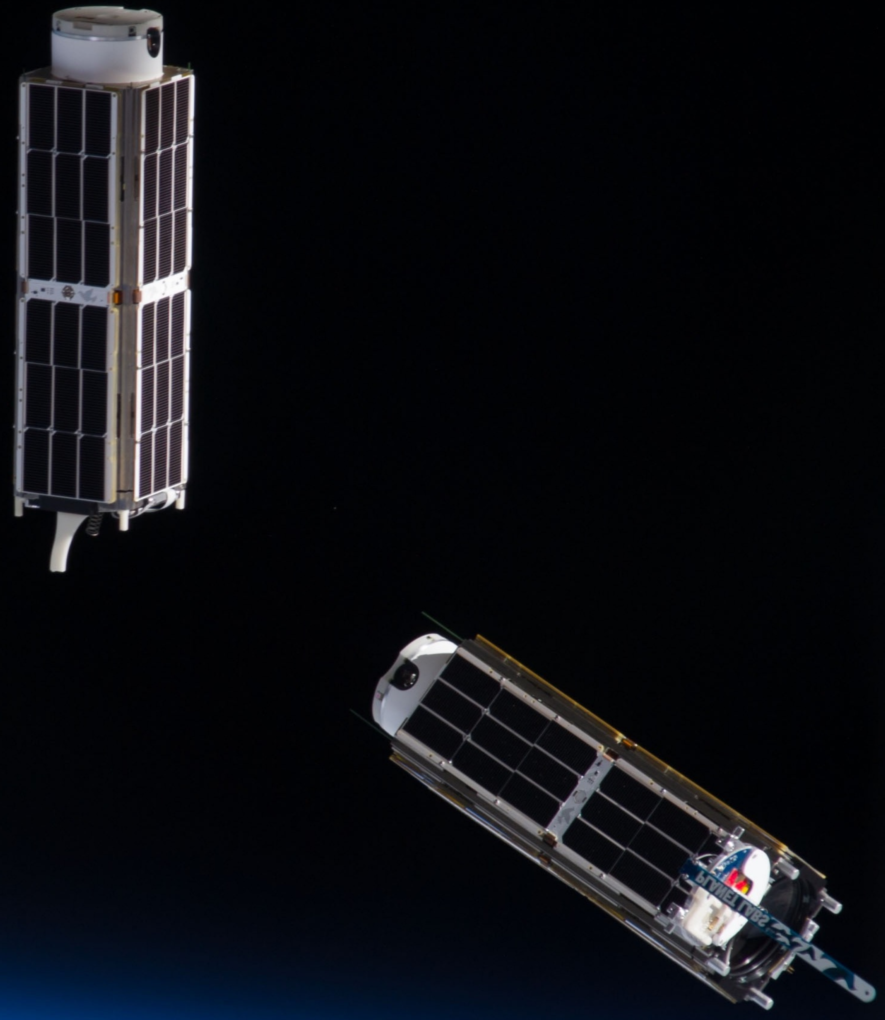
Kintex UltraScale FPGAs with Radiation-Hardened ARM Companion Microcontrollers

5th SpacE FPGA Users Workshop



Martin J. Losekamm | Technical University of Munich (TUM)

Mar 14 – Mar 16, 2023

ORIGINS Excellence Cluster

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

MAX-PLANCK-GESELLSCHAFT

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Technical University of Munich

Who We Are

Excellence Cluster ORIGINS

- Funded by the German Science Foundation (DFG) under Germany’s Excellence Strategy (EXC 2094 – 390783311)
- Consortium of universities and research institutions in Munich
  - **Technical University of Munich (TUM)**, Ludwig-Maximilians-Universität (LMU)
  - Max Planck Institutes for
    - Astrophysics (MPA)
    - Extraterrestrial Physics (MPE)
    - Physics (MPP)
    - Plasma Physics (IPP)
    - Biochemistry (MPIB)
  - European Southern Observatory (ESO)
  - Leibniz Supercomputing Centre (LRZ)
- Common goal: Investigate the development of the Universe from the Big Bang to the emergence of life

➢ Space missions at the core of many research areas within ORIGINS
  - Big-budget missions like Chandra, XMM-Newton, Euclid, Athena, …
  - Smaller missions fostered through a **Laboratory for Rapid Space Missions**
    - Science missions on small satellites
    - Technology demonstrations
    - Experiments / instruments hosted on larger spacecraft

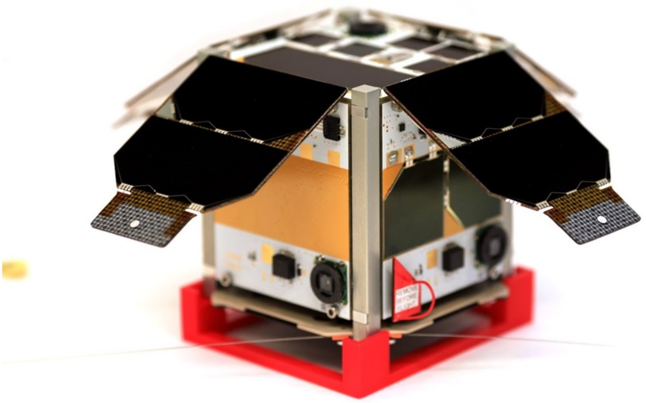
What We Do

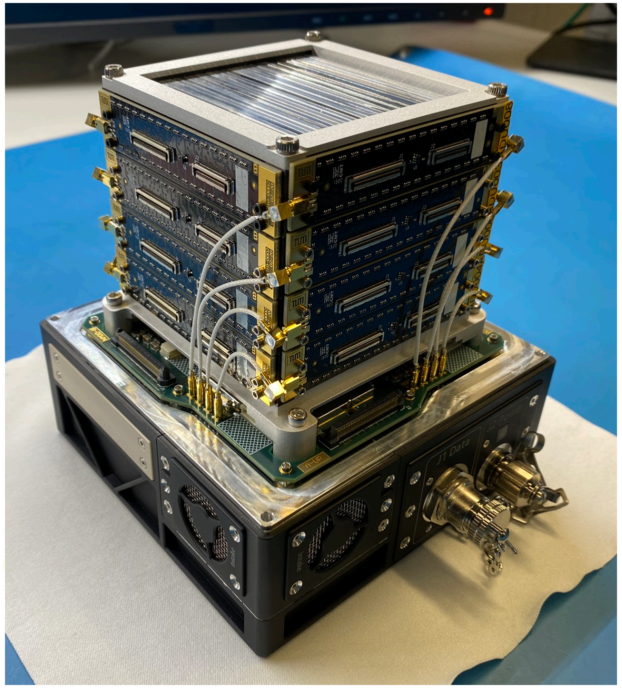
Small Science Missions and Hosted Payloads

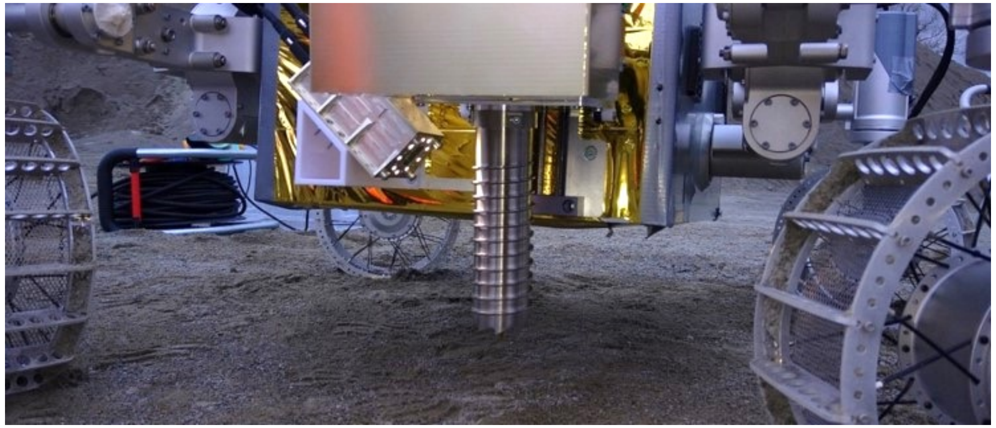
Hosted Payloads / Experiments

Launched on SpX CRS-27

- RadMap Telescope on the International Space Station
  - Performs radiation measurements inside the U.S. Orbital Segment
  - Demonstration of technologies for future human and robotic exploration missions
  - Sponsored by the U.S. ISS National Laboratory
- IOV-1 experiment on the ArgUS M1 payload carrier
  - Deployed to the Bartolomeo platform on the ISS
  - Technology demonstrations & proof-of-principle tests
- Lunar Cosmic-Ray and Neutron Spectrometer (LCNS)
  - Search for the signature of subsurface water on the Moon
- Lunar Volatiles Scout (LVS)
  - Investigation of volatiles in the Moon's shallow subsurface
- Contributions to ESA's PROSPECT







Science Missions on (Dedicated) Small Satellites

- Antiproton Flux in Space (AFIS) – 3U or 6U CubeSat
  - Measurement of the antiproton content in Earth's Van Allen belts
- Compton Polarimetry (ComPol) – 3U or 6U CubeSat
  - Long-term observations of the X-ray spectrum and polarization of Cygnus X-1

General Objective: <u>Rapidly</u> develop application-specific and reliable data-handling and processing solutions.

More widespread use of commercial / industrial-grade electronics

- Sensible choice for low-cost missions with limited duration & low reliability requirements
- **BUT:** Risk of failure is hard to mitigate and may be unacceptable

Small satellites (i.e., CubeSats) are evolving from educational / demonstrational platforms to scientific ones

- Longer mission durations required to successfully achieve scientific objectives
- Stricter reliability requirements
- Stricter data-integrity requirements
- Increasing computational demand for payload data processing

‘Traditional’ high-reliability solutions oftentimes not compatible with cost-constrained missions / payloads

- High costs & long lead times
- Technically not compatible: too large & too power-hungry
- ‘Outdated’ products with small user community

➢ **‘Intermediate’ solutions must provide sufficient reliability and flexibility at acceptable cost**

- Caveat: Exact reliability requirements often hard to quantify due to cost / schedule constraints

Data Handling for Small Satellites and Hosted Payloads

Requirements and Design Philosophy

Functional Requirements (from reference missions)

- Interfaces to sensor front-end electronics & housekeeping
  - 64 custom serial links (up to 16 MHz)
  - 64 trigger inputs / outputs
  - 64 SPI interfaces (multiplexed)
  - 40 LVDS inputs / outputs
- In-orbit reconfiguration
- Trigger rates up 100 kHz

Reliability Requirements

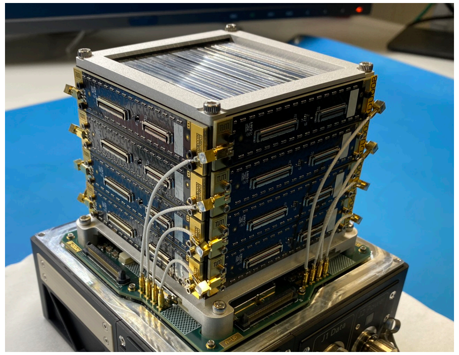
- Baseline design lifetime of either
  - Three years in high LEO (1000 km reference altitude) or
  - Two years on lunar surface
  - ➢ Survival of respective radiation / thermal / … environments
- Ensure integrity of science data during repeated passes of radiation belts / SAA for LEO missions
- Bit flips / SEU acceptable if they (randomly) affect less than 1% of science data and are detected reliably

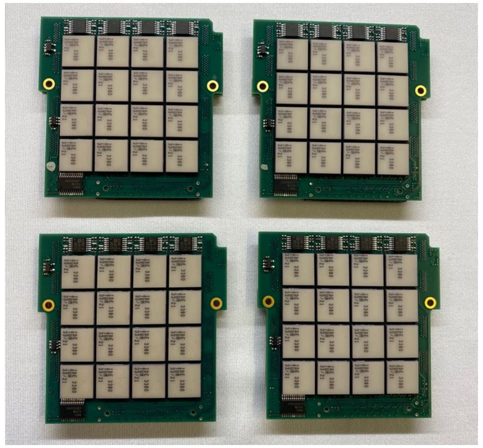
Design Philosophy

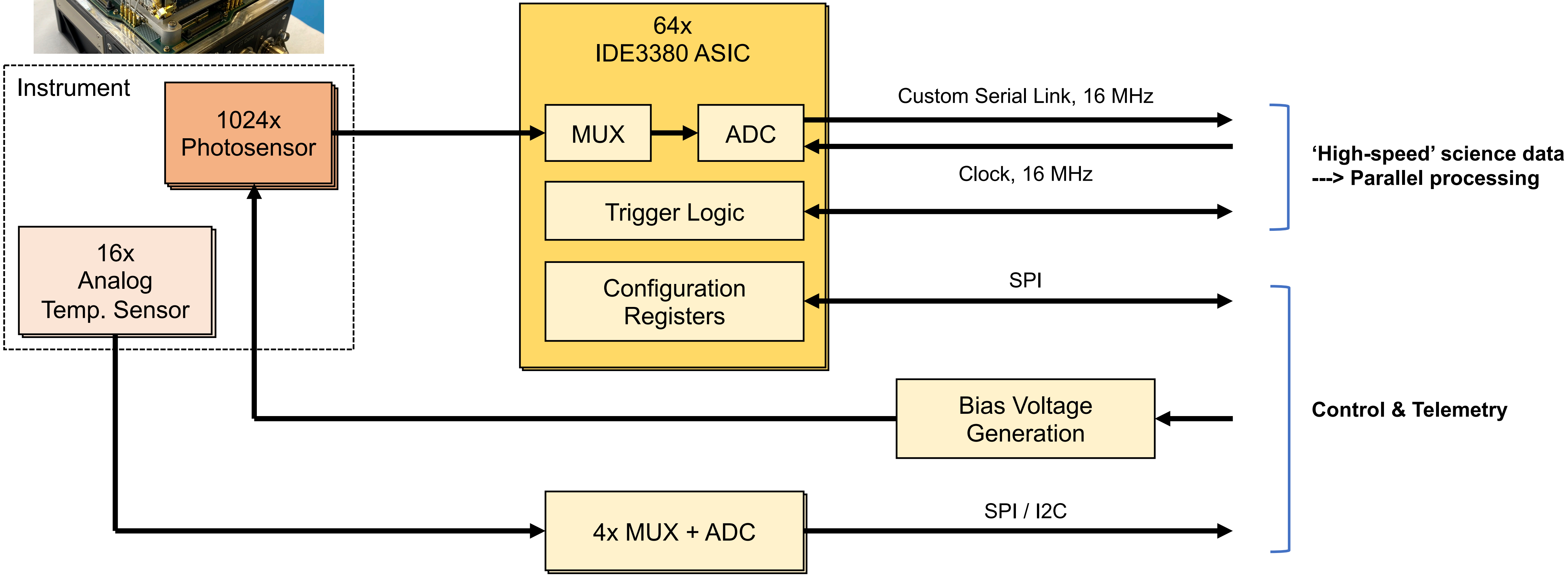
- Strict separation of payload data handling / processing and satellite telemetry / control (often not done for small-satellite missions)
- Use radiation-tolerant (‘NewSpace’) components wherever possible
  - If possible, use components with footprint-compatible and functionally equivalent commercial / automotive versions
- Use enhanced / screened components for non-critical functions
- Prefer components with a large user base / community
  - **ARM-based microcontrollers**
  - (Xilinx FPGAs (most in-house expertise))

Application Example

RadMap / AFIS Sensor







The Challenge

RadMap / AFIS Sensor

We require:

- Large number of (custom) interfaces
- Fully parallel data acquisition from (up to) 64 read-out ASICs
- Real-time trigger decisions, zero suppression, and pre-filtering of data (reconfigurable on orbit)

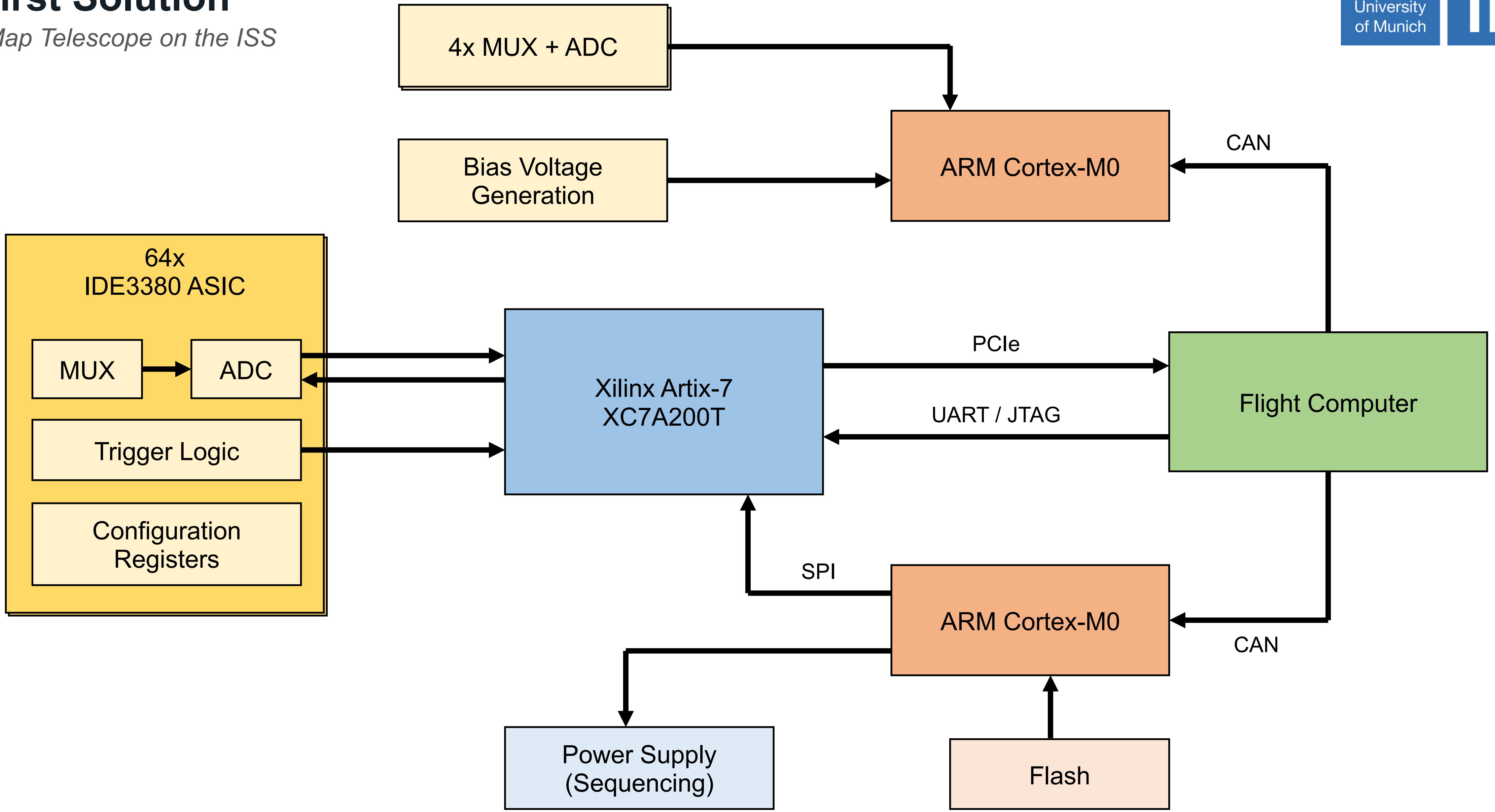
➢ **Use of an FPGA is the ideal solution**

Challenges of using FPGAs on small satellites / for small instruments (on a limited budget)

- Radiation-tolerant / radiation-hardened FPGAs are expensive
    - ‘NewSpace’ products not (widely) available
- Graduate students at universities have no experience with space-grade FPGA ecosystems
- Comparatively high power consumption

A First Solution

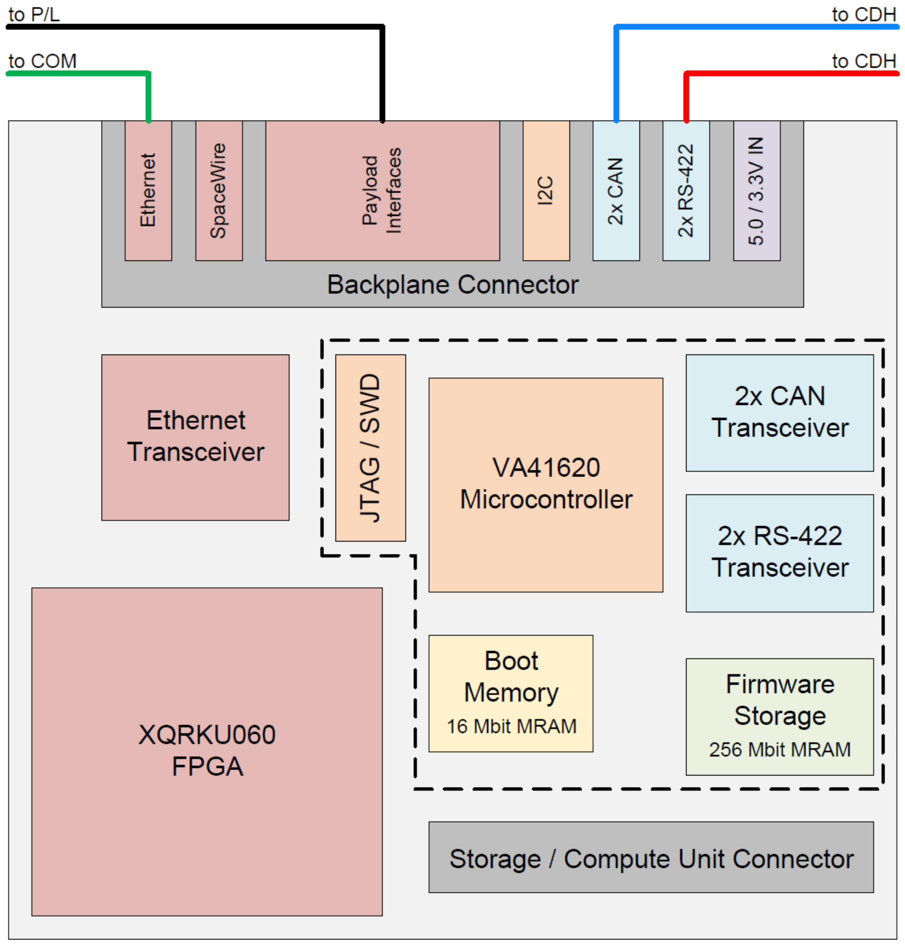
RadMap Telescope on the ISS



Future Solution

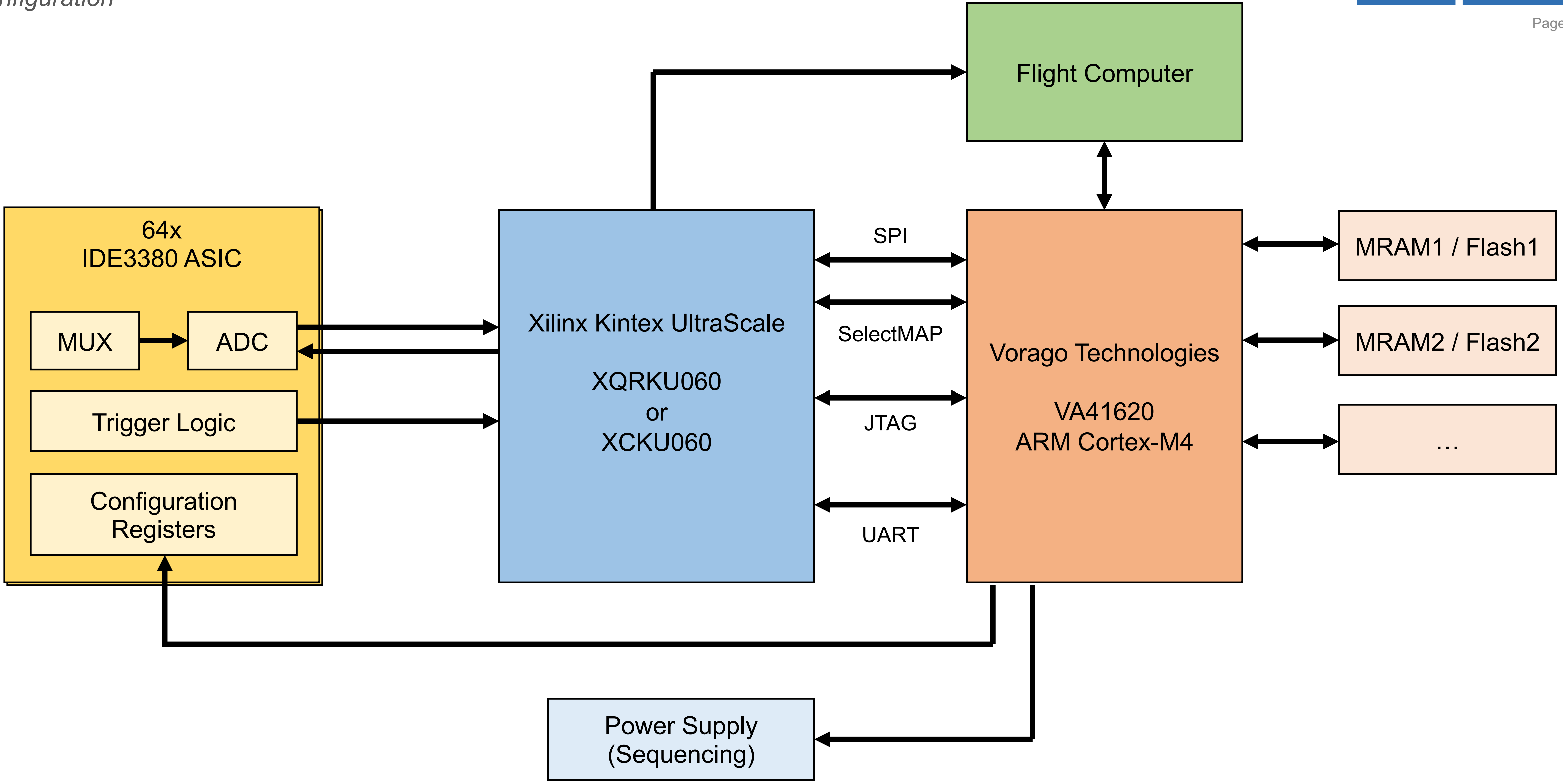
Hardware: Payload Data Processor (PDP)

- Xilinx XQRKU060 field-programmable gate array (FPGA)
  - Radiation-hardened (100 krad), high-performance FPGA
  - Pin-compatible commercial equivalent available (XCKU060)
- Vorago Technologies VA41620 companion microcontroller
  - Can be used to control FPGA configuration and for scrubbing
  - Provides additional payload control and telemetry functionality
  - FPGA can be switched off without losing control over payload
- MRAM for boot memory (16 Mbit) and FPGA configuration (256 Mbit)
- Interfaces: 100-Mbit Ethernet, SpaceWire, 2x CAN, 2x RS-422, I2C
- Add-on cards for
  - Science data storage
  - Computational accelerators (GPU, TPU, CPU)



Future Solution

Configuration



Advantages of Cortex-M4 Companion

Affordable Reliability

Using the VA41620 as companion for an FPGA has several strong **advantages**:

- Reliability of radiation-hardened microcontroller
- Comparatively inexpensive solution
- Potential of working with commercial-grade FPGA (depending on mission requirements)
- Variety of memory solutions become available
- Familiarity of (graduate) students with ARM-based systems

Functions that the companion provides:

- Scrubbing (!)
- On-orbit reconfiguration
- On-orbit debugging
- State machine control
- Off-loading of control / telemetry functions
- Power sequencing

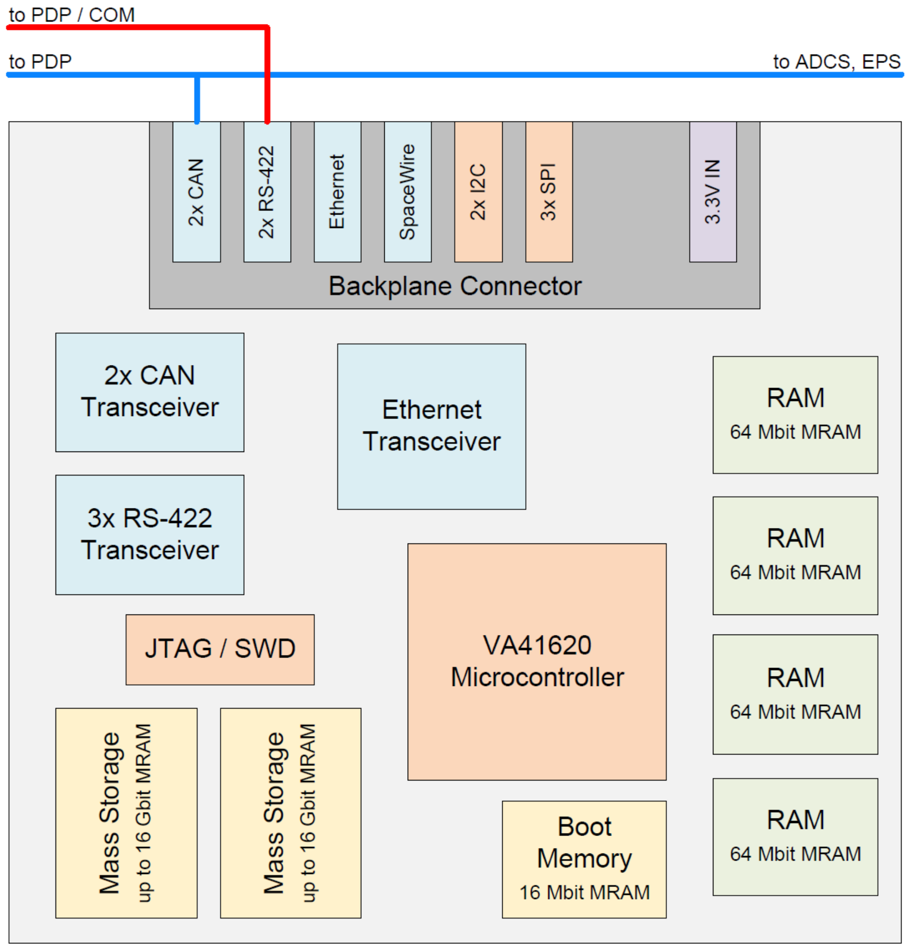
Command and Data-Handling System

Common Hardware

- Vorago Technologies VA41620
  - 32-bit ARM Cortex-M4 microcontroller @ 100 MHz
  - Good radiation hardness (300 krad TID) at affordable price tag
  - Low power consumption
  - Widely familiar instruction set

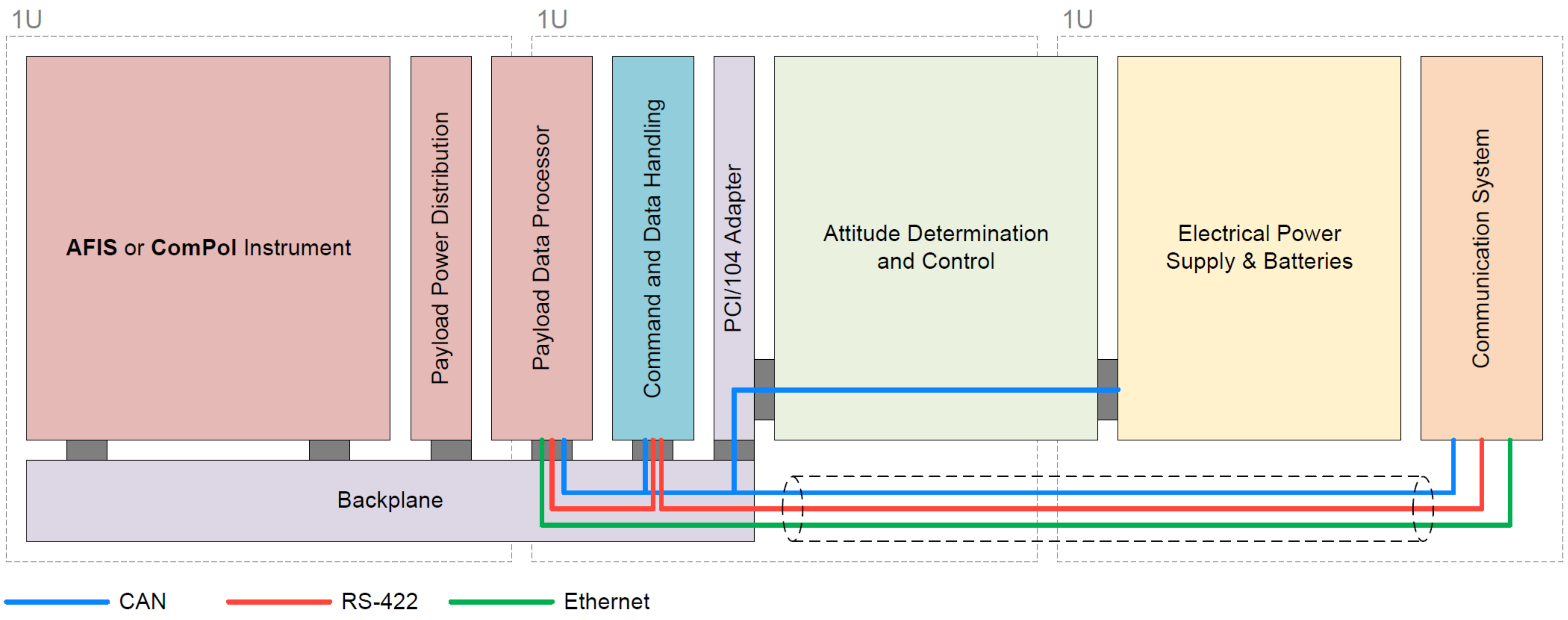
- Aerospace-grade MRAM for
  - Program / boot memory (2 MB)
  - RAM (32 MB)
  - Mass / data storage (up to 4 GB)

- Interfaces
  - 2x CAN
  - 2x RS-422
  - 100-Mbit/s Ethernet
  - SpaceWire
  - 2x I2C
  - 3x SPI



Overall System Architecture

Satellite Bus for AFIS and ComPol



- Most bus systems provided by commercial partners; PC/104 to custom backplane adapter for in-house systems
- System-wide, redundant CAN bus for telemetry and control
- Direct 100-Mbit/s Ethernet connection between payload and communication system; back up via RS-422 / CDH

Software Architecture

Operating System

Future use case is distributed control system with multiple nodes that flexibly share workload to increase fault tolerance

- Available frameworks, such as NASA's cFS and F', do not support such distributed systems out of the box

➢ Development of DOSIS (Distributed Operating System Initiative for Satellites) at TUM

- Based on DLR's RODOS (Realtime On-Board Dependable Operating System)
- Network-centric operating system with simple publisher-subscriber message-passing system
- Simple hardware abstraction
- Thread-safe communications
- Priority-based real-time scheduler

- DOSIS-based firmware is a collection of interconnected component instances, each representing a single functional entity
  - Modular approach to firmware design eases late addition of software components
  - Independent components provide additional abstraction layer that allows distribution of task over multiple nodes

- Precise time synchronization in distributed systems
  - Less than 2 ms timing uncertainty between nodes

DOSIS

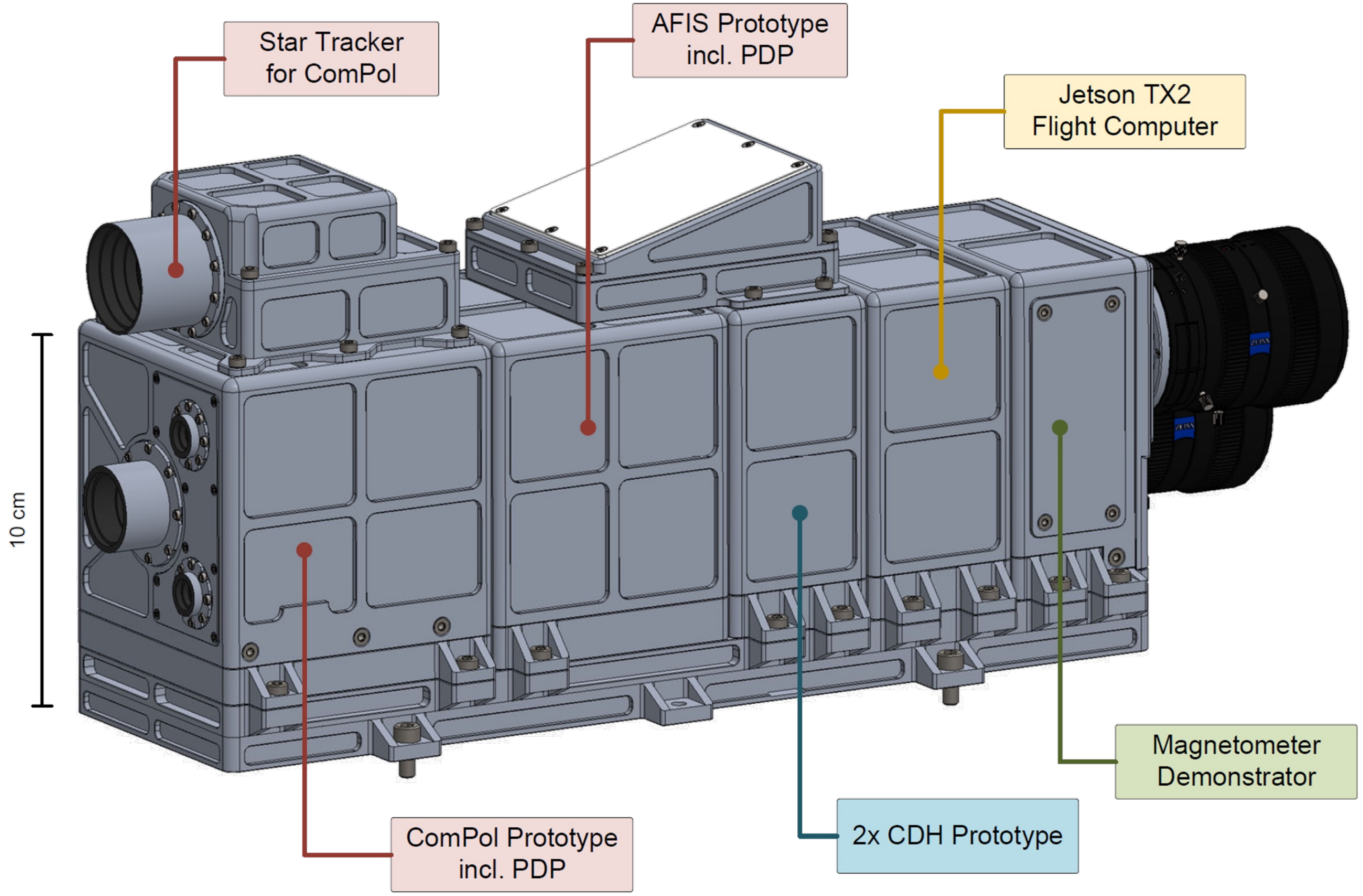
In-Orbit Demonstration

IOV-1 on the International Space Station

- In-orbit verification of instruments and data-handling systems aboard ISS
- Background measurements for later science missions

- Scaled-down instruments, each equipped with its own PDP
- 2x CDH prototypes
  - Demonstration of distributed computing

- Attached to Bartolomeo platform on the European Columbus module
- 12-month operational period starting in early 2024



Summary

Technical University of Munich

- On-going development of two data-handling systems for small satellites based on microcontroller / FPGA combination
  - Focus on reliability, flexibility, and ease of use
  - Acceptable price tag for small-satellite missions and hosted payloads

- Flexible hardware and software architecture allows use beyond the two reference missions presented here

- In-orbit demonstration on the ISS to fully verify reliability and gain flight heritage

Please let us know in case you have any questions!

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