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Coral: A High Performance Design Expanding CubeSat Mission Options

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ABSTRACT

The Coral bus design meets the stringent pointing/slew requirements of Electro-Optical (EO) or Space Situational Awareness (SSA) missions, as well as the higher payload power requirements for Communications or Synthetic Aperture Radar (SAR) missions. The power design features two deployed solar array wings along with a Lithium-Ion battery that provides significant payload power during all mission timeframes. The Attitude Determination and Control Subsystem (ADCS) features excellent agility/stability performance and excellent pointing accuracy performance through the use of a Miniature Star Tracker (MST) developed by CAA. Coral's Communications system features a high data rate transceiver for support to these specialized missions. Coral's Avionics subsystem communicates over a high bandwidth, standardized bus that provides a number of external interface options to the payload. The Command and Data Handling (C&DH) software architecture allows rapid integration of any payload hardware or software option with little or no impact to the bus architecture design at any point within the program timeline. Coral facilitates rapid assembly and disassembly of the Coral spacecraft and provides clear access to external interfaces at all times. The Coral bus also provides the ability to be easily upgraded for additional capabilities (e.g., addition of propulsion and power, downlink, and encryption upgrades).

INTRODUCTION

Over the past several years, CubeSats have evolved from excellent hands-on teaching tools in the university domain into high performance, high reliability picosatellites with increasing interest from the Department of Defense (DoD) space community for experimental and operational applications. The vision for future CubeSat mission types range from technology demonstration missions to augmenting larger satellites to performing stand alone operational missions, with dedicated payloads. Comtech AeroAstro, Inc (CAA) and the Space Dynamics Laboratory (SDL) have teamed together to develop a high performance CubeSat design that is able to meet the requirements of these more stringent mission types.

With the rapid advancement of CubeSat capabilities, there are still several key areas that are lacking the maturity or capability that is needed to fully realize the potential these small satellites have. The highest priority capabilities that currently fall short of mission needs include attitude control, power, and payload volume.

The capability to accurately point a spacecraft is still not a proven CubeSat practice. Many of these spacecraft rely on periodic pointing knowledge data from the sun and magnetic field, an inherently low-accuracy method. Additionally, these spacecraft lack a mature and proven capability for agile, three-axis control. Although many missions do not require this kind of capability, this is an area that would enable a greater number and variety of missions with stringent pointing/slew requirements such as EO or SSA missions.

The spacecraft power system is an additional area where further maturity is needed. Progress has been made in providing reliable power management, power generation, and power storage; however, the current systems are mostly limited to the lower range of what is possible with CubeSats and rely primarily on body mounted panels. Payload diversity is severely limited by the small amounts of available power from existing Electrical Power System (EPS) designs. Greater power production capability is required to support payloads such as Communications or SAR.

The physical size of the CubeSat is another key limiting factor. The basic unit for CubeSat size is 1U. This is defined to be ten centimeters on a side. This size has primarily been used by educational institutions to train students in spacecraft design. Other sizes have also been defined and are multiples of the 1U form factor along one dimension. To enable the greatest number of missions, the payload volume needs to be maximized.

Program Objectives

In response to this growing interest from DoD, commercial, and university organizations, CAA, drawing on lessons learned from development and test of the Standard Interface Vehicle (SIV) microsatellite bus for the DoD Space Test Program (STP), has developed the “Coral” picosatellite spacecraft bus design. This development was performed in conjunction with SDL at Utah State University, drawing on their Pearl CubeSat experience. The goal was to design a robust, flexible, and reconfigurable CubeSat bus with sufficient performance and design margins to meet the increased performance requirements of Pointing, Power, and Volume. In addition to the three primary design objectives, the Coral bus design incorporates the following points to ensure reliability and mission success.

1. High performance components
2. Standardized and non-proprietary interfaces
3. Proven software architectures
4. Support for a large majority of mission and payload types
5. Standard quality processes and procedures
6. Spacecraft experience

CAA has targeted these areas to increase the performance over current capabilities and rigor in traditional CubSat designs. The combination of these enhancements has resulted in a CubeSat design targeted for a wide variety of missions, beyond just demonstration, to include operational missions as well.

THE CORAL SPACECRAFT BUS

CAA’s/SDL’s technical approach features a commoditized Coral bus, utilizing a high performance PCI-104 architecture (commercial, non-proprietary architecture) which offers a flexible, modular, and standardized Payload (PL) Interface (I/F) that meets or exceeds the majority of published Government and civil requirements. The Coral bus is a standard 3U design that meets all of the requirements of CubeSat spacecraft. The Coral bus is compatible with the Cal-Poly P-Pod launcher and can therefore be launched on any launch vehicle designed to carry CubeSats into orbit.

The technical approach focused on pointing accuracy, power, and available volume. The key to accurate pointing is precision attitude sensors and stable torque capability. Our team has internally developed and externally identified ADCS components that increase agility, stability, and provide excellent pointing accuracy. Kalman filtering will also be included to maintain attitude control throughout the entire orbit.

For power, our team has worked with industry leading manufactures to develop a high power deployable solar array design. The new solar array design is capable of providing 5 times more power than traditional arrays. This extra power enables the use of better processors for data manipulation and spacecraft control. Most importantly, it makes available more power to the payload for greater mission utility.

For volume, our team has chosen the 3U size as the baseline configuration. All of the spacecraft avionics and control components fit into one half of the total spacecraft volume. This leaves a total of 1.5U of spacecraft volume for the payload use. In addition to this 1.5U for payload volume, we have reserved a mission unique payload interface card that resides on the PCI-104 bus. This card can be customized for payload support electronics use. Figure 1 shows the Coral bus technical baseline including the stowed dimensions and deployed views. Figure 2 shows an exploded view of the Coral bus including PL envelope.

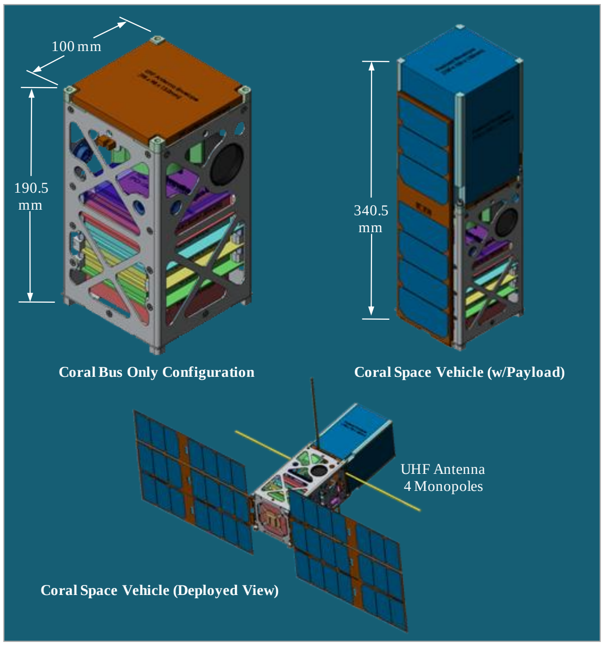
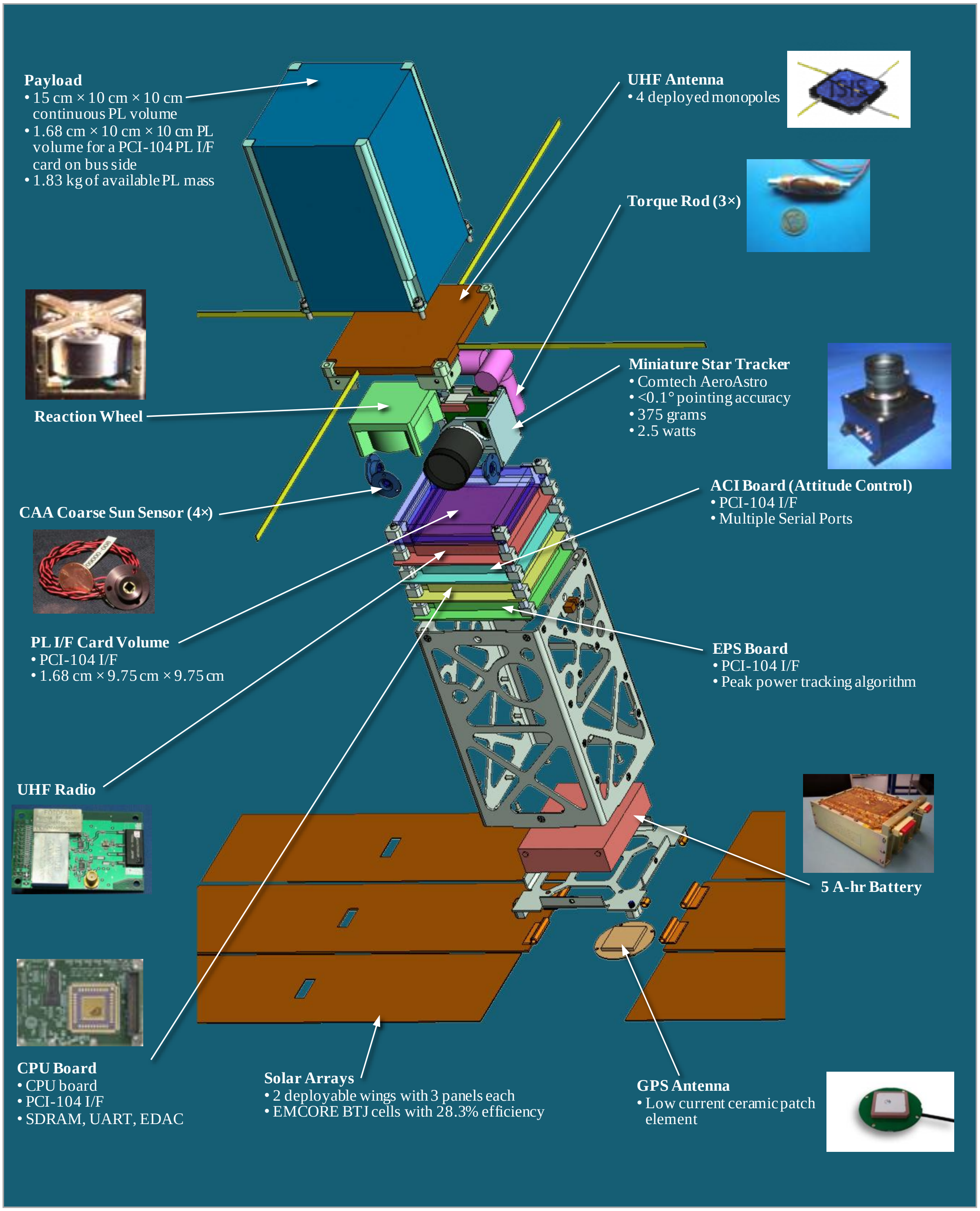


Figure 1: Our Innovative Coral Design Provides Significant Size /Volume Allotments



Payload
- 15 cm × 10 cm × 10 cm continuous PL volume
- 1.68 cm × 10 cm × 10 cm PL volume for a PCI-104 PL I/F card on bus side
- 1.83 kg of available PL mass

UHF Antenna
- 4 deployed monopoles

Torque Rod (3×)

Reaction Wheel

Miniature Star Tracker
- Comtech AeroAstro
- <0.1° pointing accuracy
- 375 grams
- 2.5 watts

CAA Coarse Sun Sensor (4×)

ACI Board (Attitude Control)
- PCI-104 I/F
- Multiple Serial Ports

PL I/F Card Volume
- PCI-104 I/F
- 1.68 cm × 9.75 cm × 9.75 cm

EPS Board
- PCI-104 I/F
- Peak power tracking algorithm

UHF Radio

5 A-hr Battery

CPU Board
- CPU board
- PCI-104 I/F
- SDRAM, UART, EDAC

Solar Arrays
- 2 deployable wings with 3 panels each
- EMCORE BTJ cells with 28.3% efficiency

GPS Antenna
- Low current ceramic patch element

Figure 2: Our Innovative Coral Bus Design Enables Mission/PL Flexibility with High-Heritage, Flight-Proven Components

To meet stringent Coral requirements, our team performed an industry-wide search of component suppliers/vendors in all subsystem disciplines to establish a technical baseline that met the required design criteria. CAA assessed current and emerging technologies in all areas to increase subsystem performance while maintaining self imposed stringent schedules.

Our technical baseline includes a significant number of innovations that provide the customer greater utility for mission and PL flexibility:

1. Simple, standard PL I/F (mechanical, electrical, and Flight Software ([FSW])
2. High bandwidth PCI-104 architecture capable of 1 Gbps data rates
3. High Precision ADCS design, including sun sensors for Safe Hold mode operations
4. High performance EPS subsystem design providing 45 Watts of Peak Power
5. Low risk, modular, existing FSW design easily tailored for custom PL FSW integration
6. High data rate/link margin Ultra-High Frequency (UHF) Radio/Antenna System with AES-256 bit encryption
7. High performance Central Processing Unit (CPU) Board based on LEON III Processor operating up to 75 MHz
8. Payload accommodations that allow all volume above the spacecraft bus to be dedicated to the Payload (except where the solar arrays stow)
9. Passive thermal control of the bus and Payload.

Table 1: CAA's Technical Approach Features an Innovative Design Supporting Numerous Government Missions and PL Types

#	Coral Features	Coral Benefits
1	Flexible PL Accommodations	• Rapid PL re-configurability with no changes required to the Coral design • High mission assurance over a variety of mission scenarios and PL types • Ample PL power and ADCS pointing accuracy available • Coral SC simulator provides PL vendors with early testbed for efficient PL I/F development and test (hardware and software)
2	Standard, Non-Proprietary I/Fs	• Industry standard, high bandwidth non-proprietary PCI-104 architecture • Simple, standard mechanical I/F consistent across all missions and PL types • Simple, modular, and non-proprietary FSW I/F • Allows custom PL FSW development with minor bus FSW updates to command/telemetry database
3	Rapid AI&T	• Low parts count • Minimal component new development • Minimal cable harness required due to PCI-104 I/F
4	PL Volume Exceeding Requirements	• 15 cm x 9.75 cm x 9.75 cm of continuous PL volume provided • An additional 1.68 cm x 9.75 cm x 9.75 cm provided for a PL I/F card on the bus side • Separate PL volumes permit larger PL aperture sizes to enhance/optimize PL performance
5	High Performance ADCS	• Agile/stable bus platform design based on a high performance MST • Slew rates of ~1 /second for optimization of optical missions in-theater • Robust ADCS Modes-and-States transition philosophy for multiple mission scenarios
6	High Performance EPS	• Significant PL power available over a 23-minute eclipse period • Supports higher power PL types (SAR, Communications, etc.)
7	High Performance TT&C Radio System	• Low risk UHF system (radio and deployable antennas) with AES-256 bit encryption • >52 kbps downlink data rate at 5 degrees elevation while meeting link margin/BER requirements • 1 Gbps internal data rates between PL and radio over the PCI-104 I/F
8	Design for Mass Production	• Well documented, simplified PL integration steps minimize PL integration timelines • Pathfinder testbeds enable early test integration of flight hardware and FSW • Innovative sparing philosophy that maintains flexibility at the component and integrated Coral levels to accommodate part, component, or system issues with minimal schedule impact
9	Streamlined Program and Process Management	• Rigorous supply chain management to manage schedule performance • Alternate electrical/mechanical piece part suppliers identified to minimize sole source concerns • Strict adherence to streamlined "production environment" documented processes and procedures

Designs and Performance

Coral's internal bus and PL electronics communicate over high bandwidth PCI-104 bus I/F, shown in Figure 3. The PCI-104 offers excellent bandwidth performance while conforming to the Coral form factor (3U-Cubesat). The Coral design permits a dedicated PL I/F card volume located on the Coral bus side to maintain a flexible, seamless PL I/F protocol (RS-422, 1553, SpaceWire). The design utilizes a dedicated fifth row, or Row E, on the PCI-104 bus to provide substantial power and General Purpose Input/Output (GPIO) to the PL. This provides a versatile and flexible electrical PL I/F residing directly on the PCI-104 bus, to provide the PL with ample power (3 Amps at 12 volts max) and 11 discrete GPIO I/Fs helping to reduce the number of external cable harnesses required for the design. As Figure 3 shows, the Coral design has two Ground Support Electronics (GSE) I/Fs to the PCI-104 bus I/F including a data GSE I/F (CPU Board) and a Power GSE I/F (EPS Board). The data GSE I/F is implemented using a high speed Ethernet interface and serves as a conduit to load FSW onto the Coral bus.

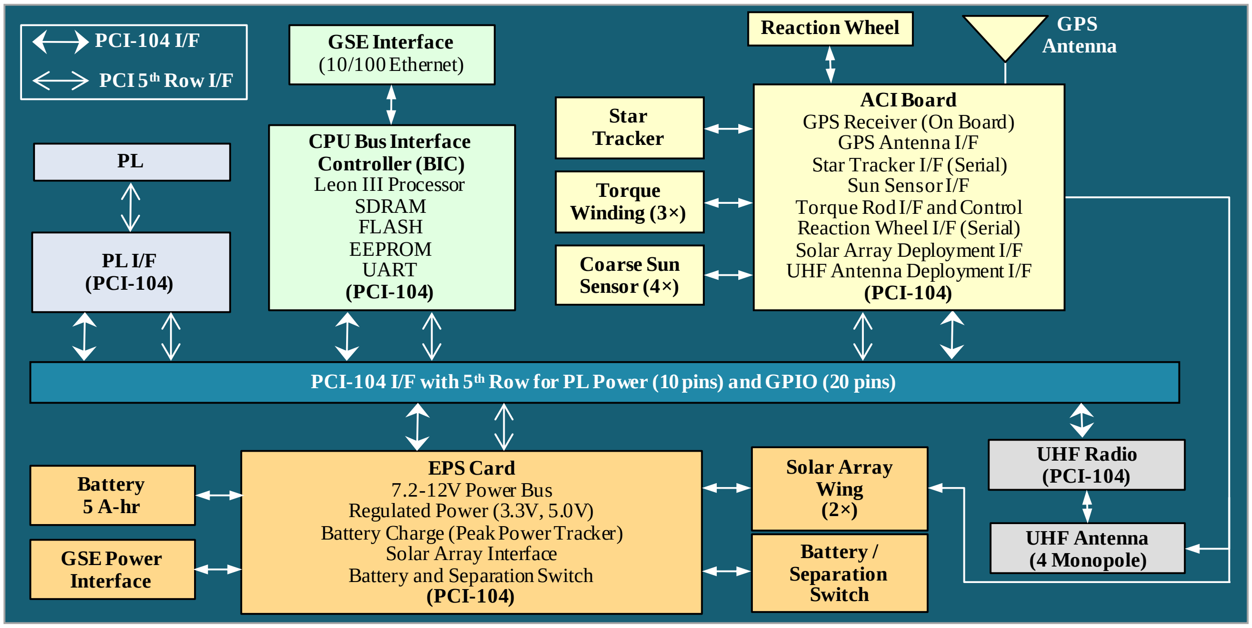


Figure 3: Coral Bus Features the PCI-104 Architecture Providing 1 Gbps Data Bandwidth Performance

SDL's PEARLsoft FSW provides the core C&DH software components required to operate the Coral bus and PL elements. Key components, shown in Figure 4, include a System Monitor, Communications Handler, Network Manager, Code Update Handler, Command Handler, ADCS Controller and Resolver, Telemetry Processor, and PL manager. The FSW uses a multi-threaded architecture providing excellent design modularity that allows a high level of reuse and adaptability to meet a broad range of mission requirements. Separate threads for communications, attitude control, and PL management allow for ease of modification, upgrade, or reconfiguration without extensive retest or recode.

The PL manager module allows custom I/Fs with minimal modifications to the Executor and Telemetry Processor.

PEARLsoft is currently running on a radiation tolerant Bus Interface Controller (BIC) Single Board Computer (SBC) utilizing the the same LEON3-FT processor. The primary operating system is Wind River Systems' VxWorks 6.5. PEARLsoft is designed to be Portable Operating System Interface (POSIX) compliant. PEARLsoft provides a verified and validated "off-the-shelf" C&DH Spacecraft (SC) toolkit, allowing CAA and it's customer to focus resources on PL-application-specific development rather than "reinventing" the C&DH infrastructure.

A typical PL FSW implementation scenario is as follows:

1. Develop PL specific command and data dictionaries
2. Add PL specific command and telemetry processing for ground station integration
3. Add required PL specific commands to PEARL command data handler tasks
4. Add required PL specific telemetry to PEARL telemetry processor tasks
5. Add required PL specific system monitoring to PEARL system monitor tasks

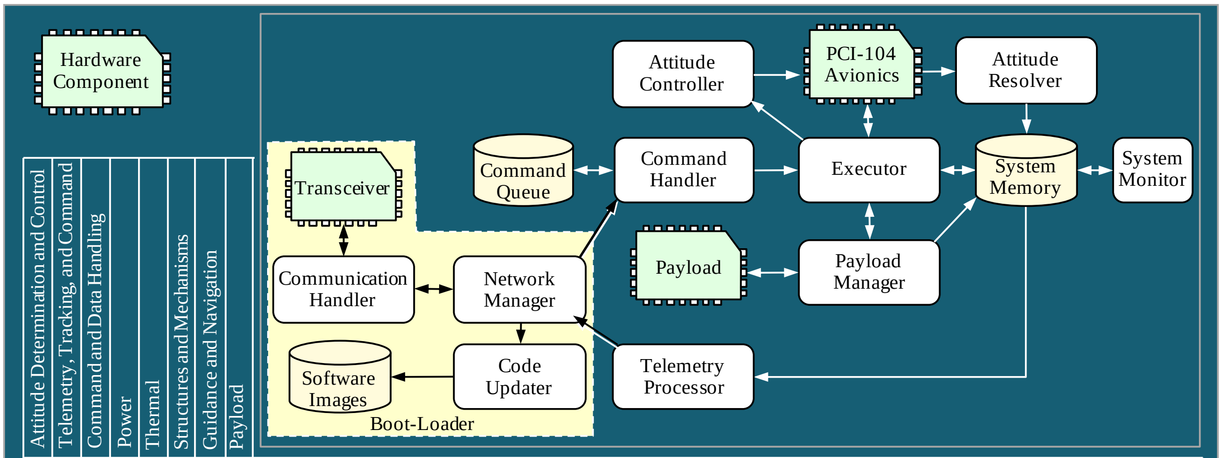
Our team estimates a code reuse of about 90% of the existing PEARLsoft code. Only minimal modifications are required to the Attitude Resolver and Attitude Controller to accommodate our Coral bus specific ADCS components, including the star tracker and torque rods. Additionally, an earth magnetic field model replaces the magnetometer hardware functionality. Our team is currently in the process of building software compatible with the AFRL Plug-n-Play architecture. This software development effort targets the same Leon3-FT processor and could be ported to the CubeSat if an application or a requirement presented itself.

Physical and Technical Specifications

The Coral bus is designed to be manufactured, assembled, integrated, and tested in a production/assembly-line environment. Missions that require multiple busses can be greatly benefitted by this approach.

Structure and Thermal

The structure, at 10% mass fraction to the overall Coral bus mass, consists of Aluminum (Al) 6061-T6 panels (sides and bottom) that have cutouts for ease of electrical integration between the PCI-104 avionics boards and peripheral components (star tracker, reaction wheel, torque rods, etc.).



Attitude Determination and Control	Telemetry, Tracking, and Command	Command and Data Handling	Power	Thermal	Structures and Mechanisms	Guidance and Navigation	Payload	Thread	FSW Module Characteristics
Subsystem									
			●	●				System Monitor	State of health monitoring and fault response with in-flight configurable error detection
	●							Communications Handler	Supports OSI link layer communications: OSI Link Layer: AX.25 Protocol
		●						Network Manager	Supports OSI network layer communications: CCSDS Space Packet Protocol
	●							Code Updater	Facilitates reprogramming of code images on orbit: Flash memory manager
	●							Command Handler	Command validation, script management and 1 sec command execution fidelity
			●	●	●			Executor	Implements system control and manages command execution and response
●						●		Attitude Resolver	High order Kalman filter for determining SC attitude from the ADCS sensor suite
●								Attitude Controller	Control law resolution of attitude aerodynamics control using ETRs and reaction wheels
	●	●						Telemetry Processor	Prioritizes and organizes data for real-time and store-and-forward downlinks
							●	Payload Manager	Primary PL software interfaces to the executor thread and on-board data storage

Figure 4: CAA's FSW I/Fs are Fully Defined and Provide Flexible PL FSW Integration

Anodized Al 6061-T6 rails are accommodated at four structure corners. A single separation spring and switch are utilized at the corner rails. Finally, the structure provides a standardized PL I/F that is precision aligned through the use of drill templates that accurately locates the PL I/F on the PL and the Coral structure. This yields a repeatable mechanical PL I/F, eliminating the need to re-align and re-verify PL alignment to the bus if the PL is de-stacked from the bus at any time. PL volume accommodations are shown in Figure 5. The thermal subsystem consists of a simple, cold biased, and passive thermal system using radiators (silver Teflon tape) on the primary structure panel external surface area. No Multi-Layer Insulation (MLI) is used in this design.

The thermal design, modeled in Thermal Desktop, is evaluated against a 700 km sun-synchronous orbit range of beta angles including 0^{o}, 65^{o}, and 90^{o}, and for a PL power of approximately 18 watts OAP.

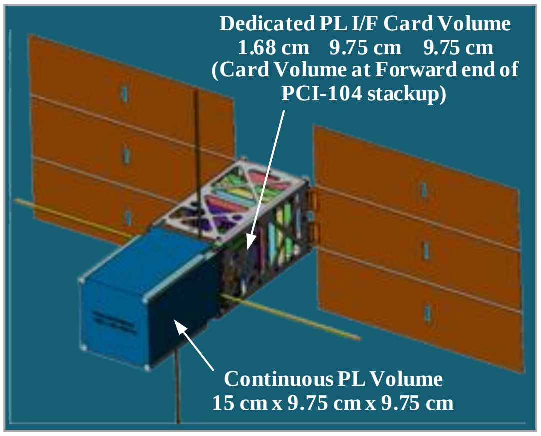


Figure 5: Coral's PL Volume

The thermal model assumes a PL I/F conductance of 0.039 W/cm^{2}/C over the available surface area. The worst case thermal model results show an average bus temperature in the 15^{o} C range for steady state temperature performance. The primary system driver is the lithium ion battery, which desires a temperature range between 0^{o} to $+25^{o}$ C. Per the analysis results, the battery, which is deliberately located on the aft end of the SC, is well within its thermal limits.

Command & Data handling

The C&DH system is designed and built by SDL. Table 2 shows the components and basic features of the system. Both C&DH boards utilize non-proprietary PCI-104 standard (32-bit, 33 MHz) allowing data rates of 1 Gbps.

Telemetry Tracking & Command

The Telemetry, Tracking and Command (TT&C) design includes a PCI-104 UHF radio and a UHF antenna system consisting of deployable 4-monopole antennas. We are also investigating the accommodation of an S-Band system for high data rates and compatibility with typical DoD missions. The UHF radio has the following features:

1. Operates at 450 MHz
2. Utilizes AES-256 bit encryption
3. RF power output of 8.1 watts
4. GMSK modulation
5. >10dB of link margin for 5^{o} – 90^{o} elevation at >53 kbps, using a BER of 10 e-5.

Table 2: C&DH Electronics Description

Component	Features
Bus Interface Controller (BIC)	Radhard Leon3 Processor
	Up to 75MHz Clock
	IEEE-754 Floating Point Unit
	128 Mbytes (EDAC) SDRAM
	512 kbytes (EDAC) EE
	512 Mbytes Flash
	10T/100 Ethernet Port
	1 UART Interface
	1 serial Debug Port
	33 MHz, 32 bit PCI Bus Master
Attitude Control Interface (ACI)	3 channel Torque Rod Driver
	2 Serial Port Interfaces
	8 Channel A/D for Sun Sensors
	4 Deployment Driver Outputs

Electrical Power System

The EPS system consists of a 42 watt solar array, a lithium ion battery, and an EPS controller board. The solar array consists of two solar array wings with three panels using second generation Triple Junction (BTJ) cells at 28.3% efficiency. The battery is configured using 18650HC cells and provides over 17,000 cycles of failure-free on-orbit performance. The battery is sized based on the mission requirements. A three cell, 12 volt battery is baselined. Larger battery packs can be configured to accommodate various mission requirements and parameters. The EPS controller board connects to the PCI-104 I/F and provides 3.3V and 5V regulated power as well as 12V unregulated power. The controller provides the ability to autonomously load shed if required due to an on-board anomaly. The board interfaces between the solar arrays, battery and the load to provide up to 60 watts of peak power. The EPS controller implements a fast converging, incremental conductance Maximum Peak Power Tracking (MPPT) algorithm to extract the maximum power from the solar arrays at varying insolation levels common to LEO orbits. The algorithm is implemented in a radiation tolerant Field Programmable Gate Array (FPGA).

Attitude Determination and Control

The ADCS design has the following components and features:

1. 3-axis stabilized, momentum biased system using a CAA MST
    a. (70 arc-second accuracy in roll about boresight, 30 arc-second accuracy in cross-boresight axis)
2. Three 0.2 A-m^{2} torque rods for momentum management

3. Four CAA coarse sun sensors for sun acquisition and safe modes
4. One reaction wheel (10mNm-sec nominal momentum and 1mNm nominal torque for stabilization)
5. GPS receiver integral to the ACI board
6. GPS antenna mounted on the aft end of the structural panel.

The ADCS modes are shown in Table 3. CAA's ADCS subsystem utilizes a momentum bias to stabilize the Coral bus about the solar array normal (yaw) axis. Three orthogonal 0.2 A-m^2 torque rods provide control about all three axes, while the wheel is employed for precise control about the yaw axis. The ADCS hardware configuration uses an on-orbit earth magnetic field model to support the torque rod control law. Figure 6 shows our Coral bus attitude control design performance based on a sun-synchronous, 700 km orbit. A field vector containing magnetic strength and direction in an earth fixed-frame (Earth Center Earth Fixed [ECEF]) is computed using GPS position data.

This information and the precise capability to transform ECEF to Earth Centered Inertial (ECI) using the star tracker attitude solution, allows for real time calculation of the Earth's magnetic field to within 10nT in the absence of solar and atmospheric magnetic disturbances. During any brief periods in which magnetic field upsets occur, table accuracy is better than 10% of the total magnetic strength. Under these conditions, the Coral design maintains better than 2^o pointing accuracy in roll and pitch and better than 0.5^o about the yaw axis. Our design incorporates the MST to provide pointing knowledge to better than 0.3^o in all three axes. Successive attitude quaternions can also be used to derive rates to within 0.05^o/sec. The control system is capable of slews about the yaw axis up to 0.5^o /sec and cross axis slews at ~0.1^{o}sec.

The CAA coarse sun sensors provide for safe operations in case of an on-orbit anomaly that requires Coral to transitions to Safe Hold mode. This design provides low-cost and low-risk redundancy sufficient to maintain power positive attitude outside of eclipse. The high precision ADCS system offered on the Coral bus design is necessitated by the substantial eclipse periods experienced at sun-synchronous orbits. In one year of mission life, a 700 km orbit has over 100 days of eclipse periods ranging up to 23.1 minutes in duration. These extended periods, without sun, render the sun sensor data unusable for precise attitude determination. Operating within this reduced-sensing regime requires orbit propagation with an inertial measurement unit and on-orbit attitude propagator. We assessed this configuration and found that the propagation error during the 23.1 minute eclipse period fell significantly outside the 0.5^o pointing accuracy goal. An alternative configuration could use earth sensors to perform continuous attitude measurements during eclipse; however, our team has determined that this configuration provides significantly degraded performance in a similar CubeSat form factor.

The Coral design meets the 25 year de-orbit requirements (NASA Safety Standard 1740.14 and DoD Instruction 3100.12, Sec 6.4) without the use of a dedicated de-orbit mechanism. Per Satellite Tool Kit (STK) modeling, The Coral bus is predicted to de-orbit in 21.4 years based on using a conservative drag coefficient of 2.0 and a SV mass of 3.83kg.

SUMMARY AND CONCLUSIONS

The Coral bus implements a technical approach that provides users with maximum PL flexibility. We have optimized several key areas, Pointing, Power, and Volume within the system design and have addressed critical areas lacking in the current CubeSat arena.

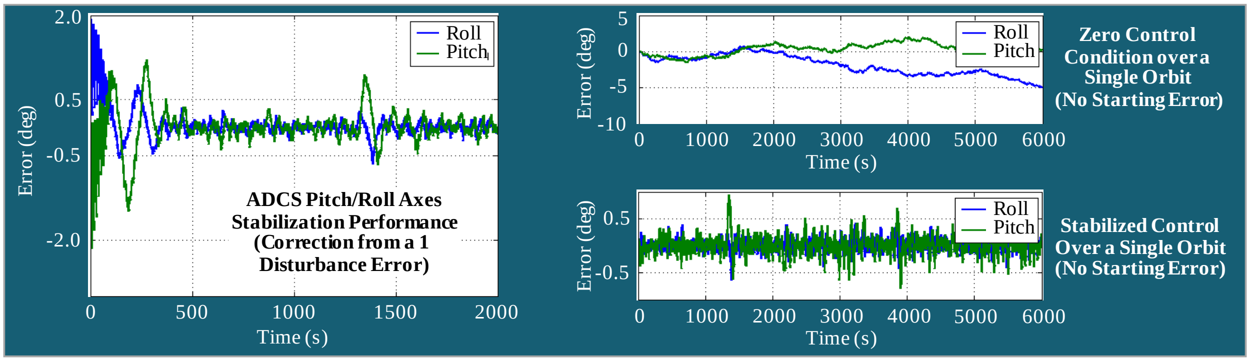


Figure 6: Our Coral ADCS Design Meets Very Stringent Pointing Accuracy Requirements

Table 3: CAA's ADCS Subsystem Incorporates Seven Separate Control Modes

Mode	Function	EMT Operation	RW Operation	Sensors/Actuator Conditions
Standby	Pass-through for open-loop mode entry	None	None	None required
Open Loop	"Open-loop" actuator commanding for ground testing, on-orbit calibration	Open-loop commandable dipole	Closed-loop commandable wheel speed Open-loop commandable wheel torque	None required
Detumble	Reduce spacecraft rates with respect to inertial space (max rate < 1°/s) and align to sun pointing axes	PID Control for CSS Alignment with sun vector	Closed-loop constant wheel speed for angular momentum stiffness	CSS, EMT, RW required Star Tracker, GPS desired
Sun Pointing	Align spacecraft in inertial sun pointing attitude for power-positive operation	PID yaw control, LQR roll/pitch control	Constant wheel speed for angular momentum stiffness	Star Tracker, GPS, EMT required RW desired
Slew	Perform slew to specified axes	PID yaw control, LQR control, pitch control	PID yaw control	Star Tracker, GPS, EMT required RW desired
Inertial Pointing	Hold spacecraft pointing to commanded inertial axes	PID yaw control, LQR control, pitch control	PID yaw control	Star Tracker, GPS, EMT required RW desired
Safe Hold	Safely maneuver to power-positive orientation with reduces sensor capabilities	Yaw control for CSS alignment with sun vector	Yaw control for CSS alignment with sun vector	CSS, EMT required RW, GPS desired

These features allow our Coral design to accommodate the stringent pointing/slew requirements of EO or SSA missions and accommodate missions requiring higher PL power such as Communications or SAR with no changes to the bus design. Mission and PL reconfiguration is simple, rapid, and reliable with minimum logistics footprint, reducing overall program cost

ACKNOWLEDGEMENTS

Not Applicable

REFERENCES

Not Applicable