# OrbFIX

## PPP GNSS Receiver for Cubesats

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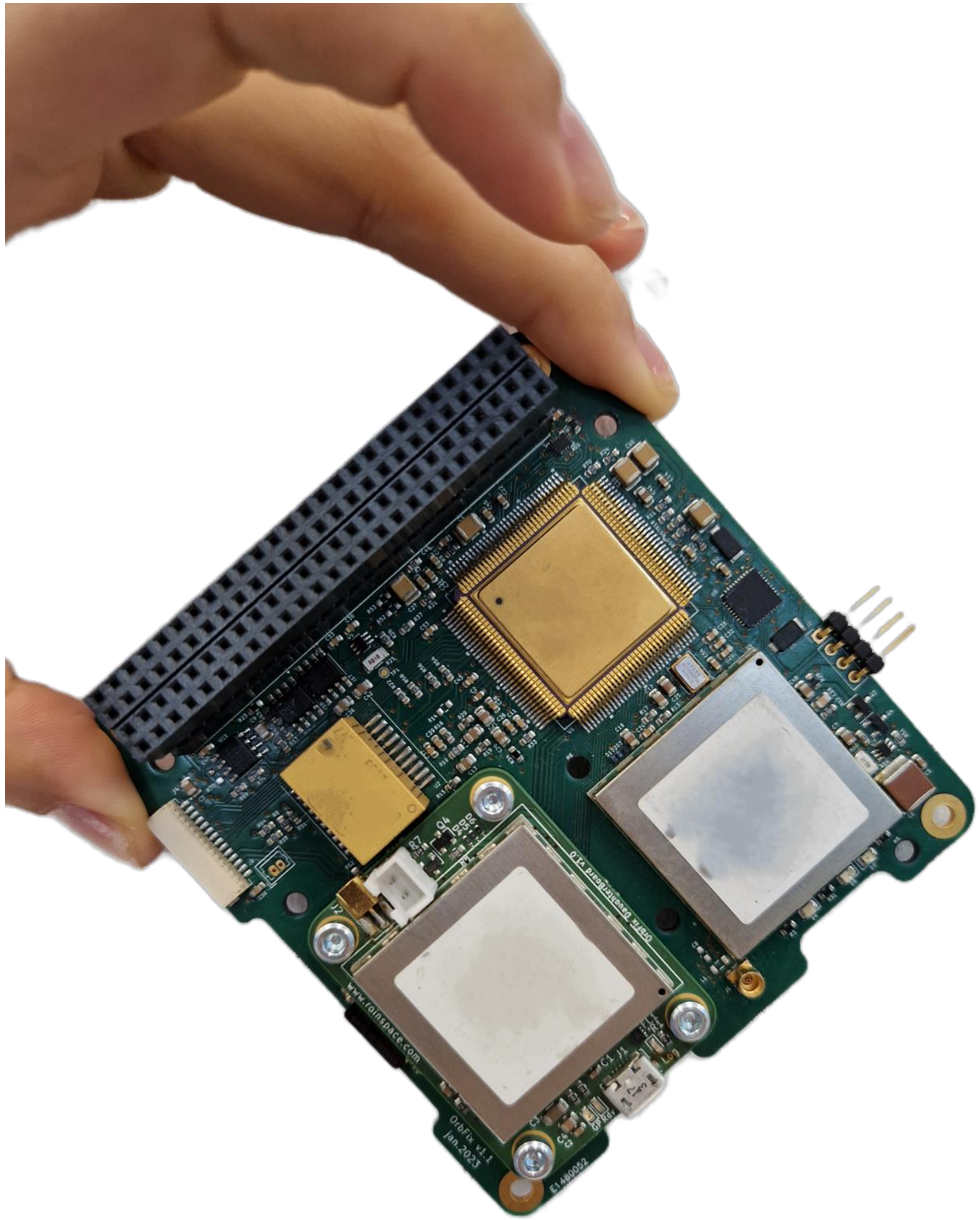
TRR/Final Review

July 11th, 2023

# Contents



# OrbFIX - Introduction

**ESA GSTP Building Blocks Activity** aiming to:

- Design a COTS PPP GNSS receiver for space (->TRR)
- Preliminary assembly, integration and test
- Plan a qualification campaign and identify IOD opportunities

OrbFiX

Precise orbit determination: COTS GNSS receiver & AI enhanced orbital propagator with three operating modes:

- low power: ANN&OP (100m in 2 hours @1.5 W)
- simple, low accuracy: GNSS (2m @ 2.5 W)
- nominal, high accuracy: PPP/Galileo HAS (10cm @ 3.5 W)

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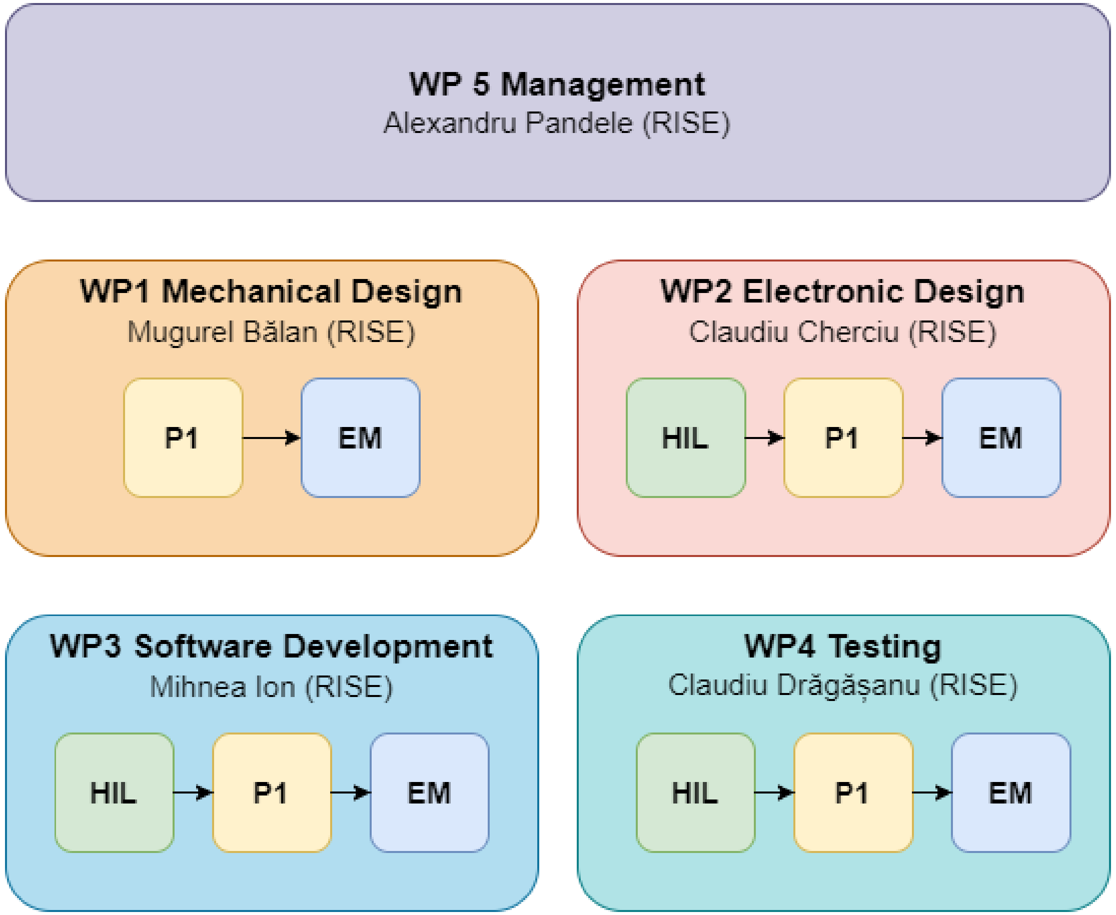
# Work Breakdown Structure

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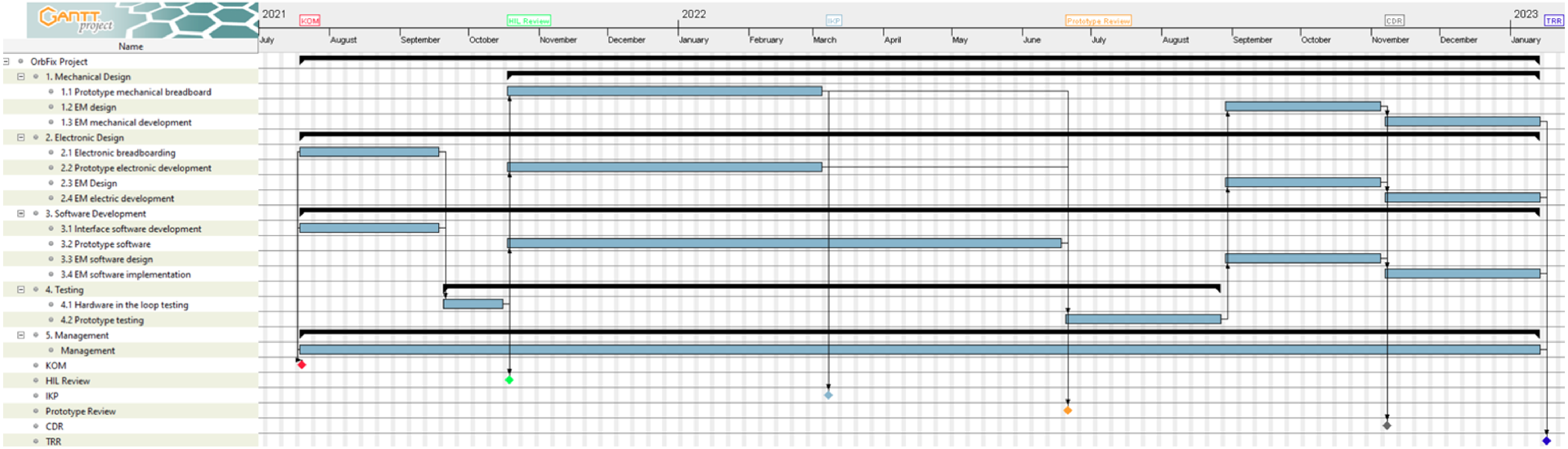
# Schedule

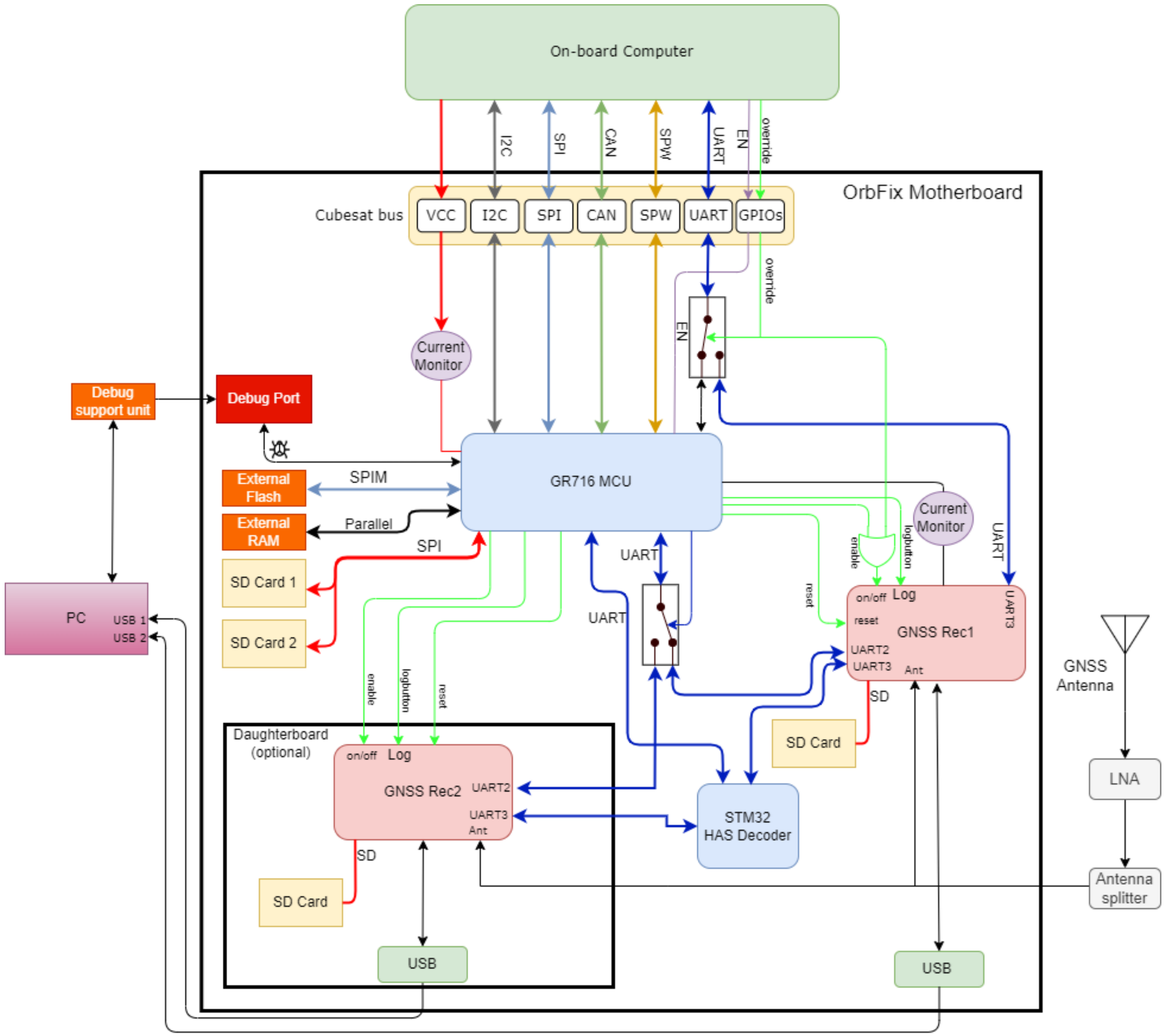


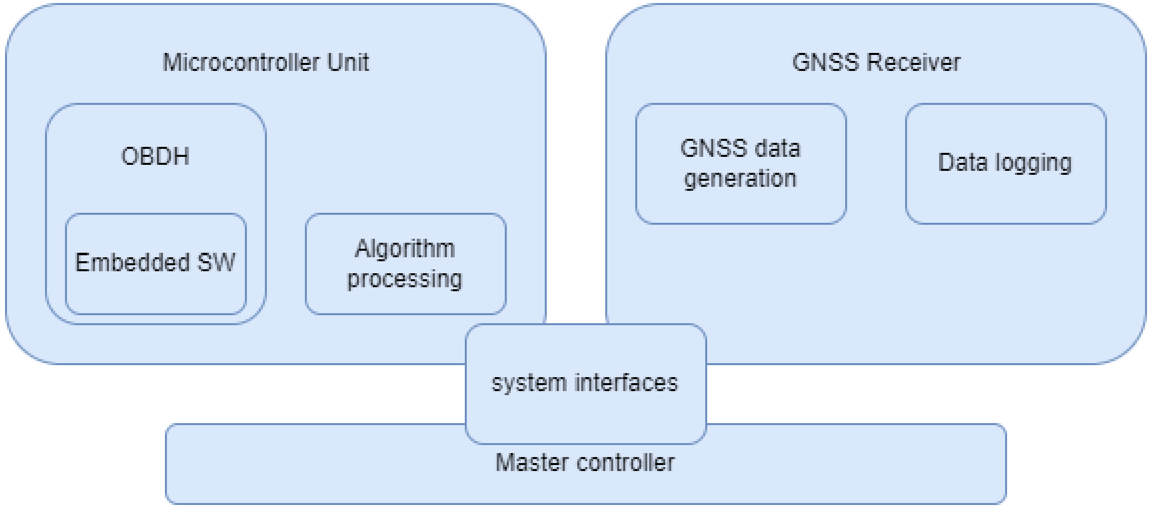
2021
KOM
HIL Review
2022
IKP
Prototype Review
CDR
2023
TRR
Name
July
August
September
October
November
December
January
February
March
April
May
June
July
August
September
October
November
December
January
OrbFix Project
1. Mechanical Design
1.1 Prototype mechanical breadboard
1.2 EM design
1.3 EM mechanical development
2. Electronic Design
2.1 Electronic breadboarding
2.2 Prototype electronic development
2.3 EM Design
2.4 EM electric development
3. Software Development
3.1 Interface software development
3.2 Prototype software
3.3 EM software design
3.4 EM software implementation
4. Testing
4.1 Hardware in the loop testing
4.2 Prototype testing
5. Management
Management
KOM
HIL Review
IKP
Prototype Review
CDR
TRR

# Electronic design

# Electrical Diagram



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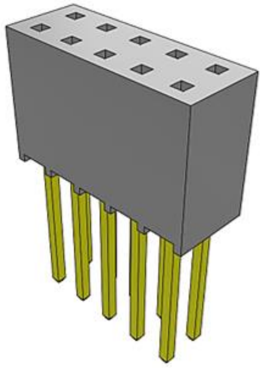
# Connectors

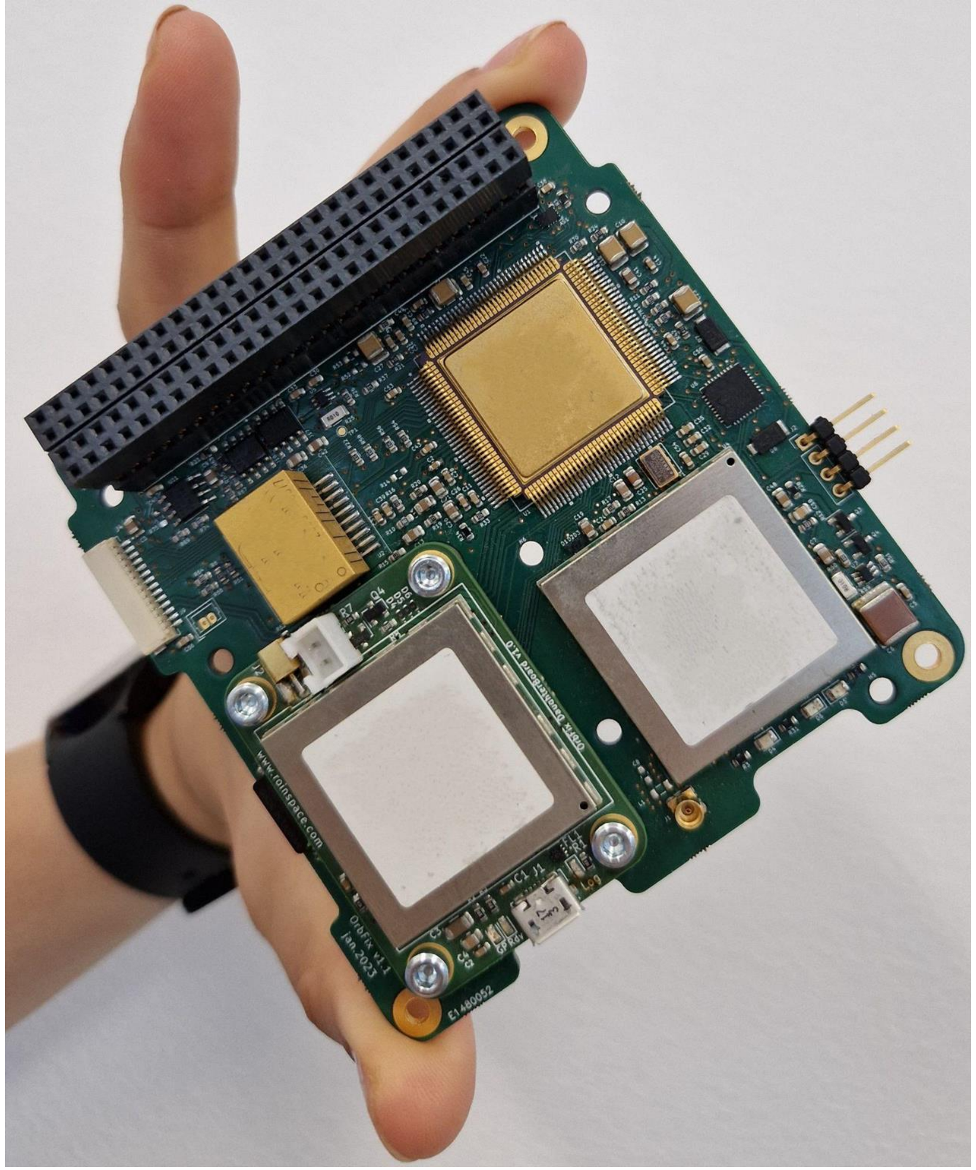
**Connectors used:**

- JST SM14B-SRSS-TB-LF - Debug Unit;
- Samtec FSI-105-03-G-D-AD - MotherBoard connector;
- Samtec SSQ-126-03-G-D - Cubesat Bus;
- Chinch DCCM9SCBRPN - SpaceWire Connector;
- Molex 53047-0210 - Antenna 5V supply;



# Features





### Interfaces

- 3V3 primary power input;
- 1 x UART (up to 4Mbps);
- 1 x I2C communication;
- 1 x SPI Slave interface;
- 1 x SpaceWire;
- 1 x CAN controller;
- RF Interface.
- microSD slot (up to 4GB)

### COTS GNSS receiver

- Multi-constellation, multi-frequency receiver in a low power module, capable of tracking all Global Navigation Satellite System constellations supporting all current signals.
- Antenna pre-amplification range: 15-50 dB;
- Antenna bias voltage: 3.0 - 5.5 V;
- Built-in current limit (150mA).

### Other hardware features

- ON/OFF high level command interface or autostart upon voltage application;
- Available to bypass the microcontroller for direct access to the GNSS receiver;
- COTS counterparts are available for prototyping purposes.

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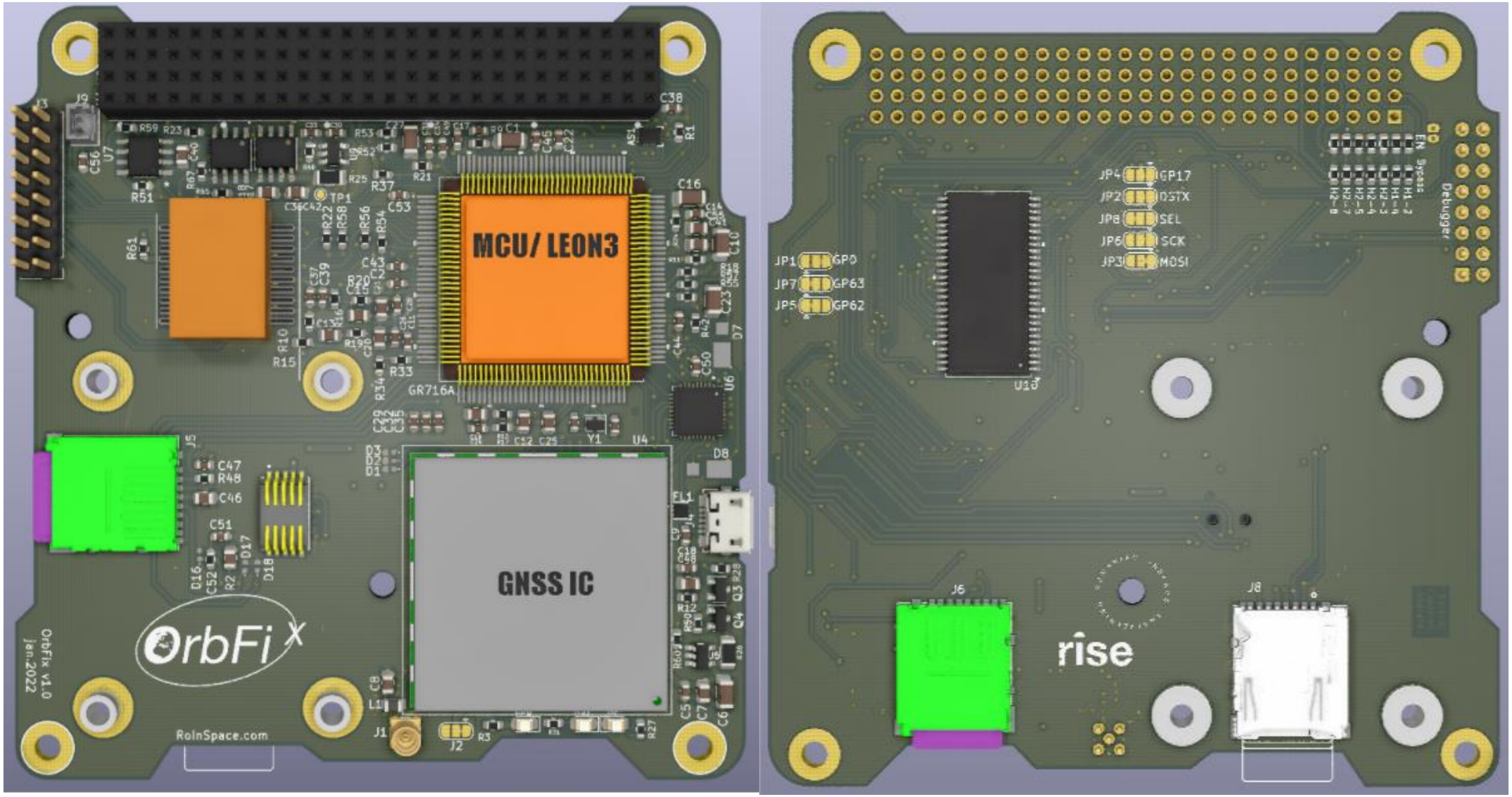
# OrbFIX - PCB Design

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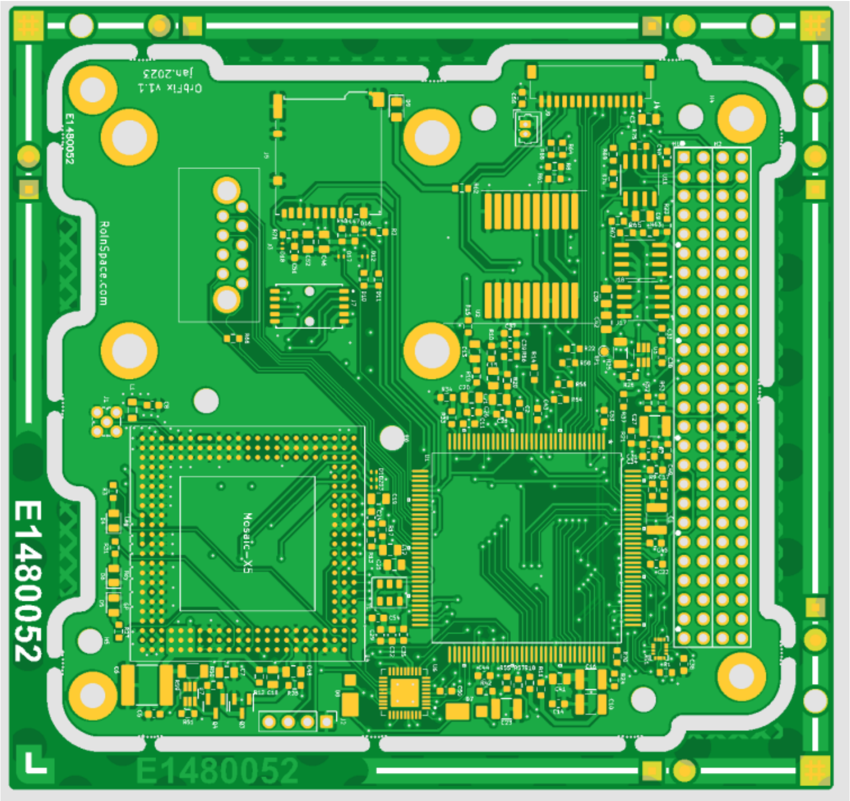
# Manufacturing



Multiple design specifications were taken into consideration, based on the CubeSat standard and the ECSS-Q-ST-70-12C ESA normative for printed circuit boards:

- The copper thickness of both the top and bottom sides are the same.
- Both the outer and the inner layers use a copper thickness of 35um.
- The distribution of copper within each layer is homogeneous.
- The fabricated thickness of the PCB is 1.6mm.
- The fabricated PCB has 4 copper layers.
- The BGA components of the PCB are circular and do not feature teardrops.
- All critical and differential tracks were routed on one single layer.

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# Engineering Model



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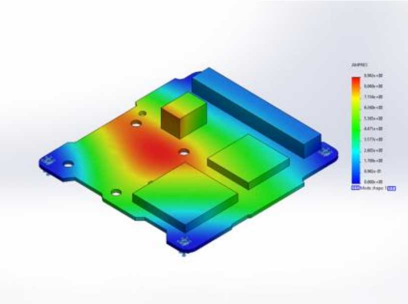
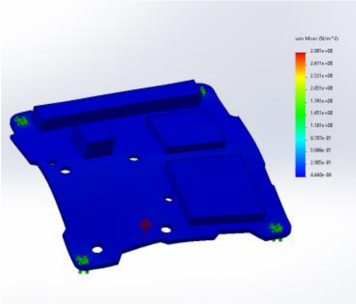
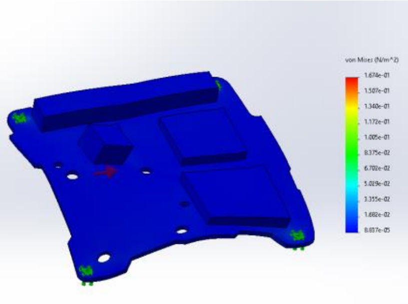
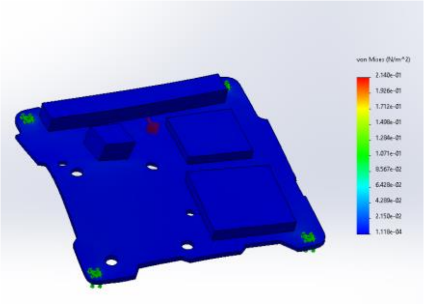
# Mechanical design

# Mechanical & thermal analysis



**OrbFIX structural analysis**

- First frequency: 191Hz
- Random vibration - Von Mises stress:
    - Axial: 2.901e+00 N/m^2
    - Lateral: 1.674e-01 N/m^2
    - Lateral: 2.140e-01 N/m^2

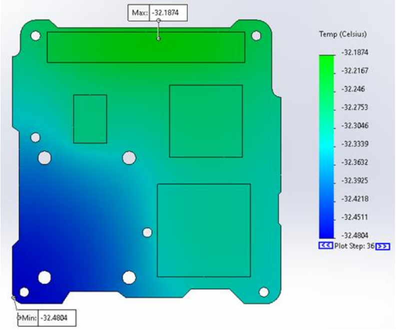
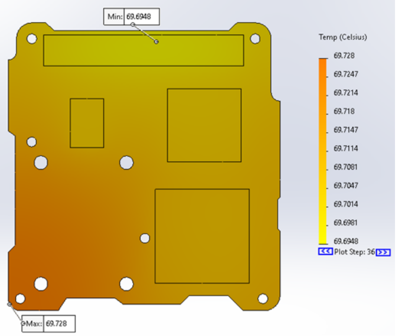
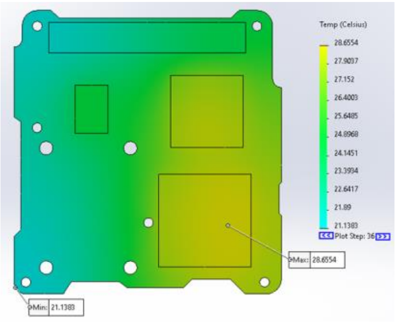
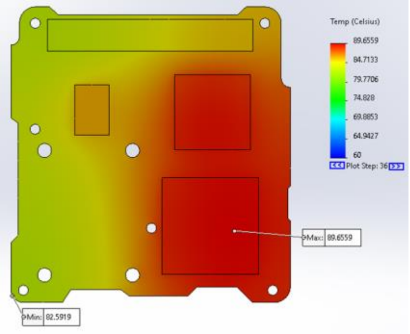





**OrbFIX thermal analysis**

- Initial temperature: 20°C
- Simulation time: 3600 s

- storage temperature testing range [-40°C; +70°C]
    - Negative plateau -40°C
        - Tmin -> Tmax: -32.48°C -> -32.19°C
    - positive plateau +70°C
        - Tmin -> Tmax: +69.69°C -> 69.73°C

- operational temperature testing range [-30°C; +60°C]
    - Negative plateau -30°C
        - Tmin -> Tmax: +21.14°C -> +28.66°C
    - positive plateau +60°C
        - Tmin -> Tmax: +82.59°C -> 89.66°C

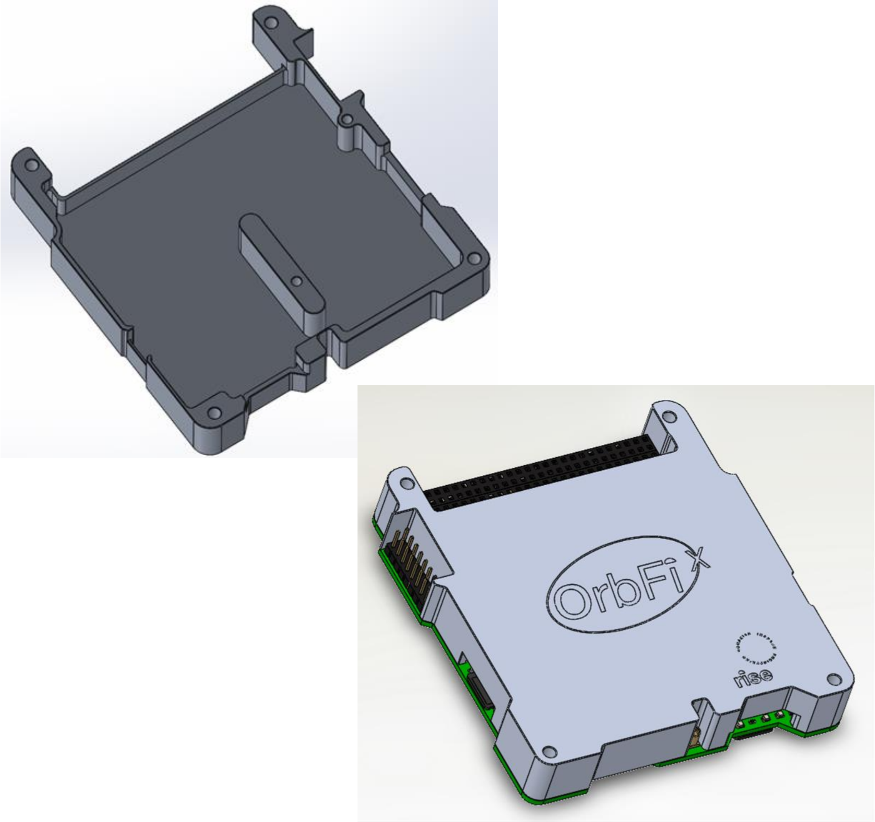





# Mechanical design

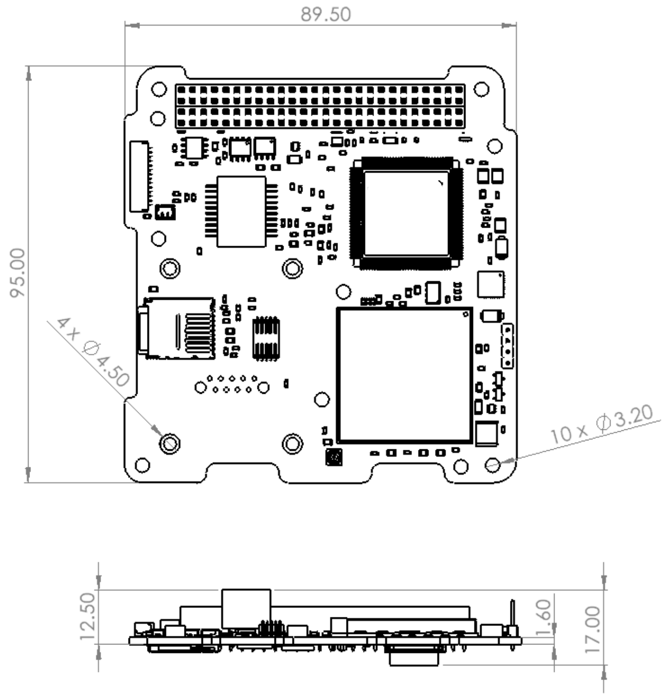


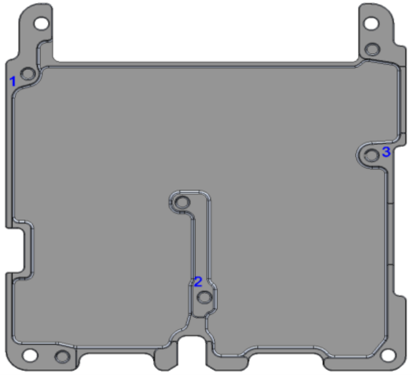
**Preliminary design** → **Final design**

- OrbFIX board + Aluminium Alloy cover
  - 4 alignment holes compliant with CubeSat specifications
  - 2 x M3 threaded holes for mounting the cover



- OrbFIX board + Aluminium Alloy cover
  - 4 alignment holes specific to CubeSat specifications
  - 3 threaded holes on the cover to better secure it on the board
  - 3 additional clearance holes in the board for optional back cover

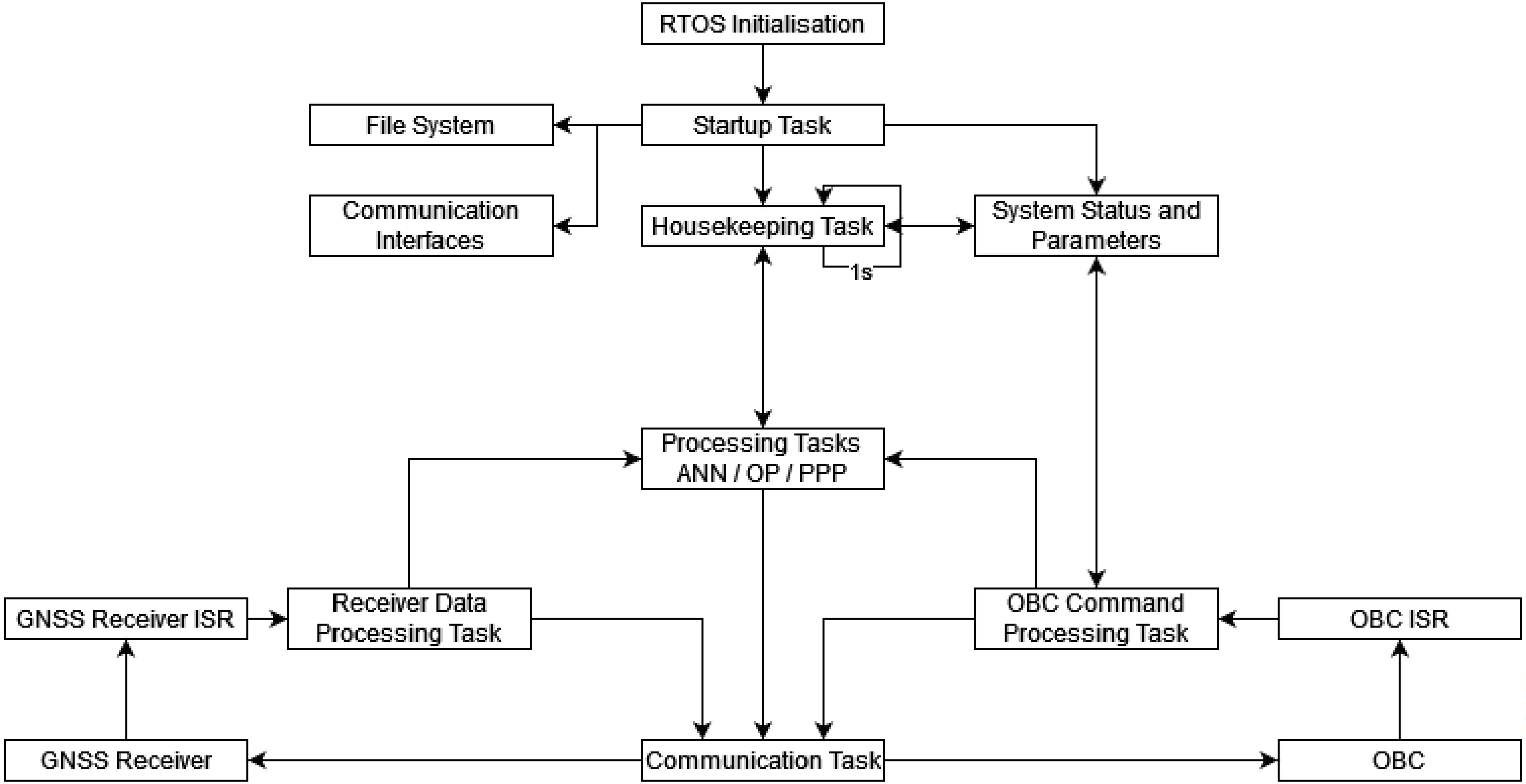


# Software

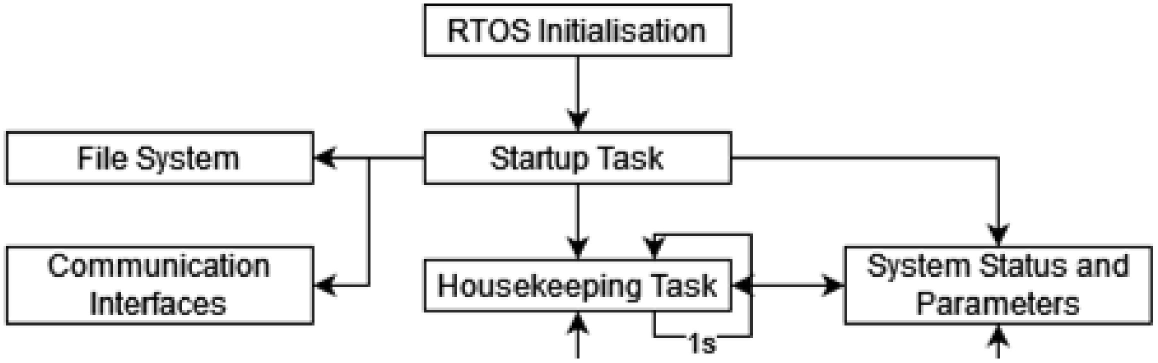
# Software Architecture





**Initialisation sequence - Startup Task**

- Initialisation of the **file system** and **communication interfaces**
- Loading default system parameters
- Starting housekeeping task




**Housekeeping Task**

- Periodic interrogation of system sensors
- Managing FDIR and operation modes
- Periodic PVT output in conformity with the current operating mode

**Operation modes**

- Low power - ANN + OP algorithms
- Nominal - PPP / high precision mode
- Simple - Receiver PVT / standard precision mode

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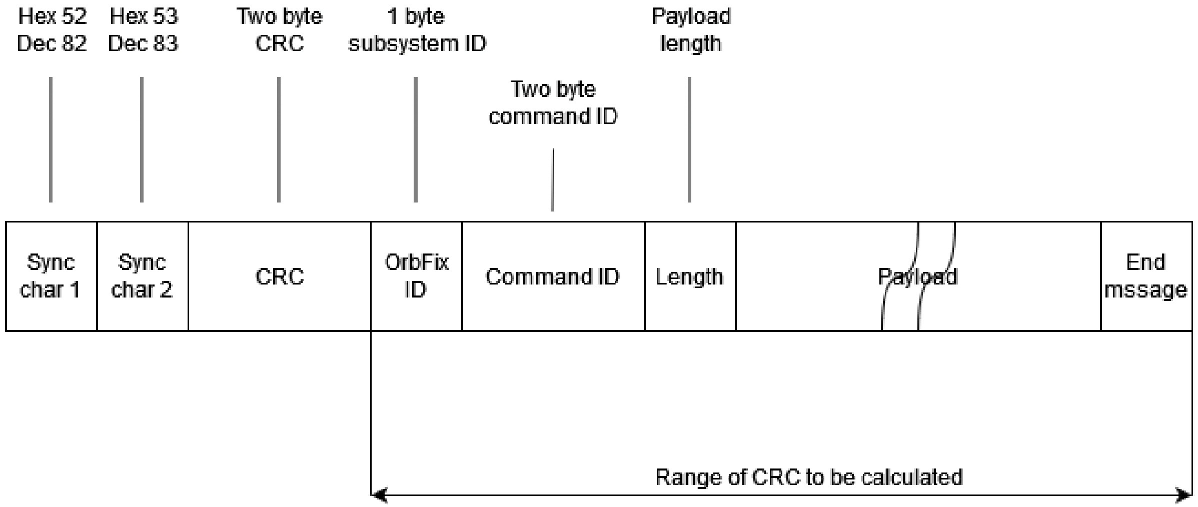
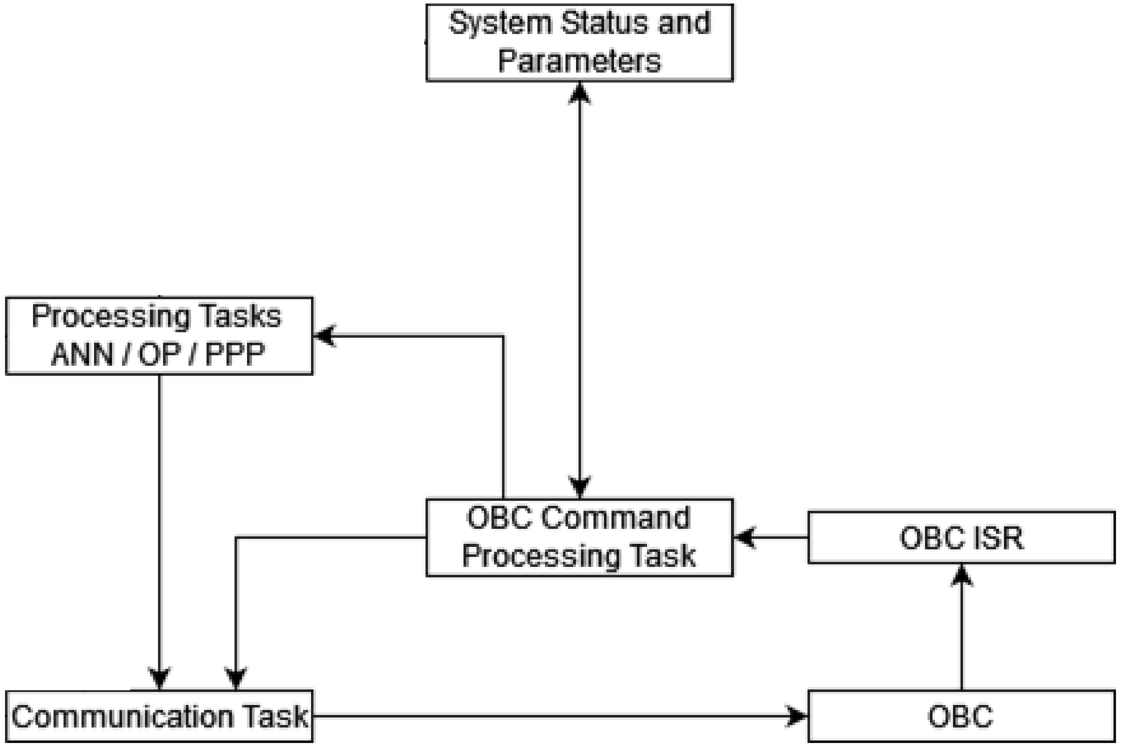
# Software Architecture

**Command Processing Task**

- Unpacking the command frame
- Dispatching commands to corresponding tasks
- Interrogating system parameters
- Configuring system parameters
- Responding to the OBC through the communication task
- Configuring GNSS module through the communication task




**OrbFIX Command Frame**



# Software Architecture



**Processing Tasks**

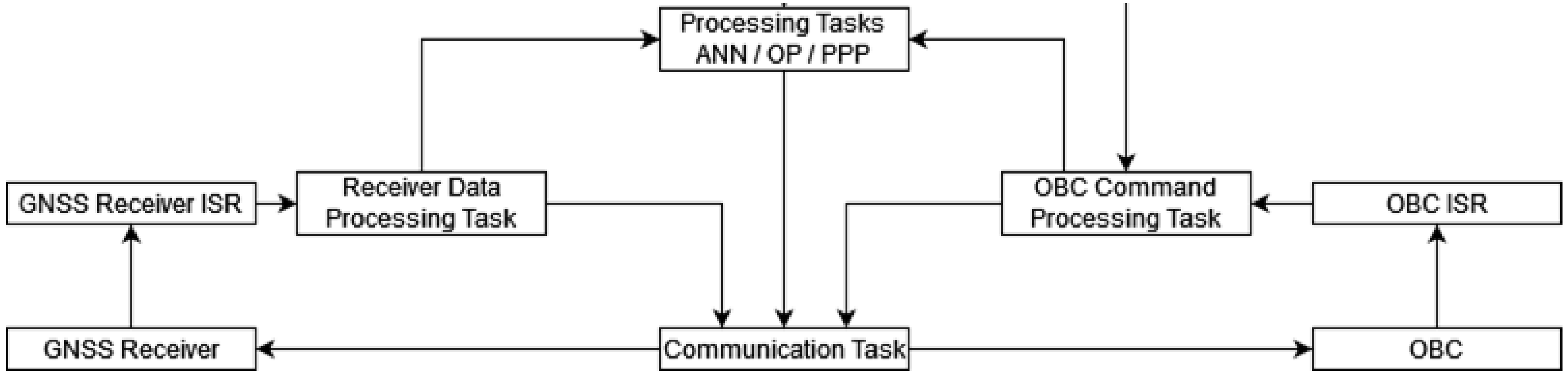
- Responsible of ANN, OP and PPP algorithms
- Run algorithms on request (OBC / Housekeeping)

**Receiver Data Processing Task**

- Delivering GNSS data to processing tasks
- Delivering periodic GNSS data to OBC through communication task

**Communication Task**

- Interface between tasks and physical subsystems



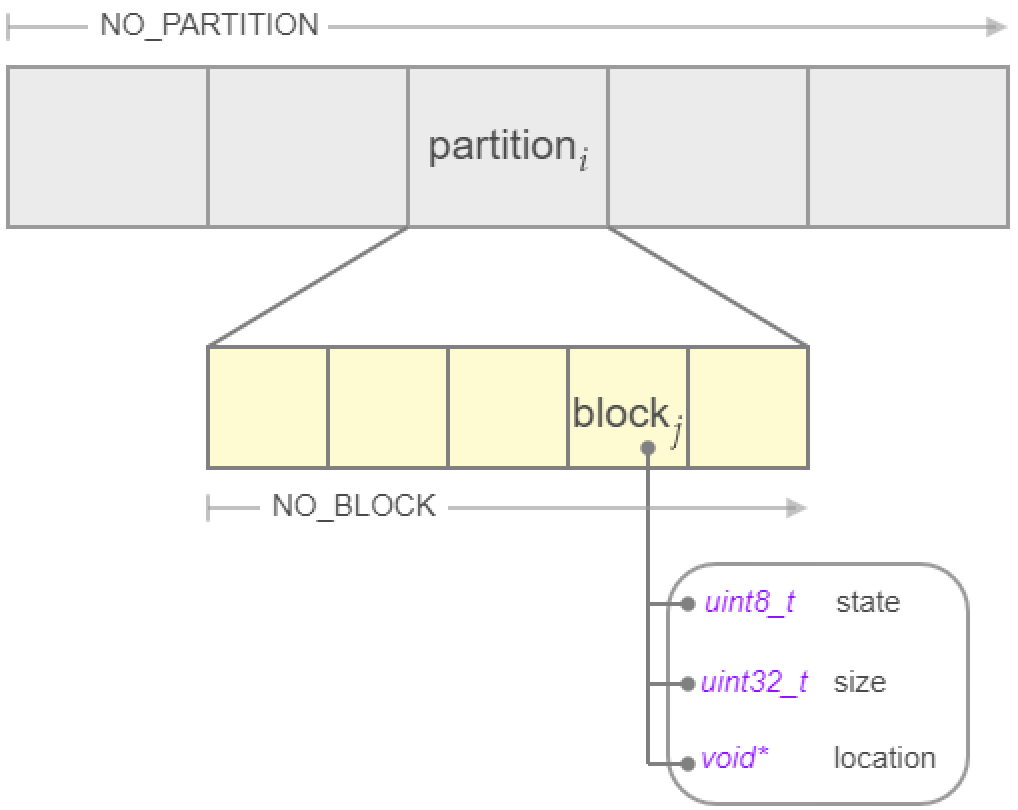
# Memory management

**Main idea**

- Use an array of blocks with the total size

  **NO_BLOCK * NO_PARTITION * sizeof(BLOCK)**

- Functionality of struct **BLOCK**
  - **state**: tells if **BLOCK** is occupied;
  - **size**: tells the **BLOCK** maximum capacity (bytes);
  - **location**: points to the memory address that can be used through **BLOCK**
- All the **BLOCK**s in a partition have a fixed size
- The memory for **BLOCK** array is allocated once



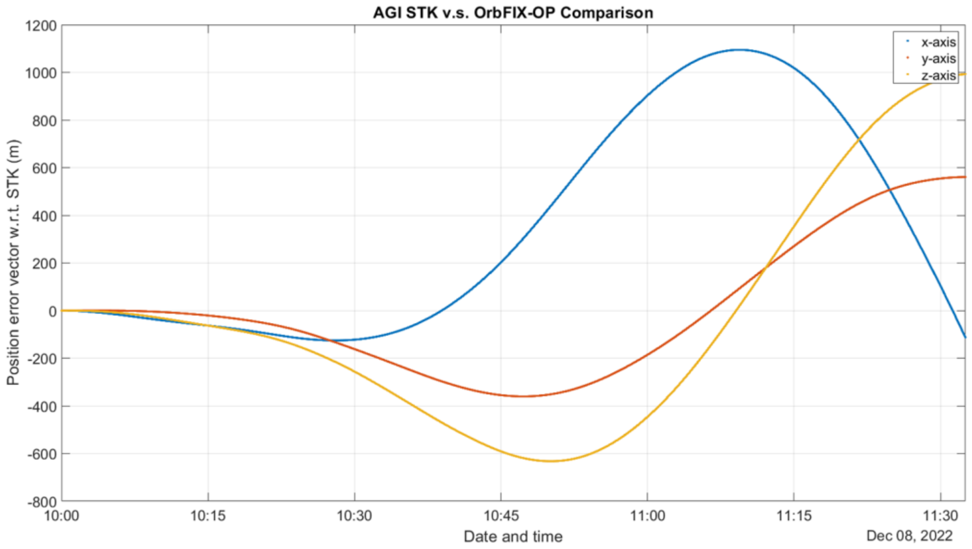
# Light orbit propagator for the Low-power Mode



### Modelled perturbations

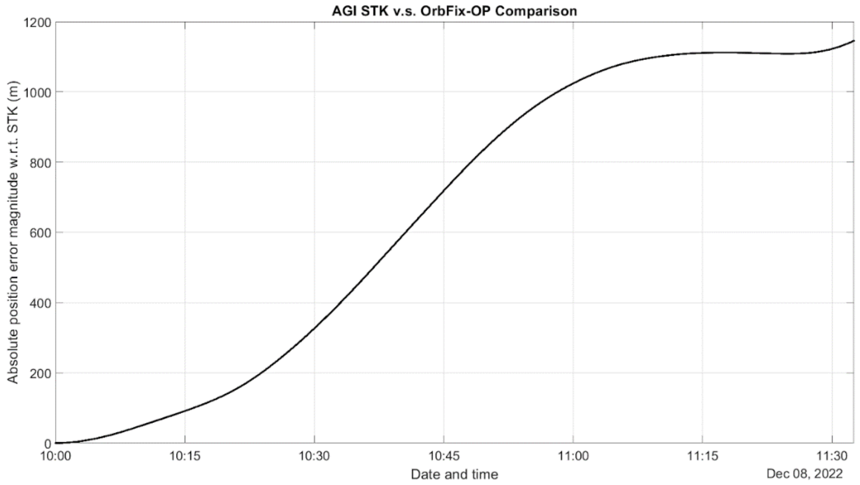
- J2
- 3rd body: Sun and Moon
- Solar radiation pressure
- Atmospheric drag (simple Jacchia-Roberts model)

### Validation with AGI STK




### Remarks

- The errors fall within the anticipated range
- Simple ANNs can be used to predict the propagation error
- These predictions can be used to reshape the trajectory

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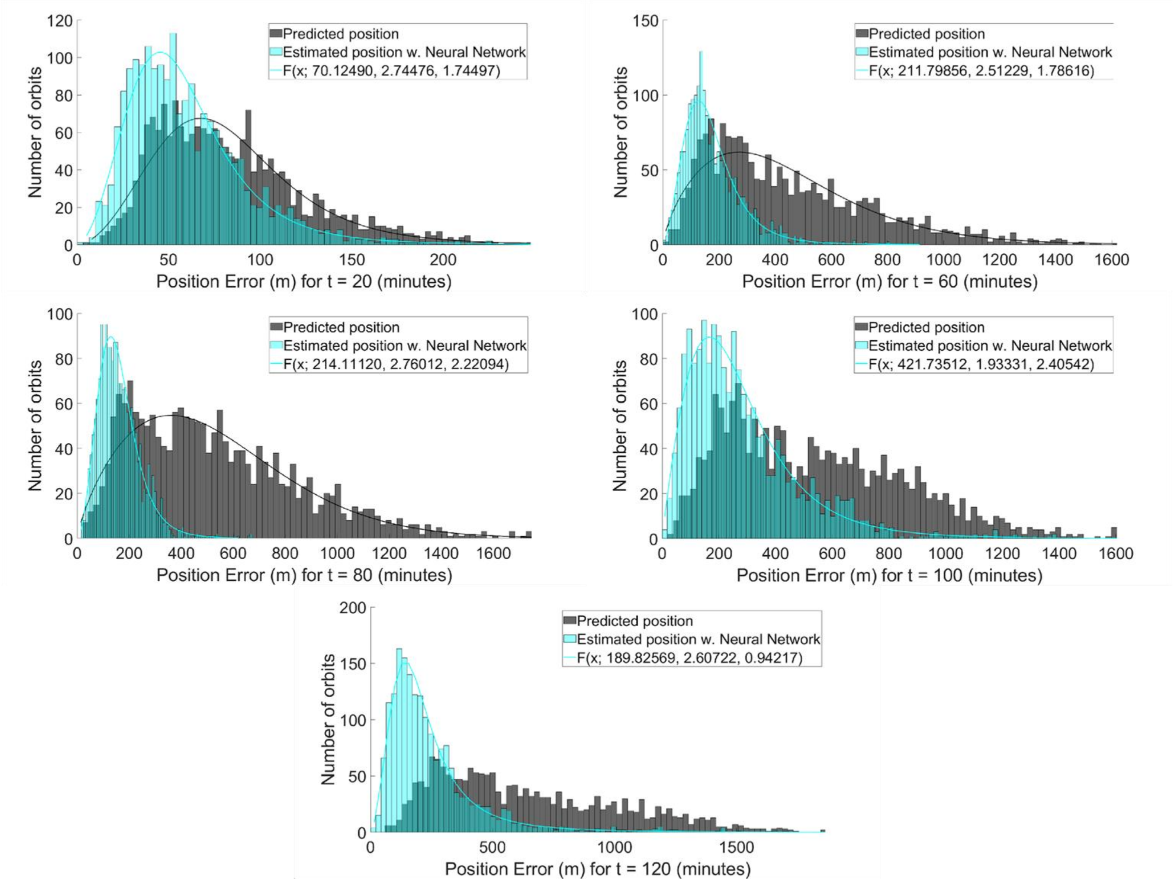
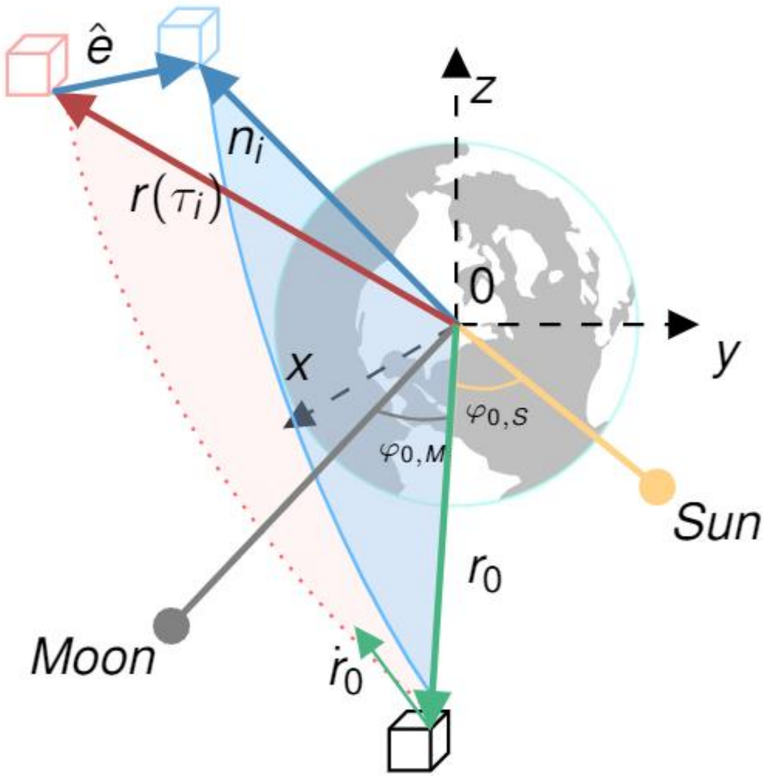
# Correcting the OP’s output with ANNs

**Main idea (from De-Risk activity)**

- Use a perceptron to estimate the OP’s prediction error at a future time
- Multiple ANNs can estimate the error at certain points and their output can be used to reshape the orbit

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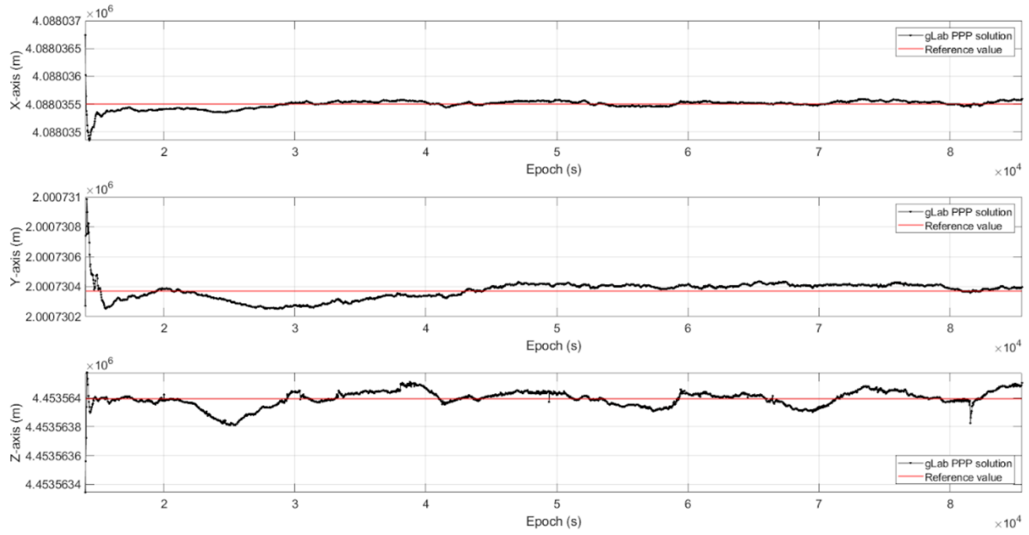
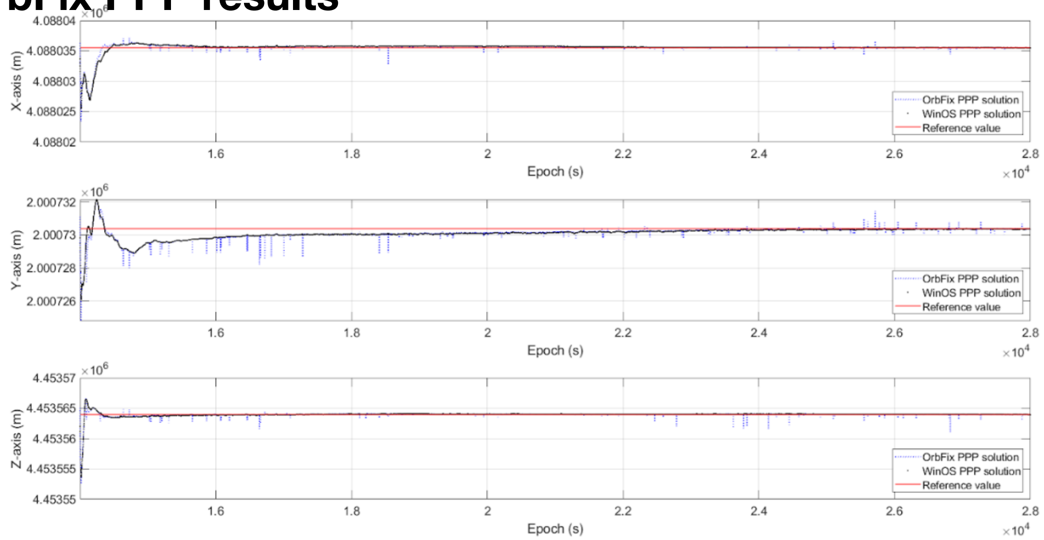
# Precise Point Positioning algorithm validation (1)

## We used gLAB PPP to determine the reference




## OrbFix PPP results




## Remarks

- OrbFix PPP algorithm is tailored for kinematic applications
- We run our algorithm on Windows and on MCU
- The accuracy of OrbFix PPP is (at 95$^{th}$ percentile)
  - X-axis: 6.886 (cm)
  - Y-axis: 5.866 (cm)
  - Z-axis: 6.786 (cm)

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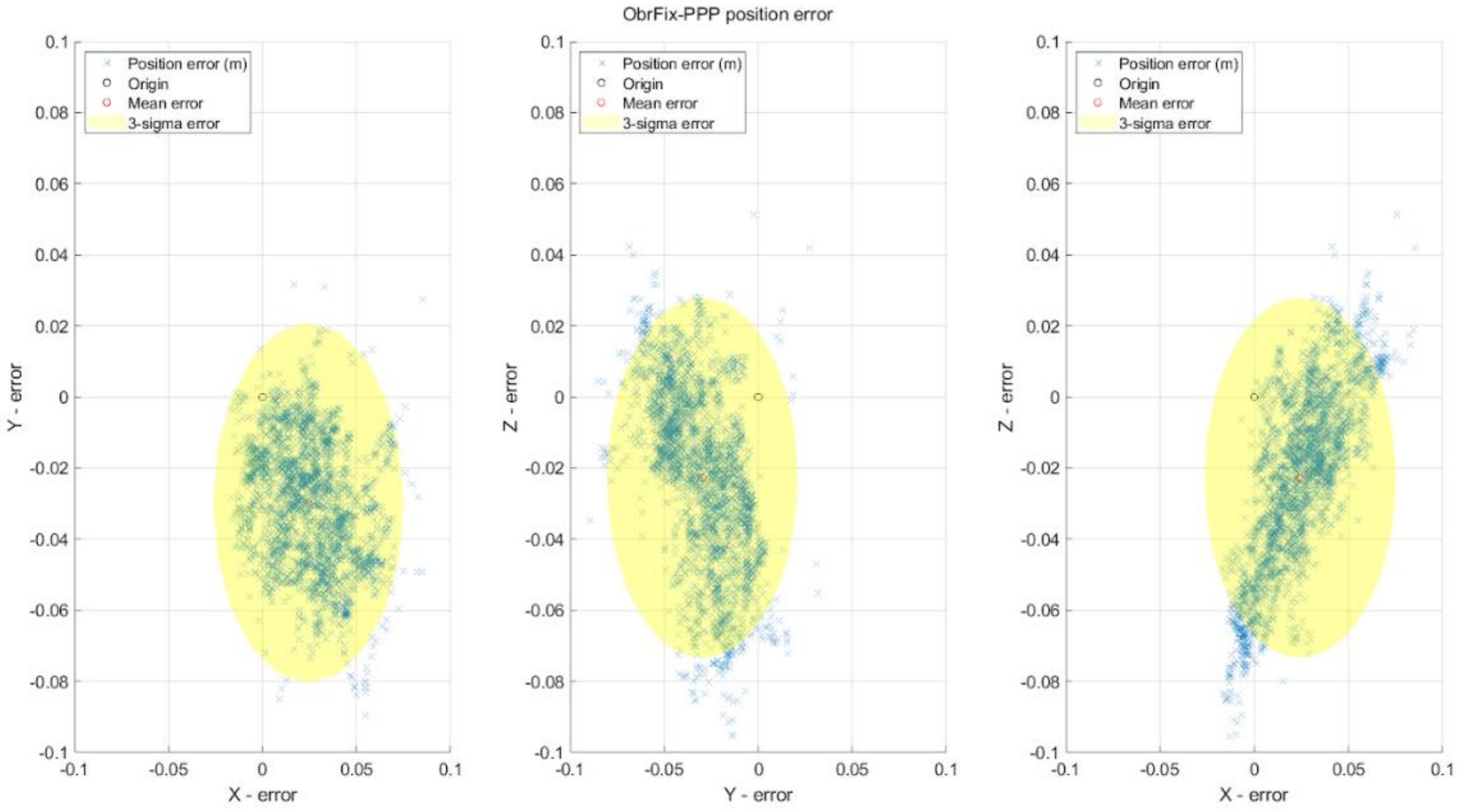
# Precise Point Positioning algorithm validation (2)

## OrbFix PPP errors

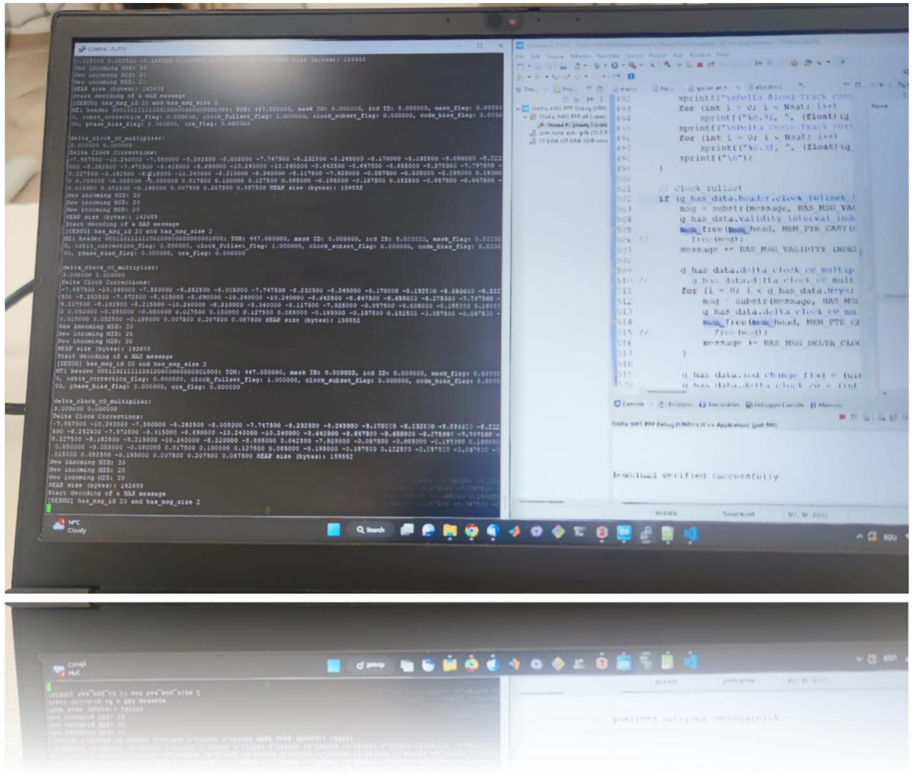


# Galileo High Accuracy Service (HAS)



**Updates on HAS**

- Successfully run the HAS algorithm as described in [RD-HAS]
- We are able to **decode live** the messages and compute the **corrections**
- Using the corrections, we can apply them as described in sec. 7 of [RD-HAS]



**Observations**

- The algorithm was implemented on GR716 and STM32
- GR716 is slow (up to 5 minutes per message)
- STM32 is much faster (up to 10 seconds per message)

[RD-HAS] GALILEO HIGH ACCURACY SERVICE SIGNAL-IN-SPACE INTERFACE CONTROL DOCUMENT

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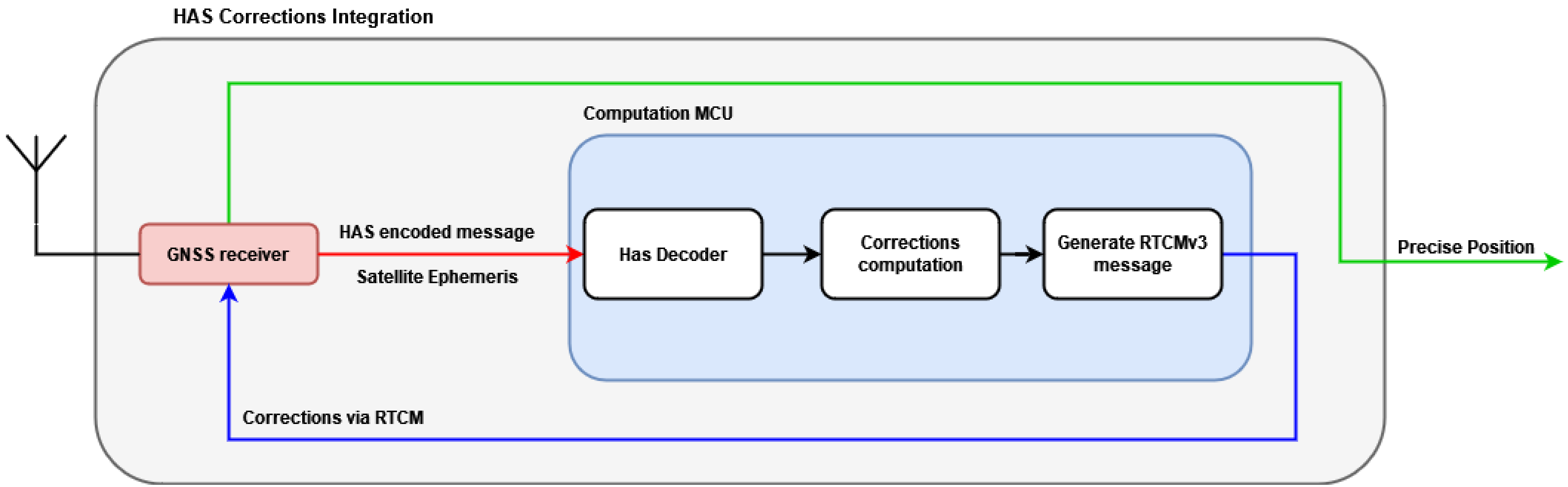
# HAS Corrections Integration



**Main idea**

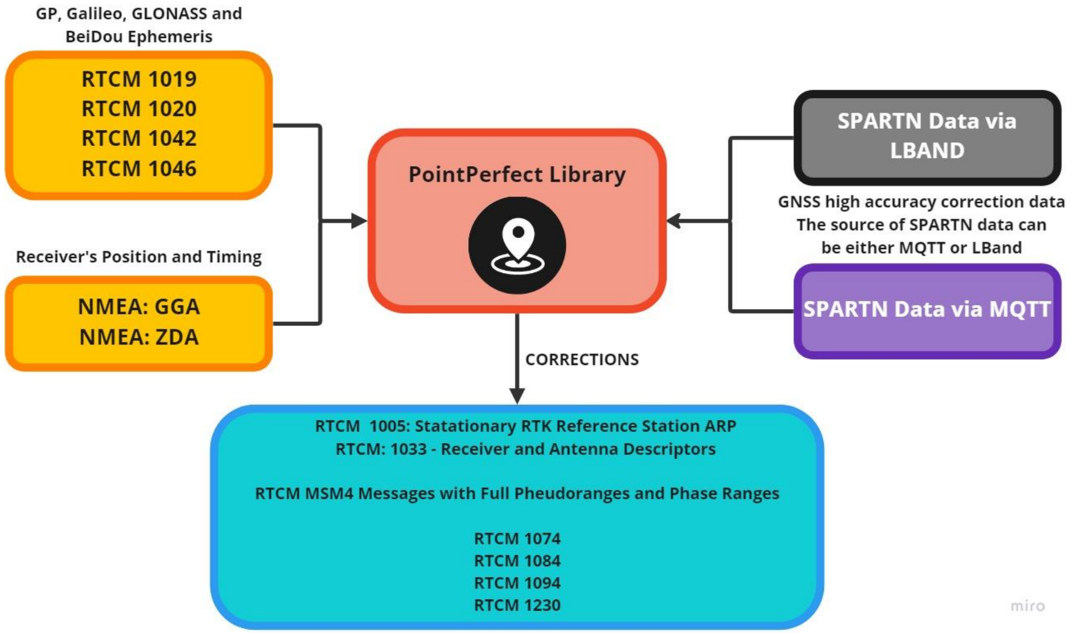
- GNSS receiver provides HAS encoded messages and Ephemeris to the Computation MCU
- Computation MCU decodes HAS corrections and packages them as RTCM correction messages for the GNSS receiver



# PointPerfect Library

## PointPerfect Library

- Accept corrections as SPARTN-SSR messages provided via MQTT service
- Alongside with RTCM Ephemeris, position and timing provides RTCM corrections for RTK




## Library Insights

- Successfully run the the PointPerfect Library on STM32 MCU
- We were able to obtain RTK Fixed precision level
- Consolidates our HAS correction integration approach

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# Challenges and Updates

# Challenges and Updates



**Hardware Challenges**

- Finding commercial components for development with RadHard equivalents.
- Needed to perform in-house procedures for pin cutting and forming for the MCU.
- Created option in which the end user may choose either the daughterboard or the SpaceWire controller due to size constraints.

**Software Challenges**

- Undefined memory usage scenario (Internal RAM + External RAM available at boot)
- Memory segmentation due to repeated allocation and deallocation of different sized blocks
- HAS decoding takes ~10 seconds (due to the Reed-Solomon algorithm)
- PPP solution computed at 0.1 Hz

**Processing Resources & Architecture Challenges**

- Small internal RAM of the MCU
- External RAM speed (~10x slower than internal)
- Tradeoff between external RAM size and price
- Limited customisation of the communication interfaces
- Slow processing speed

**Testing Challenges**

- small dimensions of the DUT in relation to the mounting adapter. Difficulties in discerning between DUT and adapter share in the test results;
- small components and overall dimensions of the device, therefore limited space available for thermal sensors.

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# Challenges and Updates



### Hardware Updates

- The PCB features the option of adding non rad-hard components for prototyping purposes.
- The PCB will feature another MCU for precise positioning algorithms

### Processing Resources & Architecture Updates

- Added 512kB external RAM for data that does not require fast access speed
- MCU has been clocked to 50MHz (from 20MHz)

### Software Updates

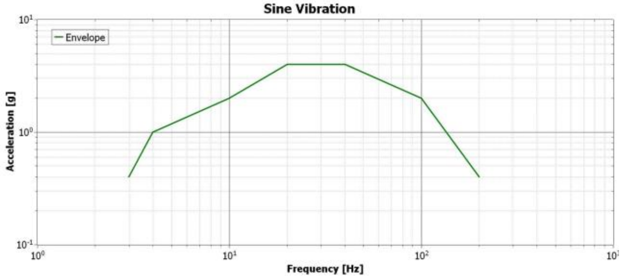
- Added custom instructions to initialise the external RAM at boot before loading the code
- Implemented custom memory allocation system to avoid segmentation
- Precise positioning algorithms will be moved to the additional MCU
- Galileo HAS decoding

# OrbFIX Preliminary Test Results

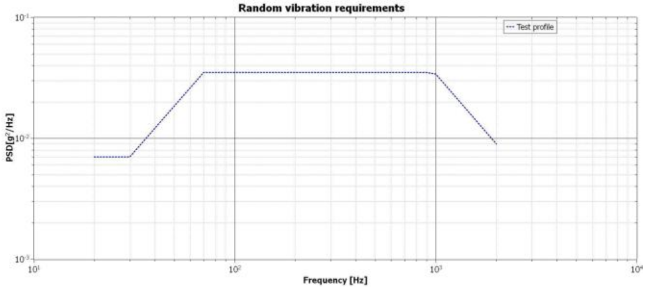
# Environmental testing

## OrbFIX vibration testing

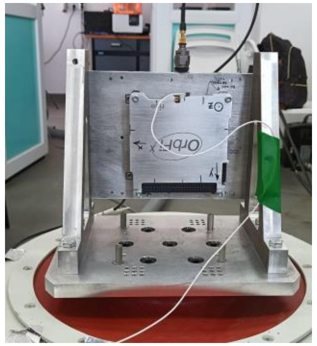
- Frequency search: 5-2000 Hz/0.25g
- Sinusoidal vibration: 3-200 Hz




- Random vibration: 20-2000 Hz



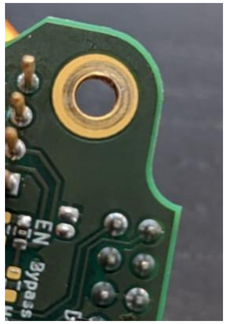

- Testing configuration:


Results:

- several spectrum changes larger than ECSS recommendations occurred during the frequency search after random vibration;
- modifications at the level of the alignment fixing holes, as a proof of mechanical stress:



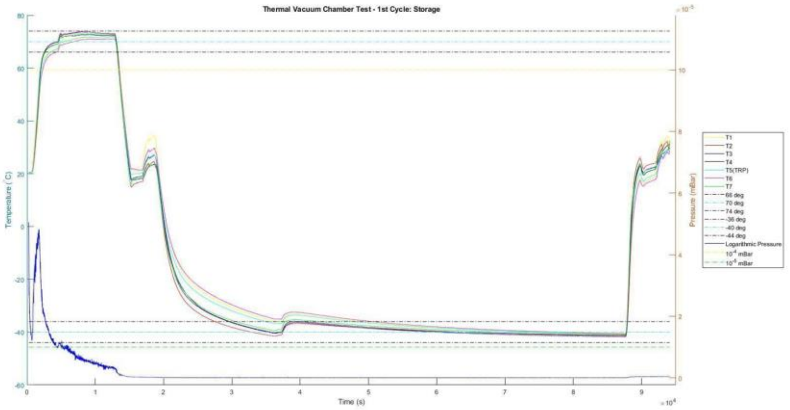



- Successful test campaign: very good results for the OrbFIX's EM particularities acting as a driver for improving tests and analysis for the final qualification phase.
- no dimensional, functional or performance modifications suffered by the DUT

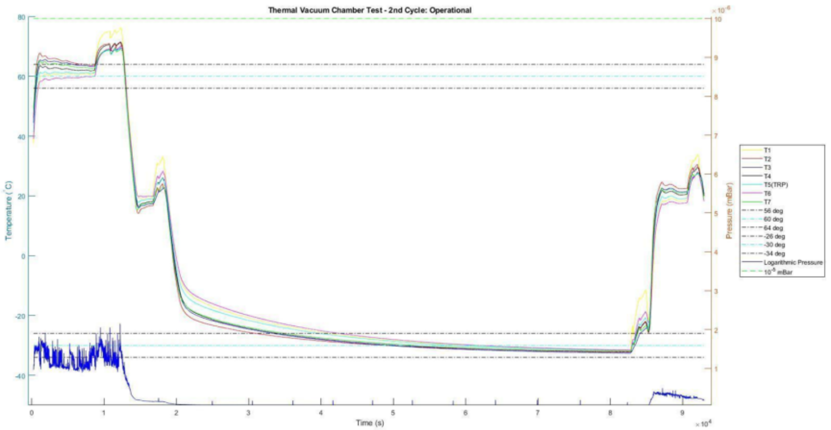
# Environmental testing

**OrbFIX thermal vacuum testing**

- Pressure: < $10^{-5}$ hPa
- Storage: -40°C -> +70°C



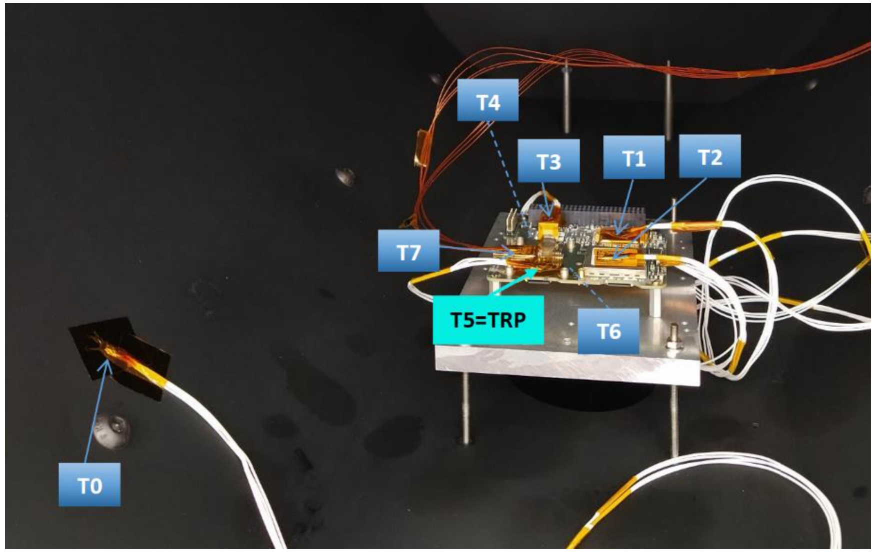

- Operational: -30°C -> +60°C




Results:

- no dimensional, functional or performance modifications were observed after the thermal testing campaign
- all functional tests at extreme temperatures were successful

Testing configuration:

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# Radiation testing

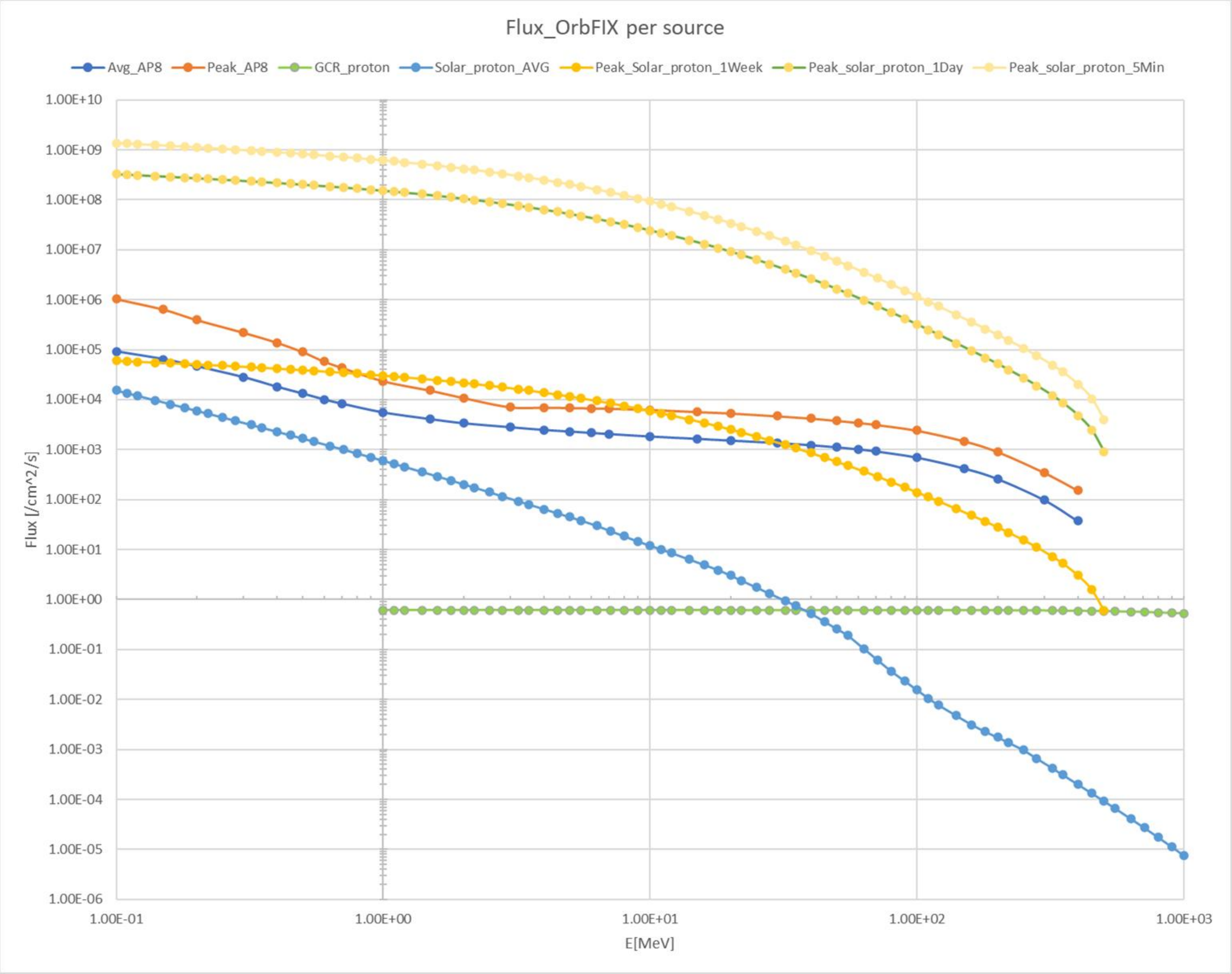
# Estimation of radiation flux

Total mission duration: 3 years

- SSO Orbit
- 800 km altitude
- at solar maximum

Sources:

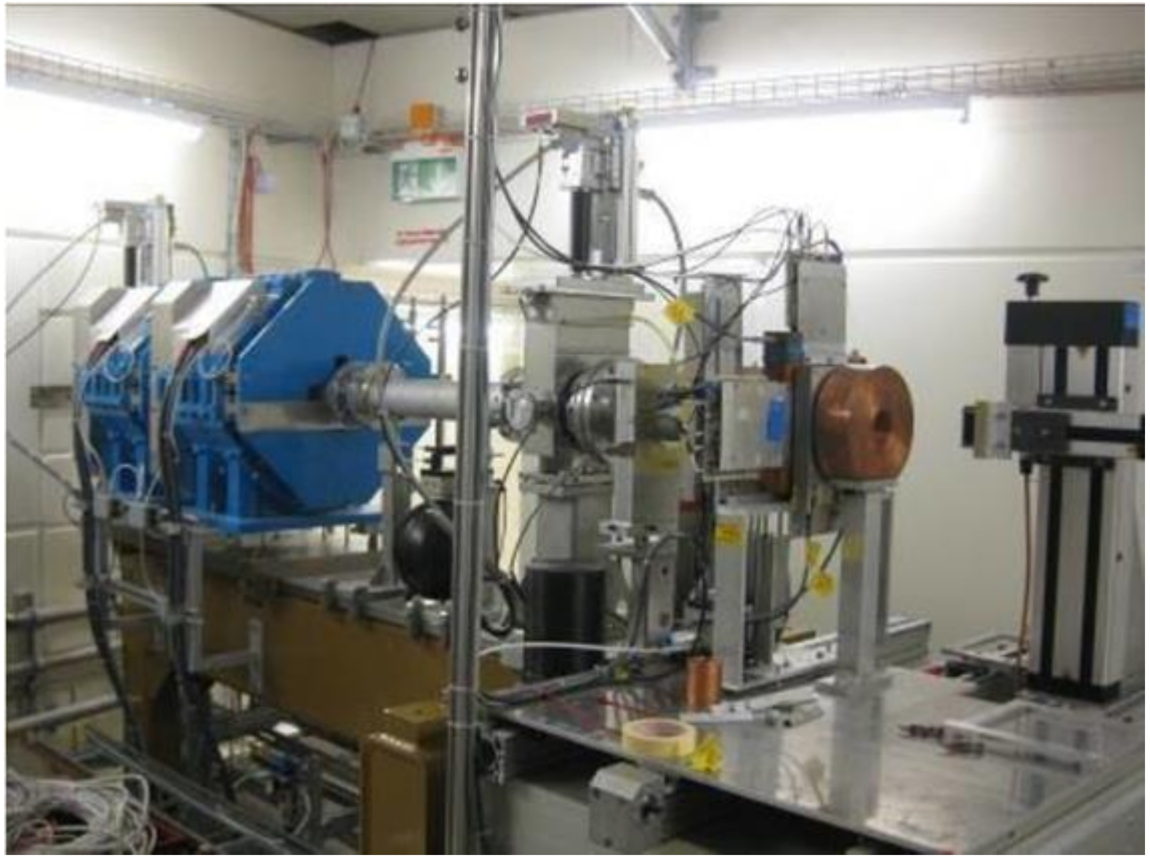
- Trapped proton flux: AP-8 Max model;
  - Average typical flux
  - Peak trapped flux
- Solar protons
  - As total fluence for the mission duration: SAPPHIRE model
  - As peak proton flux (worst week): CREME-96 model
- Galactic cosmic protons (only the hidrogen component of the GCR).

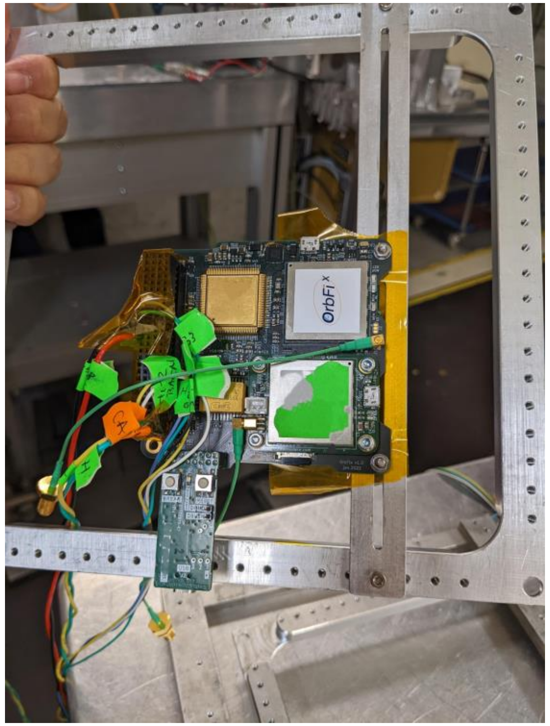


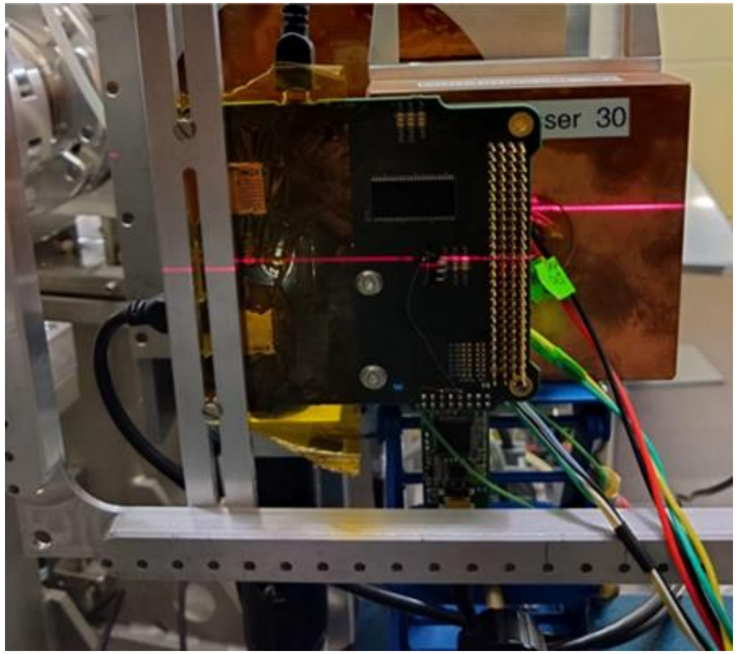
# Set-up and installation - PIF



- Proton energies 30 MeV - 200 MeV
- DUT:
  - OrbFIX 1st hardware iteration
  - Two GNSS receivers:
    - on main board
    - on daughter board
  - partial shielding for: MCU, RAM, Flash



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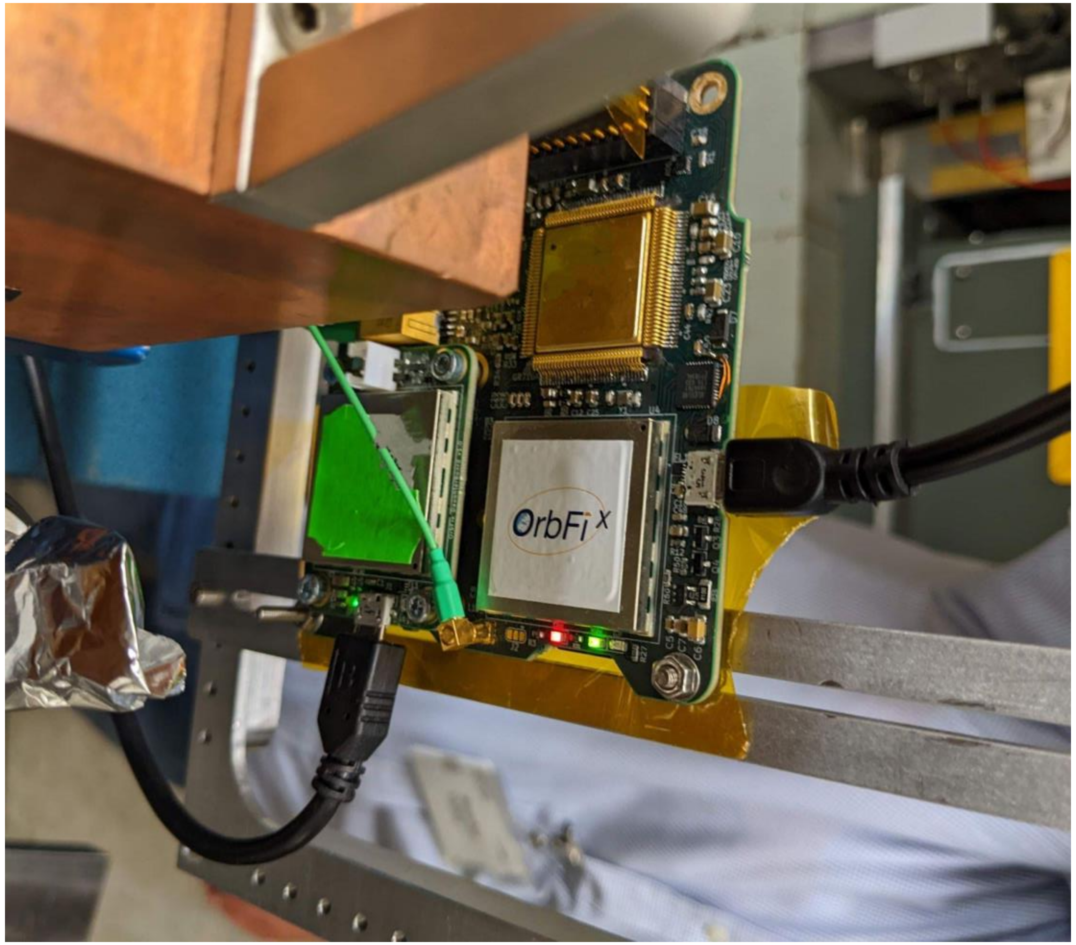
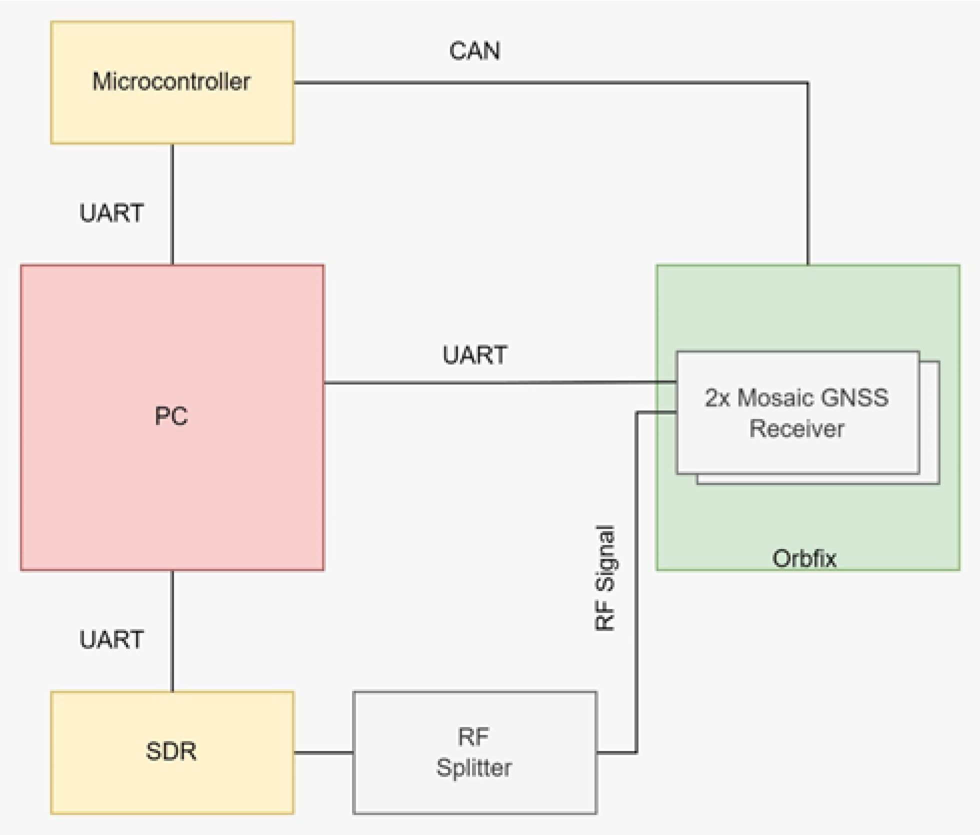
# Set-up configuration



- MCU provided power control for receivers
- each receiver connected to PC for detailed debugging
  - USB connection
- each receiver logging on each SD Card (unshielded)



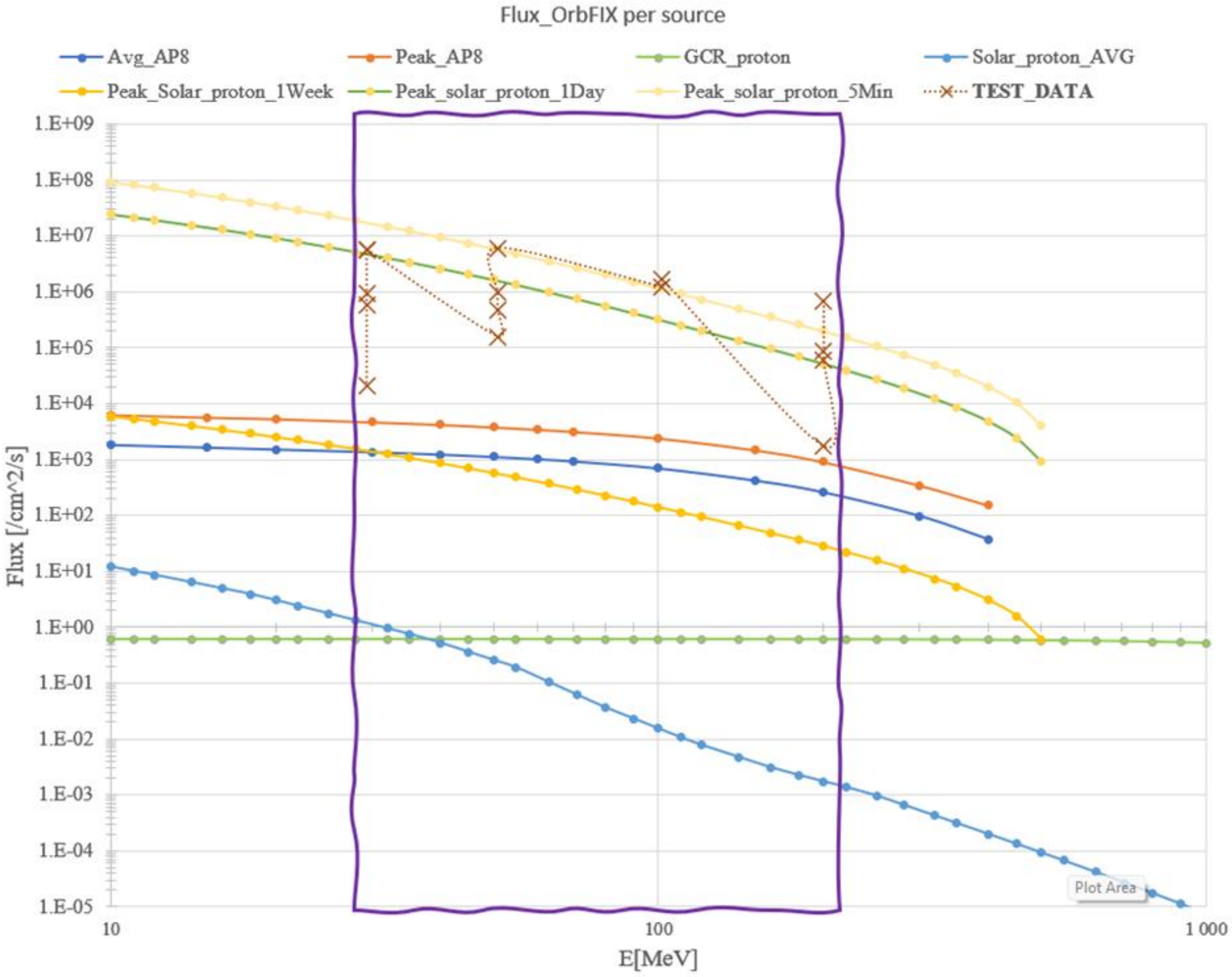
# Experimental fluxes



- Irradiation at 200 MeV, 100 MeV, 50 MeV, 30 MeV
- Flux was targeting worst week or increased:
  - but was adjusted to reduce rate of resets
  - kept at high values to obtain relevant total fluences

Irradiation sequence:
200 - 100 - 50 -30 - 200 - 50 - 100 - 30

- Irradiation at fluxes:
  - above worst trapped proton
  - above worst week solar flux
  - up to worst 5 minutes in orbit

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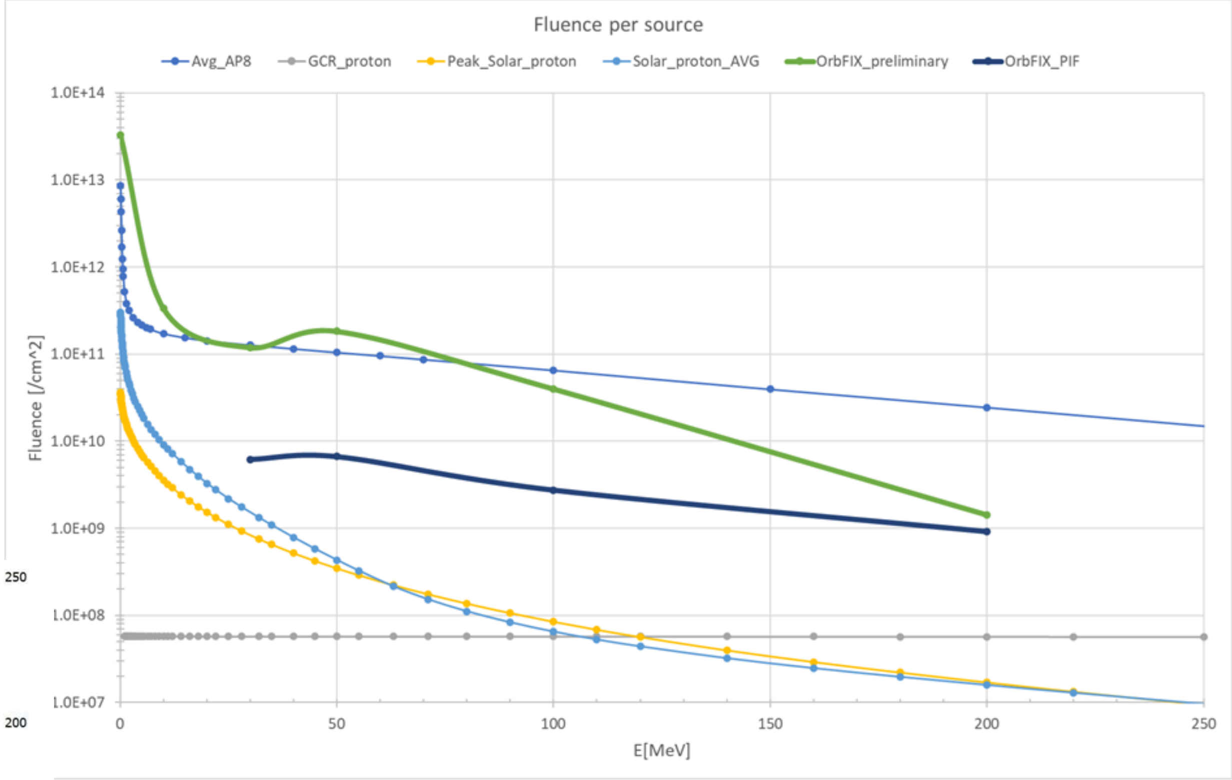
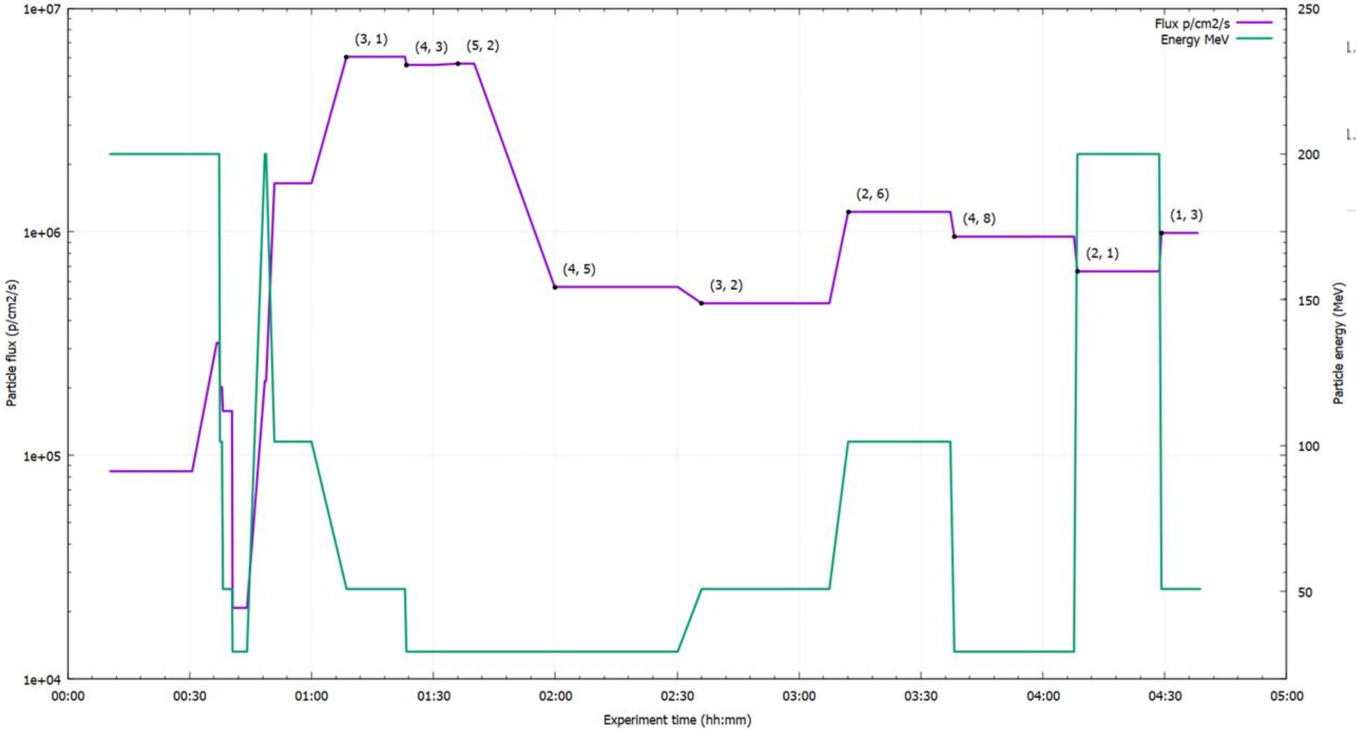
# Experimental fluences



- Total tested fluence in 5 hours
    - ~ 1e10 p/cm$^2$
    - ~ 1 order of magnitude below mission lifetime
    - but at **higher** fluxes
    - TID accumulated in the experiment 2.8 krad

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# OrbFIX - Environmental testing



## Lessons learned

Vibration testing

- Increase the stiffness of the cover (a third screw was added for the cover mounting)
- Optimize the fixtures, to reduce its contributions during testing and better secure its alignment

Thermal testing

- The GNSS receiver’s temperature was approximately 20°C degrees higher than the shroud temperature, but within normal limits.
- easy and fast access to data (live temperature data and specification data for critical components) make difference in taking decision during testing campaign.
- Test time could be reduced with a smaller testbed mass and an optimized adapter

Proton irradiation testing

- A dedicated testbench would have accelerated the operations during testing
- The support equipment (eg: debugger) should be kept away from the irradiation area
- SD cards which are space-proven shall be tested
- The communication interfaces should be kept simple (UART instead of USB)

- Functional testing discovered a software bug, but a workaround was implemented and still confirmed the SD card functionality

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# Way forward

# Qualification plan



- Qualification according to ESA's ECSS testing standards
- Relevant margins, tolerances, levels and durations for a space segment equipment will be used
- Functional and environmental tests will be conducted in the campaign

**Vibration testing**

- Equipment needed: vibration shaker, mounting adapter
- Control and monitor accelerometers on the mounting and on the DUT, respectively
- Powered off DUT

- Vibration testing campaign with the following sequence for both sinusoidal and random vibrations: **low level sine run**, **full level run**, **low level sine run**
- Functional verifications to be run at specific moments of the test(before, intermediary, after)
- Resonance search(low level sine profile): 5-2000 Hz with 0.25g amplitude
- Testing profiles:

| Sinusoidal | |
|---|---|
| Frequency [Hz] | Acceleration [g] |
| 5 | 1 |
| 10 | 2 |
| 20 | 4 |
| 40 | 4 |
| 100 | 2 |
| 140 | 1 |

| Random | |
|---|---|
| Frequency [Hz] | PSD [$g^2$/Hz] |
| 20 | 0.007 |
| 30 | 0.007 |
| 70 | 0.035 |
| 900 | 0.035 |
| 1000 | 0.034 |
| 2000 | 0.009 |

# Qualification plan

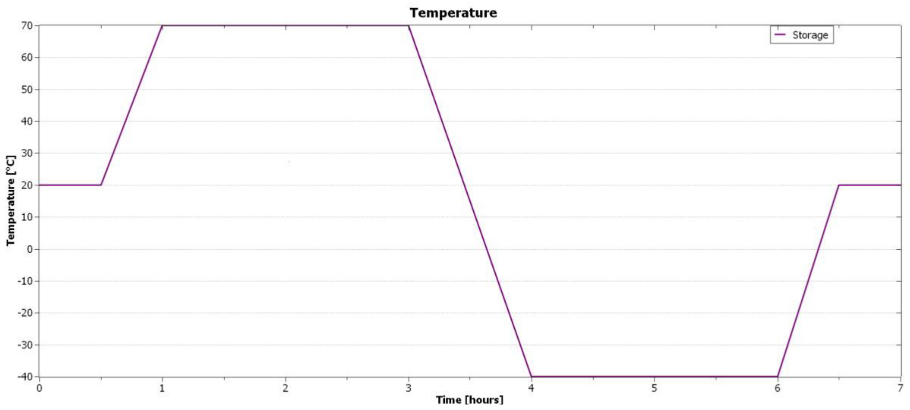
## Thermal vacuum testing

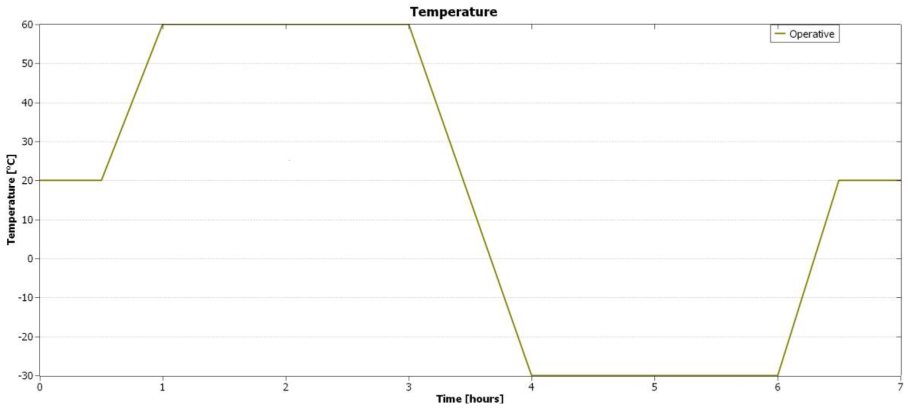
- Pressure: < $10^{-5}$
- Equipment needed: thermal vacuum chamber, mounting adapter
- Temperature sensors placed in specific places
- A TRP shall be selected
- Powered on at functional testing

- 8 complete cycles for qualification
- Functional verifications to be run at specific moments of the test(before, intermediary/at plateaus, after)

- Testing profiles:

| Thermal vacuum | |
|---|---|
| Storage | Operational |
| -40°C -> +70°C | -30°C -> +60°C |



# Qualification plan



**Functional testing**

- Prove that the DUT withstood any required test while performing its routine in nominal manner
- Benchmark functional tests will be conducted before, during and after every other test in the qualification plan
- Board expected to perform nominally
- Any deviation shall be documented and analysed
- Organisation of the test:
  - Cycle through the operating modes (low power, simple, nominal)
  - Perform ADC readings of current consumption.
  - Perform GNSS data acquisition.
  - Perform communication with a target host by cycling through the provided commands
- Minimum EGSE:
  - Debugger for the DUT, jumper wires, OBC Emulator, power source, GNSS antenna / GNSS simulator, RF cable, voltage and current measurement tools

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# Qualification plan



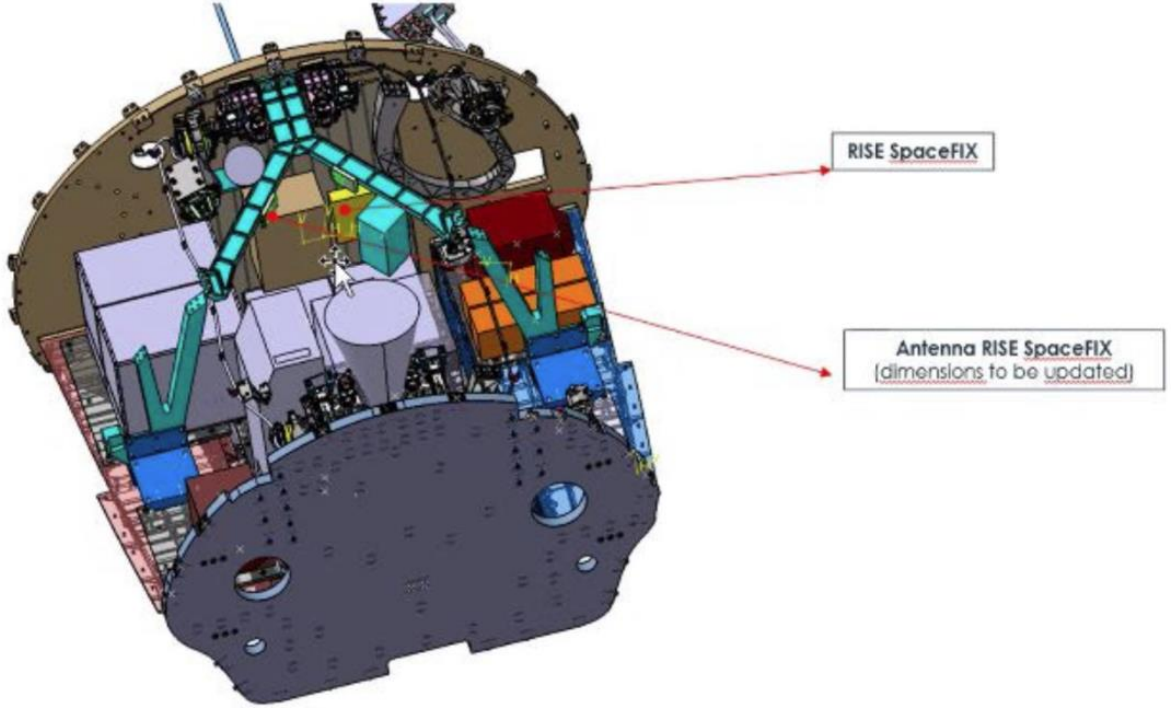
**Radiation Testing**

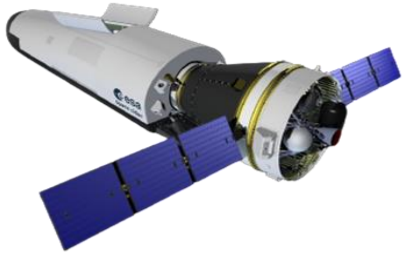
- Ionising test
    - 30 krad ~ 3 years in LEO
    - gamma ray source
    - characterization after test and after 48 hours
    - 1 CPU & 2 COTS GNSS receivers || 2 CPU & 4 COTS GNSS receivers
    - destructive
- High energy proton test
    - procedure modified by lessons learned
    - 30 - 200 MeV
    - 1 CPU & 2 COTS GNSS
    - non-destructive

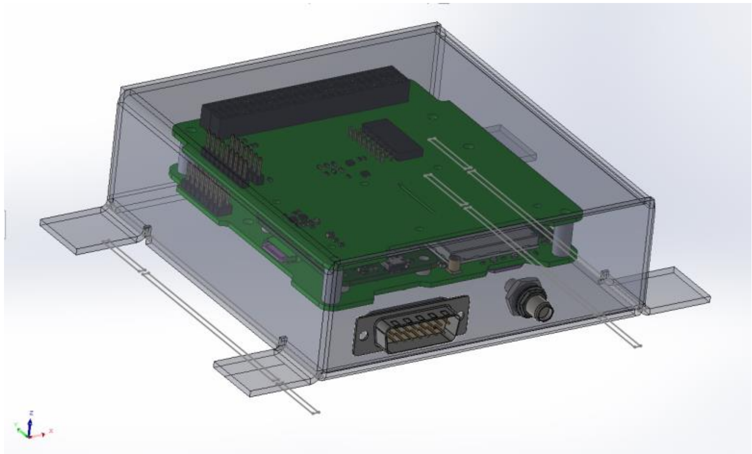
# IOD and potential users



- In-orbit validation
  - Space Rider – maiden flight agreed (signed MOU)
  - Potential satellites for IOD
- Commercial
  - Pitching to satellite developers
  - Discussions with OneWeb
  - Interest from constellations **and launchers**





# Conclusions



## OrbFIX BB Phase 2 outcome:

- Design of a COTS PPP GNSS receiver for space
  - Capable to receive & decode Galileo HAS corrections
  - Additional microcontroller for HAS decoding and PPP
- 1 assembled prototype and 1 EM, **TRL 5**
- TVAC, vibrations & proton irradiation testing of prototype
- Qualification plan -> ESA GSTP BB Phase 3 -> **TRL 8**
- Planned Space Rider IOD -> ESA GSTP BB Phase 3 -> **TRL 9**

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# Thank you!