

# Collaborative Research/Cubesat: Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics (FIREBIRD)

A Collaborative Proposal to NSF from  
Boston University  
Montana State University



The FIREBIRD mission (Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics) is a targeted, goal-directed, space weather Cubesat mission to resolve the spatial scale size and energy dependence of electron microbursts in the Van Allen radiation belts. Relativistic electron microbursts appear as short durations of intense electron precipitation measured by particle detectors on low altitude spacecraft, seen when their orbits cross magnetic field lines which thread the outer radiation belt. Previous spacecraft missions (e.g., SAMPEX) have quantified important aspects of microburst properties (e.g., occurrence probabilities), however, some crucial properties (i.e., spatial scale) remain elusive owing to the space-time ambiguity inherent to single spacecraft missions. While microbursts are thought to be a significant loss mechanism for relativistic electrons, they remain poorly understood, thus rendering space weather models of Earth's radiation belts incomplete. FIREBIRD's unique two-point, focused observations at low altitudes, that fully exploit the capabilities of the Cubesat platform, will answer three fundamental scientific questions with space weather implications: What is the spatial scale size of an individual microburst?; What is the energy dependence of an individual microburst?; and How much total electron loss from the radiation belts do microbursts produce globally?

Intellectual Merit: In addition to revealing the energy spectra of microbursts (which contain information on the very physical processes producing them) FIREBIRD resolves microburst spatial and temporal scales by measuring electron precipitation at several energies on two identical spacecraft, co-orbiting with a small in-track separation. One candidate production mechanism of microbursts is whistler-mode chorus in the equatorial region of the outer radiation belt; size-scales of chorus waves are well-constrained in the magnetospheric source region. The two-spacecraft FIREBIRD mission in low-Earth orbit will explore, characterize, and compare the spatial scale of microbursts, the possible low-altitude manifestation of chorus scattering regions, to assess a physical connection. Some researchers argue that microbursts can explain all electron losses in the radiation belt, however there are other mechanisms believed to cause radiation belt electron losses, such as EMIC waves, outward radial diffusion to the magnetopause, and loss of adiabaticity on stretched magnetic field lines. FIREBIRD will isolate and quantify the characteristics of microbursts and establish their relative importance to global radiation belt dynamics.

FIREBIRD employs a heritage sensor design based on a single large-geometry-factor, solid-state detector on each of the two spacecraft, sensitive to electrons precipitating from the radiation belts. These measurements not only provide data useful for space weather assessment, but also produce understanding for improved space weather prediction models, thereby yielding an even larger impact. FIREBIRD's design provides maximum science return on the three focused questions while remaining low risk with a high probability of success. We combine an established science team possessing significant expertise in microbursts, radiation belt physics, and charged particle detection with teams highly experienced in relevant Cubesat satellite engineering, management, and mission implementation.

FIREBIRD's scientific niche complements NASA's Radiation Belt Storm Probes (RBSP) and Balloon Array for RBSP Relativistic Electron Losses (BARREL) missions. RBSP and BARREL are targeted at different aspects of the radiation belt system and thus cannot answer FIREBIRD's three targeted questions. While the science goals of RBSP and BARREL are indeed noteworthy, FIREBIRD's focused science goals, too, represent another "next logical step" in radiation belt physics. FIREBIRD does not merely repeat a measurement made earlier by sophisticated instruments on more capable satellites. Rather, FIREBIRD provides transformational science on microbursts otherwise unattainable through existing or previous spacecraft and unobtainable from ground observations. The mission thus embodies the Cubesat ideal: high science return provided at low cost through focused and novel investigation of an unexplored yet important phenomenon in a region easily accessed by nanosatellites.

Broader Impacts: In addition to addressing fundamental space physics research and space weather applications, the FIREBIRD investigation also contributes to the training and education of a diverse population of university students in all phases of the project. Students will have major responsibility for the design and implementation of the instruments and the spacecraft while at the same time being mentored by professionals in each expert area. The impact is that the fruits of this investigation will continue strongly for years, if not decades, as the twenty or more students who "cut their teeth" on this science mission become practicing scientists and engineers.

## 1. Science objectives and planned measurements

There are four major candidate processes for losses of relativistic electrons from the outer radiation belt [see review by Millan and Thorne, 2007]: wave-particle interactions with whistler-mode chorus, wave-particle interactions with electromagnetic ion-cyclotron (EMIC) waves, outward radial diffusion to the magnetopause, and loss of adiabaticity on stretched magnetic field lines. Of these, chorus and radial diffusion have also been identified as possible acceleration mechanisms. We propose to further investigate the role of whistler-mode chorus, by examining the microburst electron precipitation phenomenon attributed to chorus. We do so because microbursts are thought to be a hallmark of rapid radiation belt losses, possibly removing the entire pre-storm outer zone in a single day [Lorentzen 2001b; O'Brien et al., 2004], yet they are also intimately tied to in-situ acceleration mechanisms [O'Brien et al., 2003; 2004; Horne and Thorne, 2003; Bortnik and Thorne, 2007]. Thus, a better characterization of the chorus-microburst interaction will provide direct insight into both acceleration and loss processes in the outer belt. The broad scientific question FIREBIRD will address is: What is the role of microburst electron precipitation in radiation belt dynamics?

Before we delve into the science to be investigated, it is important for the reader to have a minimum understanding of the FIREBIRD mission. FIREBIRD consists of two 1.5U (10 x 10 x 15 cm) Cubesats placed into a common, inclined, low-Earth orbit (LEO), for a 120 day mission. Each Cubesat will have a large geometric factor, solid-state detector capable of measuring multiple electron energy channels from 30 keV to 3 MeV, with 100 msec time resolution. Telemetry constraints limit the downlink of no more than 3 energy channels at any given time, but the channels can be reconfigured while in-flight for different studies. Using a spring separation mechanism, the relative inter-spacecraft distance will extend up to a few-tens of km over the 120-day mission. As we will see, this mission is designed to examine the spatial and energy coherence lengths of microbursts, key quantities heretofore unmeasured or obtainable on any missions presently in development.

Quantitative estimates of radiation belt electron precipitation loss require knowledge of the size of the microburst loss region. Single satellites are inherently incapable of distinguishing spatial variability from temporal dynamics. Simultaneous dual measurements provided by the twin FIREBIRD satellites will permit, for the first time, the determination of spatial scales of single microburst events. Along with three-point, energy-resolved spectra, these measurements will provide the critically needed answers on the radiation belt loss rate and will quantify the crucial role that microbursts probably play. This critical issue remains unanswered even after 16-years of operation of NASA's single SAMPEX satellite.

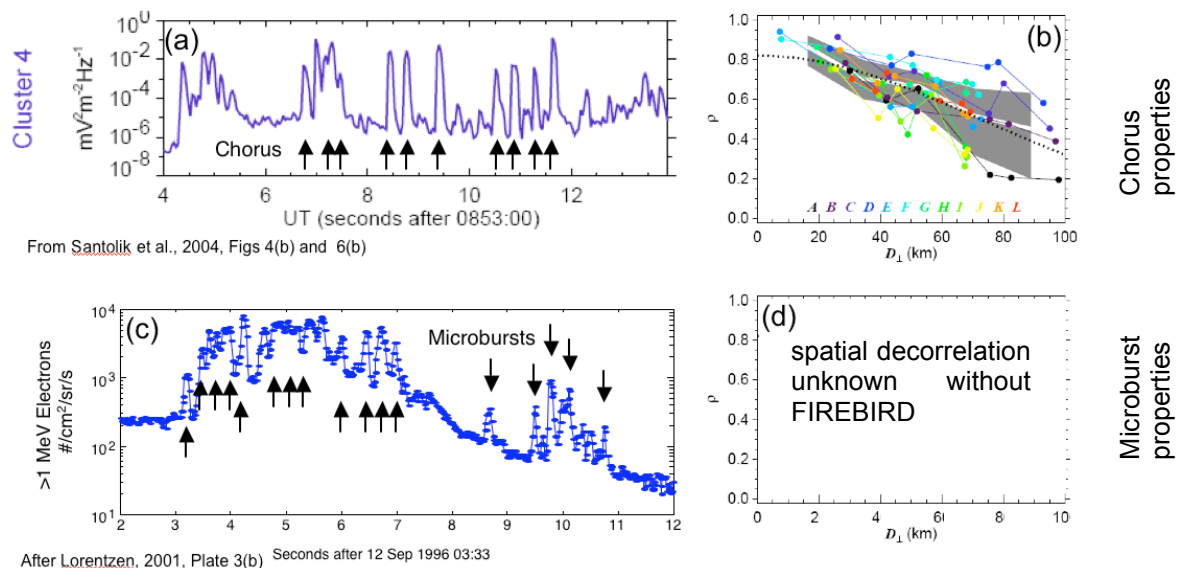
Relativistic electron microbursts have been associated with whistler-mode chorus [Lorentzen et al., 2001a] based on their similar temporal and spatial signatures, correlated wave observations, and theoretical considerations. However, to date, the association with chorus and the impact on the radiation belts remain unconstrained due to limitations on past observations of microbursts. In this regard, there are three critical questions about relativistic electron microbursts that FIREBIRD can answer:

- 1) What is the spatial scale size of an individual burst?
- 2) What is the energy dependence of an individual burst?
- 3) How much total electron loss do bursts produce globally?

Questions 1 and 2 constrain the physical process that generates relativistic electron microbursts, and Question 3 quantifies its geoeffectiveness and overall space weather impact. Questions 1 and 2 are entirely within the capabilities of our proposed twin Cubesat mission with multiple energy channels and spatial in-track separations of a few-tens of km. Question 3 requires cross-track separations of multiple hours of MLT on the dawn side, which is not possible within the resources available for the FIREBIRD mission alone. However, FIREBIRD would be able to answer Question 3 with the aid of other current and planned LEO assets (e.g., SAMPEX [Baker et al. 1993]) or high altitude balloons (e.g., a test flight of

BARREL [Millan, 2006], or some other dedicated balloon campaign). We describe these three questions next.

**Question 1 – Spatial Scale Size:** Using 4 Cluster spacecraft in the magnetosphere, Santolik and Gurnett [2003] and Santolik et al. [2004] found scale sizes for the source region of coherent chorus emissions of 60-200 km. Depending on the geometry of such emissions, they map to as little as a few to tens of km at LEO. Figure 1 shows the comparison of chorus to microbursts in the time domain and the missing pre-FIREBIRD spatial analysis. The twin FIREBIRD mission will establish the scale length at LEO of coherent microbursts, which can be directly compared to the projected chorus source region size. To date, only high altitude balloon missions have been able to provide simultaneous multi-point measurements of microbursts [Sample et al. 2003]. Balloons have different strengths relative to LEO platforms: Balloons sit and stare, giving temporal variation without spatial aliasing, but the Bremsstrahlung response cannot often be inverted to provide a detailed energy spectrum. Balloon-borne platforms respond to Bremsstrahlung covering a spatial scale that approximates nearly 2-pi field-of-view above the balloon. The scale is far too broad to define the spatial extent of individual structure within microbursts. On the other hand, single LEO vehicles move quickly, sampling a large spatial region, but with inherent spatio-temporal aliasing. In addition, LEO vehicles can directly measure electron energy with high resolution. Thus, a two-spacecraft LEO mission improves on the advantages of past LEO observations, with some of the additional advantages of a balloon mission. **Answering Question 1 requires two FIREBIRD spacecraft.**



**Figure 1** (a) typical series of chorus risers at  $\sim 0.5 f_{ce}$  on 18 April 2002; (b) decorrelation with Cluster's 4-s/c separations used by Santolik et al. [2003] to estimate chorus source region scale size; (c) typical series of microbursts on different date; clear similarity between chorus and microburst signatures; (d) spatial analysis needed to establish correlation lengths of microburst source regions.

**Question 2 – Energy Dependence:** Microbursts at  $>150$  keV and  $>1$  MeV electrons on SAMPEX showed occasional, but not systematic correlation (see Figure 2 top). STSAT-1 data [Lee et al., 2005] showed systematic correlation from 170-360 keV, as in Figure 2, bottom. So, the typical energy scale length is likely larger than 190 keV and smaller than 850 keV. It is also possible that there is a cutoff energy that separates two distinct families of microbursts. The location of resonance with chorus should move systematically up a magnetic field line with energy (higher resonant energy at higher latitude) [Lorentzen et al, 2001a; Horne and Thorne 2003]. Thus, the absence of microbursts at high energy but not at low, or vice versa, would indicate reflection or deflection of chorus from one field line to another [see, e.g., Bortnik and Thorne, 2007; Bortnik et al., 2007]. FIREBIRD energy range and resolution will be superior to

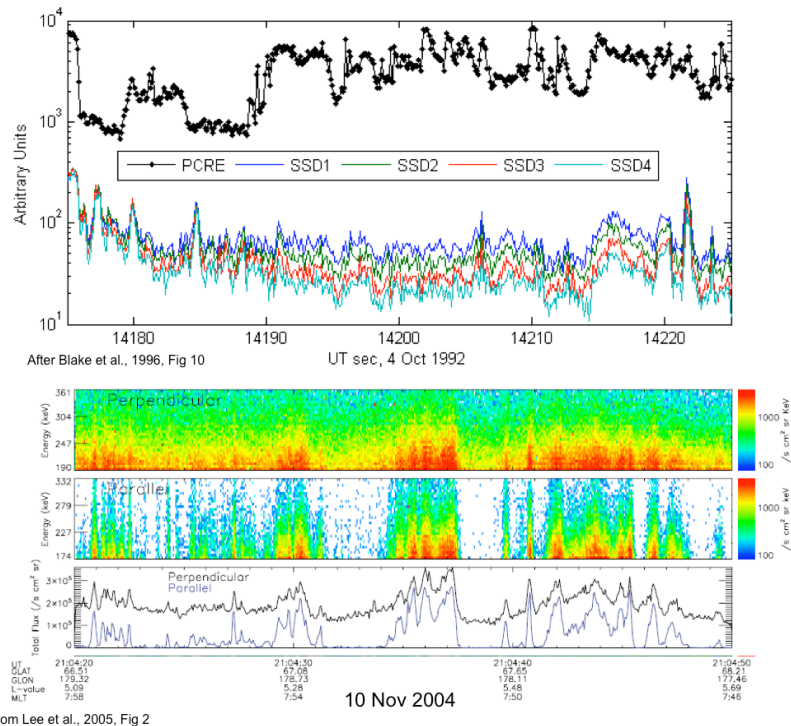
balloons, SAMPEX, and STSAT-1, allowing a first-of-a-kind investigation of the energy coherence scale of microbursts. **Question 2 can be answered with even a single FIREBIRD spacecraft.**

**Question 3 – Electron Loss:** When estimating the geophysical impact of microbursts, Lorentzen et al. [2001b] and O'Brien et al. [2004] had to estimate the L and MLT extent of the precipitation. Since the inferred global microburst loss rate was comparable to the total estimated belt content, even a factor of 2 error leads to the ambiguity between a single loss process (microbursts) being sufficient, versus multiple processes (e.g., microbursts plus EMIC wave-induced scattering). FIREBIRD's reconfigurable energy range and resolution allows for fairly precisely tuned complementary energy channels for coordinated multipoint measurements with other missions. To fully answer Question 3 we need concurrent LEO measurements in addition to the FIREBIRD mission but we expect to make significant progress even with FIREBIRD alone.

In summary, the FIREBIRD mission makes first-of-a-kind multipoint, energy-resolved measurements of relativistic electron microbursts. These observations provide new constraints on the wave-particle interaction with whistler-mode chorus that is thought to be the cause of microbursts. Such a wave-particle interaction is also thought to play a dual role in acceleration and loss of radiation belt relativistic electrons. FIREBIRD represents a unique, economical method to constrain observationally a fundamental physical process that likely plays a major role in outer radiation belt dynamics, a National Space Weather priority. The tiered scientific questions and number and quality of measurements required demonstrate the significant robustness and low risk of FIREBIRD, providing high science return with a mission that degrades gracefully.

## 2. Relevance to current space weather research goals

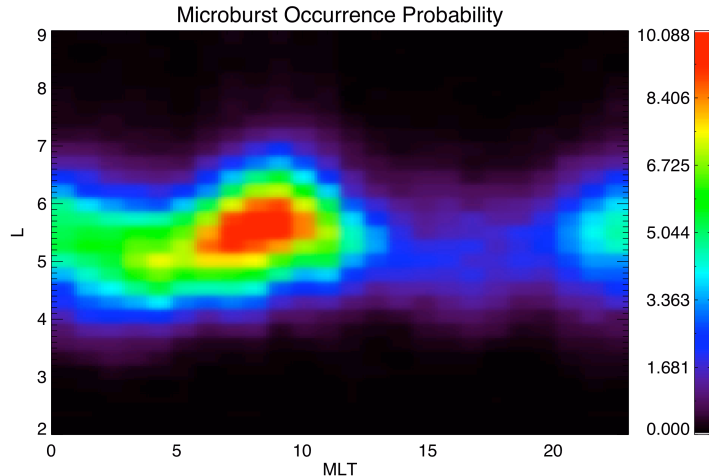
In July 2000, the National Space Weather Program (NSWP) Council released the second edition of “The National Space Weather Program Implementation Plan” [Williamson et al. 2000]. That interagency council, with significant leadership from the NSF and partner agencies, identified those “natural conditions in the space environment that may have an impact on technical systems and human life or health”. Within this overall program scope, the Implementation Plan further identified energetic electrons in Earth's radiation belts as a major source of space weather effects on satellite systems, including but not limited to deep dielectric discharge phenomena and energetic particles in general as a radiation risk to manned spaceflight at high altitudes. These space weather threats were identified more specifically in Appendix A of the Implementation Plan. Namely, for Earth's magnetospheric radiation belts, “the research objective is to understand the transport, production, and **loss processes that determine the intensity of radiation belt particles** in both quiet and storm times.” The FIREBIRD mission specifically targets a key



**Figure 2** The top panel shows an example of the lack of one-to-one correspondence between microbursts observed in the >150 keV (PCRE) channel and in the >1 MeV (SSD) channels on SAMPEX/HILT. The bottom panels show strong microburst correlation across the ~170~360 keV range from STSAT-1.



loss process, electron microbursts in a way that will not be addressed by other upcoming and larger radiation belt projects. FIREBIRD provides measurements required to answer the key questions posed in Section 1 and thus contributes significantly to the understanding needed to develop predictive space weather models of the radiation belt environment. Furthermore, FIREBIRD's discoveries will engage dozens of student engineers and scientists in a significant way at all phases of the project, thus empowering a new generation of professionals imbued with the practical values of space weather research, another goal of the NSWP.

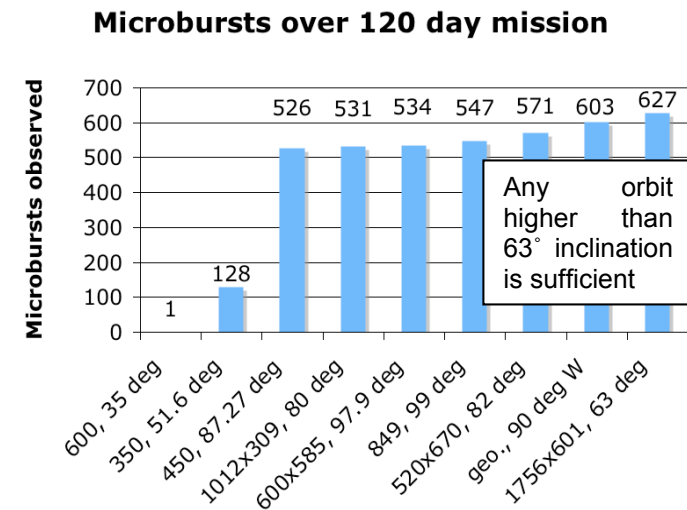


**Figure 3** Microburst occurrence probability extended from O'Brien et al [2003] to cover 1996 to 2005.

### 3. Orbital requirements and impact

Microburst occurrence probability has been characterized using more than a solar cycle of single-satellite SAMPEX data. This characterization enables the FIREBIRD mission to be targeted in local time and location to maximize science return and reduce measurement risk. We find that a large number of justifiably possible orbits that will accomplish the mission. Shown in Figure 3 is the microburst occurrence probability over all geomagnetic conditions ordered by L and MLT as found by O'Brien et al [2003]. Microbursts primarily occur from 5-12 MLT and between L=5-7.

As microburst probability peaks in the post-dawn sector, any orbit that passes through the post-dawn sector and traverses the needed values of L is sufficient for FIREBIRD. Upon folding together orbit probability and microburst probability the number of detectable microbursts expected was derived for a variety of orbits over a four-month mission. Our analysis shows that FIREBIRD mission science is not strongly tied to any particular orbit. Figure 4 shows the expected microburst counts for a variety of different orbits. Any orbit with an inclination higher than 63° that passes through the post-dawn sector will have sufficient microburst coverage (many hundreds of events during the mission). A sun-synchronous orbit that passes through dawn will have uneven MLT coverage over the 120-day mission but will fulfill all FIREBIRD measurement goals while allowing for a closer focus on an important range of MLT. Conversely a non-sun-synchronous orbit has more uniform MLT coverage allowing for studies of MLT dependence. **In sum, FIREBIRD will succeed in any LEO orbit that provides lifetime against orbital decay of >120 days, and an inclination of greater than 63 degrees.**



**Figure 4** Summary of the number of microburst events expected for each of several select possible orbits, any orbit of higher inclination than 63 degrees is sufficient. The orbits are defines by altitude and inclination, for example 600, 35 deg is a 600 km 35 degree inclination orbit.

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Key to the full scientific success of FIREBIRD are simultaneous 2-point closely-

spaced measurements of individual microburst regions to probe their spatial extent. To accomplish this, satellite separations must remain within the probative scale-sizes of anticipated microburst footprints during the 120-day mission. Propulsion for station keeping is not required. The FIREBIRD twins are ejected simultaneously from a single P-Pod. The P-Pod spring-plate ejection mechanism imparts the same ejection velocity to each spacecraft. Without further deliberate action the two satellites would only drift apart very slowly, if at all. In normal Cubesat ejections of unrelated satellites, foot-springs built into each Cubesat provide a push-off from neighboring spacecraft. This provides a relative velocity between the cubes for separation to assure no interference between the unrelated cubes. Normally these springs are chosen to provide up to 5 cm/sec relative separation velocities [Cousins, 2008]. In the case of the twin FIREBIRD satellites we achieve a finite, but well-controlled relative separation rate by careful choice of the spring constant for the separation springs that impart this differential velocity and by controlling the frictional drag between the satellites and the P-POD rails. The foot springs will be chosen to provide a relative separation velocity of 3 cm/sec, so that the inter-satellite separation over the course of the 120-day mission does not exceed 300 km. We chose this number by mapping the extent of chorus regions detected near the equator as reported by Santolik and Gurnett [2003] and Santolik et al. [2003] to the low altitude FIREBIRD orbit along magnetic field lines. Since the inter-satellite separation distance will grow linearly with time, if we have underestimated the size of the microburst footprints, an extension of the mission operations will provide ever-increasing separations, all of high scientific interest and of discovery class.

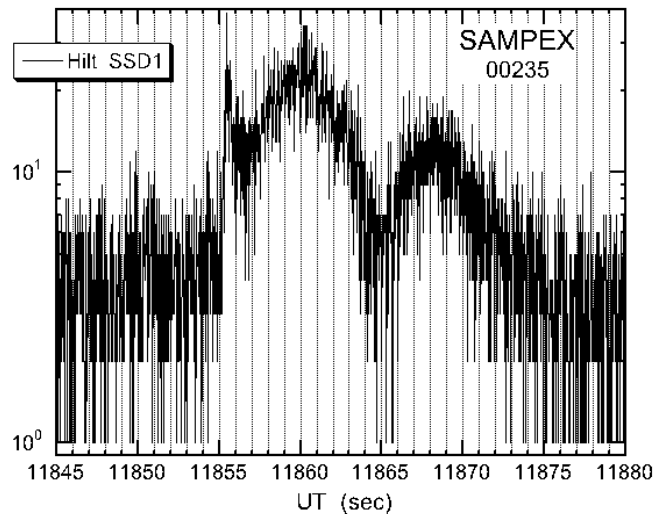
#### 4. Technical approach

##### 4.1. *Technical approach of the instrument*

The FIREBIRD instrument is designed to be simple to achieve focused science goals with limited risk. The instrument itself is simplified so that it requires no data processing unit (DPU) or FPGA of its own, all processing is accomplished by the central FIREBIRD computer. This is primarily a power saving feature but also simplifies the sensor development allowing the Boston University (BU)/Aerospace Corporation sensor team to focus on the sensor and the Montana State University (MSU) spacecraft team to focus on the spacecraft, both developing to a well defined, common interface.

The instrument has three integral energy channels that will be fed into a counting and timing interface board on the spacecraft (see Section 4.2.5). The discriminator voltage, and hence the energy range, can be changed on-orbit to allow for optimization of the energy measurements to accomplish the mission science goals. The nominal energy channels are >300 keV, >500 keV, and >700 keV.

The inherently power limited Cubesat does not allow for high-speed data downlink. FIREBIRD's relatively low downlink rate (9600 baud) requires a selection scheme to be implemented in order to optimize data collection in most probable microburst regions (independently on both spacecraft). This will be accomplished by implementing a large onboard storage at full time resolution. Regions of interest will then be flagged on the ground and the data subsequently requested from the spacecraft for those time periods. This scheme allows for a "smart" ground system to interact with a simple on-orbit system further reducing spacecraft complexity and minimizing measurement risk. The regions of interest are identified



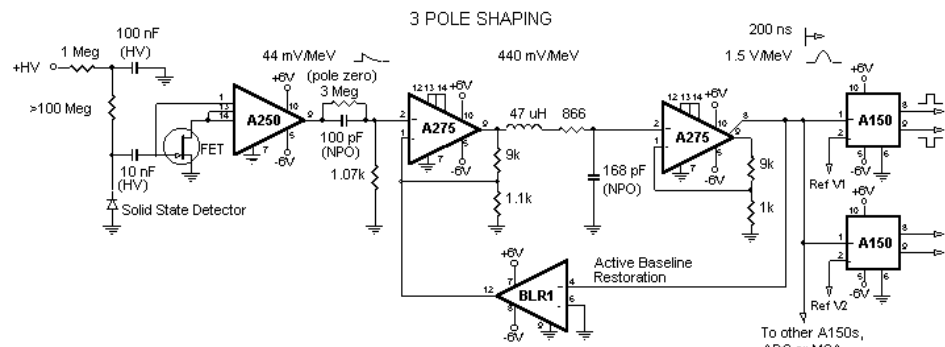
**Figure 5** SAMPEX-HILT high-resolution microburst measurements. Notice the significant spread due to low count rates.

first by regions of high microburst probability then regions where summary data sent to the ground show possible microbursts.

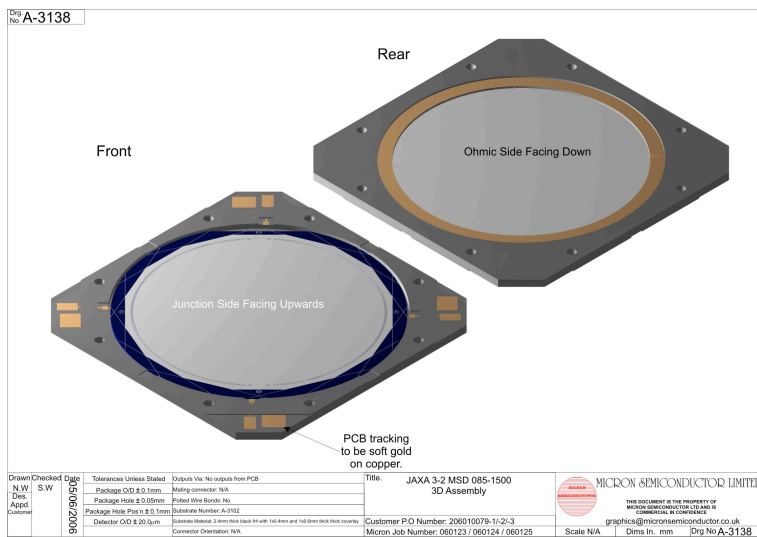
In order to achieve the scientific goals, a large geometry factor (GF) charged particle sensor is required. Shown in Figure 5 is a time series from SAMPEX-HILT illustrating the need for a large geometry factor. The shortest time variability in the data is a consequence of the counting statistics limiting the HILT time resolution however two broad microburst pulses at rates  $\geq 10^1$ /sample are easily seen. To answer the FIREBIRD science questions more counts per unit time are needed to better resolve structure within a single microburst. HILT has a GF of  $60 \text{ cm}^2\text{sr}$  [Klecker et al. 1993] while FIREBIRD, with its 85 mm diameter detectors has nearly 6 times the geometry factor, at  $356 \text{ cm}^2\text{sr}$ , allowing for a high time resolution (20 msec) measurement with good counting statistics. An instrument without a large geometry factor like the one based on FIREBIRD will not significantly add to the scientific understanding of microbursts due to poor counting statistics.

The FIREBIRD sensor is a heritage design based very closely on team experience from POLAR/IPS [Blake et al., 1995], LRO/CRaTER [Spence et al., 2009], and two current NASA spaceflight instrument projects involving an ongoing BU/Aerospace partnership on RBSP/ECT and MMS/EPD. FIREBIRD's instrument development is led at BU with a professional and student team.

The Aerospace Corporation is a collaborating institution and provides technical and scientific expertise to the program. Students have opportunities under existing summer internship programs to spend summers at Aerospace working on various projects. One BU graduate student, Alex Crew, already spent one summer at Aerospace (2008) and will be going back this summer also to work on RBSP instrumentation and microburst physics. There is significant interest at Aerospace in radiation belt physics and models, deep professional experience in similar instruments, and significant laboratory capabilities, making this a natural partnership with BU.



**Figure 6** Schematic of the detector pulse shaping circuitry to be used for FIREBIRD. Image from Amptek website, [www.amptek.com](http://www.amptek.com).

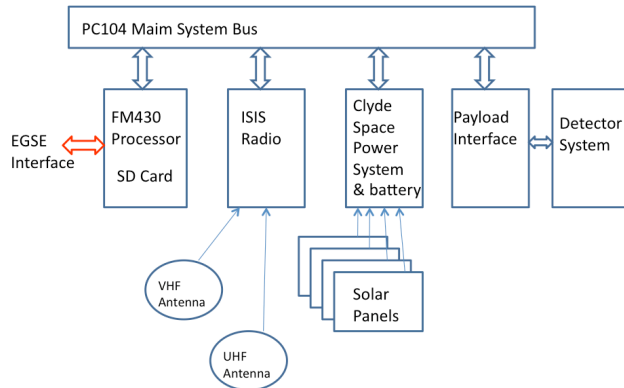


**Figure 7** Schematic of detector and housing. These off-the-shelf detectors are directly applicable to FIREBIRD.

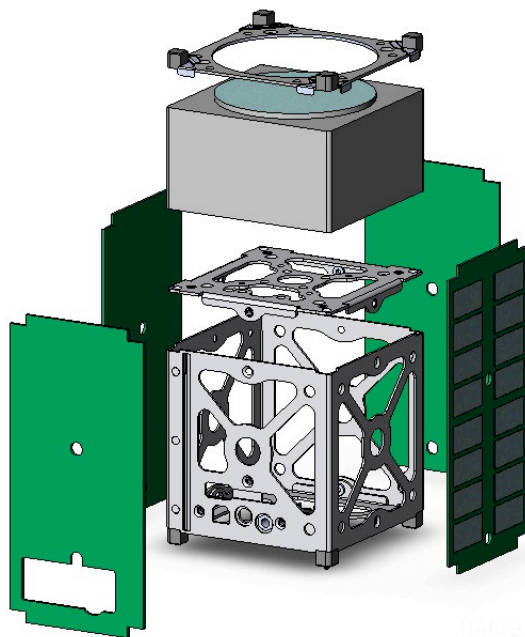


spacecraft. Shown in Figure 6 is a schematic of the detector chain to be used on FIREBIRD. This heritage is a major advantage to a program of this scope, as it simplifies the development allowing for efforts to be focused on the details that make an instrument great; calibration and characterization. Boston University professionals and students will elad the design of the sensor system, supported by Aerospace through student summer programs and collaborative consultancy.

FIREBIRD detectors are off-the-shelf items from Micron Semiconductor Limited. The silicon, ion-implanted detectors were developed for a Japanese JAXA mission and meet FIREBIRD requirements. Flight detectors will be procured with no NRE cost to the project, thus providing for detectors that are of high scientific quality and cost effective. The detector active area (85 mm diameter) provides for a sufficiently large geometric factor while the detector thickness (1500 microns) permits sufficient depth to collect up to ~5 MeV electrons. The low energy threshold will be established early in the development and is set by the front detector window required to make the sensor light tight. Shown in Figure 7 is a solid model rendering of the detectors for the JAXA mission from the Micron Semiconductor catalog; only minor modifications to the housing will be required for FIREBIRD. The detectors require a bias of ~300 V, a voltage easily attained within Cubesat resources.



**Figure 8** FIREBIRD electronics block diagram showing all the system components.



**Figure 9** Solid model of the FIREBIRD spacecraft. The instrument is housed within the top 5cm of the stack in its own structural element. The other spacecraft subsystems are all housed within the 10cm cubesat on the bottom.

The sensor/spacecraft interface is designed to be as simple as possible. Mechanically the instrument and all associated electronics will be contained in a 1/2U (10x10x5 cm) section of the spacecraft that will then be attached to the main satellite bus. There will be an interface board to convert signal voltages and to mate to the PC-104 stack of spacecraft boards. This simple interface allows for the interconnection to be defined in a technical interchange meeting between BU and MSU very early in development. Electrically the instrument will require regulated 5 V, 3.3 V, and the unregulated 8.2 V battery bus. Conversions will take place inside the instrument to provide the high voltage and -5 V required by the sensor electronics. Commanding signals will be passed to the instrument electronics via an I2C bus. This bus will directly control the high voltage, the discriminator settings, and gather housekeeping data. The particle count signals will be passed to the interface board as digital pulses where they will be counted, binned, and passed to the computer for storage and downlink, (see Figure 8 for a diagram of this interface).

#### 4.2. Technical approach of the s/c

Our technical approach to the spacecraft derives from direct experiences in the implementation of Cubesat-class satellites for space weather applications. MSU's Space Science and Engineering Laboratory (SSEL) has

been designing, building, and launching Cubesats carrying space radiation detectors since 2001. We have developed intimate familiarity with the limited capabilities that the Cubesat platform is capable of supporting. The approach to our previous Cubesat developments has been to undertake the complete design and development of the entire satellite and its subsystems, maximizing the educational value accruing to both engineering and science students. These previous Cubesat-class projects have placed technical training value as the highest programmatic priority. Starting with a nearly clean slate students apply their creative talents to the development of each subsystem through orderly flow down from the top level mission statement, to the mission requirements, leading, ultimately, to the engineering implementation. In this tedious process, carried out at the component level where the printed circuit boards are designed, layed out, and populated in house, the students innovate and create novel solutions to the difficult task of developing an entire functioning satellite in a very small package. This creative process, under which each subsystem element is designed from “scratch” requires significant time to result in a flight article; in our experience four years, or more.

For the present investigation, driven by the increased importance of and need for high scientific value in limited development time, we intend to depart from this design-from-scratch approach while retaining much of the educational value that the student team accrues. Spacecraft support subsystem modules, fully designed and commercially manufactured under controlled standards by specialist companies will be selected, procured, and integrated by the FIREBIRD team. Through increased use of flight-proven subsystems, where practical, our development efforts for the FIREBIRD mission put greater emphasis on returning high quality, well-calibrated scientifically valuable data. By using high-heritage, high-TRL support subsystems our student development teams will focus on requirements flow down, subsystem level specifications development, and in-house integration and rigorous testing to implement an engineering solution that assures enhanced emphasis on mission success and system reliability, while providing significant educational opportunities in design, integration and test, systems engineering, program management, and satellite operations.

Figure 8 shows a block diagram for one of the Firebird satellites. Figure 9 shows a mechanical layout of a FIREBIRD satellite showing how the functional modules will stack together. The design of the S/C bus will be based on commercially available modules designed to the Cubesat architecture by Pumpkin, Inc, a commercial specialist in Cubesat subsystems.

For the newly developed electronics, the FIREBIRD payload and payload to satellite interface, we will use a phased approach. This starts with a Breadboard built early in the program to verify the design functionality. The breadboard is built for accessibility and will not have the correct form factor. Then we will build an engineering model (EM) of a complete FIREBIRD spacecraft. This EM will be form, fit and function equivalent to the flight model but will not be built to flight workmanship standards. The EM will be used as a pathfinder to develop the process, procedures and tests for the flight models. Finally the two flight model spacecraft, and a fully qualified flight spare will be built and tested.

#### **4.2.1. Structure Subsystem**

The structure subsystem must support the Cubesat during launch loads, including the compressive load of the P-Pod, and must accommodate separation springs and kill switches (i.e. power interrupts). It must support solar arrays and any externally attached subsystems. Its component elements must be electrically and thermally interconnected. The Cubesat specification standard (Cubesat specification, [http://cubesat.atl.calpoly.edu/media/CDS\\_rev11.pdf](http://cubesat.atl.calpoly.edu/media/CDS_rev11.pdf)) sets forth the specific dimensions (height, width, diagonal size and requires that the external dimensions be controlled to within  $\pm 0.1$  mm. The structure further provides for interface access ports to the satellite at a specified location for testing and battery conditioning subsequent to integration into the P-Pod.

Early in the definition phase a “make or buy” study will be conducted to determine if the mission is better served by purchasing the structure components from flight proven Pumpkin Inc (<http://www.cubesatkit.com/>) or to develop a custom structure based on previous MSU Cubesat

programs. This trade study will evaluate the accommodations provided to the instrument and the ability to provide support for suitable antennas for the communications system.

MSU has considerable design heritage for Cubesat structure including the standard 1U Cubesat and an extended Cubesat-Plus bus, originally designed for the RocketPod deployer. The latter approximates the size of a 1.5U Cubesat like those proposed here for FIREBIRD.

A commercial Cubesat structure is available for purchase from Pumpkin, Inc that allows flexibility to attach an external payload in a 0.5U configuration to a standard 1U Cubesat structure. These two structural elements are designed by the vendor to be mated together to produce a 1.5U Cubesat, with two such Cubesats forming a complete complement for a single P-Pod launch. The FIREBIRD satellites have been designed to be compatible with these Pumpkin, Inc structural elements.

#### 4.2.2. Environmental Control Subsystem

The FIREBIRD spacecraft will be designed to provide passive environmental control to the greatest extent possible. The external surface finishes will be selected to provide a nominal operating temperature of the instrument and internal electronics of -10 to 40 degrees C.

The FIREBIRD spacecraft will be built with normal good practices to provide a visibly clean spacecraft built with materials that meet the standard NASA Total Volatile Condensable Material (TVCM) requirements.

On a spacecraft of this small size differential surface charging is unlikely to be an issue. However the exposed surfaces of the FIREBIRD spacecraft will be selected to have a surface conductivity sufficient to minimize the potential of surface charging where possible.

#### 4.2.3. Command and data handling system

The Firebird spacecraft will be built around the Pumpkin FM430 Flight CDH Module. This unit uses a PC104 Modular stacking connector to interface with the other spacecraft subsystems. It is based on the TI 16bit MSP430 microcontroller and provides 50KB of flash memory and 10KB of RAM memory as well as an SD Card slot for up to 2GB of storage. These are available as a standard product from Pumpkin, Inc (part number 710-00252) and have

<b>Power Budget:</b>		<b>Firebird</b>
<b>Parameter:</b>	<b>Value:</b>	<b>Units:</b>
Solar Cell Size (Area):	27.3	cm <sup>2</sup>
Solar Cells Per String Per Spacecraft Side:	3	
Parallel Strings Per Side (Facet):	1	
Solar Cell Efficiency at Reference Temperature:	0.28	
Reference Temperature:	28	C°
Power Per String (0 deg. Beta Angle):	3.10	watts
Average Sunlit Power:	3.44	watts
Orbit Average Power:	2.21	watts
Solar Array Orbit Average Energy Output:	218.27	watt-min.
<b>Energy Summary:</b>		<b>watt-minutes</b>
Sunlit Minutes per Orbit:	63.48	min.
Eclipse Minutes per Orbit:	35.29	min.
Energy Generated per Orbit:	218.27	watt-min.
Energy Consumed by Loads per Orbit:	123.69	watt-min.
<u>Energy Available to Recharge Battery:</u>	<u>94.58</u>	<u>watt-min.</u>
Energy Stored in Battery (100% S.O.C.):	540.00	watt-min.
Energy Drawn from Battery During One Eclipse:	44.19	watt-min.
Capacity Drawn from Battery During One Eclipse:	5.52	amp-min.
Battery Depth of Drain After One Eclipse:	0.07	
<u>Energy Required to Recharge Battery (per Orbit):</u>	<u>49.10</u>	<u>watt-min.</u>
Energy Generated Per Minute for Recharging:	1.49	watt-min./min.
Time Required to Recharge Battery After E.O.E.:	32.96	minutes

**Figure 10** FIREBIRD power budget summary. The underlined values show the energy required to recharge the batteries in eclipse and the energy available to recharge the batteries. The difference shows this is a power positive mission.

flight heritage on the Libertad 1 program.

#### 4.2.4. Power System

FIREBIRD will use an Electrical Power System (EPS), batteries, and solar panels from Clyde Space Ltd. The EPS board provides maximum power point tracking battery charger control for the 1.25 Ah 8.2V lithium polymer battery system that mounts directly to the EPS board. The EPS board interfaces to the system with a PC104 connector that is compatible with the Pumpkin Cubesat implementation. The solar arrays use Advanced Triple Junction cells and are compatible with Pumpkin's standard mounting hardware. The ClydeSpace EPS system is designed to be fully compatible with the Pumpkin structure and the Pumpkin FM430 CDH module and has significant Surry Satellite Ltd heritage. Figure 10 shows the power budget demonstrating that the system is power positive. Figure 11 provides a subsystem level power breakdown.

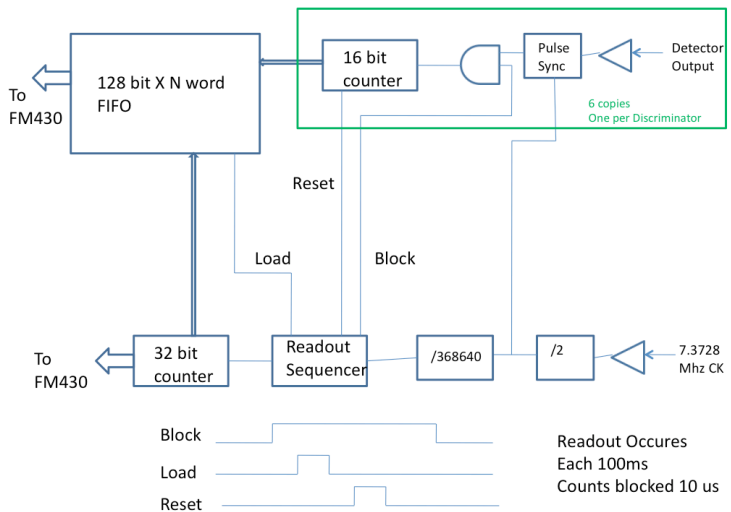
Load Characteristics: Component:	Current: From BAT(8.0V):	Current: +5V Reg:	Orbit Avg Duty Factor:	Peak Sub-system Power:	Avg Sub-system Power:	Orbit Avg Energy:	Orbit Avg Energy:
Flight Computer:	A	0.02 A	1.00	0.10 W	0.10 W	9.88 W-min	592.61 J
Command/Data Receiver:	0.03 A	A	1.00	0.20 W	0.20 W	19.75 W-min	1185.23 J
Telemetry/Data Transmitter:	0.19 A	A	0.13	1.50 W	0.19 W	18.93 W-min	1135.84 J
Detector HVPS Sourced from +5	A	0.07 A	1.00	0.35 W	0.35 W	34.57 W-min	2074.15 J
Detector Electronics	A	0.05 A	1.00	0.25 W	0.25 W	24.69 W-min	1481.53 J
Total Output Power/Energy Per Regulator:	1.70 W	0.70 W		2.40 W	1.09 W	107.82 W-min	6469.36 J
Total Input Power/Energy Per Regulator:	1.89 W	0.86 W		2.75 W	1.25 W	123.69 W-min	7421.13 J

**Figure 11** FIREBIRD power usage chart. This mission utilizes low power systems in order to maximize detector duty cycle.

#### 4.2.5. Payload Interface Board

There will be an MSU designed board on the top of the electronics stack to provide an interface from the S/C CDH and Power system to the Instrument. This board will mate with the Pumpkin PC104 bus and provide the electrical interfaces required for the instrument electronics. The initial version of this board will be a breadboard built with discrete logic to verify the functional design. Then the design may be moved into an FPGA. An Engineering model will be built and tested and the flight version of the board will be built and extensively tested.

The baseline plan is to keep the detector electronics simple. The data interface between the detector system and the S/C will be 3 digital lines that indicate an event at different energy levels. The detector interface (Figure 12) contains a counter for each energy level and a time base that is driven from the FM430 master clock. Each 100ms the data from all the counters and the time are loaded into the FIFO and transferred to the processor. The flight computer will then store the data on a 2GB SDRAM card. At each station pass the flight software will transmit the requested data to the ground for processing. Using Doppler measurements and sufficiently accurate clocks, the timing accuracy required to meet FIREBIRD science objectives will be achieved.



**Figure 12** Detector interface used to capture time tag detector output for onboard processing and storage.

#### 4.2.6. Communications Subsystem

The design of a communications system for a Cubesat is a challenge because no clear standard or best practice approaches have been developed [Klofas et al 2008]. For FIREBIRD the ISIS communications system has been chosen. This system provides a clean 9600 baud BPSK downlink sufficient to close the link. This 9600 baud system provides enough data to allow FIREBIRD to be successful. The radio will mate to the Pumpkin PC104 standard allowing for easy integration into the spacecraft stack. The FIREBIRD team will work closely with the NSF program office, or its designated representative (e.g. WFF) to make frequency and other regulatory selections early in the program in order to finalize the communication system.

We calculated a preliminary link budget using the AMSAT/IARU Annotated Link Model System (ver 2.4.1 Jan A King) assuming the ISIS TRXUV flight communication system with simple monopoles on the S/C and the capabilities equivalent to the MSU ground station. Based on an 800km circular orbit we should be able to obtain an uplink margin of 16dB and a downlink margin of 6dB.

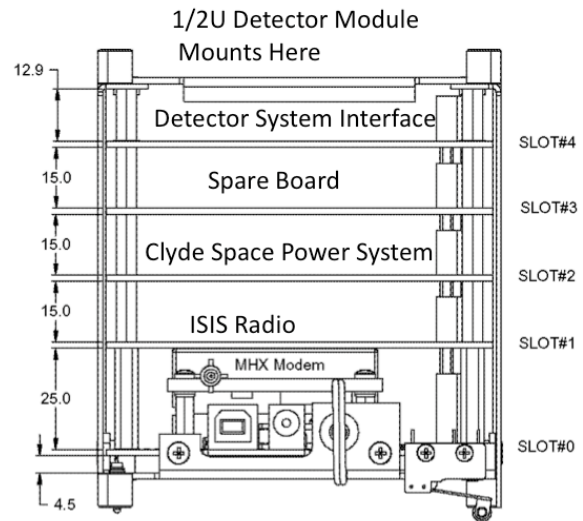
#### 4.2.7. Instrument Flight Software

The software for the FM430 processor will be developed using the Pumpkin Salvo RTOS. Because of the limited capability of the TI MSP430 microcontroller the software must be kept simple. This limits the on-orbit processing but makes for a simple, robust, low-risk system. We will break the software into two packages. The first package will handle all of the core functions of controlling the spacecraft and will be an MSU responsibility. The second package will handle the movement and storage of the detector data as well as onboard analysis of the data to identify microbursts. This will be a shared MSU and BU responsibility.

Software will use a phased development that closely follows the hardware development. First a breadboard version will concentrate on the hardware drivers and will be used for testing of the breadboard electronics. Next an EM version will contain all the basic functionality needed to support the EM functional tests. This will be very close to the flight version but will not have a full complement of observational and analysis modes. Then the full flight version will have the complete version of the code and will be used to support the FM functional and environmental tests. Finally FM software will be updated to correct any problem found during FM testing. This will be the operational version of the software. The operational version will be used for mission simulations and the pre-delivery baseline test and the post delivery testing as well as on-orbit operations. While it is possible to update the software in orbit, no such operation is planned because of the short nominal mission and significant parameter tuning that can be done on-orbit.

#### 4.2.8. Attitude Determination and Control Subsystem

The FIREBIRD spacecraft will use simple passive magnetic alignment attitude control with damping rods. This is a common Cubesat method for attitude control as used in the Swedish Space Corporation scientific nanosatellite, Astrid, and several very successfully AMSAT satellites (see Ovchinnikov et al. [2002] for passive magnetic attitude control).



**Figure 13** FIREBIRD bus layout. The instrument mounts on top of the standard cubesat sized bus. The separation makes the interface and teaming of the mission clean and workable.



There is no active station keeping between the two FIREBIRD spacecraft. The normal slow separation of two Cubesats launched from the same P-POD will provide the slowly increasing separation that is required to determine the scale size of the microbursts.

Cubesats released from the same P-POD have been observed to have a separation rate of 0.3 to 5 cm/s [Cousins 2008]. This natural separation will allow the two Firebird spacecraft to sample microbursts over a range of size scales without active station keeping. This will represent a separation of 0.24 to 4.3 km per day or 28 to 516 km at the end of the nominal 120-day mission. During the definition phase a trade study will consider the benefit of designing the separation springs to obtain a specific separation rate and the potential advantage of requesting a specific orientation of the P-POD upon release.

### 4.3. Spacecraft Integration and Test Plan

#### 4.3.1. Integration

The process of spacecraft integration will be basically the same for the Engineering Model and the two Flight FIREBIRD spacecraft and flight spare. The engineering model will serve as a pathfinder and be used to develop the procedures for the FM integration.

The basic structure, CDH, Power, and Communications systems will be purchased COTS units as described in section 4.2. A bus layout using these COTS units is shown in Figure 13. There will be some mechanical modifications and antennas that will be needed to accommodate the FIREBIRD requirements. When the COTS hardware arrives it will be assembled and tested one module at a time in the order that the modules are in the stack (CDH then COMM, then power). The required modifications will be made and the system reassembled and tested. Then the detector interface and the detector subsystem will be integrated and tested. Finally the solar panels will be added to complete the integration of the spacecraft. A full functional test will be performed to verify that the integration was completed correctly.

### 4.4. Integration of Spacecraft with Launch Vehicle

Integration into the P-Pod and to the launch vehicle will be carried out with NSF program office selected integration team. We foresee no special difficulties in the integration of FIREBIRD. The team has significant experience with Cubesat to P-Pod integration as well as NASA instrument integration on far more complex programs. This prior, relevant experience should make this process run as smoothly as can be expected.

### 4.5. Technical approach of ground segment

#### 4.5.1. Payload Operation and Control Center

The FIREBIRD Mission Operations Center (MOC) will be located in the MSU SSEL Satellite Earth Station (K7MSU) on the Montana State University (MSU) campus. The MOC is responsible for receiving the spacecraft housekeeping and science data, as well as the uploading of spacecraft operational schedules and commands. The MOC is managed and operated by a small group of MSU students and has been in near-continuous operation since 2004. The FIREBIRD Science Operations Center (SOC) will be located at BU.

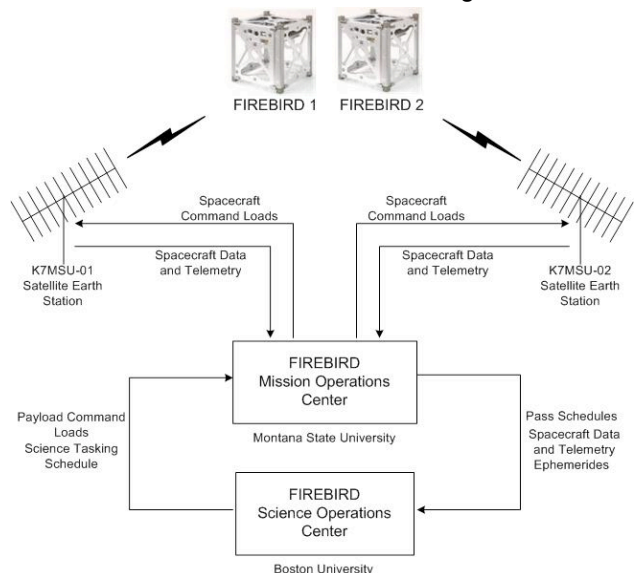


Figure 14 FIREBIRD Ground Segment Architecture

The SOC will have a internet link with the MOC and will be responsible for processing the received payload data and generating the required data products. The project scientist at BU will manage the SOC. In addition to analyzing data, the SOC will also assist in organizing the mission timeline and operations schedule. The SOC/MOC separation is desirable, as the BU team will have more intimate experience with the particle sensor, making BU the natural choice for the science operations and analysis center.

The K7MSU satellite station was designed using commercial-off-the-shelf (COTS) technologies to communicate with small orbiting student satellites developed at MSU. The station uses both amateur and commercial radio equipment and accessories to send and receive both analog and digital data from a variety of terrestrial and orbiting sources. Since 2004, K7MSU has acquired significant experience tracking numerous Cubesats, microsats, and other such small spacecraft. K7MSU was recently recognized for its participation in NASA Ames' GENESAT-1 Cubesat mission for timely downlink and return of data to the GENESAT mission control center. The schematic in Figure 14 provides an overview of the FIREBIRD ground segment architecture.

#### **4.5.2. Flight Operations**

The FIREBIRD flight operations plan calls for continuous operation of the payload and uplink commands requesting data from segments of the orbit with sufficient probability of encountering microbursts.

Given the requirements from Section 3 for the FIREBIRD orbital inclination, at least two ground contacts per spacecraft per day are expected. The received data will be decommutated and stored in an on-site database for preprocessing. During each data download period a new sequence of time-tagged operational commands will be transmitted to each spacecraft to control bus and payload functions. A second, duplicate ground station will be set up at or near MSU to enable simultaneous tracking of the two FIREBIRD satellites transmitting on separate frequencies. The Level 0 data will be transferred to a server at the SOC in Boston for additional processing to higher-level data products and ultimate dissemination to the science community. It is our intention to have an open data policy similar to that of NASA's LWS mission line.

### **5. Data processing and Analysis Plan**

The data will be housed on a server at BU for analysis and for dissemination to the science community. BU has experience in the construction and running of these science operations centers (SOC) having the Lunar Resonance Orbiter (LRO) and Interstellar Boundary Explorer (IBEX) SOCs. The FIREBIRD SOC will be a scaled-down version but all the elements are identical. The SOC will process the data into various higher-level data products, to be made available to the science team and community at large. We envision most of the analysis being done by the mission team. This analysis will occur at BU, MSU, and The Aerospace Corporation. With FIREBIRD being a targeted mission the team is already planning the way to incorporate the FIREBIRD data into current understanding, both theoretical and data-based, as well as to inform design and operation of mission in development and future missions.

### **6. Technological readiness and heritage**

This mission brings significant heritage in every facet of the hardware development and teaming. MSU/SSEL has significant experience with the Cubesat standard through its missions MEROPE and Explorer-1 Prime. These two programs have developed a basis of experience at SSEL in the development, integration and test of Cubesats to the Cubesat Standard. For FIREBIRD we will reduce risk and schedule by purchasing Cubesat satellite subsystems with a proven flight heritage where they are available. The technological readiness and heritage of the subsystems is discussed below.

**Power Subsystem** The FIREBIRD Power subsystem will be purchased from Clyde Space. Design of this system derives from Clyde Space Power System for SOHLA-2 a micro satellite, and other projects.

**CDH Subsystem** The FIREBIRD CDH system will be the FM 430 purchased from Pumpkin. This system has been flown successfully on the Delfi-C3 a 3U Cubesat launched in April 2008. This system was also used on Libertad-1 a 1U Cubesat launched in April 2007. This system operated flawlessly for the 34-day mission until the Libertad-1 battery was exhausted (It used a primary battery power without solar arrays).

**Communications Subsystem** The FIREBIRD communications subsystem will be purchased from the ISIS Group. ISIS communications systems have been flown successfully on Delfi-C3 satellite.

**Detector Interface** The Detector interface will be a new but simple design by MSU. It will be designed and built using the proven techniques and conservative design guidelines that Larry Springer used on many successful missions while at the Lockheed Martin Solar and Astrophysics Laboratory.

**Detector Subsystem** As discussed above the detector system is a simpler version of the POLAR/IPS and LRO/CRaTER systems. This directly traceable heritage to specific team members (Drs. Blake, Spence, and Larsen) allows the detector system to be regarded as a heritage design using both flight proven parts and design. Calibration of the instrument will follow standard particle instrument calibration of which the entire team has significant experience and resources are available.

## **7. Deviations from accepted Cubesat standards**

Our mission plan contains no deviations from the Cubesat standard. The standard allows for differing heights of satellites, the standard 1U (10cm) Cubesat fits 3 spacecraft in the P-Pod deployer. As this mission requires a two-point measurement we will be building two 1.5U (15cm) Cubesats to fill a single P-Pod. A larger spacecraft simplifies the interface between the spacecraft and the instrument. This simplification significantly reduces risk to the mission as the geographically dispersed team requires a well-defined and simplified interface in order to meet the schedule of this program.

## **8. Student training opportunities and student involvement**

The technical, educational, and scientific success of the FIREBIRD investigation depend critically upon achieving proper balance between the activities of the professionals and those of the students. We ensure educational success by giving the students significant responsibility in the management, systems engineering, design, implementation, operations and science while ensuring technical success by providing consistent, competent professional mentoring and oversight, principally by the two lead institutions (BU and MSU) but also collaboratively through the Aerospace Corporation.

The educational benefit of the FIREBIRD investigation affects both undergraduate and graduate students, and recently graduated interns at MSU and BU, as well as faculty researchers at both institutions who broaden their research interests and enhance their own professional development. We aim to retain students with an already established interest in space-related careers and to further inspire and engage them in the space enterprise. Our experience with student hands-on space projects has shown that those undergraduate students who persevere through one flight project seek and excel at additional challenges. Upper level undergrads, recent graduates retained as early-career interns, and graduate students are the key targets for participation in FIREBIRD. Thus the dual educational goals are STEM pipeline retention and advanced training to further develop the critical skills required to support future space research. Our student involvement process within the FIREBIRD team supplements the students' formal education in the traditional STEM disciplines through in-depth extracurricular spaceflight systems development. Students in interdisciplinary teams are challenged to put their formal education skills to work in an environment that emulates the technical workplace. They develop project management skills, learn systems engineering practice, and experience the value of teamwork as they design, build, test, rebuild, integrate, and operate their experiment and analyze the data. FIREBIRD will engage approximately 10 students at any one time at MSU and BU. Over the three year program, ~20 individual students will be directly impacted through participation in the project. In addition to student training at MSU and BU there will be summer internships for student scientists and engineers at The Aerospace Corporation. These are often transformative experiences where students work alongside professionals to accomplish tasks.

During these internships students will be a part of the team working on FIREBIRD mission and instrument development and science. The vast majority of FIREBIRD development will occur at MSU and BU. Aerospace Corp will provide in-kind technical expertise and support to help ensure mission success.

Student turnover is inevitable given the duration of the mission. This potential issue for project continuity is transformed into an educational opportunity by three means: (1) rigorous documentation standards; (2) formal configuration management techniques; (3) a team environment in which senior students have a role in training juniors, and all are mentored by professionals who are involved in all key decisions. Co-PI David Klumpar and Program manager Larry Springer, with extensive program management experience in space science instrumentation will work with the students on a continuing basis, maintaining careful balance to foster a creative learning environment, while maintaining technical rigor. Co-PI's Spence and Klumpar have decades of experimental space science experience and both are well-practiced at working with students in the university environment; both MSU and BU have programs in place to not only work with students, but also to enhance diversity with graduate bridge programs to HBCUs (Fisk University) and Native American programs.

The intended educational outcomes of the proposed investigation are 1) to retain students in the STEM pipeline and provide advanced training through engagement in a cutting edge space science mission; 2) to entice additional students to examine and subsequently enter the high tech workforce; 3) to place program graduates in space-related careers; and 4) to promote faculty development, both at MSU and BU, in an area that extends and complements their ongoing research. Assessing the achievement of these primary outcomes will require measurement both during the program and at five years after project completion. During the program we document participating students annually by assessing their scholastic standing, current academic major, degree intentions, degree schedule and career goals. Recent graduates participating as early-career interns will be annually polled about advanced degree and/or career plans. Faculty and student research will be gauged by publications related to the project. Students will engage in professional presentations and publications and will be measured, in part, by their participation in such activities. Post project, our evaluation metrics strive to assess the impact of the project on the students' careers. The program size (<20 participants) eases the burden of longitudinal tracking.

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## **Montana State University Facilities, Equipment and other Resources available to FIREBIRD**

Montana State University has established a specialized facility for the design, development, test, and operation of spaceflight systems. The Space Science and Engineering Laboratory consists of five newly refurbished and newly equipped laboratories, and a space telecommunication operations center. The SSEL labs include a Small Satellite Laboratory for design and hardware development of small satellites and satellite subsystems, the Space Environmental Test Facility with a class 10,000 cleanroom, class 1000 flow bench, and vacuum systems that include the 14 ft x 4 ft diameter "Rocket Chamber," capable of better than  $10^{-6}$  torr, the Space Optics Laboratory with a 12' x 5' optical prototyping table, and the Space Operations Center housing a remotely controlled earth station for uplink commanding and direct downlink of satellite telemetry. Test equipment includes a thermal test chamber, laminar flow bench, GHz oscilloscopes, analog and digital data acquisition systems, power sources, and signal generators. A newly commissioned three-foot diameter stainless-steel hydrocarbon-free high-vacuum system is being upgraded for thermal-vacuum capability. Modern electronics workstations provide electronics test and assembly in an ESD safe environment. Electronics design software tools by Cadence Design Systems (OrCAD) are routinely used to document, design, and layout printed circuit boards. A T-Tech rapid prototyping mill permits the in-house manufacture of two-sided PCBs, while more complex boards are manufactured by outside suppliers to our specifications. Electronic boards, including those that use surface mount technology, are populated by hand, or with the assistance of a reflow soldering station available in the ECE department. Mechanical systems are analyzed (finite element modeling) and designed on a dedicated 10-workstation SSEL server-based computer network using Professional/ENGINEER ("Pro/E"), COSMOS, and SolidWorks, and are fabricated in one of MSU's CNC-equipped machine shops, or contracted out to professional machinists. A unique partnership with Montana Tech College in Butte, Montana allows students at Tech's manufacturing center to manufacture mechanical parts to the engineering drawings supplied by MSU engineering students. Space thermal modeling is performed using Thermal Desktop. Other software analysis tools such as Autocad, Matlab, Mathematica and IDL are routinely used on our servers for analysis and display.

The Physics and Electrical and Computer Engineering (ECE) departments, have well-equipped, state-of-the-art facilities. Research and instructional laboratories are well equipped with high-speed network access and the engineering building complex is wired for 100 megabit networking, with gigabit Ethernet fiber links to the campus network and the university Internet2 connection point. IP-based and ISDN teleconferencing facilities in the Burns Telecommunications Center, located in the engineering complex are available for use to support periodic meetings between Montana State and other collaborators. We also have an Access Grid Node that will support high-quality, IP-based multi-point video teleconferencing. The project will have full access to a fully equipped machine shop and a newly renovated electronics shop in the MSU physics department. Both of these shops are managed by fulltime professionals who are expert in their disciplines.

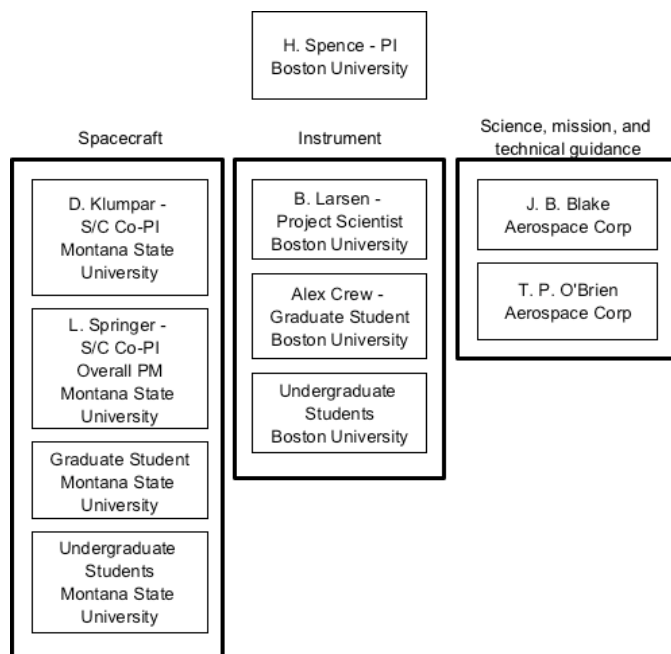
## 1. Management Plan and Risk Reduction Approach

The Firebird Program will be managed as a Principal Investigator (PI) led program with a veteran and accomplished Program Manager (PM) leading the spacecraft hardware development program. The PIs are Dr. Harlan Spence at Boston University (BU) and Dr. David Klumpar at Montana State University (MSU). The Program Manager is Mr. Larry Springer at MSU. There will also be a Program Systems Engineer (SE) at MSU. This will be an MSU graduate student or a recent graduate with experience in space systems. This individual will be closely advised and mentored by Mr. Springer.

### 1.1. *Management Division of Responsibilities*

The division of responsibilities between Boston University (BU) Montana State University (MSU) and the Aerospace Corporation makes best use of each organization's strengths and maximizes the opportunities for student involvement in the program.

We note that several strong partnerships already exist between the BU, MSU, and The Aerospace Corporation teams and FIREBIRD heavily leverages these established collaborations. The FIREBIRD PI (Spence) and collaborator J. Bernard Blake jointly developed spaceflight hardware (POLAR/IPS) and LRO/CRaTER, and are jointly developing spaceflight hardware through the same BU/Aerospace partnership on two in-development NASA missions (RBSP/ECT and MMS/EPD). Current BU graduate students have been working on research projects with Aerospace scientists and a BU graduate student (Mr. Alex Crew completed a summer internship in 2008 at Aerospace) is continuing a summer internship at Aerospace this summer (2009) in preparation for FIREBIRD development and microburst physics. This BU/Aerospace relationship is important for FIREBIRD, while the work will be performed at BU, mentoring and expertise from Aerospace will play an important role in reducing risk and assuring successful instrument design and performance, and contributing to mission success.



**Figure 1** FIREBIRD organizational chart displaying organizations, roles, and flow.

Furthermore, the FIREBIRD Project Scientist (Dr. Brian Larsen, BU) completed his PhD at MSU under the guidance of FIREBIRD co-PI Dr. David Klumpar. While at MSU, Larsen played major roles in several MSU student-led satellite projects, working also with the MSU PM and SE, and brings that considerable experience to BU. As lead of the FIREBIRD sensor development, Larsen's strong ties to the MSU spacecraft and mission team will assure a tight coordination of effort, cementing the BU/MSU partnership.

#### **BU, the PI Institution, will be responsible for:**

- Mission development and planning
- Science planning and data analysis
- Development of the detector subsystem including design, fabrications, testing, and calibration
- SOC lead

**MSU, the Spacecraft Developer, will be responsible for:**

- Spacecraft and ground support equipment development program management
- Spacecraft and ground support equipment development systems engineering
- Spacecraft and ground support equipment development mission assurance
- Program risk management
- Selection and procurement of COTS spacecraft elements
- Development of modifications and additions to the COTS hardware
- Development of the interface to the detector subsystem
- Integration and test of the spacecraft and ground support equipment
- Integration of spacecraft into the P-Pod
- Support of pre-launch activities
- MOC Lead; Operation of the spacecraft on orbit
- Data analysis

**The Aerospace Corporation will be responsible for:**

- Assistance with detector and EEE parts acquisition
- Consulting on mission and science planning
- Consulting on instrument and spacecraft design
- Mission review participation
- Data analysis

**1.2. Management Plan and Approach**

The Firebird Program Manager (Larry Springer) will be responsible for overall management and systems engineering for the Firebird Program. Early in the Program a detailed Work Breakdown Structure (WBS) will be developed and the budget will be allocated to the second level of the WBS. Approximately 15% of the budget will be held as management reserve. This management reserve will be tracked separately and used to solve problems and manage risk on the program. The allocation of management reserve will require the concurrence of the PI, PM, and PS. The PM will compile a monthly update of the program schedule, budget, technical, and scientific progress to program (NSF) officials.

The coordination of the multi-institution program will be done with a series of scheduled meetings with the team (students and professionals) that are organized around a formal agenda and a formal system to track action items. There will be quarterly management meetings lead by the PI. About 2/3rds of these meetings will be done through telephone and/or web conferencing with the remaining in-person meetings rotating between the institutions. These will be supplemented by weekly management telecoms led by the PM. At each institution there will be weekly team meetings with the key members of the technical team. Students will lead meetings, as relevant, with senior staff in attendance.

The instrument development will be led by the project scientist (PS) (Dr. Brian Larsen) and performed at BU. Instrument development will be directly managed at BU with the FIREBIRD PM at MSU holding overall management of the mission. Inputs will be given to the PM for monthly reports including schedule, budget, technical, and scientific progress; these reports will also be sent to the program office if desired. The majority of the development will occur at BU during the academic year, with the possibility of exploiting outstanding summer internship opportunities for students at The Aerospace Corporation where flight builds could be done leveraging Aerospace personnel and equipment. To demonstrate this internship relationship, we note that Mr. Alex Crew, a BU graduate student, completed a 2008 summer internship at The Aerospace Corporation and will return there in summer 2009, becoming familiar with sensors similar to those used in FIREBIRD and working on electron microburst science.

After launch the PS will oversee the science operations center at BU and facilitate and organize research among the FIREBIRD team. The project scientist has working relationships with each of the other scientists. Larsen is currently the Instrument Suite Scientist of the RBSP-ECT suite (of which Spence is the overall PI, Blake is the instrument lead of the relativistic electron instrument, and collaborator Dr. Paul O'Brien is a co-investigator).

### **1.3. Risk Management**

The FIREBIRD Program will implement a professional risk management plan that is similar to the one used on NASA's flagship missions, including Solar Dynamics Observatory and Radiation Belt Storm Probes. This involves implementation of a Risk Management Board (RMB) consisting of the SE/PM (chairman), PI, PS, and mission assurance lead. Technical experts, as needed, will supplement the basic board.

The RMB will meet monthly by telecom to identify, evaluate, rank, and track identified risks. Each risk will be evaluated on the basis of its likelihood and consequence in order to obtain its ranking. The RMB will develop and implement mitigation and contingency plans for the more significant risks. All the risks identified will be given a unique Identifier and will be tracked in a database. At each RMB meeting all of the open risks will be discussed so that any changes to its status can be evaluated. The program office is not mandating the use of a RMB, but, based on prior spaceflight hardware development projects managed at BU, MSU, and The Aerospace Corporation, we collectively believe that this activity is of critical importance to assure the success of FIREBIRD. This will also serve as an educational component for students: to experience a formal risk management process in a small satellite setting as a practical experience for eventual larger missions for which this is a standard practice.

### **1.4. Project Schedule**

Figure 2 on the following page is the initial FIREBIRD Project Master Schedule which is the roll-up of a more detailed task schedule. (The detailed budget developed by BU and MSU were based on the Master Schedule). The more detailed version of this schedule will be statused and updated by the PM on a monthly basis. As this program has an aggressive schedule, special attention will be paid to keeping the program on schedule, and carefully watching critical paths, in order to avoid cost overruns and missed launches.

### **1.5. Satellite and Subsystem Environmental Testing**

The California Polytechnic Cubesat Design Specification calls out a minimum of Random Vibration to Qualification Levels, Thermal Vacuum bake out to ensure proper outgassing of components, and Visual Inspection to verify conformance to the Cubesat Acceptance Checklist. To that the FIREBIRD Program will add EMI/EMC to assure self-compatibility and an absence of spurious radiation, and thermal vacuum cycling to verify that the spacecraft can survive its predicted orbital environment. These tests will be performed on the completed spacecraft. They will also be performed on the EM spacecraft to verify the design and find any design problems early in the program.

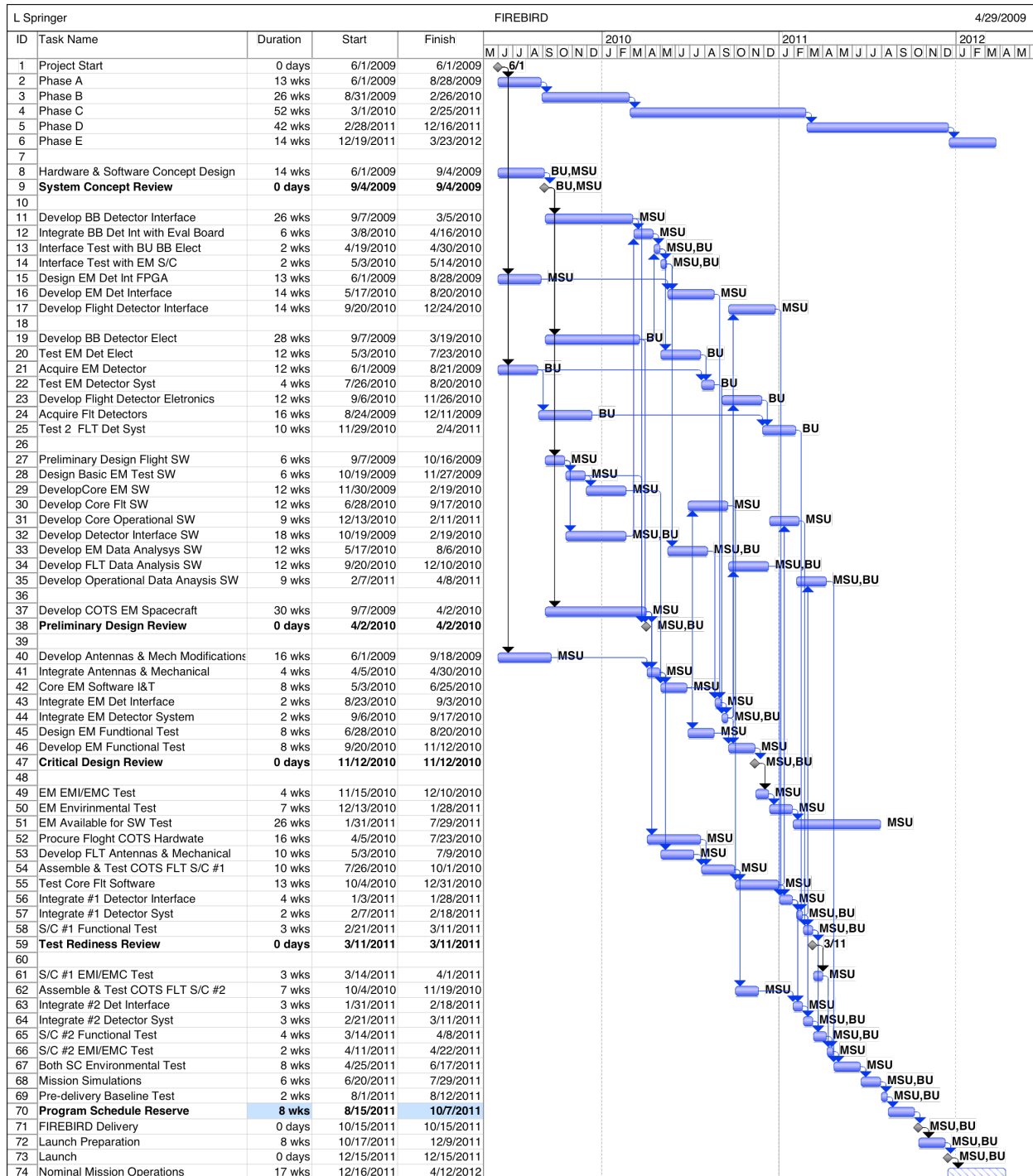
The EMI/EMC will be done after the integrated (EM or Flight) spacecraft have completed their functional tests. The primary function of this is to verify the self-compatibility. The detector system will be placed in its most sensitive mode and the other systems will cycle through their noisy modes. The data will be analyzed to show that the detector does not suffer any unacceptable interference. It will also include a test to show that the two Firebird spacecraft do not interfere with each other when they operate in close proximity, as they shall will early in the flight program.

The thermal vacuum bake out required by the Cubesat Specification will be followed by thermal cycling to the predicted on orbit thermal environment with 10 degrees C of added margin. The spacecraft will be functionally tested at each temperature extreme. There will be 4 complete thermal cycles with sufficient dwell at each extreme to assure the spacecraft has reached equilibrium. This is an excellent verification that the spacecraft design and workmanship is adequate to assure a successful mission.

The random vibration will be done to qualification levels (3dB above the launch predicts) prior to delivery in all three axes. The random vibration will be followed by a detailed visual inspection and a baseline comprehensive performance test prior to delivery.



MSU has experience with all of these tests for cubesats and either in-house equipment or external relationships to facilitate this testing.



**Figure 2** FIREBIRD schedule showing phases, milestones, and major tasks. This schedule includes 9 weeks of schedule reserve (task 69) before spacecraft delivery. Phase A takes place before proposal selection to enable the program to “hit the ground running”

## **1.6. Program Review Plan**

The FIREBIRD mission will implement a series of formal reviews that follow the program phase. These reviews will be patterned after those typically used on NASA programs, however they will be right-sized for this NSF-led program. As with the Risk Management program discussed earlier, these tailored reviews will provide FIREBIRD students the opportunity to experience the flow and formality of a larger program within a right-sized environment. Independent, qualified peer reviewers will be invited to participate in these reviews as well as any interested NSF program office personnel. The reviews will be held at Aerospace Corporation to facilitate the participation of the programmatic and technical experts there in a manner that will keep overall mission cost low.

### **1.6.1. Systems Requirements Review (SRR)**

A Systems Requirements Review (SRR) will be held about 3 months after program start when the mission requirements have been flowed down through the spacecraft to the subsystems. At this point the Spacecraft and Detector Subsystem concept designs are complete and the Detector Subsystem to Spacecraft Interface Control Document (ICD) is complete. The purpose of this review is to verify that the requirements are sufficiently understood that the program can proceed into Phase B (Preliminary Design).

### **1.6.2. Preliminary Design Review (PDR)**

The Preliminary Design Review (PDR) is held at the end of Phase B when the design trade studies and preliminary designs have progressed to the point where the team can demonstrate how the proposed design can meet the program requirements. For FIREBIRD we will have tested initial breadboards of the design electronics prior to the PDR. The purpose of this review is to verify that the proposed design of the system and subsystem can meet the requirements for the program and that the preliminary design is mature enough to proceed into the detailed design phase (Phase C).

### **1.6.3. Critical Design Review (CDR)**

The Critical Design Review (CDR) is held when the detailed design is complete and the team is ready to start the production of Flight hardware. For the CDR nearly all design drawings will be completed and enough testing and analysis is completed so that the performance of the final system can be predicted. For FIREBIRD this will be held when the EM Spacecraft has completed its functional test. The purpose of the CDR is to verify that the design is complete and the team is ready to build flight hardware (Phase D).

### **1.6.4. Test Readiness Review (TRR)**

The Test Readiness Review (TRR) is conducted after the flight hardware has completed its first "baseline" performance test. It is at this point when test plans are complete and the test facilities for the acceptance test are identified. For FIREBIRD the TRR will be conducted after the EM has completed the environmental tests as a pathfinder for the flight units. At the TRR the results of the baseline performance test will be verified to show that the spacecraft and its software meet the mission performance requirements and that the test plans will adequately qualify the spacecraft for launch.

### **1.6.5. Mission Readiness Review**

The Mission Readiness Review (MRR) is conducted just before the spacecraft is integrated into the P-Pod. All requirements are shown to be met, all environmental tests adequately qualify the spacecraft for launch, and the mission is ready for P-Pod and launch vehicle integration with a high probability of success.