosatellites that are being developed for ejection by SSDL's OPAL microsatellite as depicted in Figure 8a. Each picosatellite will be packaged in a 3 in. x 3 in. x 1 in structure and is designed for a lifetime on the order of hours to days. The picosatellites and their mothership transponder will be developed for $10,000 within one year by an undergraduate SCREEM student team; the OPAL mothership and its picosatellite ejection system is being developed by a graduate SSDL student team. OPAL is currently being prepared for a 1999 launch with the JAWSAT spacecraft, which is being developed by the Air Force Academy and Weber State University.

Each picosatellite will house a VLF receiver in order to acquire the impulsive radio waves generated by thunderstorms. Baseline science processing will consist of these signals being time-tagged and rebroadcast via FM amateur radio. As shown in Figure 8c, an amateur radio repeater on OPAL will receive and broadcast these signals to the ground. With knowledge of satellite position, these broadcasts can be used to study thunderstorm intensity and location. Furthermore, the combined broadcasts can be analyzed to estimate VLF wavelength using a mothership/daughtership satellite architecture.

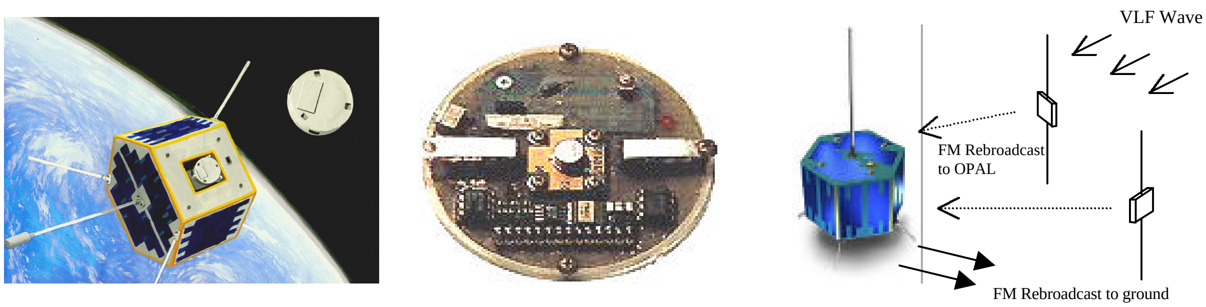
Development of a picosatellite capable of performing these functions, especially given the resource limitations, is by no means assured. Several key challenges exist and are currently being addressed through analysis and prototyping:

- The VLF receiver must be miniaturized.
- A GPS receiver CMOS chip capable of producing precision timing is being investigated for use. This chip is being developed by Stanford's Electrical Engineering Department.
- Physical separation via an extended boom may be necessary to reduce noise between the FM transmitter and the VLF receiver.
- Power management and operational policies are being traded to conserve picosatellite lifetime.

Doubling the picosatellite's size is being considered as a fallback option. Furthermore, if the project proves too challenging, a study of the limiting factors will be accomplished and used to drive SSDL and STARLAB initiatives in the future so that the mission can be attempted once again in approximately three years. If such a delay is necessary, the current picosatellite development team will redirect their efforts to produce picosatellites that demonstrate several MEMS components.

The picosatellite structure will most likely be composed of a plastic material. On the circuit boards; surface mount may be incorporated in order to conserve space. A single lithium ion cell phone battery is being considered for initial prototyping. Body mounted and fold-out solar panels using silicon cells are being prototyped for subsequent versions in order to extend mission life.

Both a digital circuit as well as a Motorola 6811 processor are being developed as picosatellite controller alternatives. A student engineered amateur radio transmitter is being designed and for data broadcasting. Passive magnetic stabilization, spin mechanisms, and simple gravity-gradient booms are being investigated for attitude control; it is worth noting, however, that the science mission can be accomplished with no stabilization. Passive thermal control techniques will be used. Figure 8b shows an early picosatellite prototype. PEARL addresses programmatic questions 5-11 and 13.



(a) Artist's depiction of an OPAL picosatellite launch [Courtesy Tillier]

(b) An early prototype picosatellite using a circular form factor

(c) The baseline mothership/daughtership configuration for science processing.

Figure 8: *The PEARL Mission*

3.4 Additional Future Missions

In addition to the three missions described in the preceding sections, two additional initiatives are being explored as part of this science program. The first involves adding a VLF receiver to the completed Santa Clara Barnacle microsatellite; several flight opportunities for this mission are currently being evaluated. The second involves building a new microsatellite with additional student teams from the University of Tokyo and Kyushu University as part of a collaborative program sponsored by the Japan-U.S. Science, Technology, and Space Applications Program. This mission, which would utilize the VLF receiver and possibly a camera, will compete for a NASDA sponsored secondary launch aboard the HII-A rocket.

4. MISSION OPERATIONS

The previously described satellite systems are only part of a comprehensive mission architecture required to fulfill the program goals. Considerable support systems are necessary to correlate science data, to manage mission products, and to maintain system health.

4.1 Science Data Processing

GOES, GMS, and Meteosat weather imagery, available directly via an SSDL weather satellite groundstation or indirectly through a NOAA link, is used to locate highly active thunderstorms for the purposes of observation planning. In addition, some of this imagery is used for post-pass data analysis.

Science data from the spacecraft, whether raw or processed on-board, is broadcast to the ground for correlation with a variety of ground-based systems such as:

- STARLAB's high resolution photometric systems which measure optical signatures above thunderstorm systems.
- STARLAB's ELF/VLF receivers which detect the lightning-radiated electrical impulses at locations such as Palmer Station, Antarctica.
- The Holographic Array for Ionospheric Lightning (HAIL) network, shown in Figure 9, which transmits and receives VLF signals in order to investigate thunderstorm phenomena over large distributed regions.
- The U.S. National Lightning Detection Network which uses tracks lightning strike locations and discharge parameters.

Science data is processed, summarized, and annotated with ephemeris, attitude, and geophysical parameters. The data is integrated with the evolving models of thunderstorm-related atmospheric interaction processes in order to meet programmatic science goals. Finally, raw and processed data products are archived in standard file formats and available to the public via the Internet with no proprietary data rights.

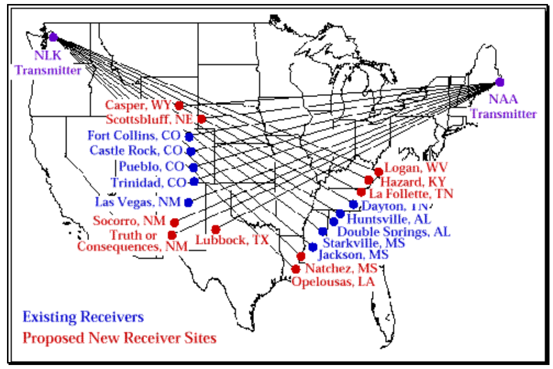


Figure 9: *The HAIL Network.*

4.2 Command and Control

On-orbit operations for each mission are conducted through the ASSET command and control network, which is depicted in Figure 10 [18]. The ASSET system, currently in development, consists of several globally distributed groundstations, radio and Internet-based communications links, a centralized mission control complex for managing mission operations, and a Web interface for Principal Investigator access to the system. This system uses automated techniques for producing mission products and managing system anomalies. A secondary mission of the program's spacecraft is to experimentally validate these techniques as enabling technologies for low cost, high quality, spacecraft operations.

5. PROGRAM MANAGEMENT

Several key aspects of the program's management strategy and structure are of particular interest.

5.1 Mission Robustness and Integration

In previous projects, SSDL and SCREEM have adopted a strategy of choosing missions and designs that are robust to uncontrollable parameters. For instance, previous missions relied on obtaining a launch on a rocket and to an orbit that were unknown

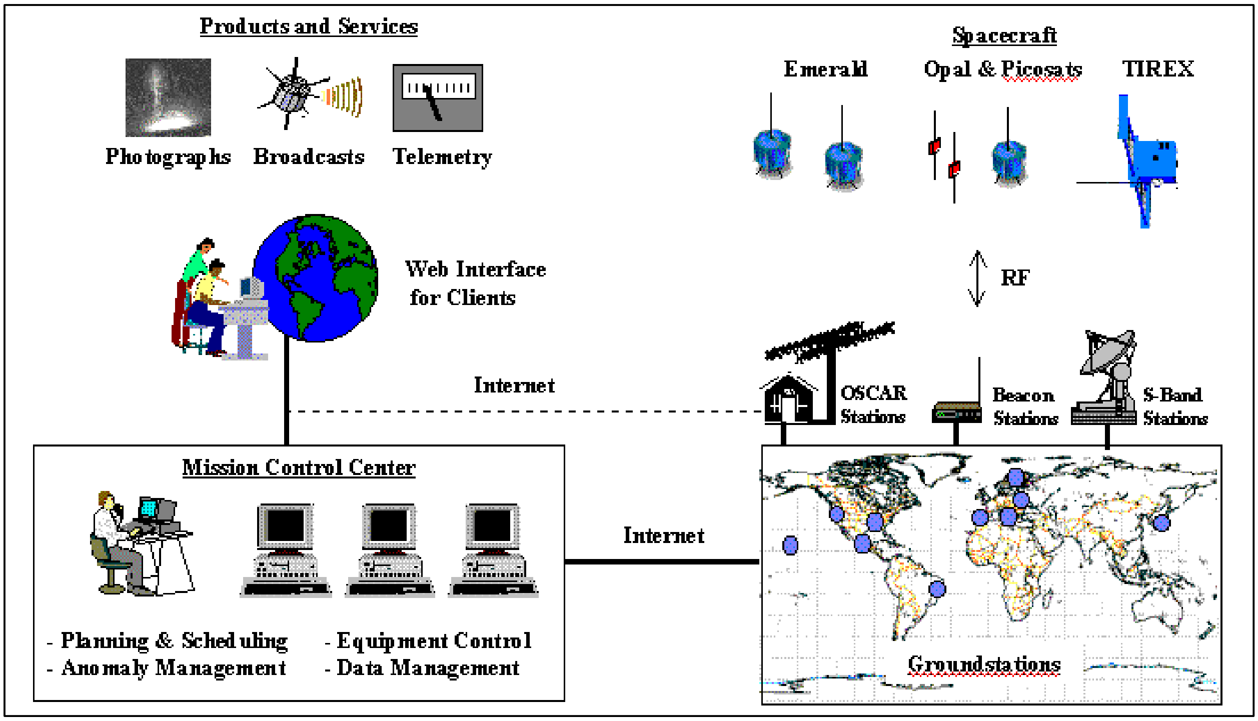


Figure 10: *The ASSET Command and Control Network*

at design time. Accordingly, the structure was designed to accommodate numerous rockets, and the mission was chosen so that it was largely insensitive to the orbit. This approach will continue and will be matured with the new spacecraft.

Because a variety of component validation experiments will be included as secondary missions on each vehicle, a rational policy is evolving concerning their selection and integration. For example, excellent choices for secondary payloads include components that could replace baseline bus equipment (such as an experimental lithium ion battery instead of the standard SQUIRT Ni-Cad battery) and which have a reasonable expectation for short term survival. Other good choices include systems that can enhance the baseline science mission (such as thrusters, which may enable relative station-keeping on the EMERALD mission). On the other hand, SSDL receives many offers to fly components that use exciting technologies but that cannot be leveraged by the baseline mission; these payload choices receive a lower priority for consideration.

Related to this is the development of a policy for adjusting the mission scope in response to variable resources and delays/advances in the schedule. This is being done by formally specifying the baseline "minimum" mission, the ideal "maximum" mission, and a variety of discrete levels of mission accomplishment in between. Using EMERALD as an example, the minimum science mission is to simply time-tag and re-broadcast the received VLF signal to the ground using low quality ground ephemeris for spacecraft position determination. A more advanced level is to incorporate on-board GPS data for precision position data. Even more advanced is to incorporate thrusters to control relative positioning. The EMERALD spacecraft teams are responsible for delivering systems capable of at least the minimum mission. While the maximum mission is an exciting goal, the team leaders will have the authority to shift the mission between levels given the available resources and contingent on a rational defense of their decisions.

Furthermore, as secondary payloads are incorporated, mission levels are structured to permit technology validation both in isolation as well as in cooperation with other payloads. Using the EMERALD thruster example, the thruster experiment has been designed to permit its accomplishment alone and as a component in formation flying based science. Similarly, the science experiment has been designed to permit its accomplishment alone and in an enhanced mode involving position control. Therefore, each experiment can be minimally performed with or without the other; this limits the impact of missed deliveries and on-orbit failures.

5.2 Resources and Schedule

For past SSDL and SCREEM spacecraft, only rough accounting has been performed in order to assess the resources required to produce student-engineered satellites. This effort is being significantly enhanced through line-item tracking and weekly reports in order to improve characterization of these quantities. This data will eventually contribute to the formulation of an SSDL spacecraft cost model.

Careful resource tracking between the two nearly identical EMERALD spacecraft teams will allow evaluation of the impact of small, controlled differences in management and process methodologies. Similarly, resource comparisons across TIREX, EMERALD, and PEARL will capture the effects of varying approaches to supporting a constant science theme.

The missions are currently being developed in parallel. TIREX is a four year project involving a large student team with representation from all scholastic levels and requires significant support from university staff and external contractors. TIREX instrumentation and mission support systems are currently in development. EMERALD is a two year project involving two SSDL/SCREEM graduate/undergraduate teams of about 10 students each. Technology prototyping for this mission includes the development of microthrusters, inter-satellite communication, and the GPS-based relative positioning system. PEARL is a one year project involving one SCREEM undergraduate team of 7 students. This team is currently building a basic picosatellite prototype and is researching crucial science mission technologies such as chip-based GPS and VLF receivers. Figure 11 presents the parallel development schedules.

```
                 1998     1999     2000     2001     2002
                 1 2 3 4  1 2 3 4  1 2 3 4  1 2 3 4  1 2 3 4
Program Def.     ----------
TIREX
  Concept/Proto   ----------------
  Development                 --------------------------
  Launch & Ops                                        ------------
EMERALD
  Concept/Proto      -----------
  Development                  ------------------------
  Launch & Ops                                       ------
PEARL
  Concept/Proto       ----
  Development           -----------
  Launch & Ops                     --
  Follow-on                                            ----------------
```

Figure 11: *Program Timeline.*

6. CONCLUSIONS

The multi-satellite atmospheric science program described in this paper is a truly ground-breaking initiative being undertaken by Stanford's SSDL and Santa Clara University's SCREEM laboratories. New, unprecedented data concerning the effects of thunderstorms on the Earth's mesosphere and ionosphere will be collected in order to provide insight to the electrodynamic mechanisms at work. The relevance of this investigation is underscored by the National Research Council's recommendation to 1) collect detailed measurements of thunderstorm-related effects leading to charge movement, and 2) further understanding of the electrical coupling between atmospheric regions [19].

In addition, this program permits SSDL to advance the understanding of small satellite technologies and strategies in performing simple, low cost, rapidly developed, high quality missions. Specific resource accounting will allow the competitive characterization of university-based space programs and the comparative analysis of process and technology innovations. The integration of advanced spacecraft technologies ranging from the component level (i.e. MEMS) to the inter-satellite level (i.e. on-board relative positioning) will validate systems and capabilities that are vital to the future of the small satellite industry. In addition, this program will enable an unprecedented comparative case study using a common science theme as a backdrop for 1) examining the capabilities and limitations of spacecraft of varying size, and 2) exploring the costs and benefits of single, mother/daughter, and collaborative spacecraft architectures.

Educationally, this student-oriented multi-satellite program allows SSDL to strengthen its current involvement with graduate and undergraduate students while also introducing 1) an associated, comprehensive science education program, and 2) exciting, project-based, hands-on engineering projects to vocational and secondary school students. The program also takes advantage of the diversity provided by a leading national research university, a top regional undergraduate institution, and an inter-city, primarily minority secondary school district.

Overall, this program provides a coherent, comprehensive strategy for advancing scientific knowledge, contributing to the evolution of the small satellite industry, and enhancing the education of future engineers.

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8. AUTHOR BIOGRAPHY

Christopher Kitts is a graduate student in Stanford University's Space Systems Development Laboratory where he is completing his dissertation on model-based mission operation systems. As part of his laboratory activities, he leads several small satellite development programs at Stanford University and Santa Clara University. With respect to the program presented in this paper, he is the operations manager for TIREX and the program manager for EMERALD, PEARL, and the TIREX student payload; he also leads development of the global ASSET mission operations system.

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