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Flight System Technologies Enabling the Twin-CubeSat FIREBIRD-II Scientific Mission

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ABSTRACT

Recent technological developments have enabled a CubeSat-based targeted science investigation to unravel a mysterious process that results in the Earth being bombarded by relativistic electrons. The Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics (FIREBIRD) mission is an-NSF funded collaboration carried out by Montana State University, the University of New Hampshire, The Aerospace Corporation and Los Alamos National Laboratory. Four satellites were placed into low Earth orbit in pairs on December 6, 2013 (FIREBIRD-I) and January 31, 2015 (FIREBIRD-II) as auxiliary payloads under NASA's CubeSat Launch Initiative. Enabling technologies carried on the twin FIREBIRD-II CubeSats include Vanguard Space Technologies, Inc. high-efficiency body-mounted solar panels affixed to the four 10x15 cm sidewalls of each 1.5U CubeSat. These solar panels provide energy to a custom MSU-designed-and-built electrical power system that includes two 2600mAh Li-Ion cells with integrated battery protection circuitry. Each spacecraft carried GPS receivers enabling precise timing and position information necessary for science operations. These technologies together with Montana State's custom avionics and operations software (built upon L-3's In-Control package) enabled exciting, unique, and insightful measurements of the near-Earth radiation environment to unravel the spatio-temporal ambiguities of relativistic electron bursts previously observed only by single spacecraft. Without these technologies the mission would not have been possible utilizing CubeSat-class spacecraft measuring merely 15x10x10 cm.

INTRODUCTION

The advent of a standard deployment canister that permits small satellites conforming to a specification standard to be launched into orbit as auxiliary payloads has resulted in the worldwide launch of more than 200 so-called "CubeSats". The Poly Picosatellite Orbital Deployer (P-POD)[1], developed in 1998 at California Polytechnical University has enabled the in-space placement of a multitude of satellites massing up to 4 kg with a square cross section of 10 cm x 10 cm and up to 30 cm in length. The earliest CubeSats were developed primarily at universities for the purposes of student training and technology demonstration. In the dozen years since the first CubeSats were launched in 2003, the developer community has expanded beyond universities to include government agencies, research laboratories, and aerospace companies, both small and large. Recently, new classes of businesses have been created whose goal is to make operational use of CubeSats, frequently flying them as elements of constellations consisting of many cooperating platforms. While still used for training, CubeSats now find utility in advancing state-of-the-art miniature technologies, developing and space qualifying small low-power sensors, and, as is the case for the FIREBIRD mission, conducting scientific research. CubeSats now regularly constitue the space segment for many different operational and applications-oriented missions.

Seeing the potential for advancing geospace and atmospheric research, The National Science Foundation initiated the "CubeSat-based Science Missions for Geospace and Atmospheric Research" program in 2008. Approximately every two years the NSF CubeSat Program solicits research proposals that employ small satellites. Typically, one to two proposals are competitively selected from each solicitation "for science missions to include satellite development, construction, testing and operation as well as data distribution and scientific analysis".[2] To date twelve distinct missions have been selected for development and flight under the NSF program.

The Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics (FIREBIRD) mission was proposed in May 2008 and re-proposed in May 2009 by a team led by Montana State University and The Boston University and selected for funding by the NSF in September 2009 (The portion of the investigation initially at BU was transferred to The University of New Hampshire in 2010).

Mission/Science Intro

The FIREBIRD missions are highly complementary to NASA's Van Allen Probes mission, a strategic mission aimed at studying the physics of Earth's radiation belts. The FIREBIRD instrumentation is designed to cover a key energy range (~200 keV to ~ 1 MeV) of electrons that make up the outer radiation belt. These energetic charged particles can penetrate spacecraft components and structures, leading to deleterious effects such as deep dielectric discharge. FIREBIRD complements the Van Allen Probes mission by measuring electrons that are lost through scattering to the upper atmosphere in a process known as a microburst; this loss mechanism has been implicated as a major source of loss of the radiation belts, and thus is important to quantify in order to develop useful predictive models of the belts. FIREBIRD provides key measurements in LEO that Van Allen Probes cannot, demonstrating the power of CubeSats in answering focused but important science questions in a synergistic way with larger spacecraft missions even when studied in a standalone manner. Moreover, when FIREBIRD measurements are combined with similar instrumentation on Van Allen Probes, namely the Magnetic Electron Ion Spectrometer[3] on the Radiation Belt Storm Probes Energetic Particle, Composition, and Thermal Plasma (ECT) instrument suite[4], the joint analysis leverages the science from both missions. See Spence et al.[5] for additional details about the FIREBIRD mission science.

FIREBIRD-I Mission Background

The FIREBIRD-I mission included two 1.5U CubeSats called Flight Unit 1 and 2 (FU1 and FU2 respectively), that were launched on December 6, 2013 into a 467 by 883 km, 121 degree inclination orbit. Directly after launch FU2 performed as expected and began taking science data while its twin, FU1, remained silent.

In January 2014 FU2's orbit transitioned to full-sun and its batteries began to be overcharged due to flaws in the Electrical Power System (EPS). This overcharging severally degraded the batteries and lead to an increased number of resets under high loads in all subsystems, notably the GPS receiver and COMM transmitter. Six weeks following launch FU2 became unresponsive, only booting and beaconing for a short time each day.

An internal failure review board determined the primary cause of both FU1 and FU2's failures to be rooted in the EPS's battery protection circuit and inability to properly boot when the batteries were depleted.

The failure review board also found a bug in FU1's stored command sequences that would cause the spacecraft to enter an infinite loop during boot. This loop prevented the configuration of the spacecraft's telemetry beacon. Following the board, a fix was found that could be uploaded to FU1 if the EPS had properly booted.

Continued attempts were made to revive FU2 and upload the command sequence fix to FU1. In March 2014 FU1 responded to the bug fix and began beaconing. FU1's batteries showed signs of degradation due to overcharging. Despite this limitation, it was still operationally possible to begin science payload runs and downlinks on a limited scale. In July 2014 FU1 became completely unresponsive, beginning a booting and beaconing cycle only once per day, the same apparent failure condition as FU2.

While meaningful measurements of low altitude Radiation Belt precipitation were obtained from both FU1 and FU2, simultaneous science operation from both satellites was not achieved. As a result of the short spacecraft lifetime, low orbital inclination, and low solar activity, no microbursts were observed in the data retrieved from FU1 and FU2.

Around the same time as the launch of FU1 and FU2, funding to turn the Engineering Development Unit and flight spare hardware into Flight Units 3 and 4 (FU3 and FU4) was procured from the NSF. Based on the on-obit problems discovered with FU1 and FU2, several key changes were made to the spacecraft bus for the FIREBIRD-II mission, as detailed below. The FIREBIRD-II spacecraft were launched on January 31, 2015 into a 440 by 670 km, 99 degree inclination orbit.

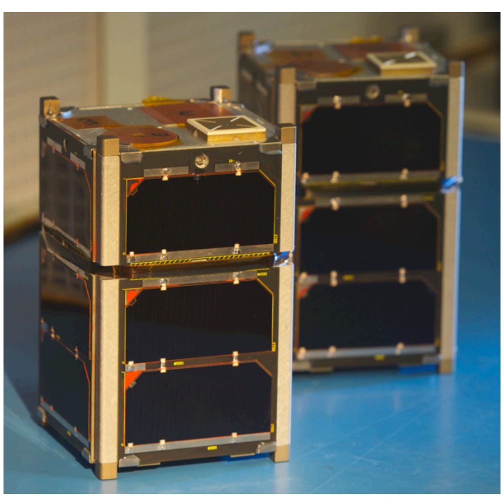

Figure 1 The FIREBIRD-II Spacecraft ready for launch.

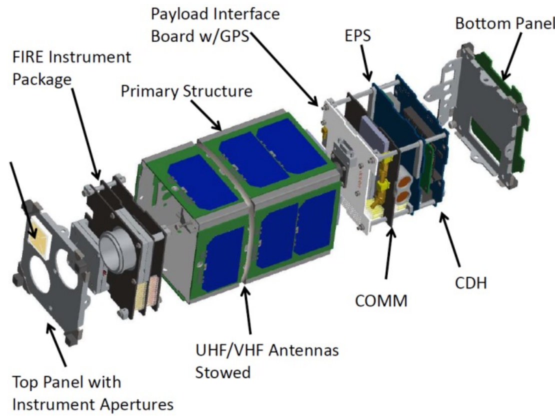

Figure 2: FIREBIRD-I Exploded View

SPACECRAFT DESIGN

For both missions, each FIREBIRD spacecraft consisted of a MSU-developed bus known as BIRD (Bus In support of Radiation Detector) and a University of New Hampshire (UNH) developed payload known as FIRE (FIREBIRD Instrument for Relativistic Electrons), as shown in Figure 1 and Figure 2.

FIRE Instrument

FIRE is the sole instrument onboard all FIREBIRD spacecraft. The FIRE payload was not changed between the FIREBIRD-I and FIREBIRD-II missions. The entire instrument fits inside a 0.5U (10x10x5 cm) volume. The FIRE instrument consists of two independent silicon solid state detectors and 3 circuit boards: the analog, digital, and power board. The analog board houses both solid state detectors and the electronics to run them. Each detector is 1500 μm thick with a diameter of 32 mm. Fortunately, UNH acquired the detectors as surplus from a previous NOAA mission that no-longer required them. At that thickness, the detector will stop electrons of energies up to 1,050 keV. Each detector is identical, except for the presence of a collimator around one detector. This collimator serves to reduce the geometric factors from 23 to 9 $cm^2 \cdot sr$. Each detector was sealed in a light-tight dog house. A thin piece of aluminum foil was placed over the active area of the detectors to keep out light and low-energy particles. For the typical energies of interest, particles lose approximately 25 keV going through the foil. The other main component on the analog board was the DAPPER. The DAPPER was developed for the FEEPS (Fly's Eye Energetic Particle Spectrometer) instrument on NASA's Magnetospheric Multiscale (MMS) mission[6]. The DAPPER provides pulse processing at very low noise and power consumption, for both detectors simultaneously. Without the DAPPER, the FIRE instrument would only be able to support a single detector.

The DAPPER provides a fixed-height variable-width pulse proportional to the energy deposited in each detector. On the digital board, the FPGA takes that input pulse and by timing, digitizes it into one of 256 discrete values. As FIREBIRD is telemetry limited, the FPGA bins this value into one of six customizable flight-energy bins, ranging from 200 keV to 1 MeV. For calibration purposes, it is possible to test with bins as small as 10 keV in size. The FPGA is also responsible for taking the data at its highest cadence, 18.75 ms, and producing two lower rate products, burst parameter and context at 100 ms and 6 sec. respectively. The digital board is also the only electrical connection to BIRD.

The final board in the FIRE stack, the power board is responsible for taking the spacecraft bus voltage (8.4V nominally) and converting to the voltages necessary for the other instrument boards, as well as the detector bias. For the flight build, the detector bias was set to 247V, well above the nominal depletion voltage for all detectors.

FIREBIRD-I Bus

The main structure of each spacecraft is a modified Pumpkin 1.5U chassis with solar panels designed and assembled at MSU. The spacecraft's five solar panels are mounted to each of the 15cm x 10cm sides of the spacecraft, as well as a smaller panel on the bottom of the satellite.

BIRD consists of four subsystems; Command and Data Handling (CDH), Electrical Power System (EPS), COMM, and Multi-Functional Interface Board (MFIB). All of BIRD is Commercial Off The Shelf (COTS) hardware, with the exception of the MFIB.

The CDH is a Pumpkin Motherboard and Pluggable Processor Module (PPM) that consists of a PIC24F microcontroller, 64MB flash memory, 2GB SD Card, hardware Real Time Clock (RTC), and Electrical Ground Support Equipment (EGSE) connections. The CDH microcontroller controls all subsystem on the spacecraft and uses the flash memory to store and execute automated Command Sequences (CMDSEQs). The SD Card can be used to store telemetry for latter downlink and the RTC is used to keep time between automated payload data runs. The EGSE consists of a standard barrel connector for battery maintenance and a USB port for diagnostic commanding and telemetry.

The EPS was developed by a commercial aerospace partner, who was considering entering the CubeSat market. FIREBIRD-I was intended to test and raise TRL of this system before it would be offered as a commercial product. This EPS featured two Lithium-ion battery cells in series with shunt-based battery protection and solar panel Maximum Power Point Tracking (MPPT). This EPS also featured a watchdog, which would reset the entire spacecraft every 72 hours, if not 'kicked" by the CDH via ground command. This EPS was designed for much higher electrical loads, such as those of a 3U or 6U CubeSat. As a result, it was very inefficient under FIREBIRD's smaller loads and solar array inputs.

The COMM transceiver is an AstroDev He-100 radio with VHF uplink and UHF downlink, operating in the Amateur radio (HAM) bands. Telemetry beacons were initially downlinked at 9.6kbps, while stored FIRE science data was downlinked at 19.2kbps. However, early in the FIREBIRD-I mission the spacecraft were reconfigured to beacon at 19.2kps to improve packet reception. All downlinks are at a power output of 1 Watt using GMSK modulation and AX.25 packets. The He-100 radio is connected to two monopole antennas, one for each band. The antennas are manufactured from spring steel tape measures and mounted to the spacecraft structure with MSU-designed and manufactured mounts.

The MFIB is an MSU-designed and built board that interfaces the FIRE payload and all other subsystems that could not be connected directly to the other COTS BIRD subsystems. The MFIB features another PIC24F microcontroller and a 2GB NAND flash for FIRE payload data processing and storage. For the FIREBIRD-I mission the MFIB microcontroller stored data to the NAND flash using a custom FAT-based file system that allowed data to be retrieved for downlink based on its storage time. The MFIB microcontroller also runs a software RTC that is synchronized to the CDH RTC at the start of each payload run and used to time-tag FIRE data as it is received from the payload. The MFIB features connections for the antenna deployment mechanism and analog temperature monitors. A NOVATEL OEMV1 GPS receiver for synchronizing the CDH RTC and recording location information is mounted on the MFIB with a patch antenna mounted to the top plate of the spacecraft.

Each spacecraft is equipped with a passive magnetic attitude control system. This includes a permanent rare-Earth magnet and two rods of hysteresis material. The magnet is aligned with the spacecraft's long axis, while the two hysteresis rods are perpendicular to the magnet and each other.

FIREBIRD-II Bus

Excluding several key changes outlined below, the FIREBIRD-II spacecraft are identical to the original FIREBIRD-I spacecraft design. For the FIREBIRD-II mission no changes were made to the design of the FIRE instrument.

Based on the overcharging and boot problems with the COTS EPS used on FIREBIRD-I, it was decided to switch to a simpler in-house design for the FIREBIRD-II mission. This new design leveraged designs used on MSU's first satellite, HRBE, which is still even operational 4 years after launch. Figure 3 shows a high-level block diagram of the FIREBIRD-II EPS design, known as Phoenix. The primary design methodology idea behind the Phoenix EPS was to Keep It Simple Stupid or KISS.

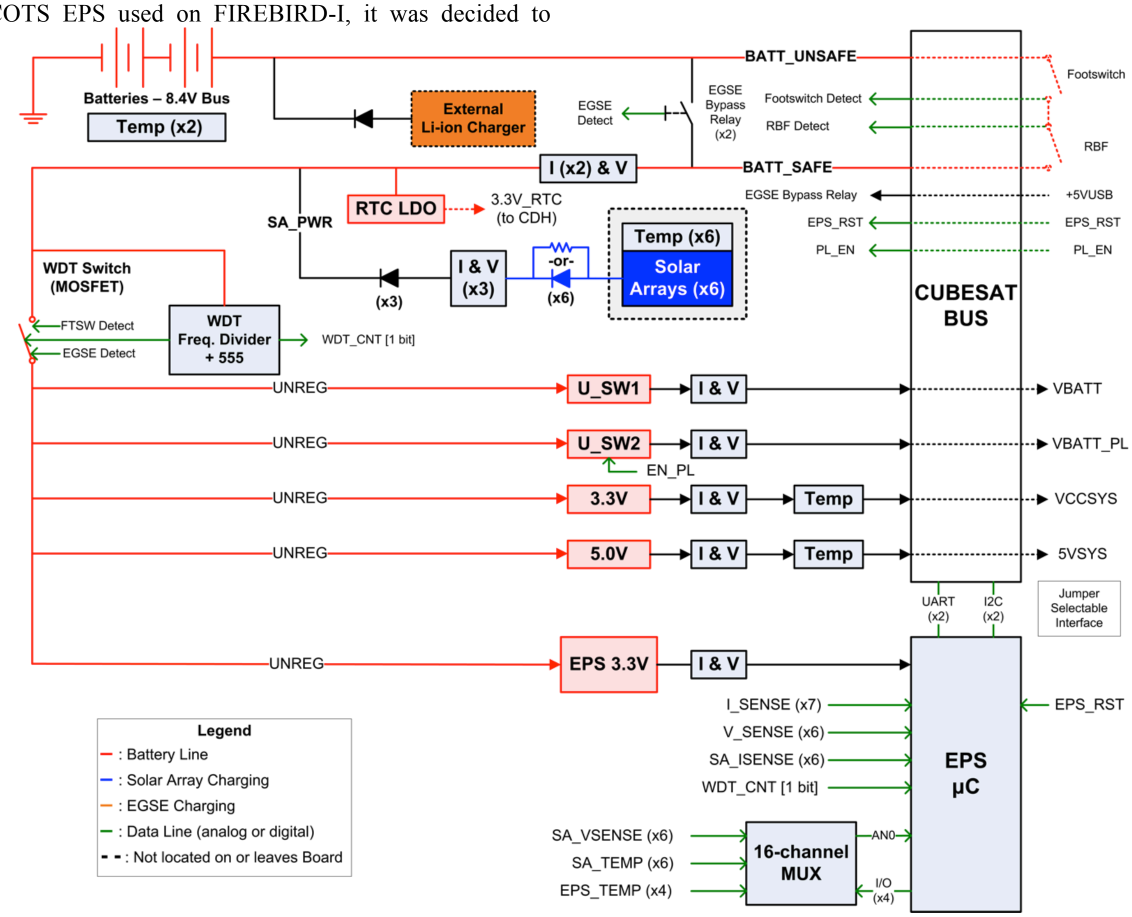

Figure 3: Phoenix EPS Block Diagram

The Phoenix EPS is based on a Direct Energy Transfer system, meaning the battery pack is directly connected to the solar arrays via protection diodes. To protect the battery cells from over and undercharging, a COTS battery protection circuit configuration was used. This battery circuit disconnects the battery cells from the system bus whenever the bus exceeds a set voltage. This means, if the battery is fully charged and the solar arrays are still providing power; the batteries will be disconnected from the system and the solar array will power the entire spacecraft. If the batteries are disconnected and a sudden load is applied, such as the COMM transmitter, the system bus voltage will drop and the batteries will be reconnected as a result.

Initially, the Phoenix EPS design called for each solar panel to be connected to a COTS buck/boost voltage regulator. This regulator would allow power to be harvested from a panel when the incident power was not great enough to produce a voltage greater than that of the battery pack. However, early testing showed that this design was not functional. The regulators chosen were not designed for use with solar cells and would pull down the voltage of the cells, by attempting to draw too much current. The final Phoenix EPS design called for the regulators to be no-loaded and bypassed with a jumper.

Another key feature of the Phoenix EPS is the hardware WatchDog Timer (WDT). This WDT is implemented using basic logic gates that count up to 12 hours then power cycle the entire spacecraft for 10 seconds. This 12 hour reset is used to resolve any single event upsets due to radiation strikes or software bugs.

The second major change from the FIREBIRD-I design was the switch to solar arrays assembled by Vanguard Space Technologies, Inc. For the FIREBIRD-I mission, MSU hand assembled solar panels through the Coverglass/Interconnect/Cell (CIC) assembly process followed by adhering them to PCB substrates. The CIC and PCB bonding process was very labor intensive and motivated the switch to professionally assembled panels. For FIREBIRD-II, as quid pro quo for Vanguard high efficiency solar panel assembly, MSU added an I-V curve measurement circuit to the back of one panel on each spacecraft. These instrumented panels are known as the FIREBIRD IMM Solar Cell Experiment (FISCE). The FISCE panels are testing a proprietary THINS assembly technique, developed by Vanguard Space Technologies, Inc. The FISCE panels are equipped with a photodiode sensor that is used to determine when the panel is at normal incidence to the light source. I-V curves are only taken when the photodiode sensor reaches a configurable threshold, indicating normal incidence.

Based on the on-orbit performance of the FIREBIRD-I spacecraft, two minor issues were found with the science data storage and downlink process. The NAND flash used to store science data on the MFIB partitions data into 4kB “pages.” Due to the downlink data rate of 19.2kbps and flight software packet size, each page has to be divided into multiple packets for downlink. The FIREBIRD-I software divided pages for downlink in a way that allowed single data samples to span multiple downlink packets. This required that all packets within a page be received sequentially in order to reconstruct the individual data samples. If one packet within a page was not decoded during downlink, all subsequent packets from that page could not be decoded. To fix this issue, logic was added to the MFIB flight software that only downlinks an integer number of data samples within one packet for the FIREBIRD-II mission. With this new downlink packet structure, an individual packet can easily be decoded, regardless of whether or not other packets from the same page were received. This reduces losses in science data downlinks.

Another issue with the MFIB science data storage was the custom FAT file system. Under the FIREBIRD-I file system, files were retrieved from the NAND flash based on the date and time when they were created. This caused problems during the FIREBIRD-I mission, because there was no way to retrieve data if the time stamps in the FAT were incorrect or corrupted. There were also several software bugs in the FAT file system. To fix this issue, MFIB data storage was simplified to an address-based file system. For the FIREBIRD-II mission data was requested simply by the page address of the data on the NAND flash. A data times file recorded the time at which each science data run started and stopped and the corresponding address in memory that was being written to at that time. Once this data times file was downlinked, ground-based processing software could convert requests for data based on UTC time to a corresponding memory address on the spacecraft.

While the FIREBIRD-I spacecraft were operational each only recorded a few intermittent GPS locks. This motivated additional ground testing of the GPS system and CDH processing of the GPS data. It was found that when GPS signals were intermittent, such as due to tumbling spacecraft, the CDH may discard valid locks and store invalid ones. By improving the robustness of the CDH GPS packet processing code, this issue was fixed.

Flight Software

The FIREBIRD CDH flight software is implemented in the C language as an application in the Micrium µC/OS-II operating system. The flight software was designed to be highly modular and configurable. The key to its configurability is the built-in command sequencer (CMDSEQ). The command sequencer allows sequences of commands to be stored and executed autonomously by the spacecraft. Sequences may contain absolute or relative wait commands. They may also initiate execution of other sequences in parallel.

On each boot, the flight software executes the first stored sequence in memory. This boot sequence configures the spacecraft by executing other configuration sequences. If a change to the spacecraft configuration needs to be made on-orbit, a replacement sequence may be uploaded for execution on subsequent boots.

Another significant part of the CDH flight software is the telemetry monitor (TLMMON) module. This module allows alarm limits to be set for specific telemetry points. If the alarm is exceeded a command sequence may be started or halted, depending on the configuration. The TLMMON is used to enter safe mode if the battery voltages drops too low and end GPS data runs if the GPS temperature exceeds a critical limit. The TLMMON module is also used during FISCE data runs, to transfer data from the FISCE panel to CDH once a status flag indicates that data is ready.

The TLMMON module relies heavily on the telemetry manager (TLMMGR) module, which is responsible for routing all telemetry within the spacecraft. When new telemetry is received from a subsystem, the TLMMGR will route it to the configured output, such as COMM, the Ground Support Equipment (GSE) port, or SD Card. The TLMMGR is also used to route telemetry to specific outputs at a configured cadence. This timed telemetry configuration is used to control the RF beacon.

Concept of Operations

Each pair of FIREBIRD spacecraft are launched together and deployed from a single P-POD. As they are deployed, one separation foot switch per spacecraft push the two apart. Based on lab testing and on-orbit data these two switches result in a relative separation velocity of 10 cm/s or approximately 9 km/day. At this rate, the first two weeks of the mission are the most scientifically interesting, due to the expected size of individual microbursts. For this reason, each spacecraft autonomously begins taking data within 2.5 hours of deployment.

After initial boot, payload data runs occur once per orbit. Initially, data runs are configured to last an entire orbit. After spacecraft and instrument checkout, data runs are reconfigured to occur only while the spacecraft is in the northern hemisphere, to conserve data storage space. By taking data only in the northern hemisphere, it will take 30 days to fill each spacecraft’s 2GB payload data memory. Once the memory is full data runs are halted. After all data of interest has been downlinked, the payload data memory is cleared and a new campaign of data runs begins.

Payload data is stored at several different cadences from 18.75 ms up to 6 sec. The 6 sec. Context data accumulates at a rate of 4 kB per orbit, while the 18.75 ms HiRes data accumulates at a rate of 1.43 kB/sec. All Context data is downlinked within days of being recorded. However, HiRes is only downlinked from small intervals of interest. These intervals are selected based on the Context data and other space weather sources.

The FIREBIRD Mission Operations Center (MOC) is located at MSU and is responsible for monitoring spacecraft health, routine commanding, and downlinking payload data. The Science Operations team (SO) consists of collaborators at MSU and across the United States who are responsible requesting processing payload data.

GPS data runs occur autonomously once per day, as do FISCE data runs. If a GPS run results in a lock, the CDH will automatically update its RTC with the current GPS time. Both FISCE and GPS data are downlinked on a regular basis.

GROUND STATION

MSU operates its own ground station for the FIREBIRD mission, with callsign K7MSU. An avid community of Ham radio enthusiasts dedicated to tracking satellites has provided beacon data from stations located in Germany, Japan and other countries. This supplemental data represents a valuable mission asset by providing spacecraft engineering telemetry in near real time from orbit locations and local times far removed from the primary ground station in Bozeman, Montana. Because FIREBIRD and previous MSU satellites have operated in the Amateur radio bands, much of the ground station is built from Amateur radio hardware, including the Yagi antennas, antenna rotators, uplink TNC, and uplink transmitter. Figure 4 shows a block diagram of the K7MSU ground station, as configured for the FIREBIRD-II mission. The ground station requires three computers, labeled SSEL-Ground1 through SSEL-Ground3 in the figure.

SSEL-Ground3 controls the Yaesu G-550 antenna rotators, based on Two-Line Elements (TLEs) obtained from www.space-track.org, using the NOVA for Windows software tool.

SSEL-Ground2 runs the Linux Mint operating system in order to run GNURadio, an open-source software defined radio toolkit. This computer runs a custom GNURadio-based program to control a USRP N200 software defined radio and demodulate FIREBIRD AX.25 packets from the USRP’s output. This computer also runs the InControl Linkage program, a MSU-written Python program that routes all uplink and downlink packets to the appropriate hardware and software, while maintaining a log of these packets.

SSEL-Ground1 runs a L3 Communications’ InControl satellite command and control software server and client. Other computers within the Mission Operations Center (MOC) also run InControl clients to allow multiple operators to monitor telemetry during a pass.

During calibration and testing, InControl was used to control the satellites and process telemetry. This proved very useful, as students who became familiar with InControl during testing needed very little training to become a member of the ops team.

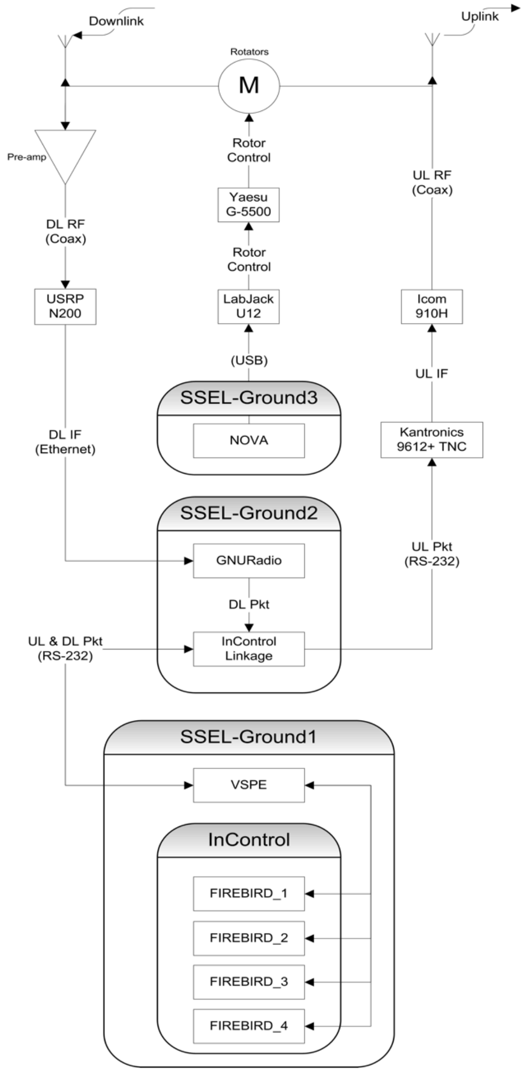

Figure 4: K7MSU Ground Station Block Diagram

ON-ORBIT PERFORMANCE

Since launch, the FIREBIRD-II spacecraft have been performing phenomenally. For the first two months both FU3 and FU4 were in a full-sun orbit. The COTS battery protection circuit worked as intended, despite higher than expected solar array voltages.

FU3 and FU4's orbits have processed to now have 30 minutes of eclipse per orbit. However, both units are still able to maintain a high state of charge, due to the low power consumption of the system. Temperatures have shifted from 30ºC in full-sun to 10ºC in eclipse season.

The improvements to the MFIB science data storage and downlink system has greatly increased the throughput of downlinks, by reducing information lost when a single packet is not decoded.

The changes to the CDH-GPS processing system have also been successful. Both flight units regularly achieve several GPS locks each week and are able to sync their onboard RTC to GPS time.

Dozens of data sets have also been collected from the FISCE experiment and are under joint analysis by MSU and Vanguard Space Technologies Inc.

CONCLUSION

The scientific success achieved with the FIREBIRD-II satellites has been enabled in part through the evolution made possible by the opportunity to discover operational vulnerabilities in the on-orbit performance of FIREBIRD-I satellites. A careful analysis of engineering data downloaded from the first pair of satellites pointed to software and hardware changes that would make the FIREBIRD-II satellites more robust. A key enabler was the presence of a fully functional Engineering Design Unit in the laboratory that could be operated and reprogrammed to diagnose issues arising during the first flight and to use as a testbed for possible work-arounds.

Acknowledgments

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