Avionics Design Architecture for Low-Cost CubeSat Missions and Lessons Learned from R5-S2 and R5-S4

IEEE Aerospace Conference

March 2025

Kathryn Knesek, Morgan Alexander, Jack Wisbiski

NASA Johnson Space Center

R5-S2 *– R5 Spacecraft 2,* ***R5-S4*** *– R5 Spacecraft 4*

R5 Project Overview

Realizing Rapid Reduced-cost high-Risk Research

Goal: integrate, launch, and operate payloads in LEO quickly and cheaply

Why:

- Host payloads to support increase in TRL level (TRL 4 to TRL 8)
  - Cost savings
  - Rapid speed: on-orbit less than a year after selection
- Increase in-space inspection technologies

How:

- Reevaluating standard processes and protocols surrounding spaceflight hardware development
- Accelerating assessment of modern COTS components
- Sharing cost and schedule saving opportunities and methods with the broader space community

***LEO** – Low Earth Orbit, **TRL** – Technology Readiness Level, **COTS** – Commercial off the shelf*

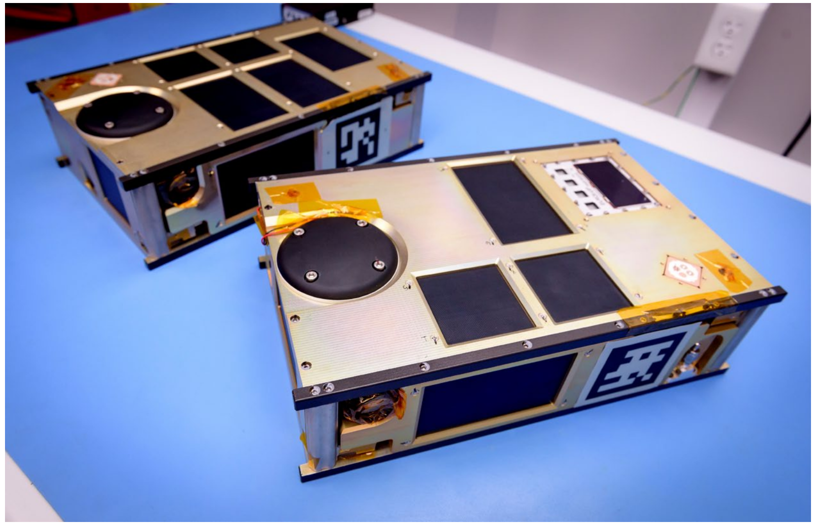
R5-S2 and R5-S4 Mission Overview

R5-S2 and R5-S4 are 6U CubeSats on the NASA ELaNa 43 mission that launched July 3, 2024 on Firefly's Alpha FLTA005.

Primary Objectives: power on, autonomously start operations, and transmit telemetry to the ground.

Secondary Objectives:

- Commanding the spacecraft from the ground
- Demonstrating the cold gas propulsion system
- Automatically power cycle:
  - Shut down
  - Recharge batteries from solar panels
  - Reboot
  - Resume mission from the previous point
- Validating environment assumptions
- Demonstrating larger messages over Iridium's SBD link
- Imaging the launch vehicle upper stage upon deployment and downlink imagery
- Exercising the GNC system
  - Star tracker
  - GPS
  - IMU



R5-S2 (left) and R5-S4 (right)

Both spacecrafts host fiducial marker payloads.

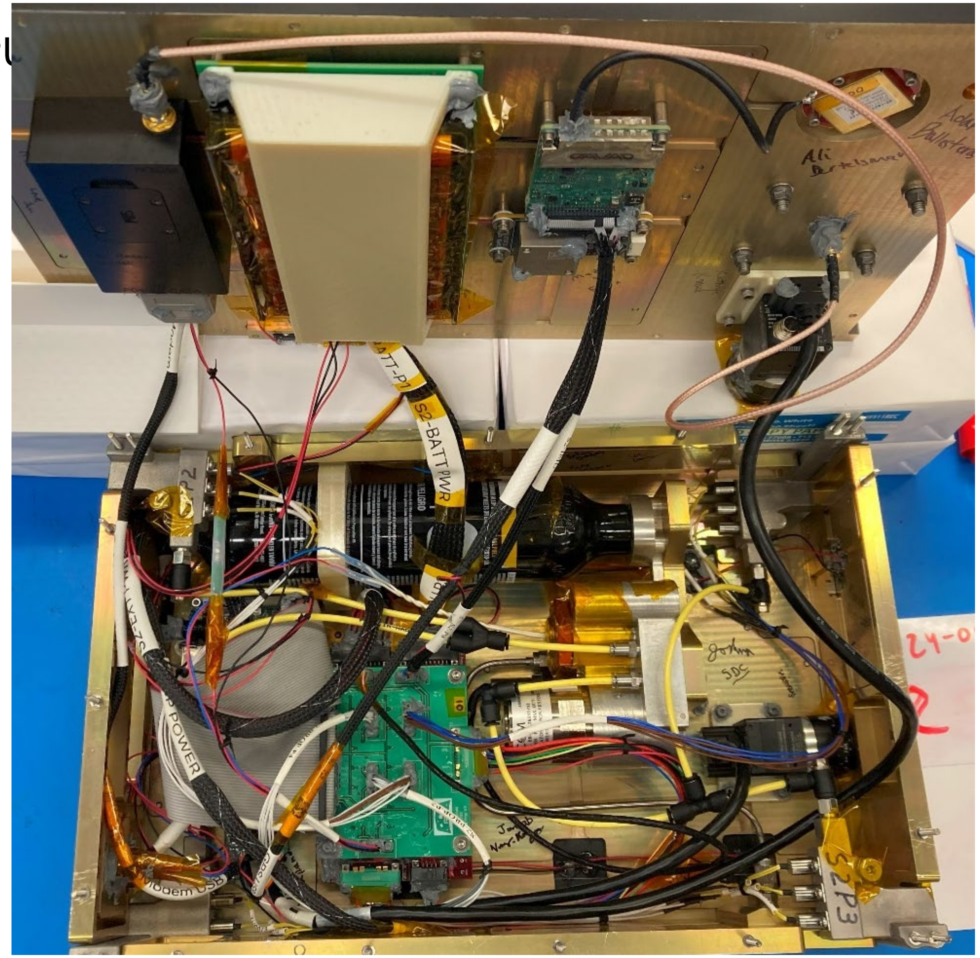
R5-S4 host an ELROI from Los Alamos National Laboratory.

ELaNa *– Educational Launch of Nanosatellites,* ***SBD*** *– short burst data,* ***GNC*** *– guidance, navigation, and control,* ***GPS*** *– global positioning system,*
IMU *– inertial measurement unit,* ***ELROI*** *– Extremely Low Resource Optical Identifier*

R5-S2 and R5-S4 COTS Avionics

Flight Computer **-** UP Board (UP-CHT01-A20-0464-A1)

- Intel Atom x5-Z8350 system on a chip with Intel Gen8 HD400 internal GPU
- 4GB of DDR3 memory and 64GB of eMMC storage
- Interfaces include:
  - USB 2.0
  - USB 3.0
  - HDMI
  - Ethernet port
  - UART/SPI/I2C serial interfaces
  - 28 GPIOs



Open View of R5-S2

Peripherals

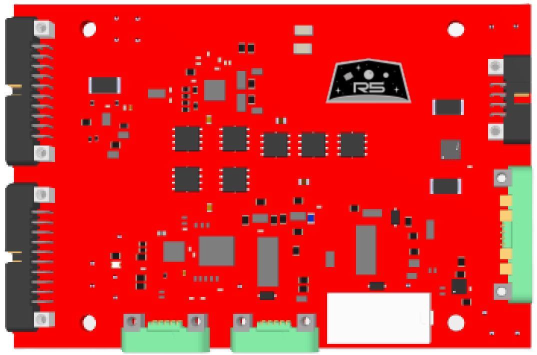
- Epson M-G370PDS0 IMU
- Ximea MQ013CG-E2 camera
- Ximea MC023MG-SY-UB camera
- JAVAD TR-2S GPS receiver
- NAL A3LA-RS Iridium Modem

***GPIO** – general purpose input/output*

R5-S2 and R5-S4 Avionics Design - Power

Power Distribution Unit — Custom PCB responsible for:

- Charging and monitoring the batteries
- Protection against power faults
- Providing 5 V, 12 V, and 3.3 V power rails
    - Support 50W
        - COTS options could not meet the power, price, or size requirements



Top View PDU for R5-S2 and R5-S4

Solar Panels — COTS Voltaic Systems P123 (0.6W) and P124 (1.2W) ETFE coated solar panels are body-mounted across the spacecraft as space allowed.

Batteries — 1S6P pack of Samsung 30Q 18650, 3Ah Li-ion batteries tab-welded on a custom PCB with fusing.

Battery pack design flown on R5-S2 and R5-S4

PDU *– power distribution unit,* ***PCB*** *– printed circuit board,* ***ETFE*** *– Ethylene tetrafluoroethylene,* ***1S6P*** *– 1 series, 6 parallel*

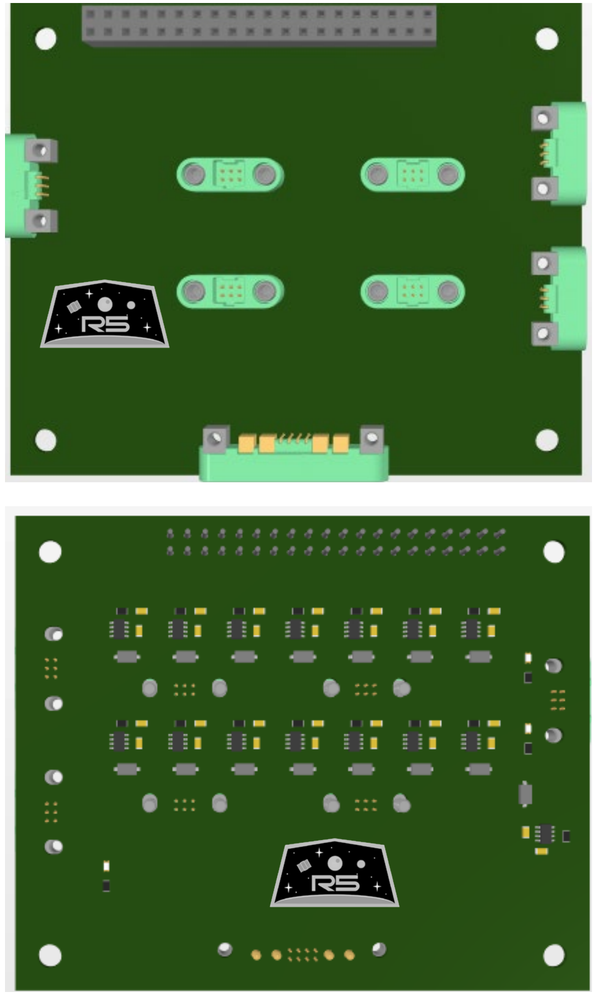
R5-S2 and R5-S4 Avionics Design - Propulsion

Propulsion Control Board — Custom PCB

- Half-bridge gate drivers for isolation and thruster valves
- Route GPIO pins from UP Board to the rest of system
- UART interface for IMU
- Load switch for Iridium modem 5V power

Cold-Gas Propulsion System Interfaces —

- 12x Parker C7 miniature cartridge solenoid thruster valves
- 1x Lee Company high-pressure isolation solenoid valve
- 1x TE Connectivity EB100 high accuracy miniature pressure transducer



Propulsion Control Board Top and Bottom Views

***PCB** – printed circuit board, **GPIO** – general purpose input/output, **IMU** – Inertial measurement Unit*

R5-S2 and R5-S4 Performance in Orbit

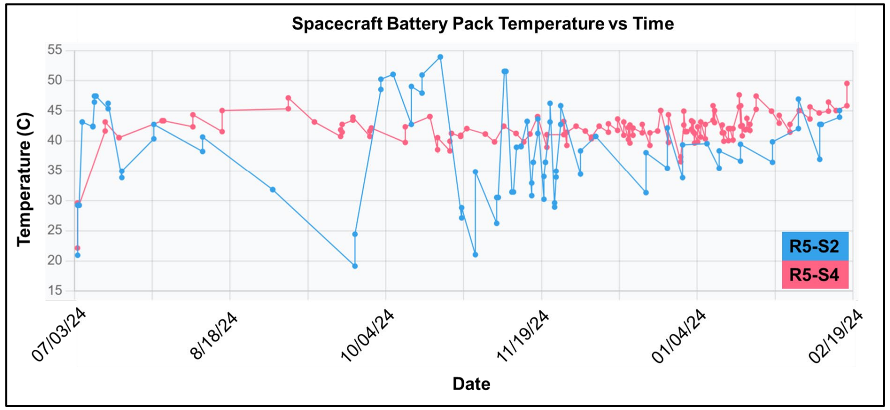
Upon deployment, both spacecrafts turned on and sent data packets, **completing the primary objective.**

Both spacecrafts:

- Responded to commands from the ground
- Completed a successful propulsion system demonstration
- Powered off and the batteries recharged. Hours later, powered back on and resumed the mission
- Downlinked imagery from the cameras
- Tested the limits of the Iridium link
    - Repeatedly sent 1kB SBD messages successfully (~3x larger than ever before)

The team validated some environmental assumptions like temperature.

- Samsung 30Q's rated discharge temperature range is -20 °C to 75 °C
- R5-S2's battery temperature reported between 19 °C and 54 °C
- R5-S4's temperature reported between 22 °C and 47 °C



There was a software bug that greatly hindered the GNC data and performance.

LANL successfully observed the ELROI payload on R5-S4.

The spacecrafts are currently still operating. They follow a cycle of ~2.5 hours on, 12+ hours off. Off-time is variable and dependent on many factors to recharge the batteries. Longest off-time was an outlier at 24 days!

SBD *– Short burst data,* ***GNC*** *– Guidance, navigation, and control,* ***LANL –****Los Alamos National Laboratory,* ***ELROI*** *– Extremely Low Resource Optical Identifier*

R5-S2 and R5-S4 Lessons Learned (COTS)

- *Grounding Scheme* — NASA handbook for grounding in unmanned spacecraft calls for a SPG. COTS parts often connect their mounting holes to ground which violates SPG. COTS parts were insulated from spacecraft structure with an Ultem bracket.

- *Battery Connection* — COTS clip-in/spring mounts failed during vibration testing. Tab welded battery packs are now used.

- *COTS Datasheets* — Components' power specifications did not match the power specifications listed in their datasheets. Measure power consumption in all operating states and during power-on to ensure system power is adequate.

- *Part Procurement* — Solar panels went out of stock and flight computer now EOL. R5 adopted a parts-rich philosophy.

Battery pack design flown on R5-S2 and R5-S4

SPG *– Single Point Ground,* ***COTS*** *– Commercial Off the Shelf,* ***EOL*** *– End of Life*

R5-S2 and R5-S4 Lessons Learned (Custom)

- *Prop Control* — Hit-and-hold solenoid driving method can reduce power consumption.
- *Board Thickness* — Confirm thickness of PCB will work with specific through-hole components.
- *Part Selection* — Small and unique footprints can limit copper weight and trace width, making manufacturability harder.
- *Complexity* — Keep the complexity of software configuration settings for hardware low to minimize time spent testing and troubleshooting.
- *Fusing* — The first battery pack design did not have a fuse; it was located on the PDU. During assembly, the battery wire harness was pinched causing a ground short of the battery pack to the spacecraft structure. Fuses are now located on both battery and PDU.

PCB – *Printed Circuit Board*, **AIT** – Assembly, Integration, and Testing, **PDU** – Power Distribution Unit

R5-S2 and R5-S4 Lessons Learned (Cables)

- *External Wall Wiring* — Components located on different external walls were bundled into a single harness. It was impossible to separate the walls of the spacecraft once assembled. Each spacecraft body face (or component) should have its own connector to simplify assembly and troubleshooting.

- *Strain Relief and Routing* — Identifying harness strain relief points would have simplified cable routing and saved rework.

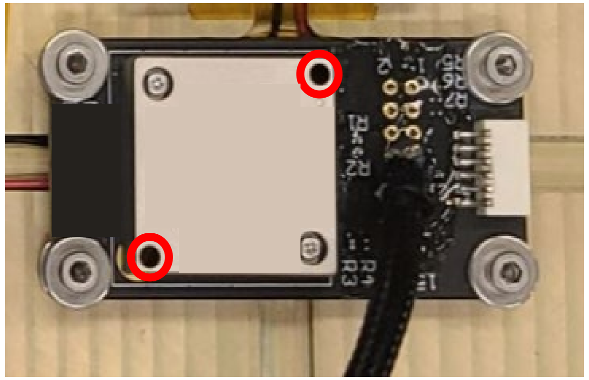
- *Cable Drawings SVN* — Altium's Wire Harness Drawing type did not integrate with Altium Vault, leading to version control issues

- *COTS Cabling* —
  - Look at materials for off-gassing properties
  - Cables did not always come in the perfect size
  - Thicker than custom cables (larger bend radii)

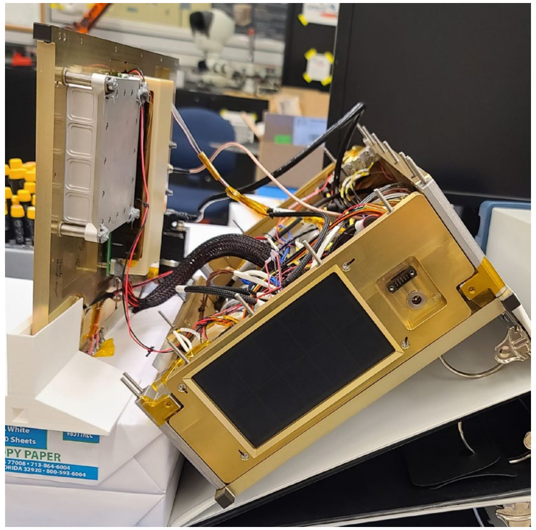
SVN *– Subversion Software,* ***COTS*** *– Commercial Off the Shelf*

R5-S2 and R5-S4 Lessons Learned (AIT)

- *System Behavior* — UP Board has transient GPIO pin behavior on startup. Our system should be protected against this or have "arm-and-fire" signals to enable.
- *Thermal Cycle Testing* — Revealed undetected workmanship errors.
- *Extra Parts* — Multiple components were accidently damaged or handled improperly during integration.
- *Communication between subsystems* —
  - IMU not bolted down during assembly, detached during vibration testing.
  - Cable lengths and routing paths were insufficiently specified.



IMU missing mounting screws

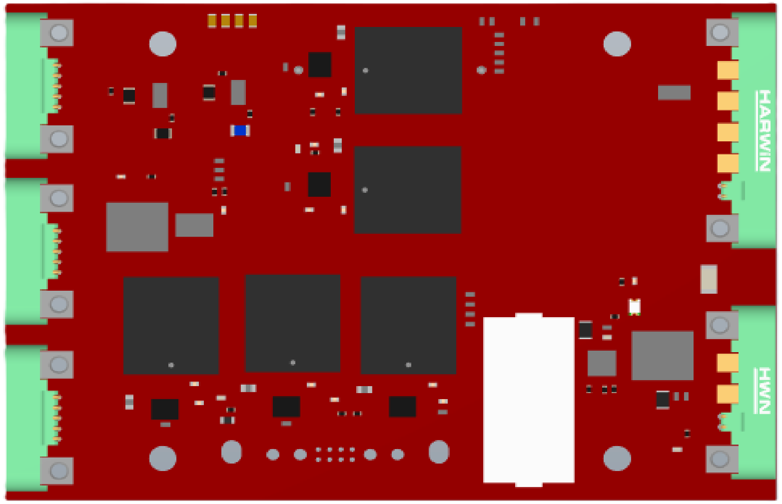


Cable lengths too short

AIT – Assembly, Integration, and Testing, **GPIO** – General Purpose input/output

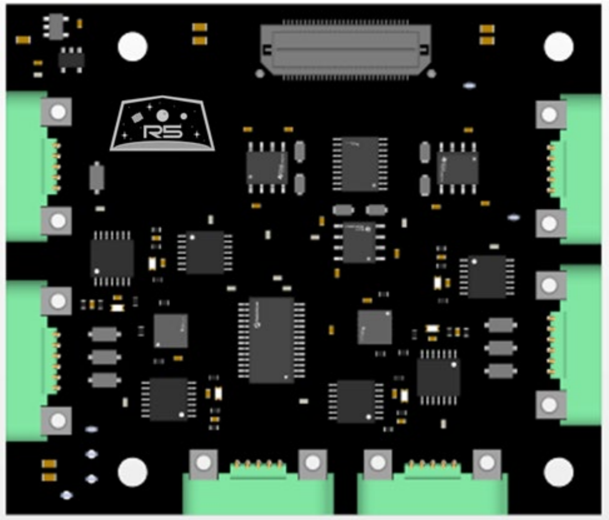
R5 Changes – Pathway to Design Reuse

PDU



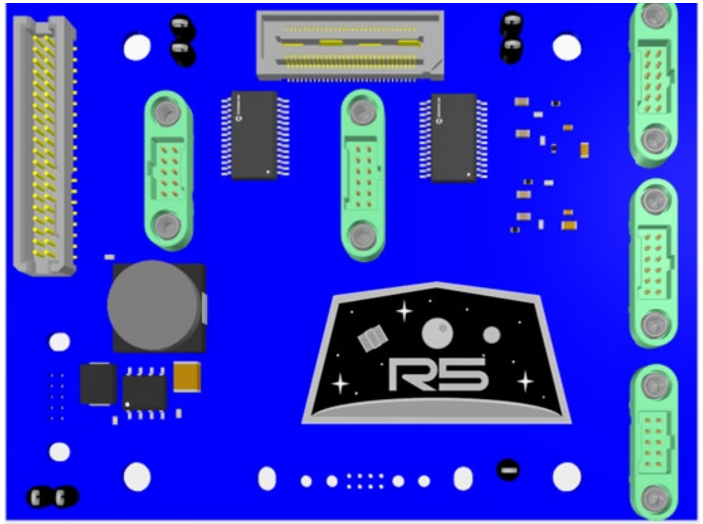
- Improved efficiency
- Simplified battery charger
- Changed difficult footprint component

Prop and Reaction Wheels



- Removed external peripheral interfaces
- Implemented hit and hold for solenoid valves
- Added reaction wheel control

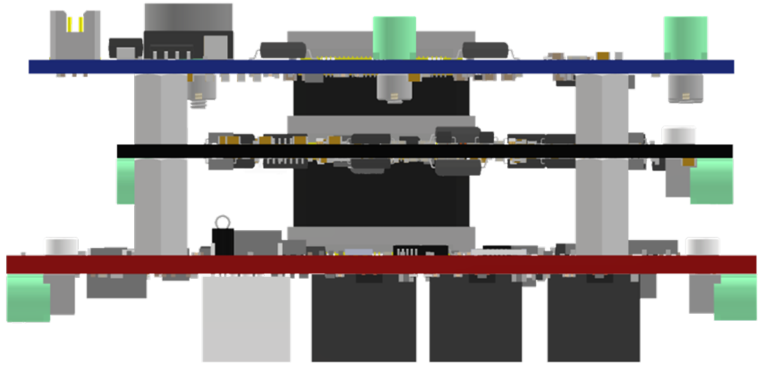
Interface Board



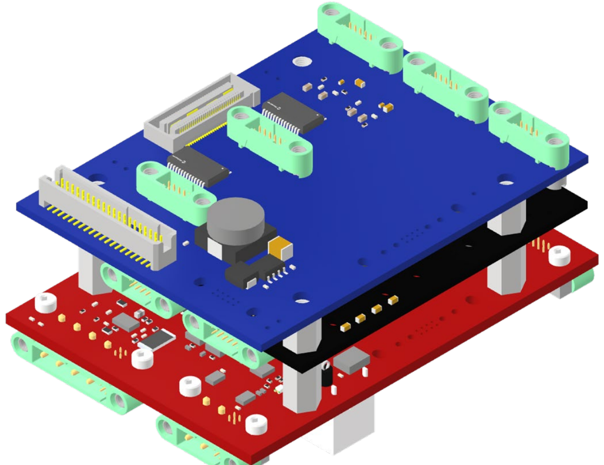
- Added load switching for peripherals and payloads
- Provide SPI, I2C, and RS232 from UP Board to spacecraft bus
- **Can be modified to integrate different mission payloads**

R5 Changes – New R5 PCB "Standard"

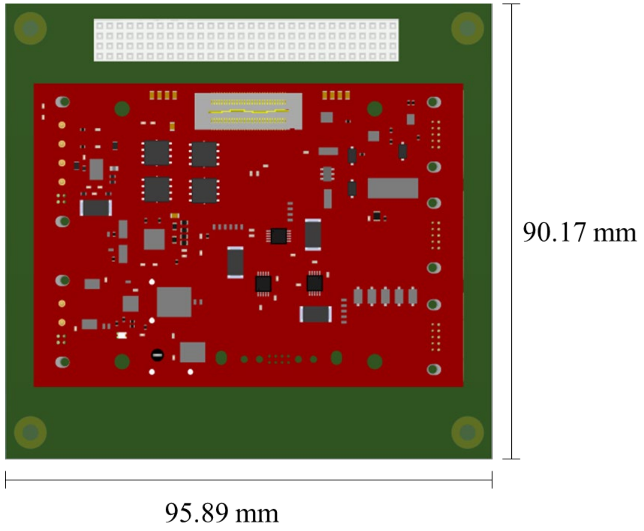
- 60x60mm base board with mounting holes 5 mm from the edges
  - 58% reduction in board area in comparison to PC/104 standard.
  - Variety of stacking connector heights can be used (5, 8, 11, 14, 16, 19, and 25 mm)
- A board design can grow in the horizontal direction only
- All inter-board connections support both Samtec QSH/QTH stacking connector and Harwin Gecko G125 connectors.
  - Allows the boards to be stacked or separated for space concerns. The R5 bus is dynamic with a variety of prop, GNC, avionics, and payload components that require a very flexible scheme.
  - The G125 series mounting holes were modified to slots to allow for right-angle or vertical connectors.
  - Connectors are located on opposite sides of the board to optimize mounting one edge against a wall.



Side view of the new avionics stack

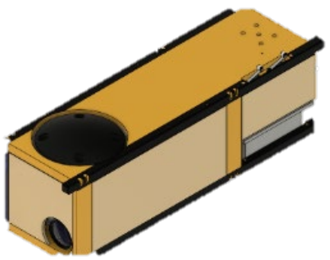


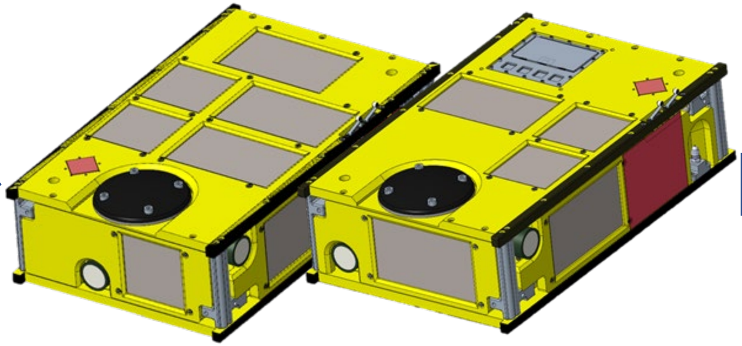
Angled view of the new avionics stack

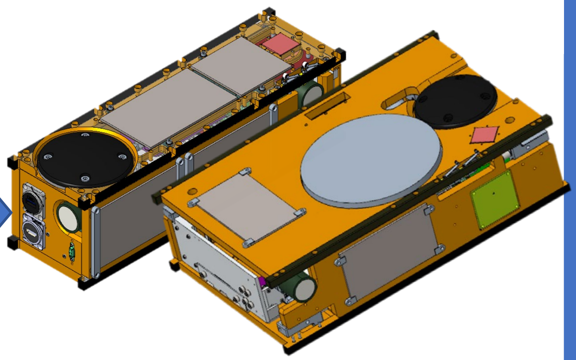


R5 PDU compared to PC/104

R5 Bus Evolution

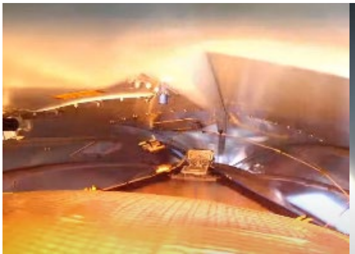






R5-S1

- **Launch: Astra LV0008 (ElaNa 41/ VCLS Demo-2A**
- **Launch Date: 02/10/2022 - LV Failure**
- Mission: hours- image, process, downlink data, demo ELROI
- **Result: lost (LV failure)**
- Systems/Capabilities:
  - Low-cost COTS radio and power
  - Low-cost, high performance COTS compute and cameras



R5-S2 and R5-S4

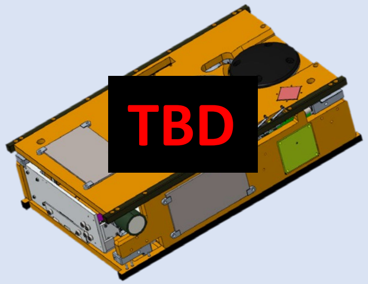
- **Launch: Firefly Alpha (ElaNa 43/VCLS Demo-2FB)**
- **Launch Date: 07/03/2024**
- Mission: weeks- image, process, downlink data, demo prop system, demo ELROI
- **Result: full mission success, still operating**
- Systems/Capabilities:
  - **R5-S1 cameras, radio, compute**
  - **R5-S1 star tracker**
  - **New prop system**
  - **New power system**
  - **Significantly more capable FSW**
  - **New GNC sensors**

R5-S3 and R5-S5

- **Launch: Firefly Alpha (FR-1)**
- **Launch Date: NET May 2025**
- Mission: months- navigate relative to upper stage, operate payloads, downlink data
- Systems/Capabilities:
  - New relative and absolute GNC system
  - Evolved R5-S2/S4 prop system
  - Evolved R5-S2/S4 power system
  - Evolved R5-S2/S4 FSW
  - R5-S1 cameras, comm, compute
  - R5-S1 star tracker

90% of baseline

Prox Ops hardware baseline



R5-S7

- **Launch: SpaceX Transporter**
- **Launch Date: NET October 2025**
- Mission: hours navigate relative to upper stage, operate payloads, downlink data
- Systems/Capabilities:
  - New relative and absolute GNC system
  - Evolved R5-S2/S4 prop system
  - Evolved R5-S2/S4 power system
  - Evolved R5-S2/S4 FSW
  - R5-S1 cameras, comm, compute
  - R5-S1 star tracker

Thank You!

- We're interested in collaborating with you, especially in:
  - "Easy-to-license" RF comm
  - Optical comm
  - Proximity operations
  - Reducing cost
  - Reducing schedule
- Tentatively planning multiple missions in CY26
  - Reach out to us to discuss hosting your payload!

Contact Jack Wisbiski (R5 Avionics Lead): jack.s.wisbiski@nasa.gov