EDHPC 2023

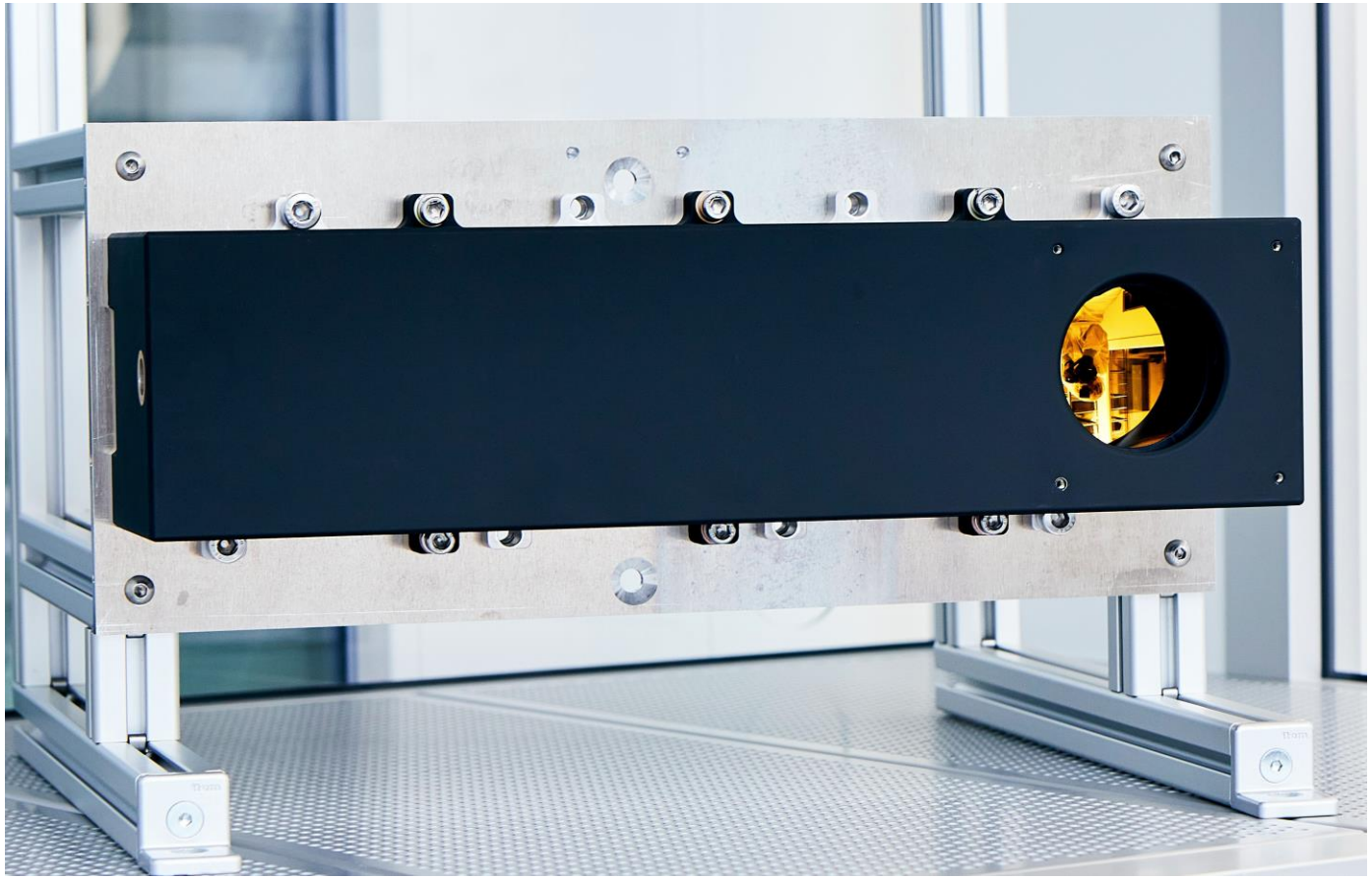
Data Processing System Architecture and Lessons Learned from the LisR Mission

Konstantin Schäfer, Clemens Horch, Atin Jain, Andreas Brunn, Marius Bierdel, Frank Schäfer

Architecture & Design

Mission Overview

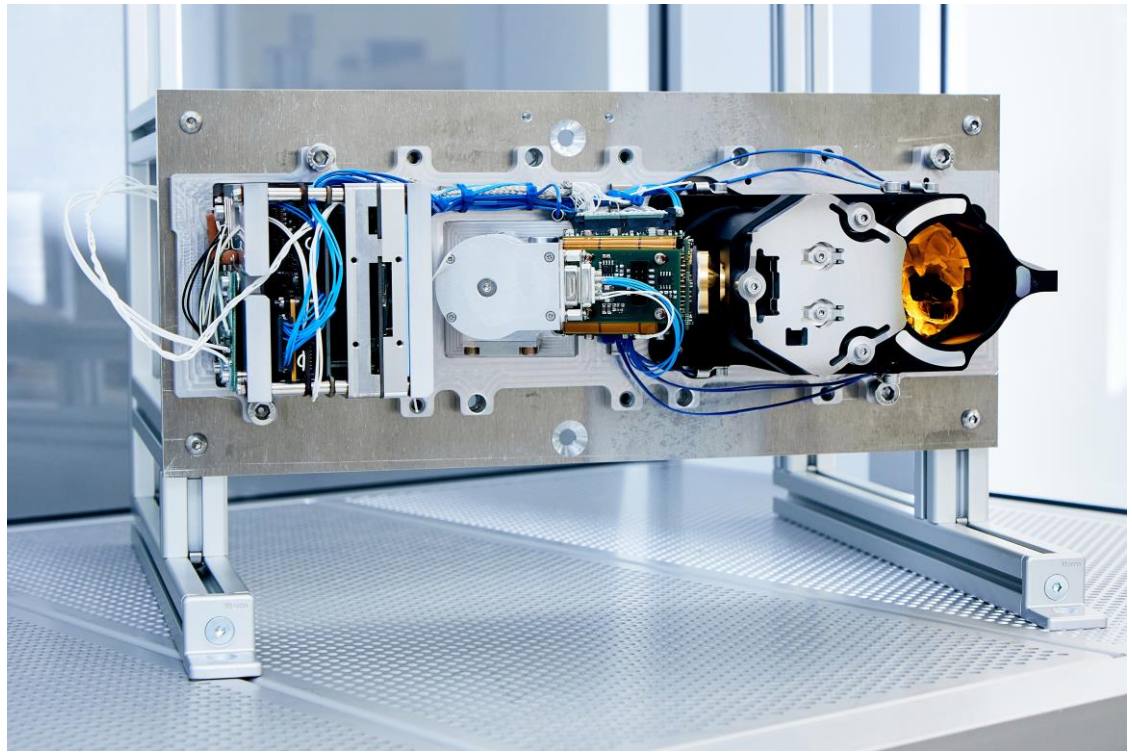
- **L**ong wave **I**nfrared demon**S**trato**R**
- Technology demonstrator for crop monitoring
- EXIST-Project of constellr
- Cryo-cooled thermal sensor
- Two bandpass filters in thermal infrared
- Mounted to NanoRacks External Platform (NREP) on ISS
- Swath width 25 km, GSD ~80 m



Architecture & Design

Subsystem Overview

- New Space approach with COTS hardware
- Two Model approach
  - Engineering and Qualification Model
  - Flight Model
- LisR consist of four main subsystems:
  - Freeform optics, designed and built by Fraunhofer IOF & SPAXEOPTIX
  - Commercial Off the Shelf (COTS) infrared Integrated Detector Dewar Cryocooler Assembly (IDCCA)
  - COTS CubeSat Electrical Power System (EPS)
  - Data Processing Unit (DPU), designed and built by Fraunhofer EMI

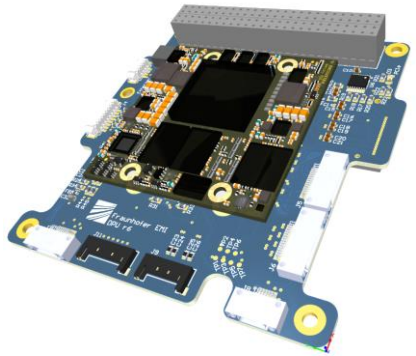


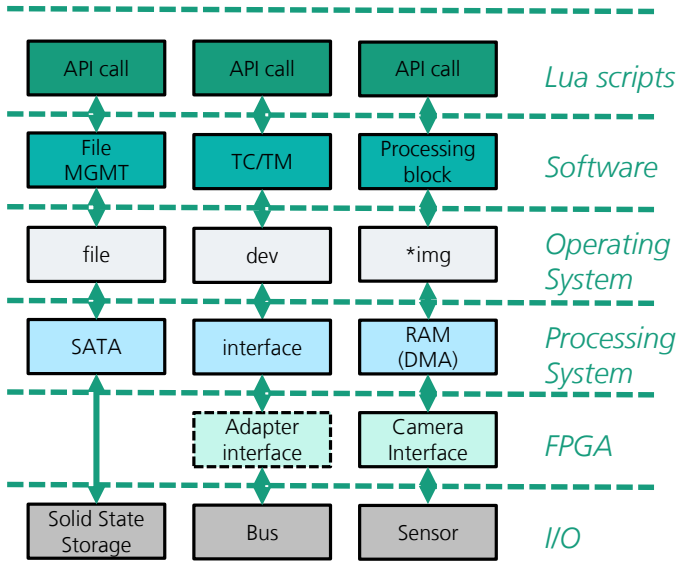
Architecture & Design

Data Processing Unit (DPU)

- Developed for Nano- & Microsatellites
  - CubeSat mounting standard (PC/104)
  - Size: ~ 100 x 100 x 25 mm^3
  - Weight: ~ 0.4 kg
  - Average power: ~8W
- Based on a ZynqMP Multi Processing System on a Chip (MPSoC)
  - Quad Core Cortex-a53 application processing unit
  - Dual Core Cortex-R5 real time processing unit
  - Ultrascale+ Field Programmable Gate Array (FPGA)
- Redundant SD-cards, eMMC & QSPI for firm- and gateware
- Single Level Cell Solid State Drive for payload data

- Payload interface implemented in FPGA of the SoC
- Main software runs on a custom built GNU/Linux operating system
- Software can be automated via embedded Lua scripting-API



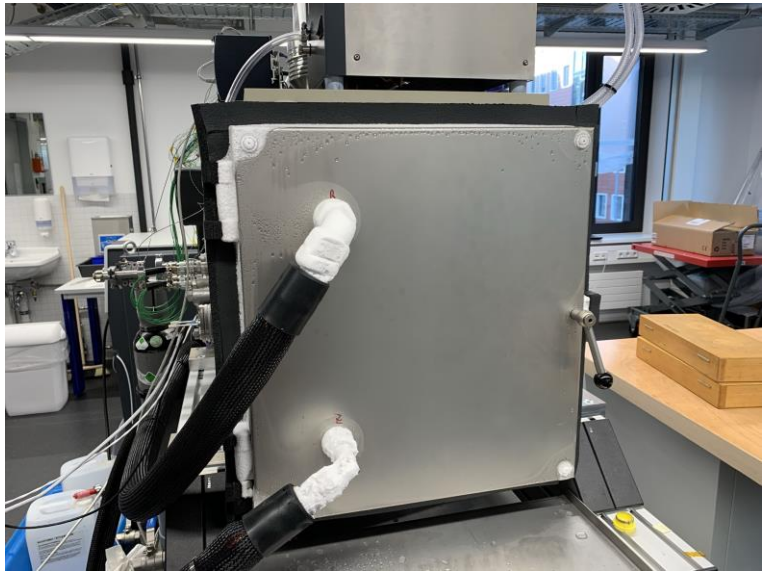


Testing & Mitigation

COTS electronics in Low Earth Orbit

Thermal environment:

- Potentially significant temperature changes during orbit
- Heat dissipation
- Unknown hot spots in COTS components
- Mitigation approach:
  - Elaborate thermal modeling and testing in thermal vacuum chamber
  - Thermal monitoring of the system in orbit
  - Detection of overheating with onboard telemetry analysis on DPU



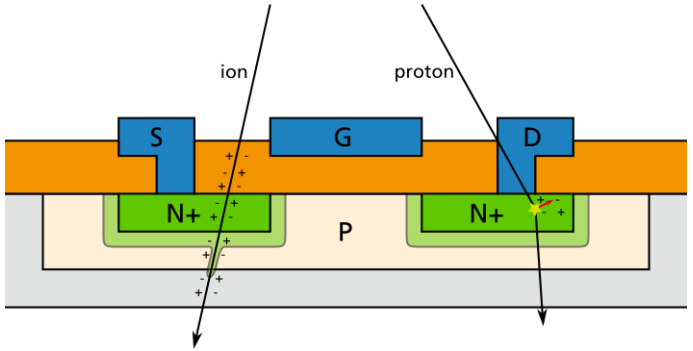
Thermal Vacuum Chamber at EMI

Testing & Mitigation

COTS electronics in Low Earth Orbit

Radiation environment:

- LEO radiation consists of high energy sub-atom particles
- Total Ionizing Dose (TID) and Single Event Effects (SEE)
- The TID evokes displacement damage → semiconductor behavior is altered
- SEEs cause Soft- & Firmware failures or create Single Event Latchups (SEL) that cause permanent damage
- Mitigation Approach:
  - Testing not possible in given project constraints
  - No universal solution available

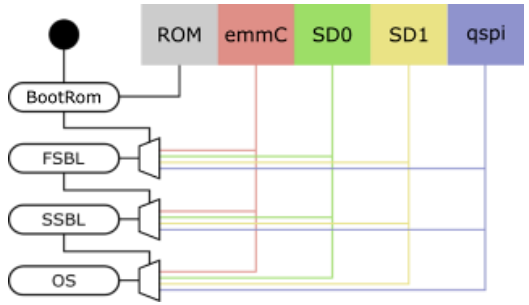


High energy particles striking a transistor

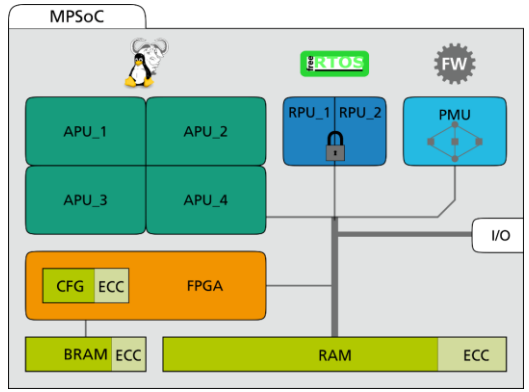
Testing & Mitigation

Radiation effect mitigation

- TID effects:
  - Less concern due to short planned mission time
  - Instrument is covered in aluminum alloy shielding
  - Single Level Cell Flash storage is used wherever possible
  - Observe telemetry and switch to redundant part if possible
- SEL detection is handled by the EPS
- Single Event Upsets (SEUs) & Single Event Functional Interrupts (SEFIs):
  - Redundant boot media
  - Checksums for boot files
  - Error Detection and Correction (EDAC) for main memory
  - Cyclic Redundancy Checking (CRC) for FPGA configuration memory
  - Software watchdog timer
  - Watchdog timer in EPS



Redundancy logic of the DPU's firmware files



Processing & memory systems of the DPU and their EDAC capabilities

Operations
Telemetry

- Telemetry values were collected by the DPU into a database
- During transmission, selected telemetry values were linked down
- Broadband downlink and onboard storage capacity enabled large scale collection and analysis of:
  - Temperature telemetry from external and internal sensors
  - Power consumption telemetry from EPS and power sensors
  - Soft- and Firmware telemetry like system load, uptime, storage, etc.
  - EDAC and SEM telemetry
  - ISS attitude & position

DPU temperature and power telemetry of LisR

Operations
Scripting

- Main DPU software implements:
  - Basic functions e.g. switch mode, get telemetry, etc.
  - Storage management
  - Telemetry collection
  - Communication Protocols
- Functionality is accessibly via Lua-API
- High level operational commands implemented in Lua scripts
  → Extendible
  → Easily adaptable
  → Enhanced Safety
  → No Need to upgrade the software
- Operations script selected, started and stopped via NREP command

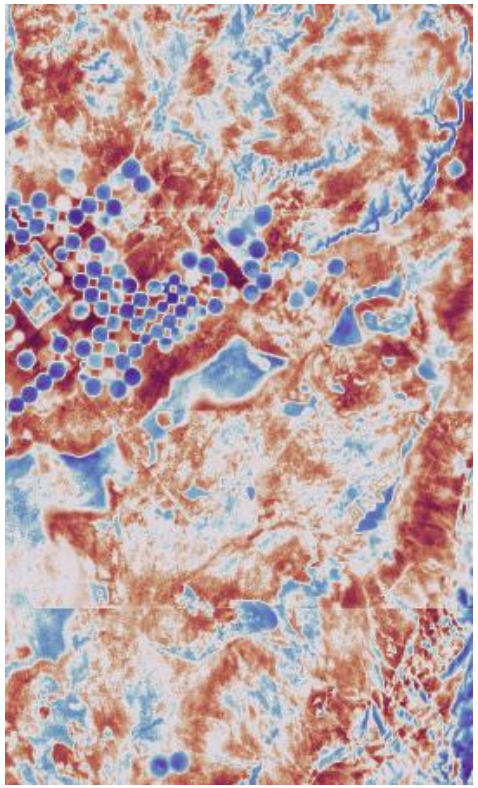
```lua
DPU.cmd.system.setOperationMode(DPU.enums.mode.CONVERT)
starttime_capture = DPU.tools.get_time()

while 1 do
    DPU.tools.sleep(sleep_time)

    if DPU.telemetry.hw.temp_camera_sensor > camera_sensor_target_temp then
        DPU.cmd.system.setOperationMode(DPU.enums.mode.IDLE)
        DPU.tools.wait_for_idle()

        record = DPU.cmd.storage.lastRecordId()
        DPU.cmd.storage.recordArchiveSftp(record)
        DPU.cmd.system.telemetryArchiveSftp(starttime - log_time_overlap, DPU.tools.get_time())

        repeat
            DPU.tools.sleep(sleep_time)
        until DPU.telemetry.hw.temp_camera_sensor < camera_sensor_target_temp

        DPU.tools.sleep(sleep_time)

        DPU.cmd.system.setOperationMode(DPU.enums.mode.CONVERT)
    end

    if DPU.tools.get_time() > starttime_capture + record_interval then
        DPU.cmd.system.setOperationMode(DPU.enums.mode.IDLE)
        DPU.tools.wait_for_idle()

        record = DPU.cmd.storage.lastRecordId()
        DPU.cmd.storage.recordArchiveSftp(record)
        DPU.cmd.system.telemetryArchiveSftp(starttime_tm - log_time_overlap, DPU.tools.get_time()

        DPU.cmd.system.setOperationMode(DPU.enums.mode.CONVERT)
        starttime_capture = DPU.tools.get_time()
        starttime_tm = DPU.tools.get_time()
    end
end
```

Example fragment of a Lua Operations Script

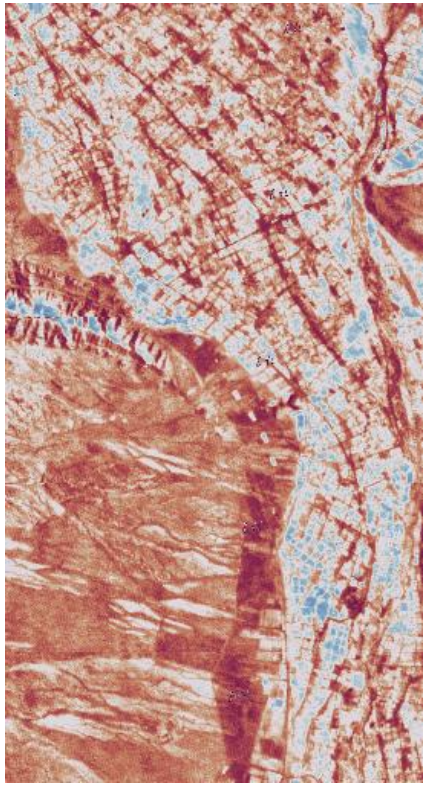
Operations
Results

- **20** weeks of recorded uptime
- **>9.3** million frames captured
- **~500** million km² land surface captured
- **6** software updates
- **2** planned reboots (0 unplanned)

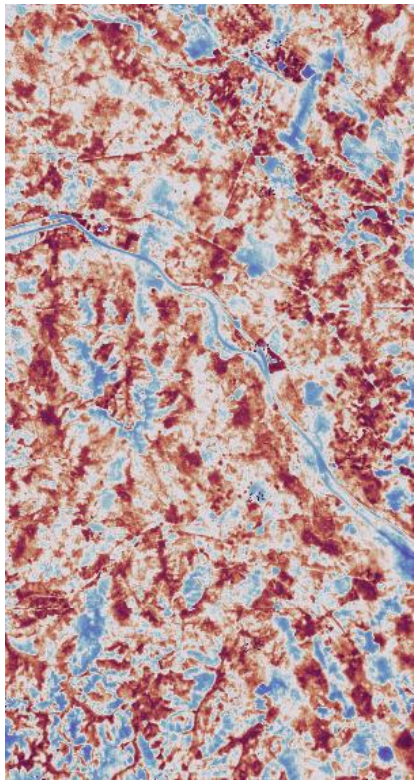
→ Mission successfully demonstrated the technology for the upcoming HiVe constellation



Irrigated fields in Texas (Apr. 22)



Town in Xinjiang (Apr. 22)



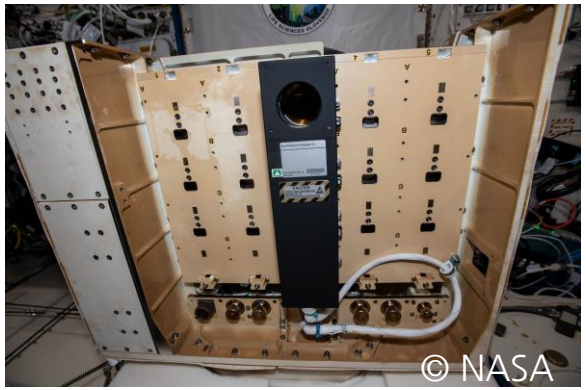
Rhine near Freiburg (Apr. 22)

Operations
Telemetry Analysis

- Thermal:
  - All measured temperatures stayed within a safe range
- Radiation effects:
  - No bit flips in main memory were detected (no active scrubbing)
  - The Soft Error mitigation Controller did not report any SEUs
  - No unexpected behavior due to SEFIs was observed
  - The EPS didn't detect any SELs in the bus & data processing electronics

→ LisR was well shielded by the ISS and the NREP

→ Mission duration was to short for long term effects



LisR mounted on NREP

Temperature sensor and EDAC telemetry of LisR

Operations
Lessons learned

- For anomaly…
  - … detection only few telemetry is necessary
  - … analysis detailed telemetry is valuable

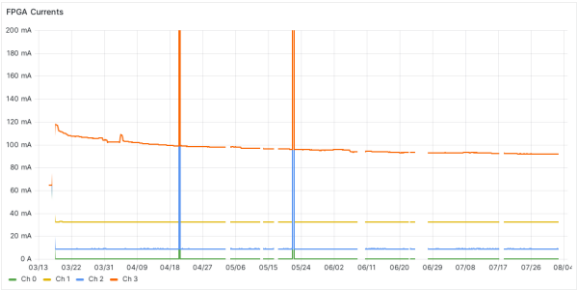
→Telemetry storage and selective downlink has shown its value

- Reference telemetry for comparison is mandatory

→If there's not enough time in advance, keep your EM running during the mission

- The more testing is done in advance, the better

- Scripting enables evolutionary in orbit operations without software updates:
  - In the beginning: Keep it as simple as possible
  - Gradually increase script complexity



Decrease of I/O current on FPGA Bank during the mission

LISR&NREP mounted on the ISS

Contact

Konstantin Schäfer
Fraunhofer EMI
System Solutions
konstantin.schaefer@emi.fraunhofer.de

Fraunhofer EMI
Ernst-Zermelo-Str. 4
79104 Freiburg
www.emi.fraunhofer.de

Marius Bierdel
Constellr GmbH

marius.bierdel@constellr.com

Constellr GmbH
Heinrich-von-Stephan-Straße 5c
79100 Freiburg
www.constellr.com