The SEAM story

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DISCOVERER, Munich, 181128

Outline

- Scientific and technical objectives
- Satellite concept
- S-band communication
- Deployable boom
- Launch
- Project achievements and lessons learned

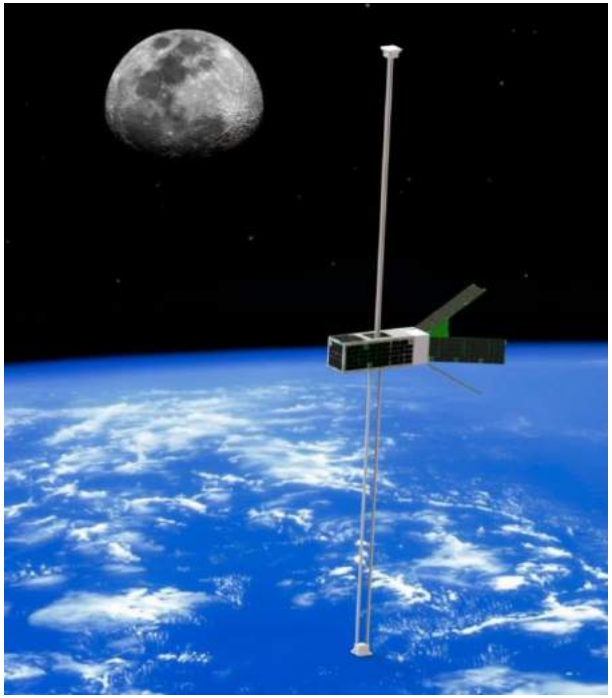
SME-oriented project – science driven

Development of new solutions by SMEs for high-end of the nanosatellite market, funded within EU FP7

- KTH (Sweden, university)
- ÅAC Microtec (Sweden)
- ECM-Space (Germany)
- LEMI (Ukraine)
- BLE (Hungary)
- GOMSpace (Denmark)
- SSC (Sweden, state company)
- Kayser Italia (Italy)

Science & Technical Objectives

- High-quality DC and AC magnetic field observations on a nanosatellite
- New approach for operation strategy
- High rate TM/TC, use of commercial ground stations on cost-effective basis



Science 1 – Auroral Currents

Space weather – monitoring

Small scale currents – high res.

Coordination with:

- SWARM
- Ground-based optics
- EISCAT
- SuperDARN
- …

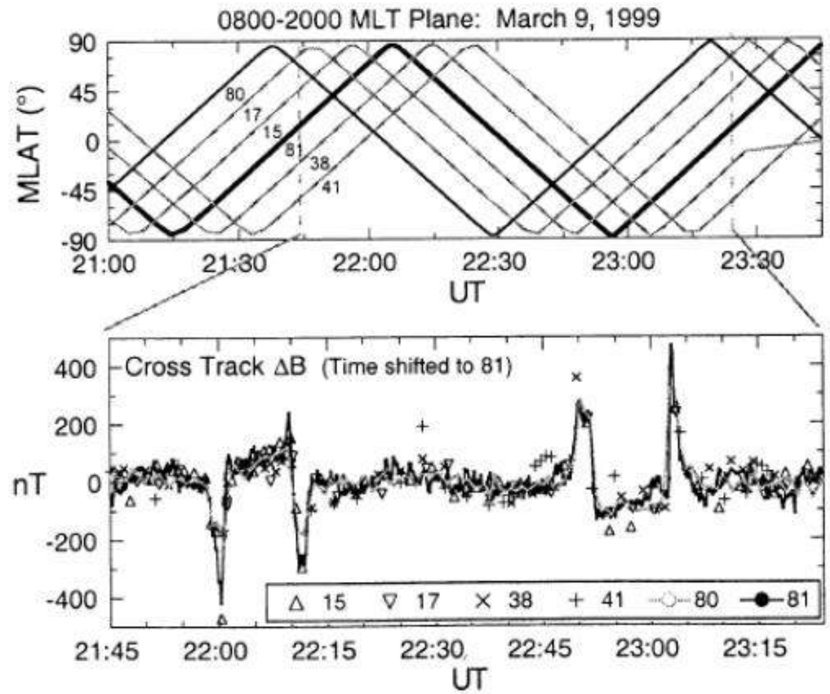


Figure 3. Example of Birkeland current signatures from multiple satellites in the same orbital plane. Magnetic latitudes (top panel) for six satellites and final cross track residuals (bottom). Cross track residuals are time shifted so that the magnetic latitudes of each satellite corresponds to that for satellite 81.

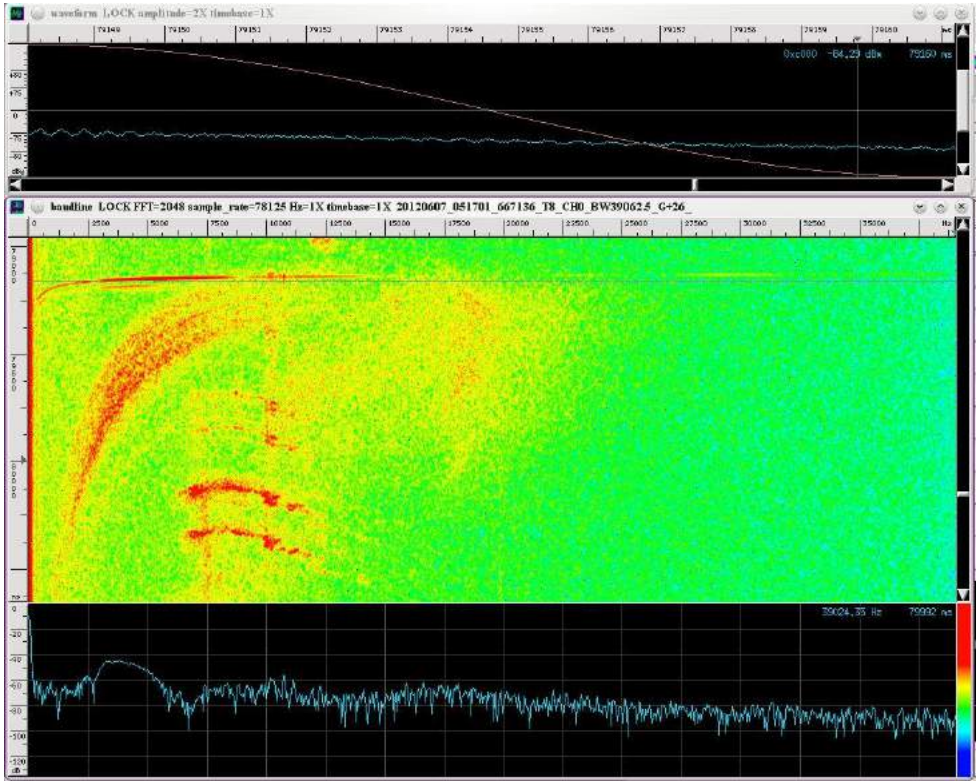
Science 2 – Natural ELF & VLF Waves in the Magnetosphere

Lightning produced waves

Propagation characteristics affect the received spectra. Together with models, plasmasphere density can be reconstructed.

Auroral waves

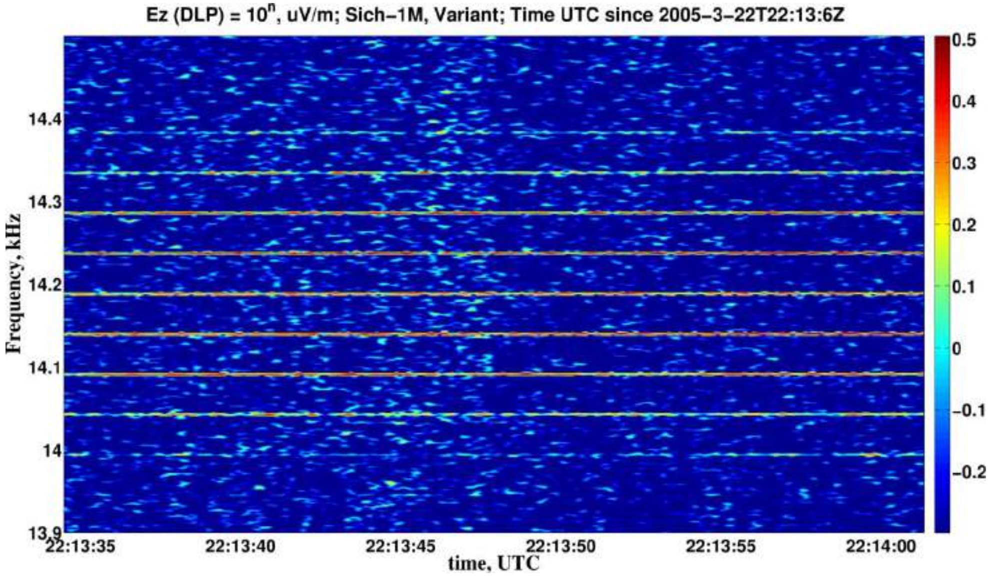
Spectra and occurrence give a ”smoking gun” of auroral acceleration processes.

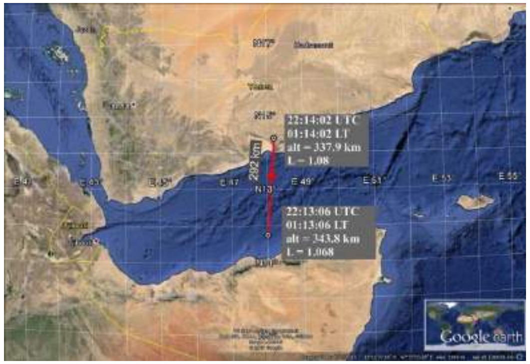


Science 3 – Anthropogenic Emissions

Power line harmonics.

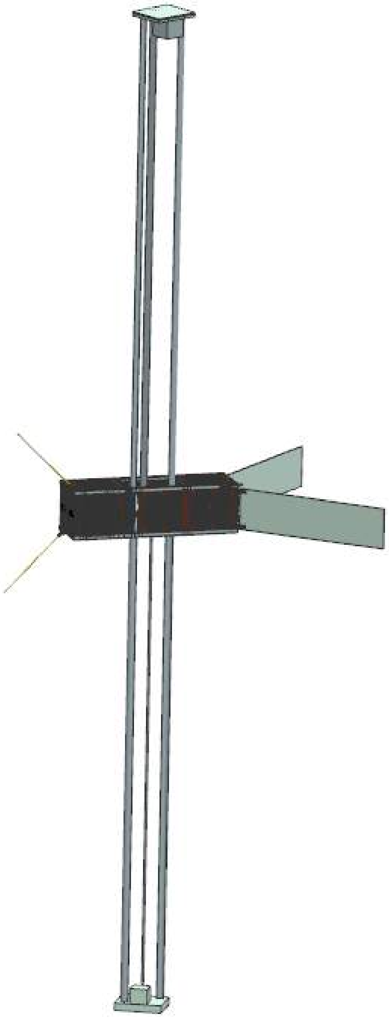
Some observations are reported, but the phenomenon is poorly understood, more data needed!





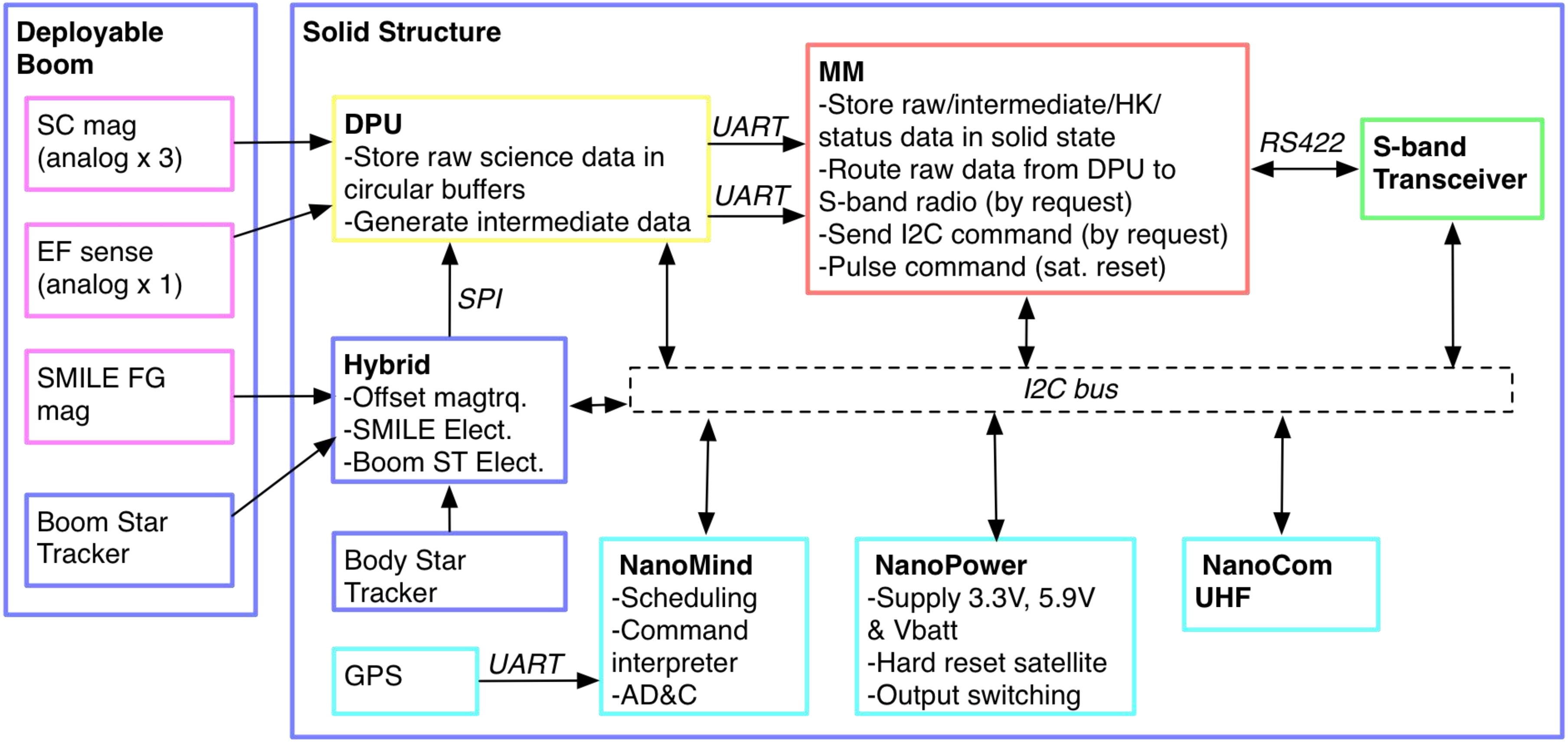
Concept

- 3 axis stabilized s/c
- Passive gravity gradient stabilisation
- Air wound magnetorquers, piecewise actuation
- Distributed system
- Magnetically clean s/c, sensors on the tips of 1 m long booms

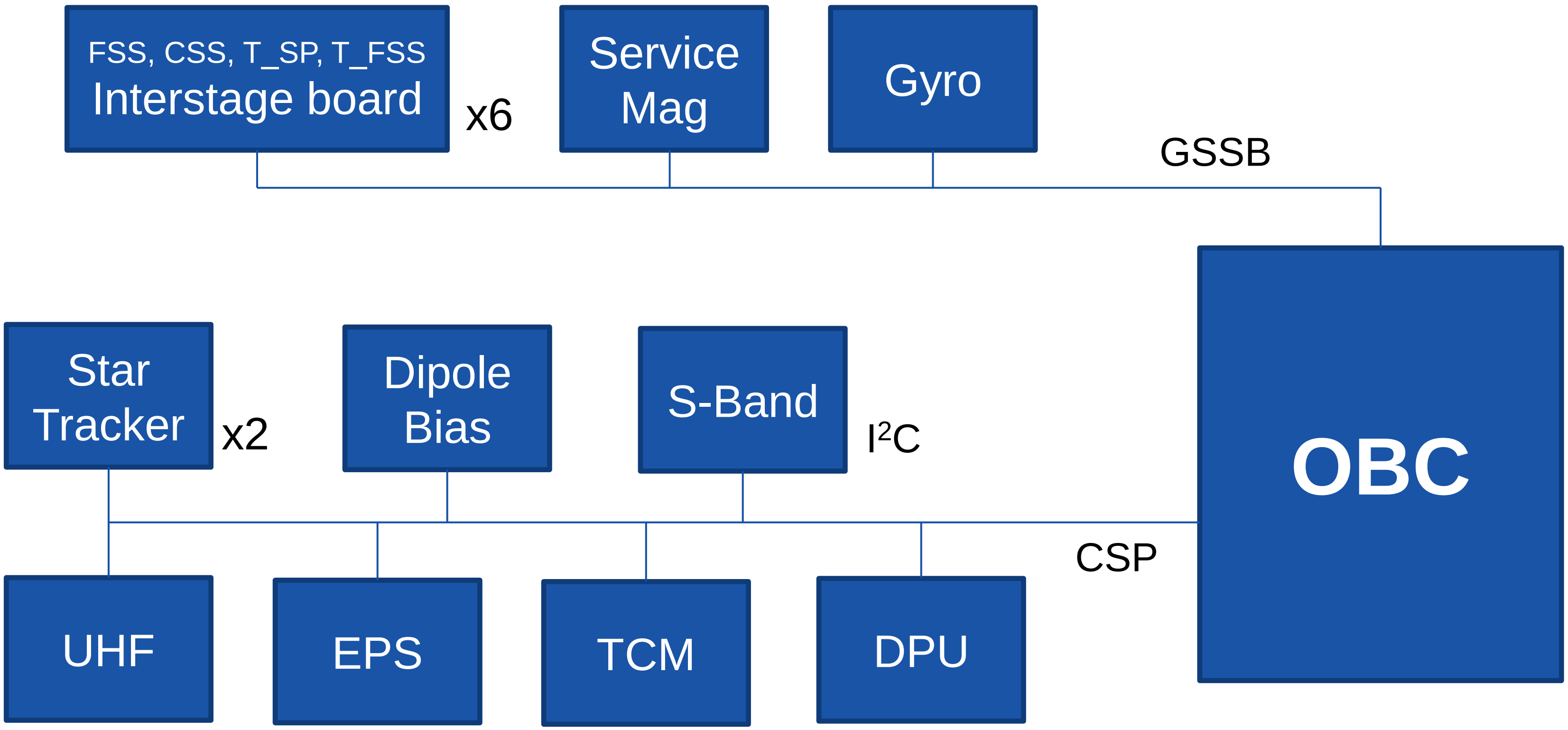


Satellite Configuration

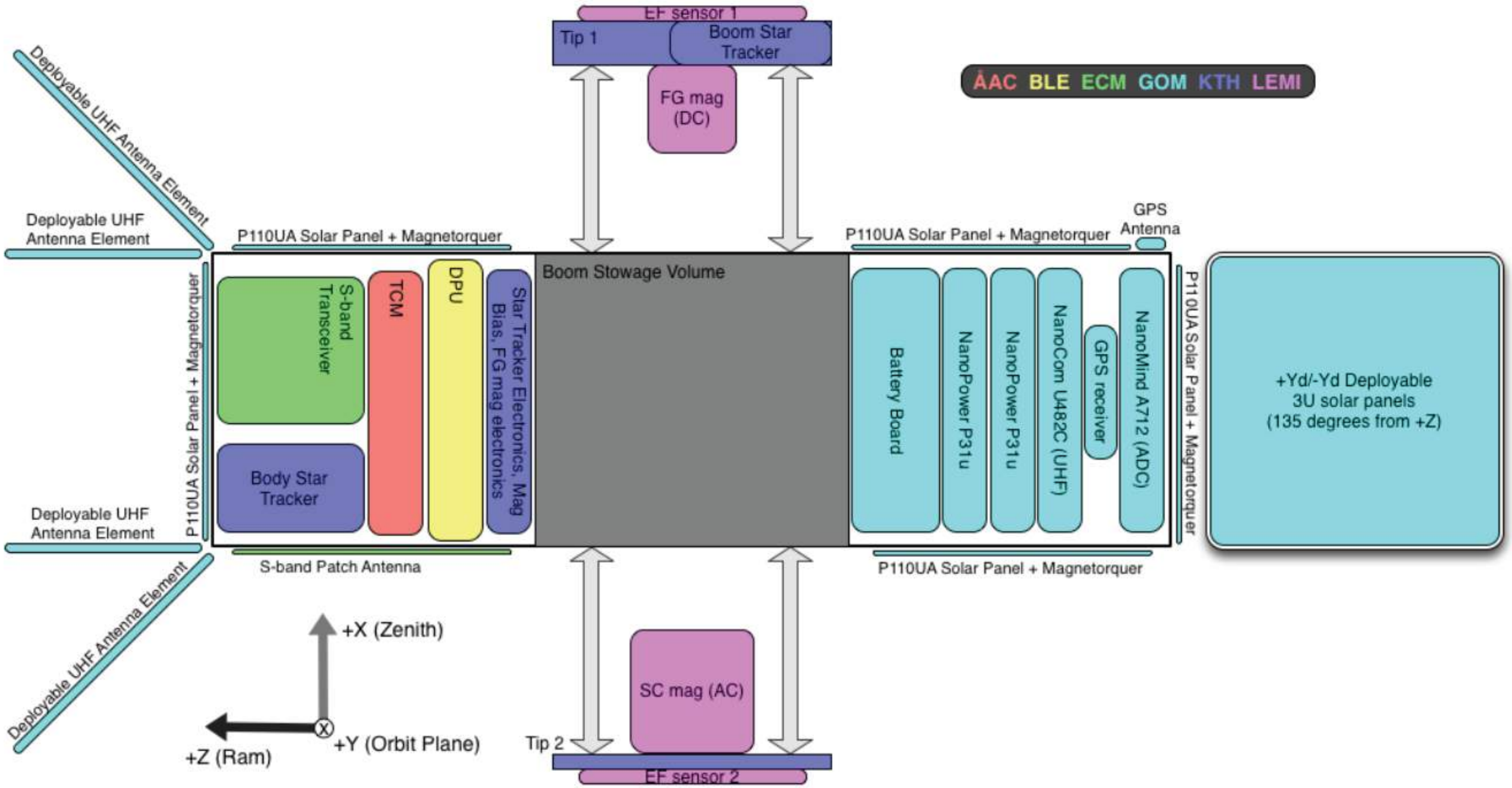
ÅAC BLE ECM GOM KTH LEMI



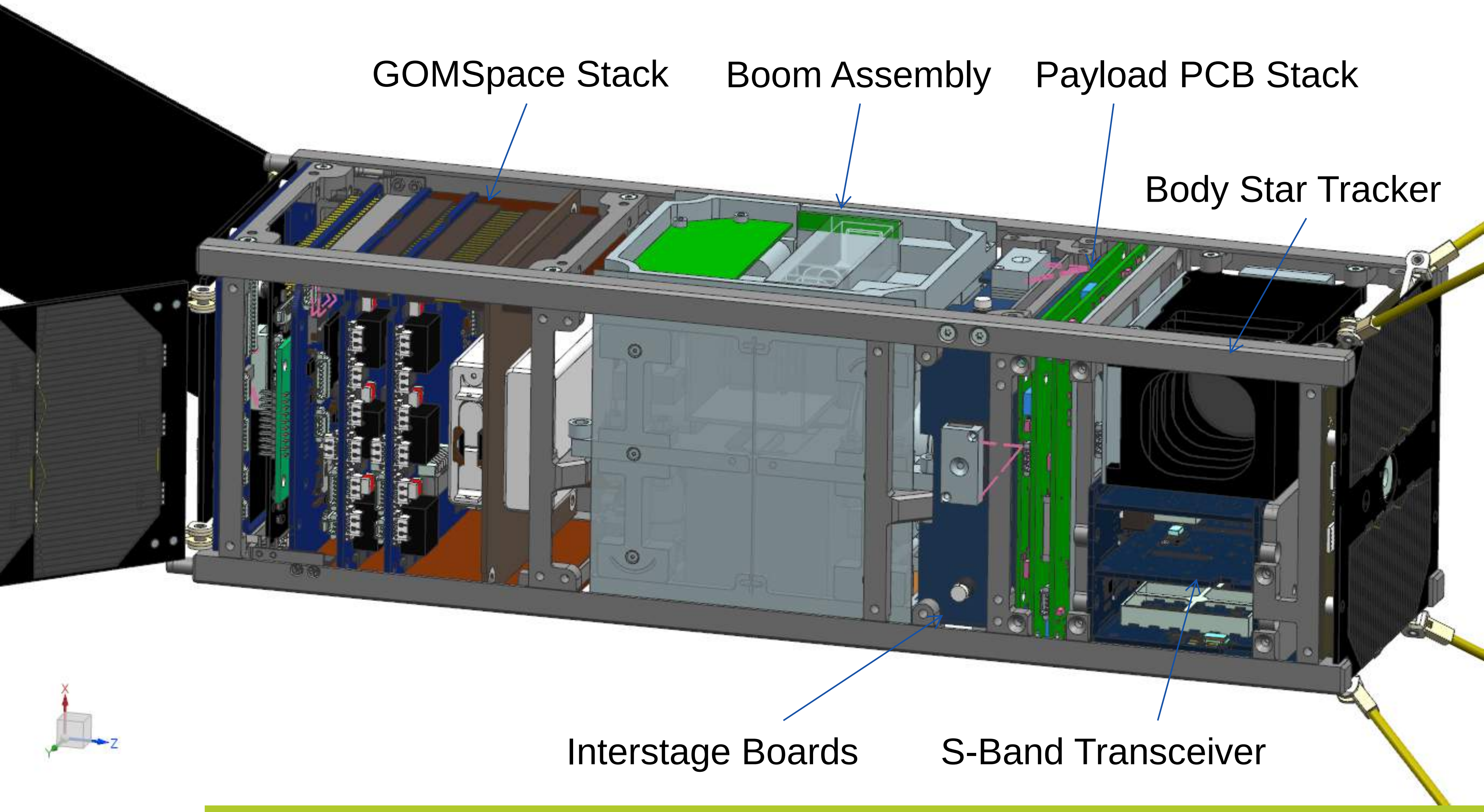
Another view…



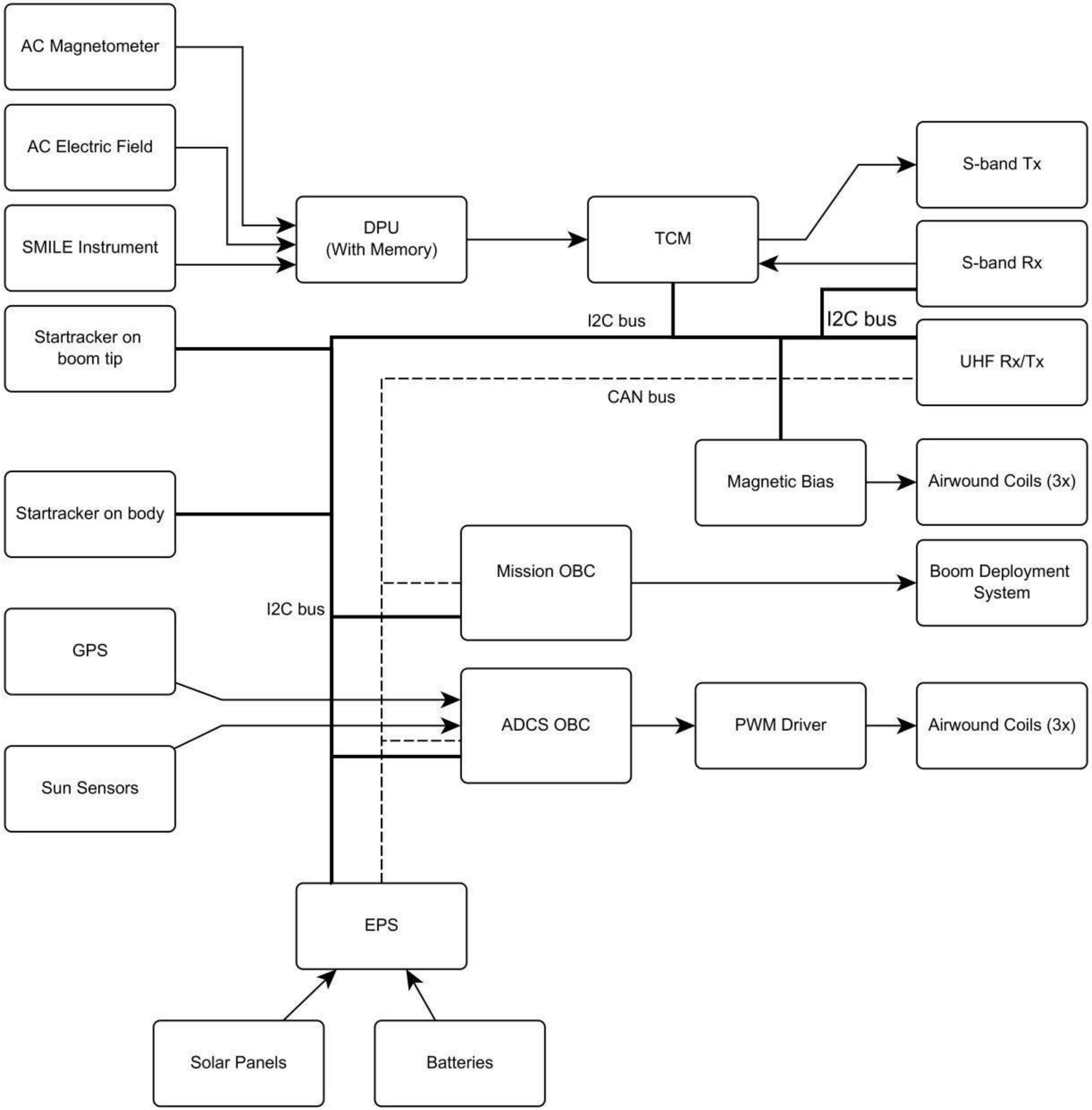
Early satellite layout



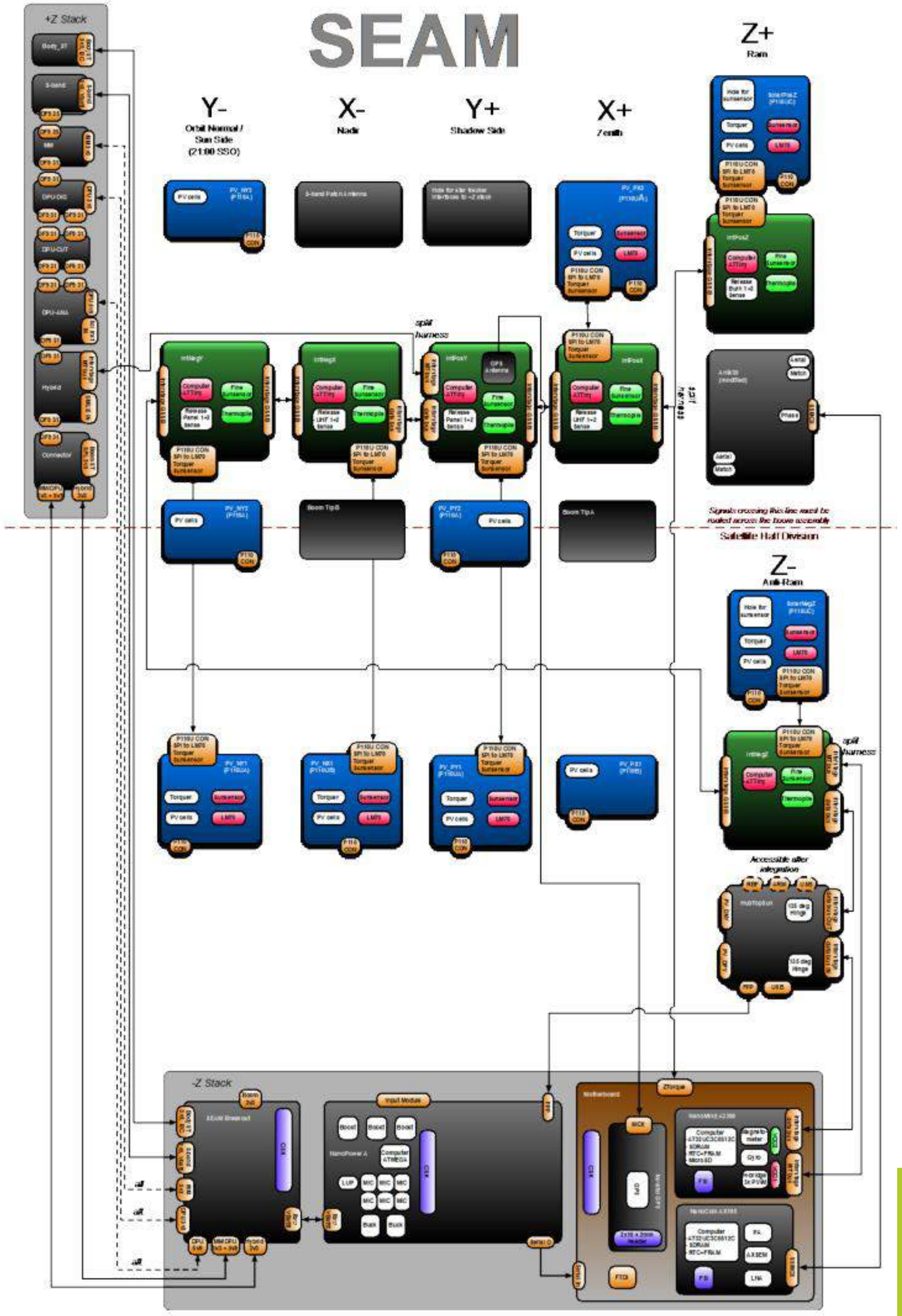
Overview


GOMSpace Stack
Boom Assembly
Payload PCB Stack
Body Star Tracker
Interstage Boards
S-Band Transceiver

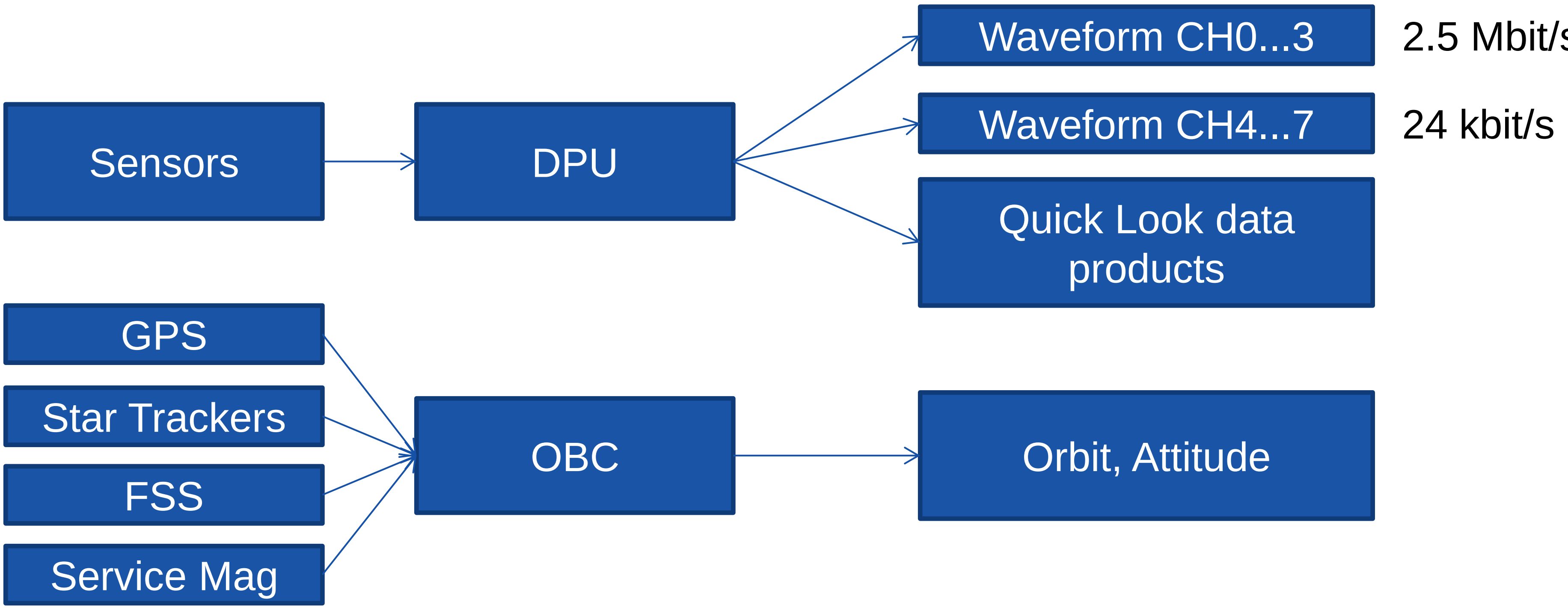
- Large number of subsystems
- Large number of uCs/FPGAs
- Large number of interfaces
- Considerable new development on many systems



- The details are even more involved…
- 101 connectors (not including permanently conneted ones in the subsystems)
- 40 cables



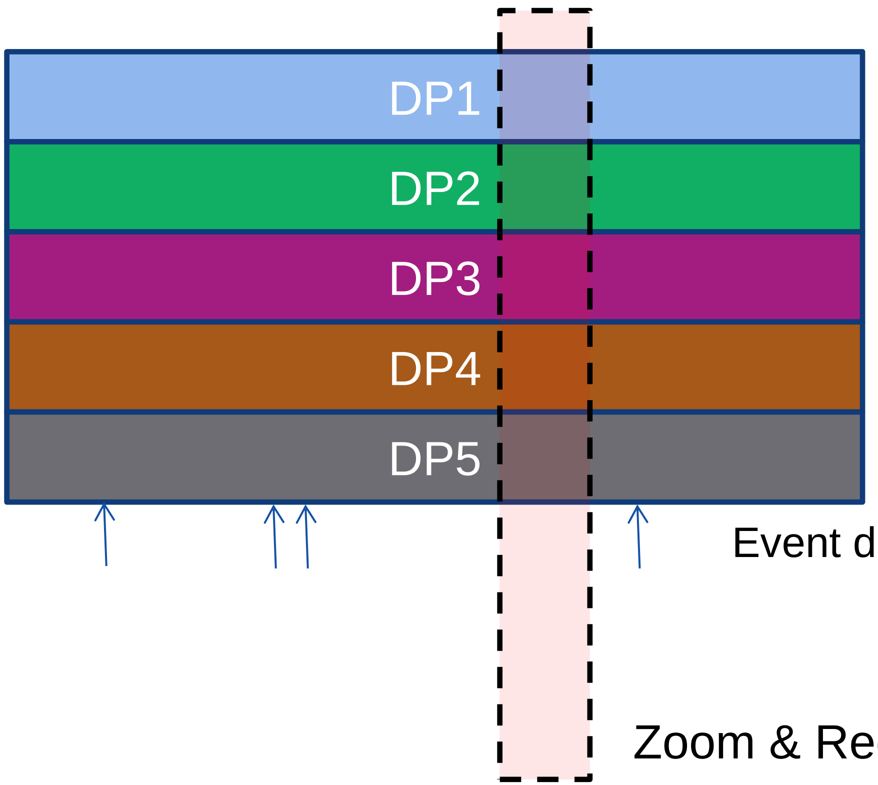
Data Flow
(Satellite objective is to collect science data!)



Quick Look Data Products

Data product	Designation
DP1	Decimated DC magnetic field data (10 samples/s)
DP2	Mains frequency spectra (40-70 Hz)
DP3	Integrated spectrum
DP4	Overview spectrum
DP5	Time series of power density

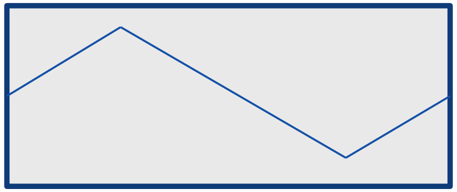
Quick Look Data archive



Event detects

Zoom & Request RAW

One Orbit

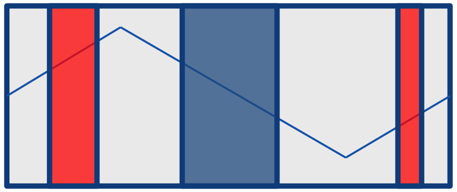


Data budget:
CH0…3 requested
CH4…7 requested

PREPARE
DPU REQUEST
FOR NEXT UPLINK

Orbit prediction, power modeling

One Orbit



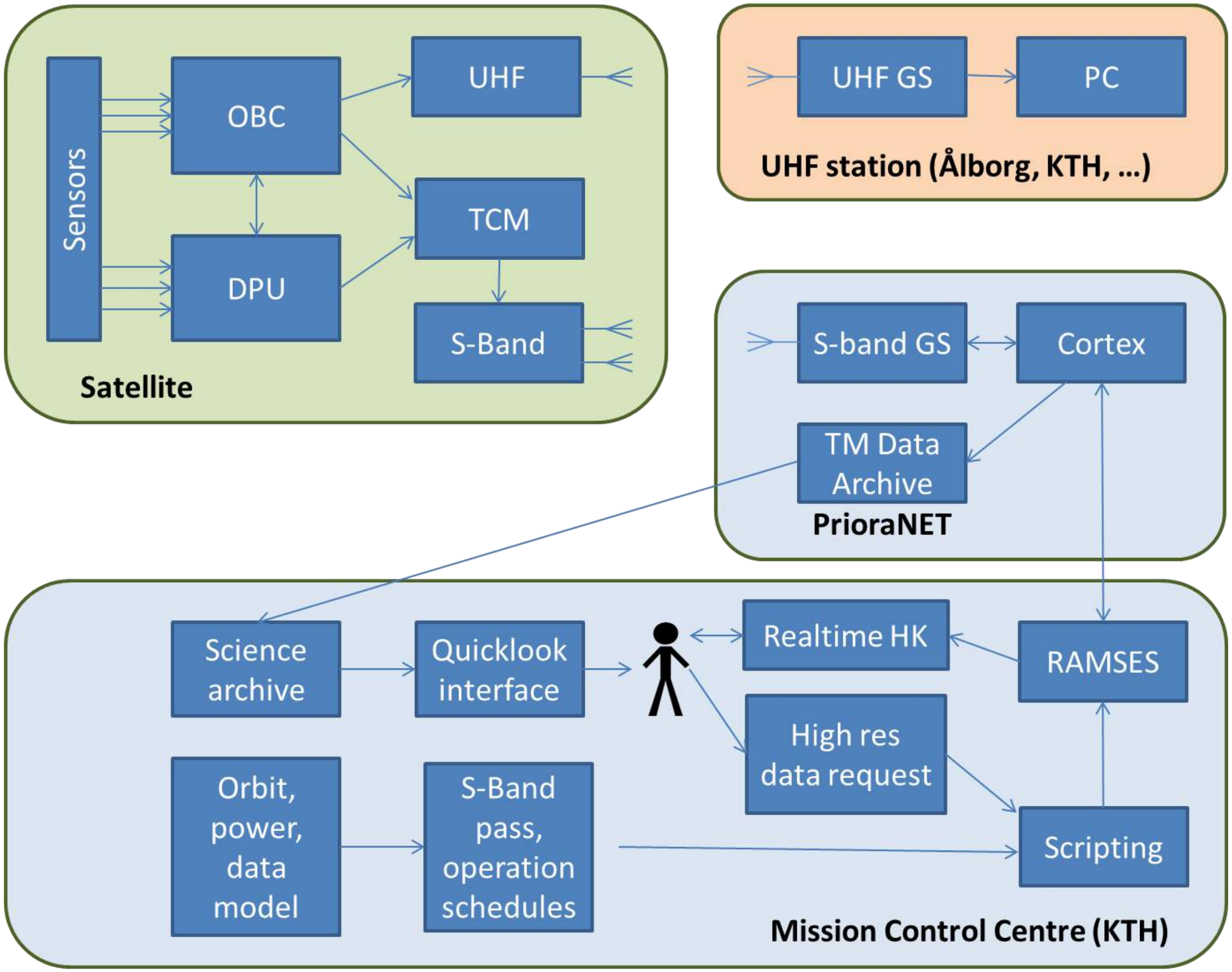
Model:

- Eclipses
- Potential S-band passes
- Power budget
- Special selection (Coast, GPS/ST force, etc)

Generate:

- Schedules and duty cycles

Yet another view of operations…



Nominal Operations

- **Upload operation schedules and duty cycles**
- **Upload high resolution data requests**

- **Get real time HK data**
- Download saved HK data
- Download IM data (S-Band only)
- Download RAW data (S-Band only)

(Bold doable via UHF also!).

Project Timeline

Extra review, October 2014

Extra review, 151201

	Start	Duration	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
WP1 Management	1	36																																				
WP2 Preliminary design	1	7																																				
T2.1 Requirement formulation																																						
T2.2 Technology survey																																						
T2.3 E-M cleanliness analysis																																						
T2.4 Mission Analysis																																						
T2.5 Satellite preliminary design																																						
WP3 Technology development	8	13																																				
T3.1 Attitude determination																																						
T3.2 Power system																																						
T3.3 Avionics																																						
T3.4 Magnetic Sensors																																						
T3.5 Deployable boom																																						
T3.6 Telemetry and telecommand																																						
T3.7 O/b processing & op. strategy																																						
T3.9 EM testing and validation																																						
WP4 Implementation	21	16																																				
T4.1 Flight hardware manufacturing																																						
T4.2 Assembly and integration																																						
T4.3 Flight model testing																																						
T4.4 Launch campaign																																						
T4.5 Operations																																						
T4.6 Flight data analysis																																						
WP5 Dissemination	2	35																																				
T5.1 Internal communication																																						
T5.2 Community dissemination																																						
T5.3 Public outreach																																						
WP6 Commercial evaluation	1	36																																				
T6.1 Market potential evaluation																																						
T6.2 Business plan formulation																																						

Project restarted August 2017

PDR, April 2014

start, October 2013

”not-FRR” Review, April 2016

CDR, May 2015

Launch

FRR, Septembe

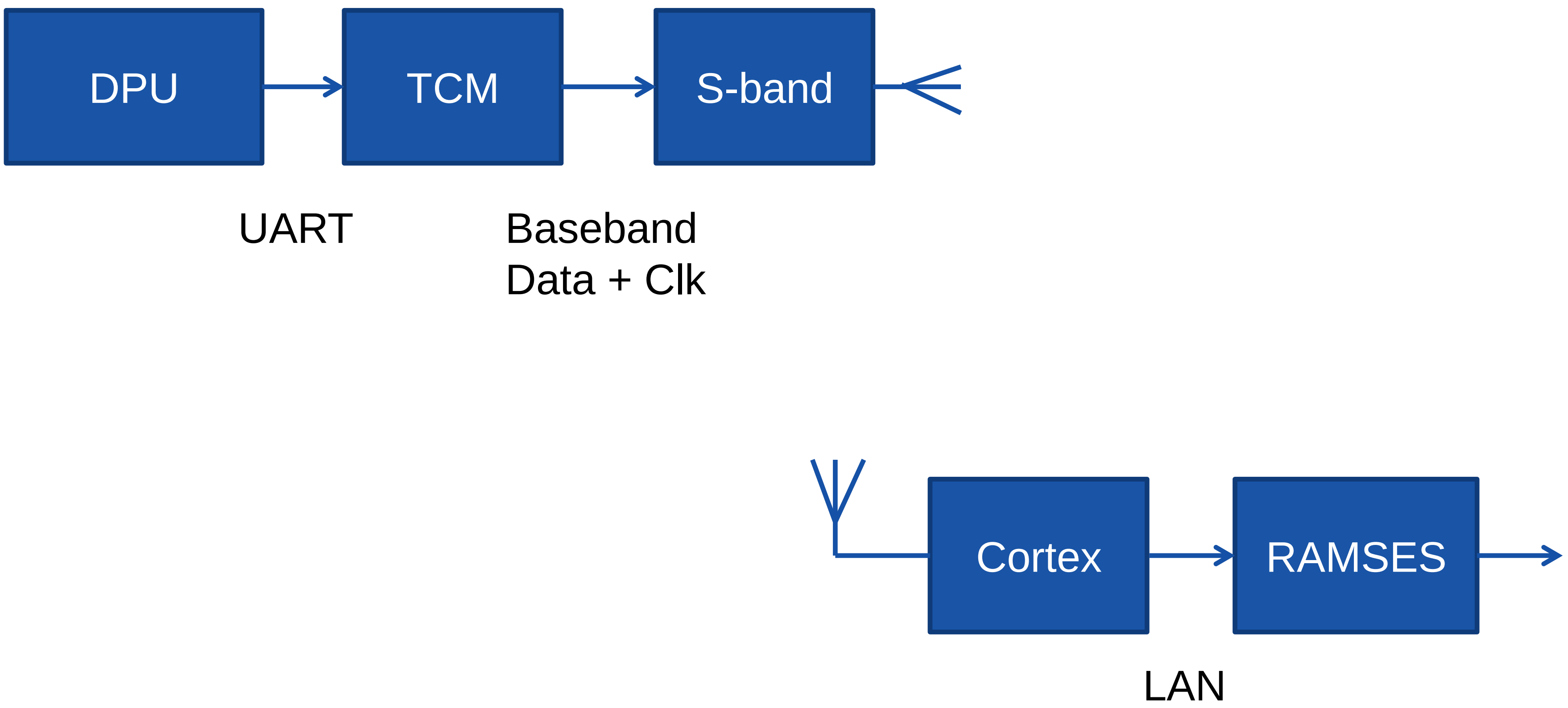
Early integration issues

Design of harnessing should be given attention early in the project.

I2C bus with multiple units built in different places can be a challenge to get working properly.

Transient currents are important to test for.

S-Band chain on SEAM



RF Tests SEAM

PLAN VS REALITY

Initially two tests was planned

One EQM

- 2 days at Esrange

One FM

- 2 days at Esrange
- End-to-End test

The updated plan:

Equipment was borrowed to KTH for in-the-loop EQM test during development

Over the air EQM test at Esrange with mixed results

Additional RF test of EQM at KTH in Stockholm using cable

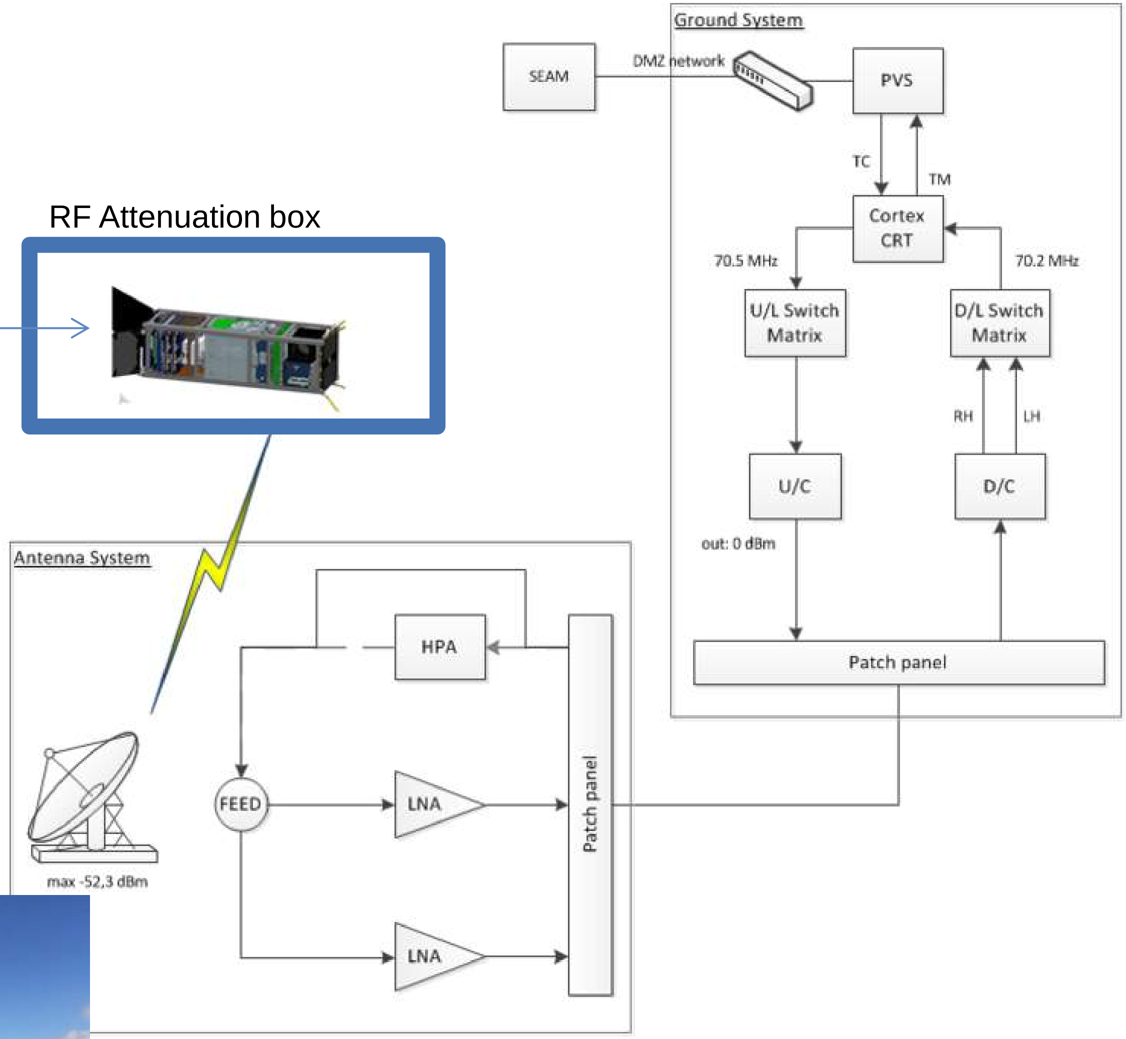
Additional RF test of EQM at Esrange using cable

Flight Model Test – end to end at KTH

SEAM RF Test campaign at ESRANGE

RF Attenuation box

Computer for direct SC interaction



First Esrange RF TEST Conclusion

- Multiple factors affected this test
  - Ground wave interference?
  - Interference with metal test tower?
  - Damping material not nominal
  - …
- The uplink did work on low command rates, but major on-board problems with higher command rate
- The downlink test had a number of peculiarities that needed to be understood, some frames came successfully through

- More testing was needed

RF Test KTH

19TH – 21ST JUL 2016

KTH RF TEST PURPOSE

Although both TM & TC was demonstrated at Esrange test there was many uncertainties

Purpose of KTH RF test was to remove uncertainties by using cable instead of air gap

Full equipment stack was brought to KTH (cortex, downconverter, upconverter, noise sources etc)

Command Receiver Acquisition Threshold

UPLINK

The purpose of this test is to determine the minimum uplink carrier power level required to achieve spacecraft receiver acquisition and drop lock at the nominal uplink carrier frequency during normal uplink sweep operations.

Link status monitored through S-band radio status value

The performance criteria: -105 dBm
(no formal requirement)

Unmodulated:

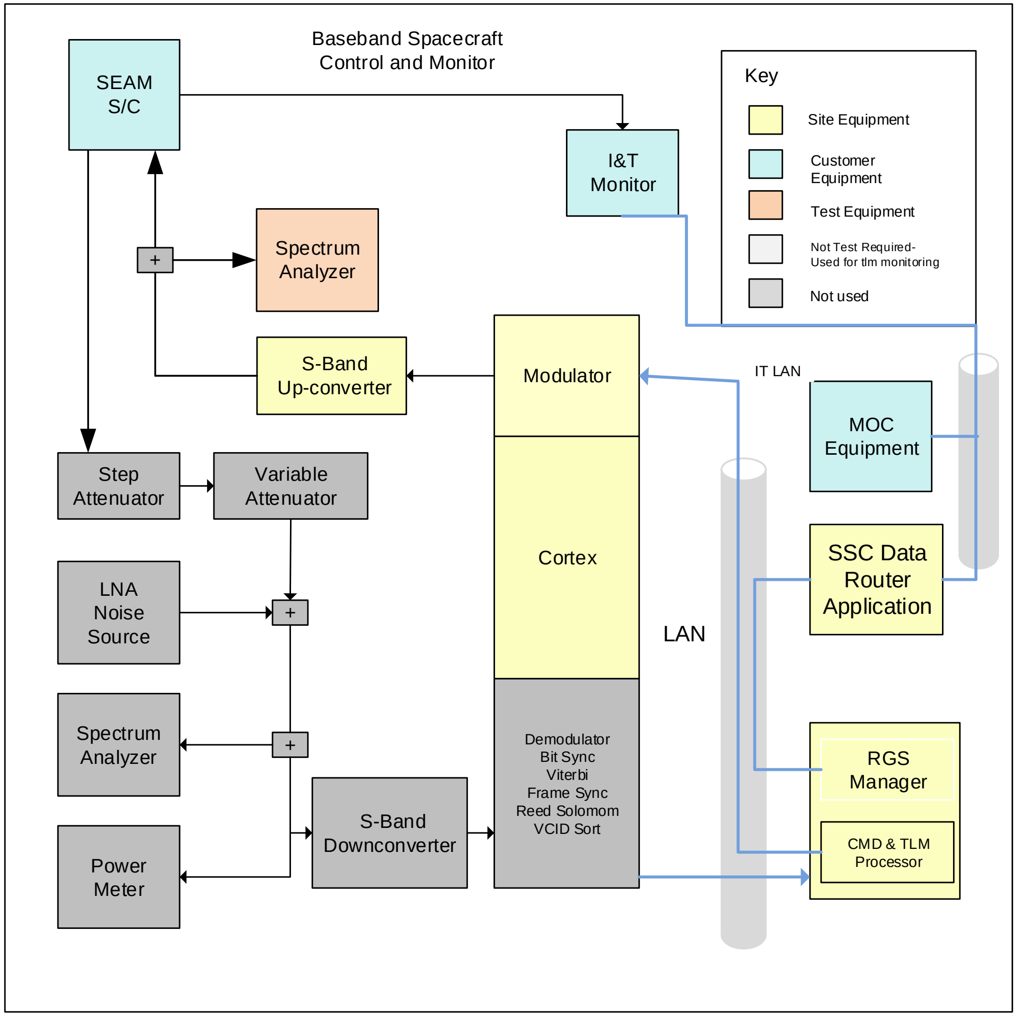
Acquisition: -109 dBm

Drop Lock: -111 dBm

Modulated:

Drop Lock: -110 dBm

Command receiver exceeded performance criteria



KTH RF TEST

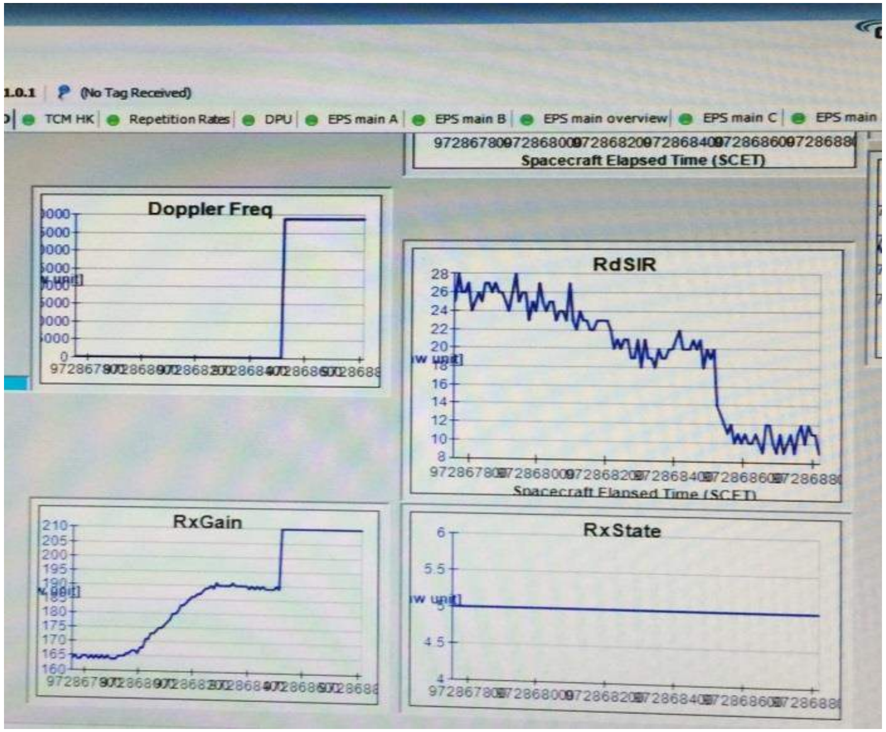
- Telemetry Receiver Threshold Test
- PCM Data Quality test (BER vs Eb/No)
- Command Receiver Sensitivity test
- Uplink Sweep Rate and Range Test
- End to End test

Uplink Sweep Rate and Range Test

It was determined that the command receiver was not able to track a Doppler shifted signal of this rate and therefore did not meet the performance criterion for a typical low earth orbit.

It was quickly identified that this is due to a bug in radio SW

A repeat test was recommended and was performed in August 2016 in the Esrange facility in Kiruna, Sweden.



Esrange 2nd RF Test

Re-Test the issue of locking on a Doppler shifted signal that was observed at the KTH test

Same equipment as KTH test

Updated radio software

Successfully performed the sweep test at a sweep rate of 700 Hz/s and a sweep range

of 160 kHz range

Conclusion is that radio is now able to lock on Doppler shifted signal

The RF compatibility between the EQM and the S-band ground network is then to a high degree demonstrated

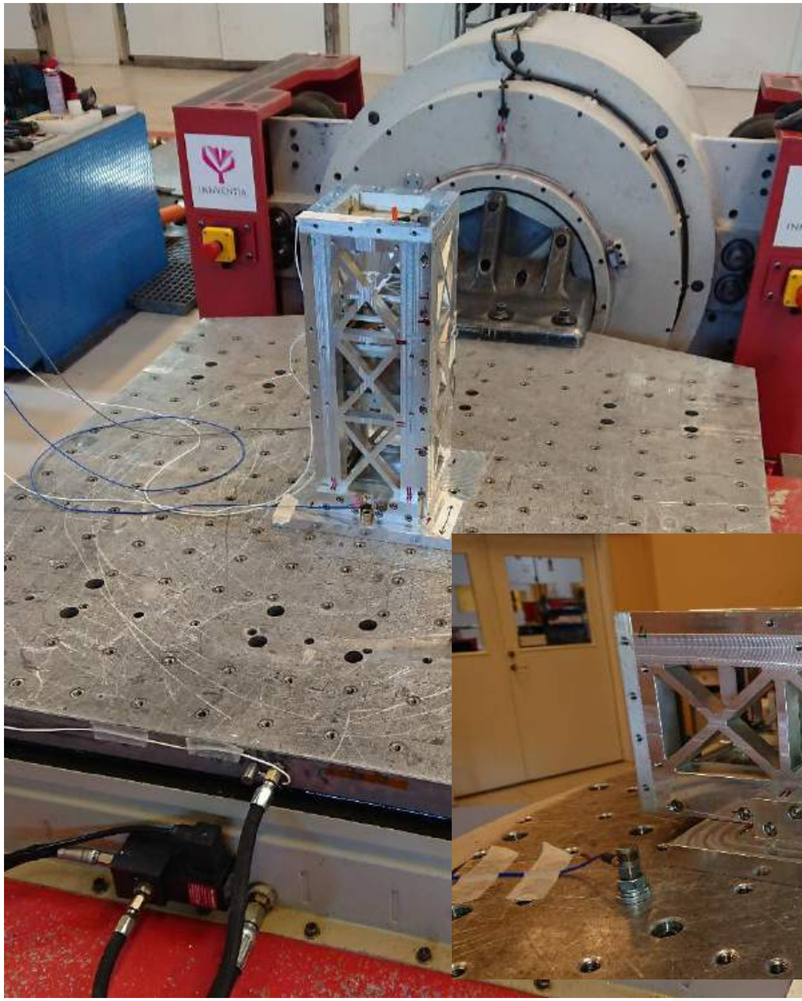
Vibration Tests of EM and FM and Subsequent Boom Deployment Tests

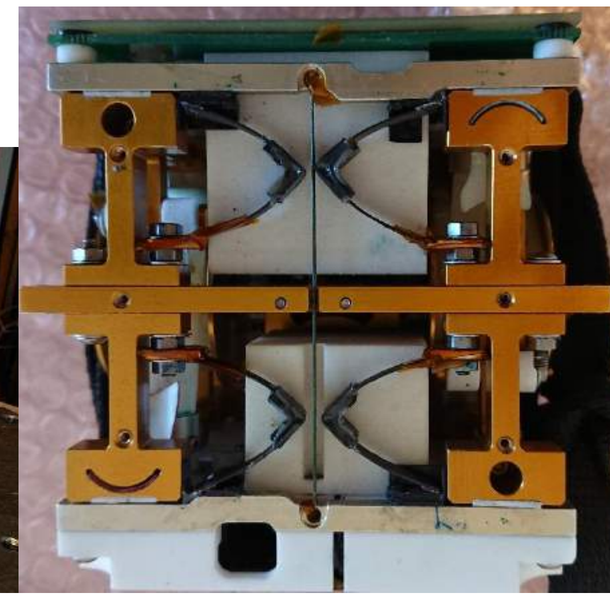
Deployment of EM of SEAM-boom

Another view…

EM boom random vibration test 2017-08-14

Purpose: to qualify the EM boom after the design change with the stronger carbon fiber kick springs attached to overcome the initial friction.



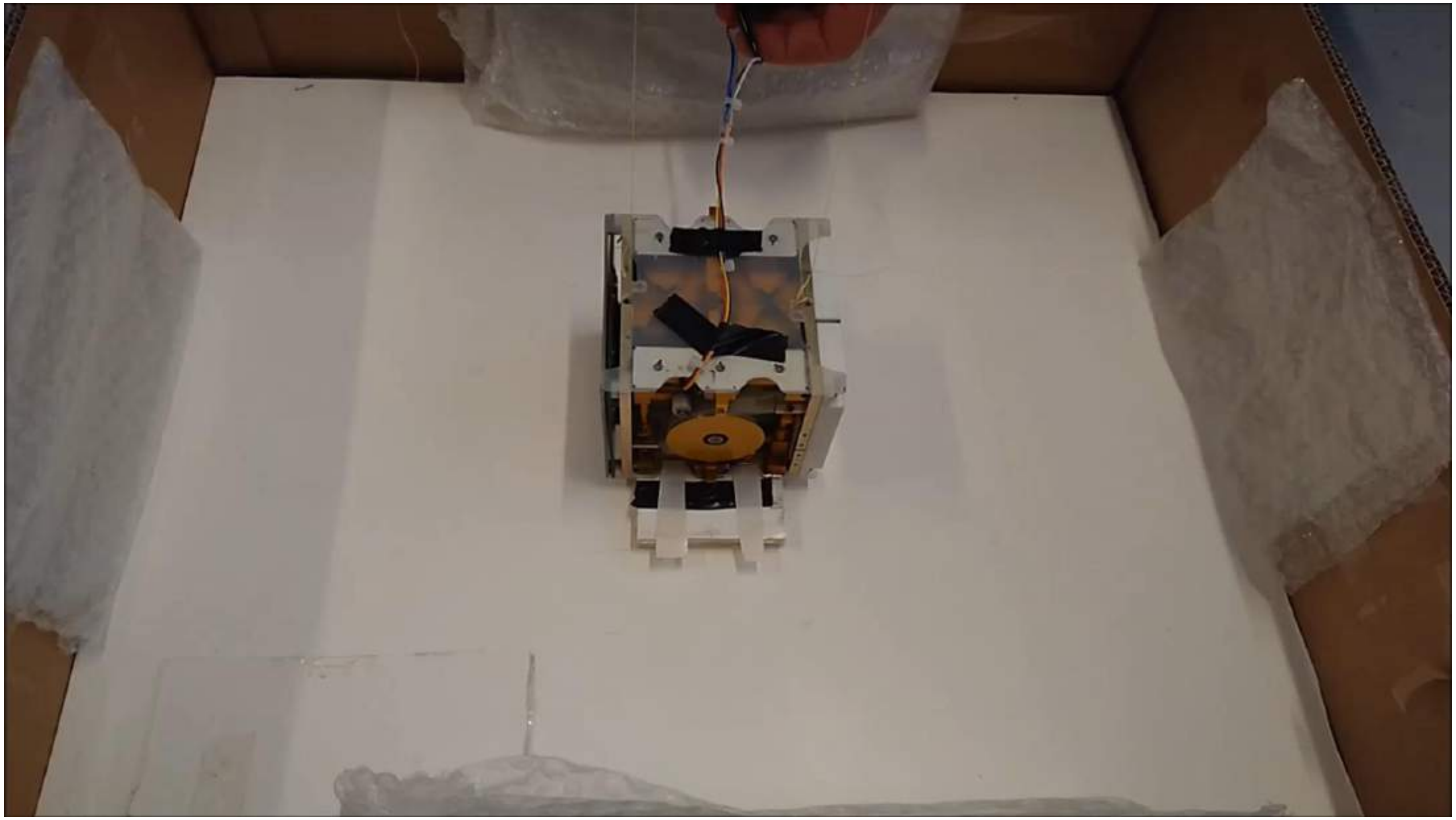


EM boom deployment after random vibration qualification test 2017-08-14

- The boom ends were not gravity offloaded → boom did not deploy directly after random vibration test due to floor friction!

EM boom deployment after random vibration qualification test 2017-08-14

- Ends were gravity-offloaded and boom repacked → boom deployed successfully, but not directly after the vibration test!

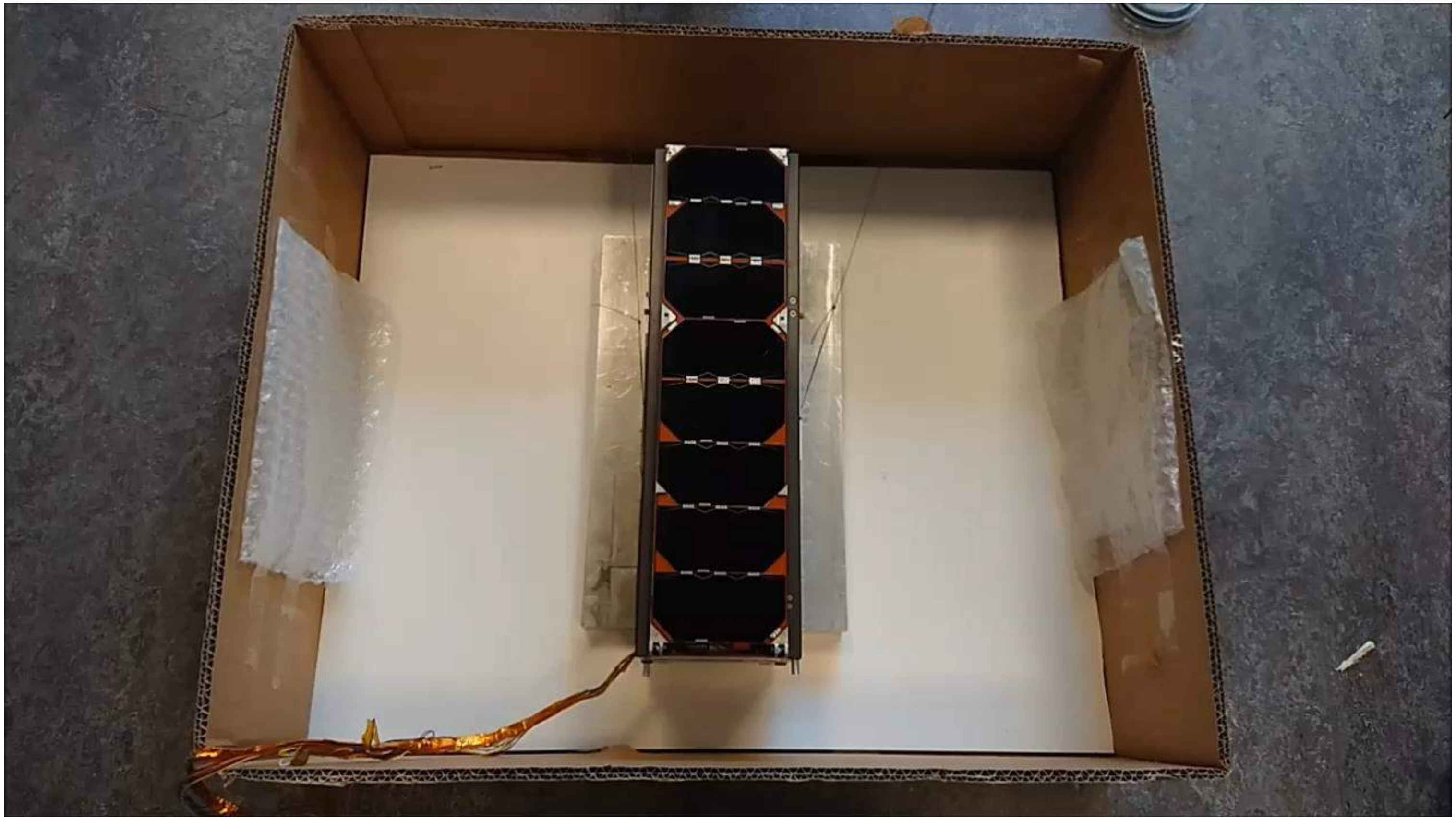


Sine burst strength test of SEAM EM 2017-08-16

- Quasi-static strength test at 10g qualification in each axis direction

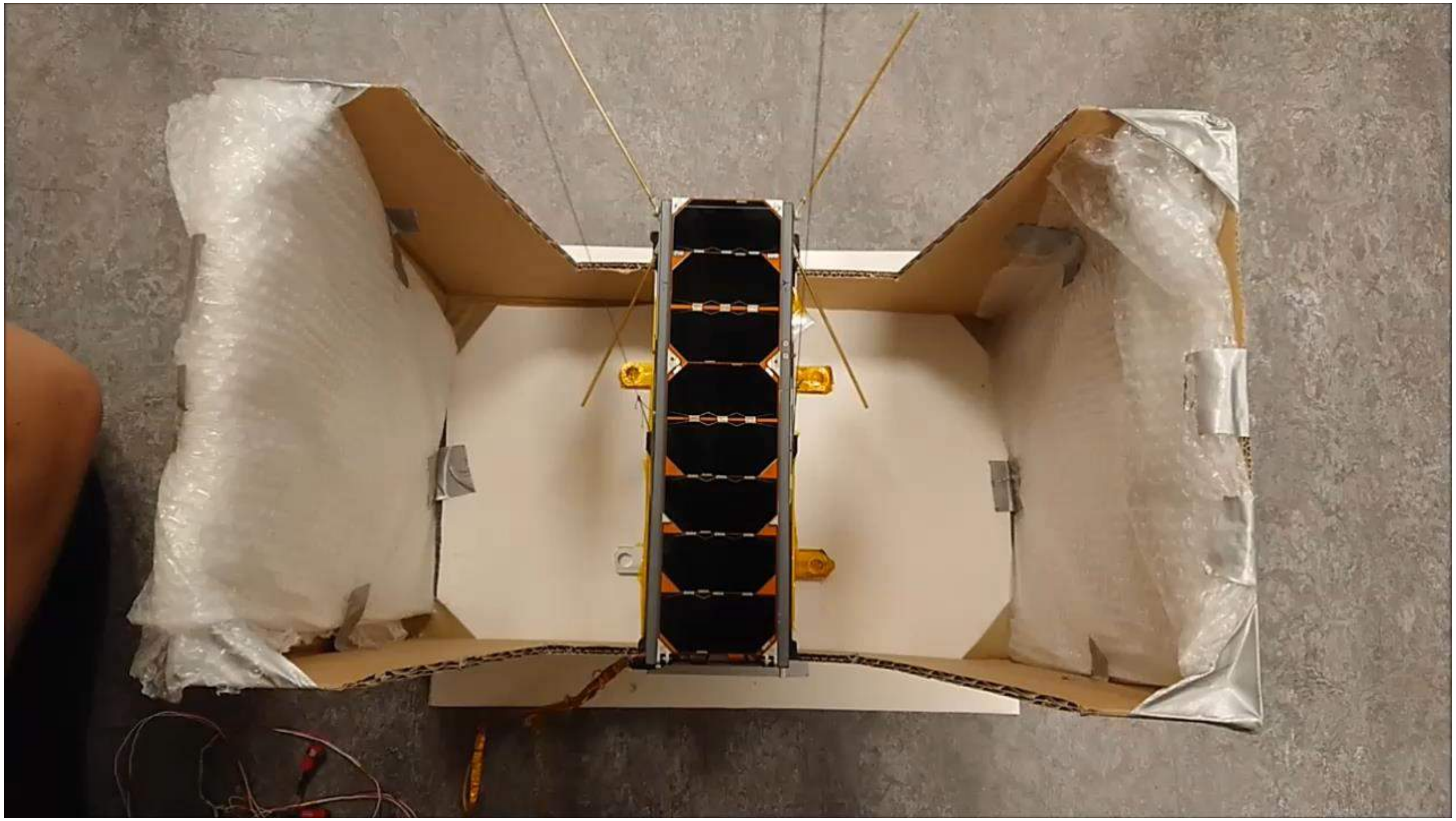
EM boom deployment test after sine burst strength test 2017-08-16

- Ends were gravity-offloaded → boom deployed successfully

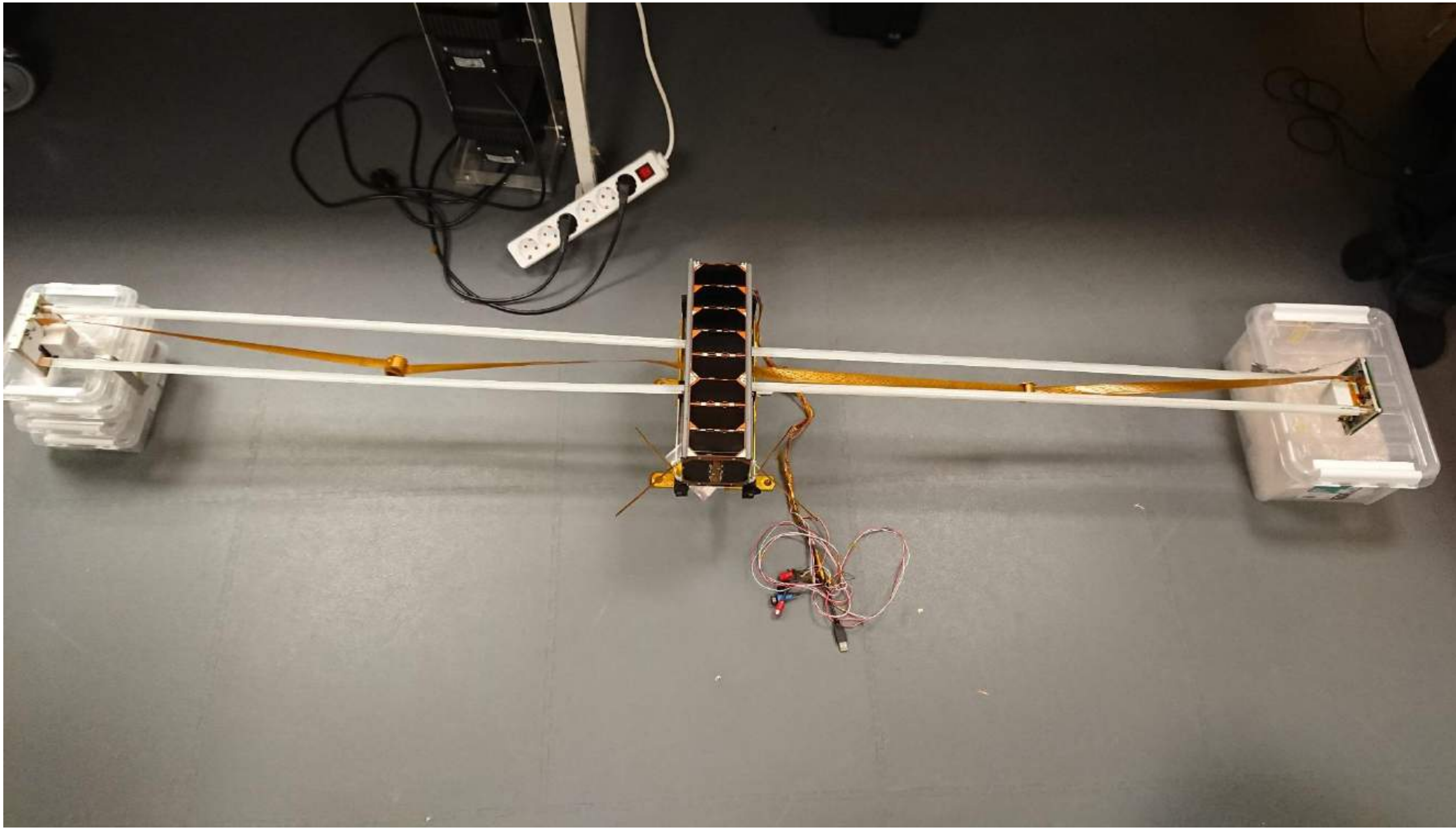


FM boom deployment after SEAM FM acceptance vibration test 2017-09-20

- Ends were gravity-offloaded → boom deployed successfully

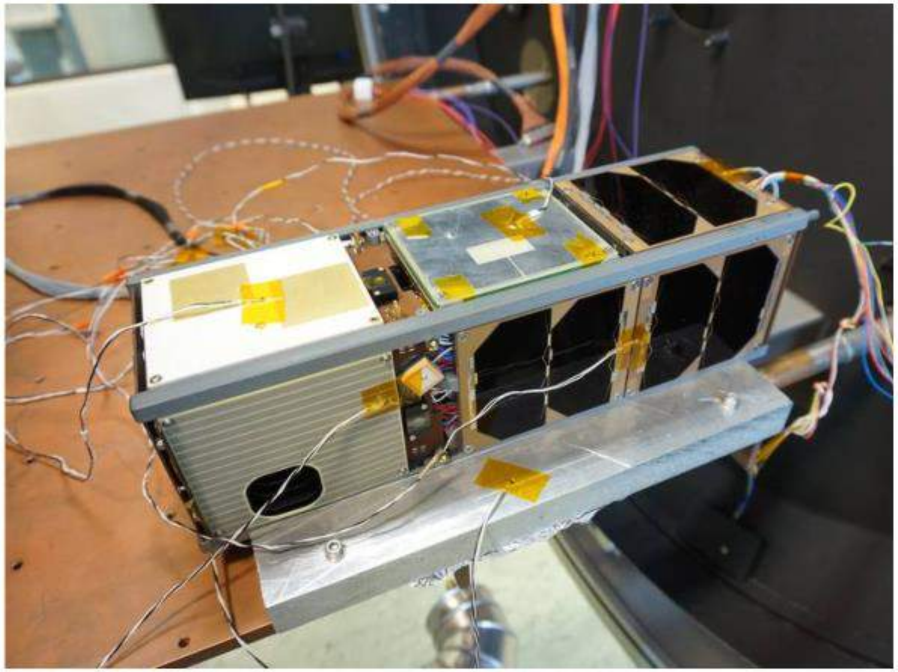


SEAM FM with deployed booms 2017-09-20

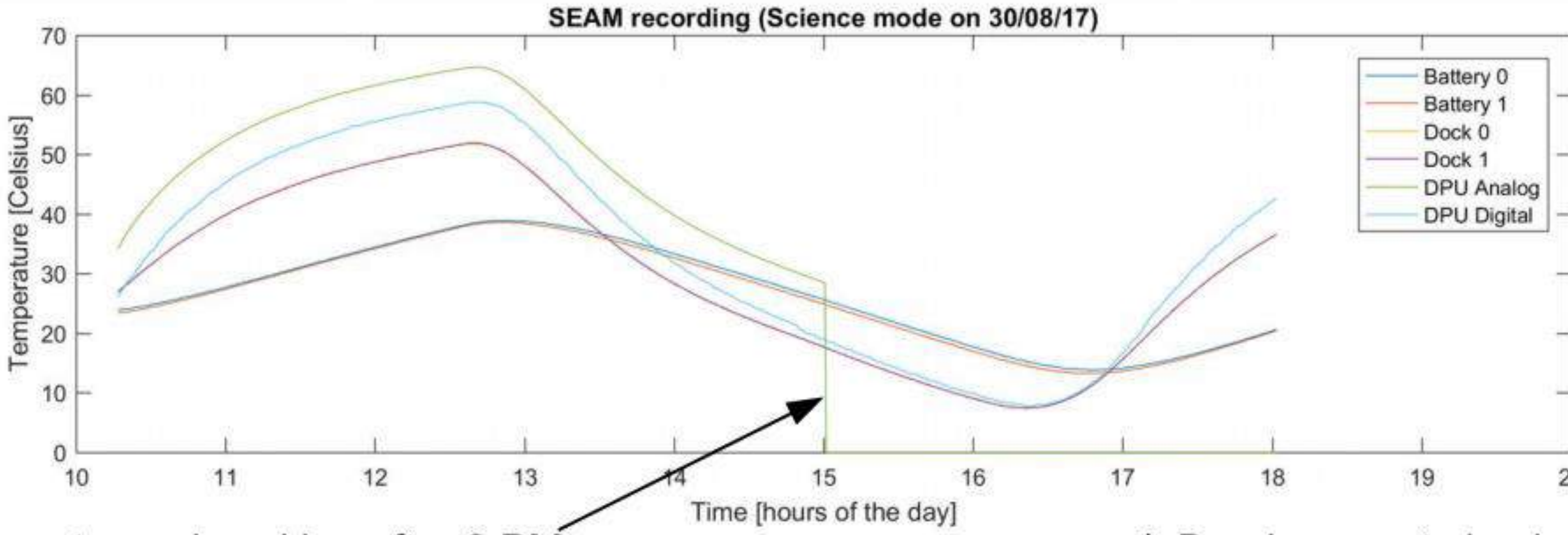


Thermal Vacuum tests

TVAC chamber at IRF.

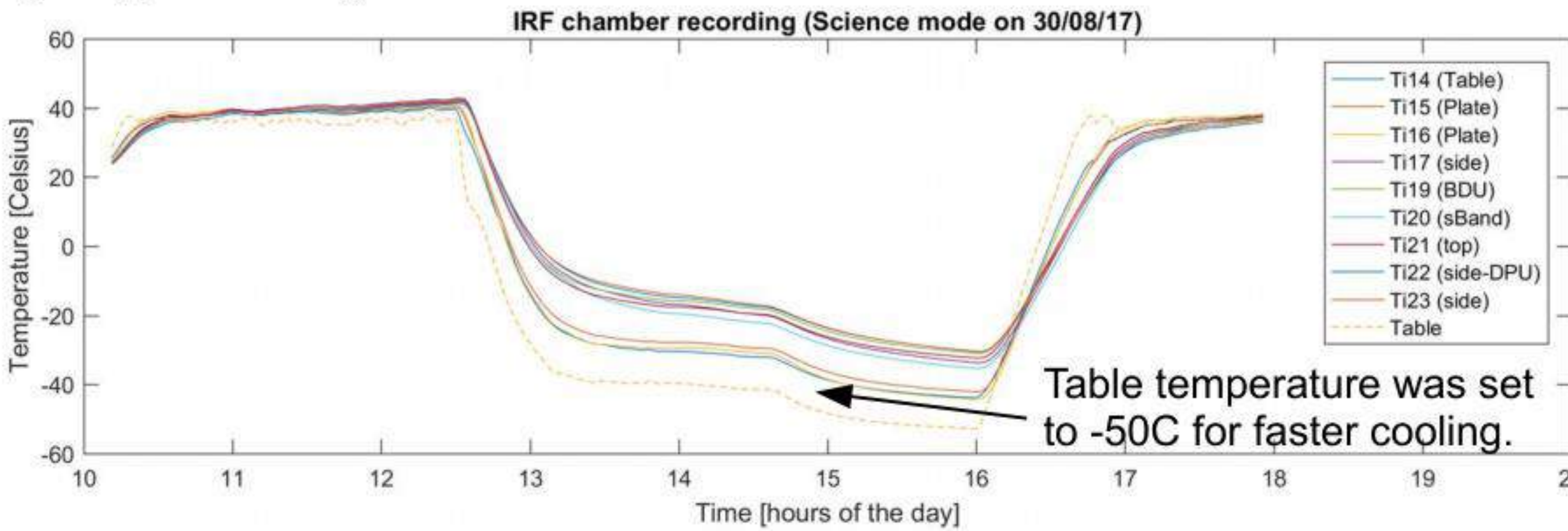


SEAM FM inside the chamber.



DPU Analog stopped working after 3 PM.

*sBand was not checked.

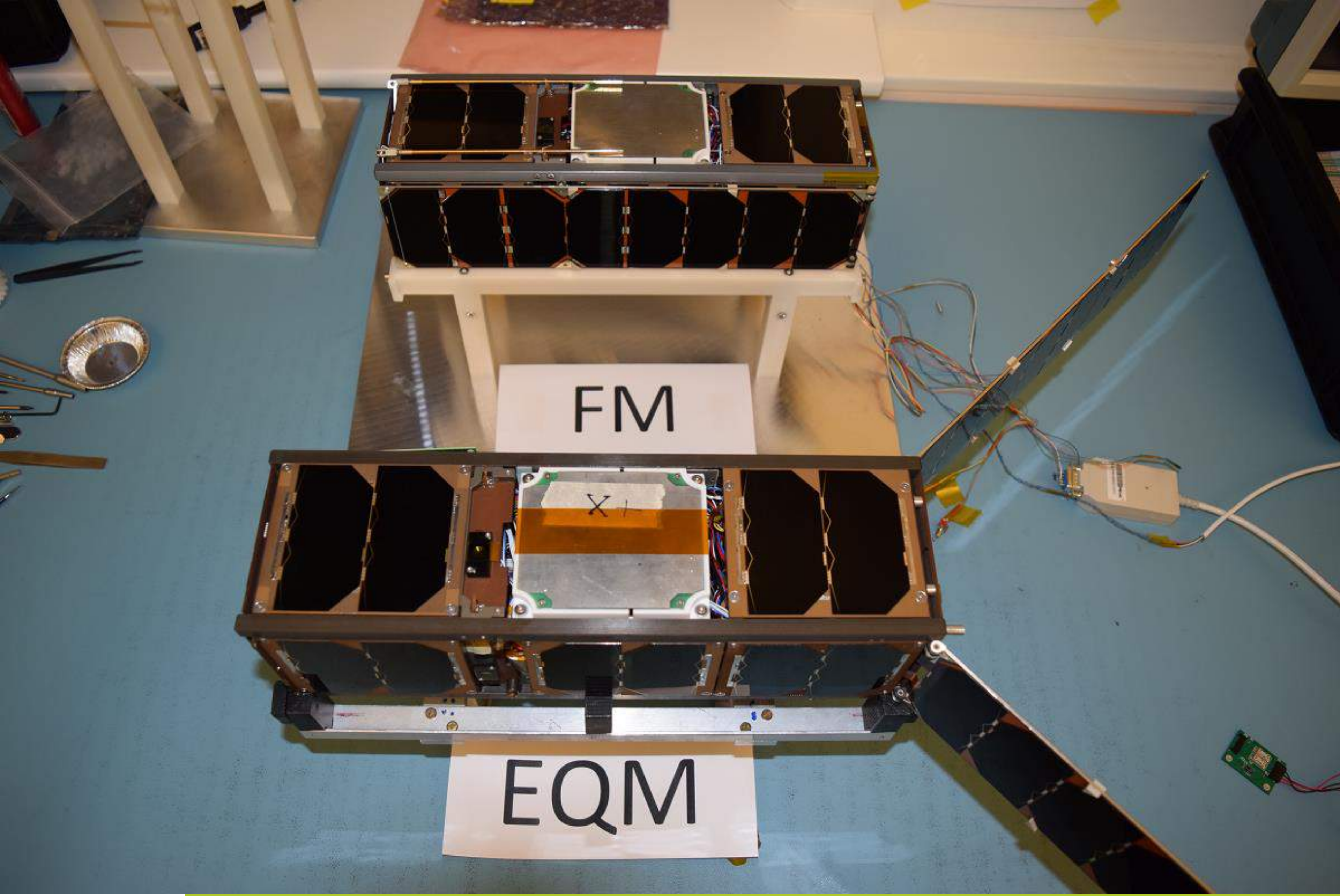


Thermal Vacuum tests

Thermal vacuum tests were conducted on EQM and FM

Operation of satellite was confirmed

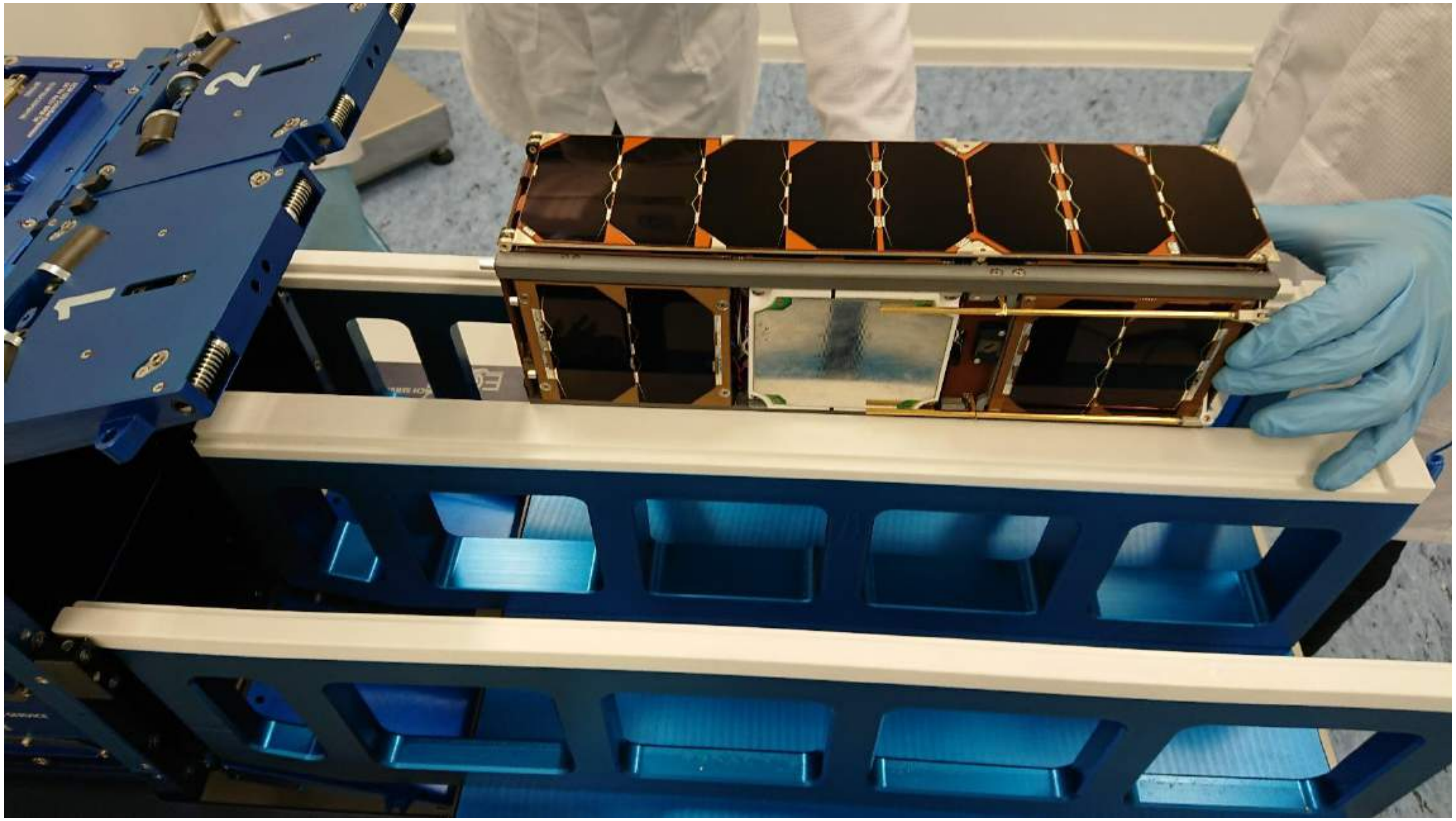
Anomaly on connector discovered, deeper cleaning resolved the issue


FM
EQM

SEAM integration in CubeSat dispenser

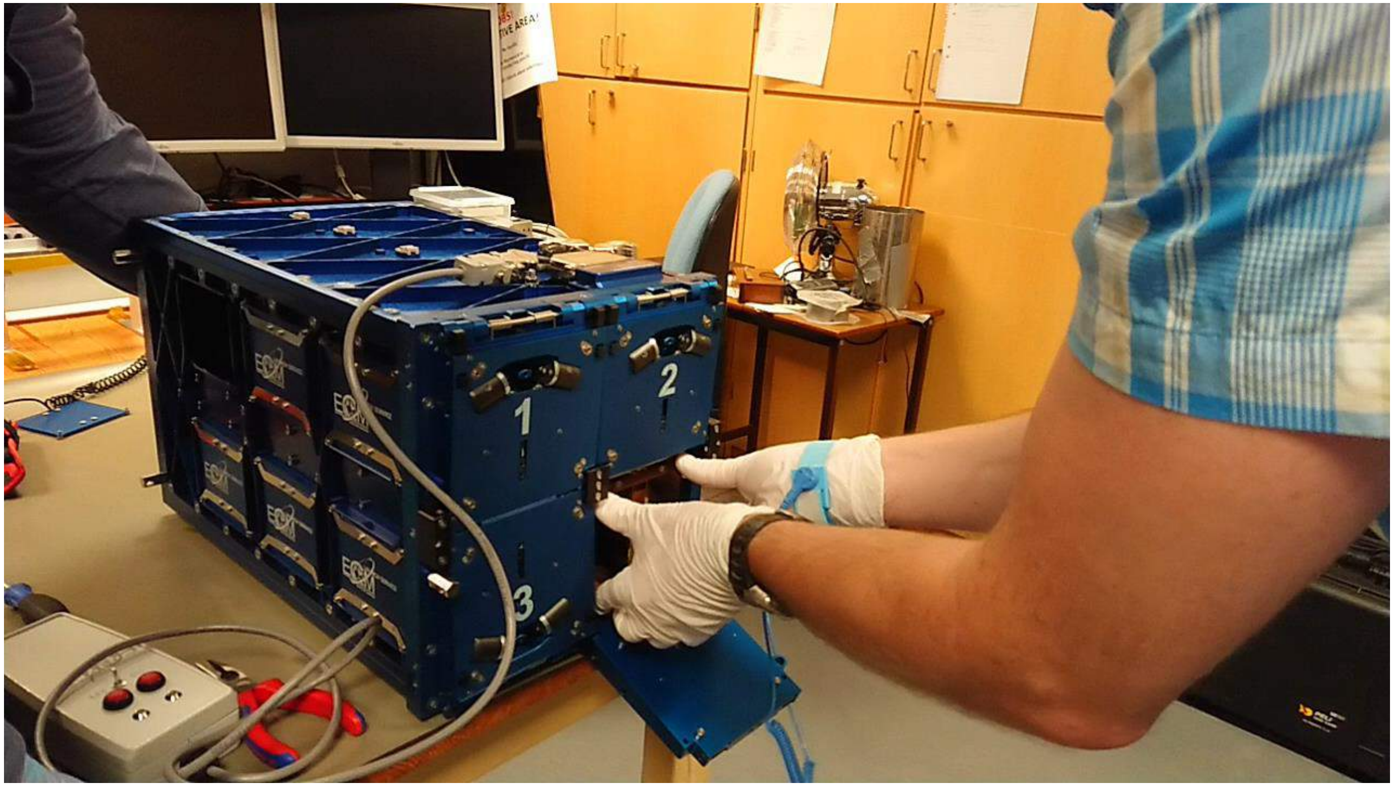
Fit check test of SEAM FM at ECM 2017-06-29

- Could only be inserted to 2/3 of the length → rails were a little too wide at one position!



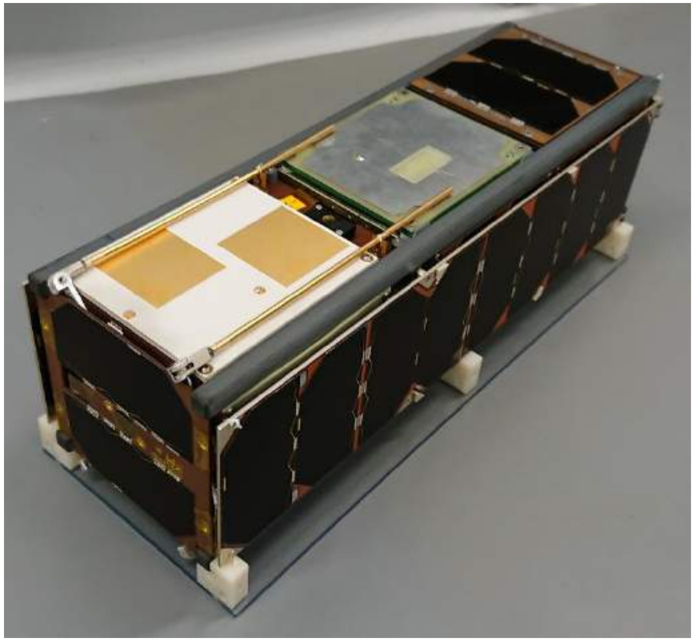
Fit check test of SEAM FM at KTH 2017-07-04

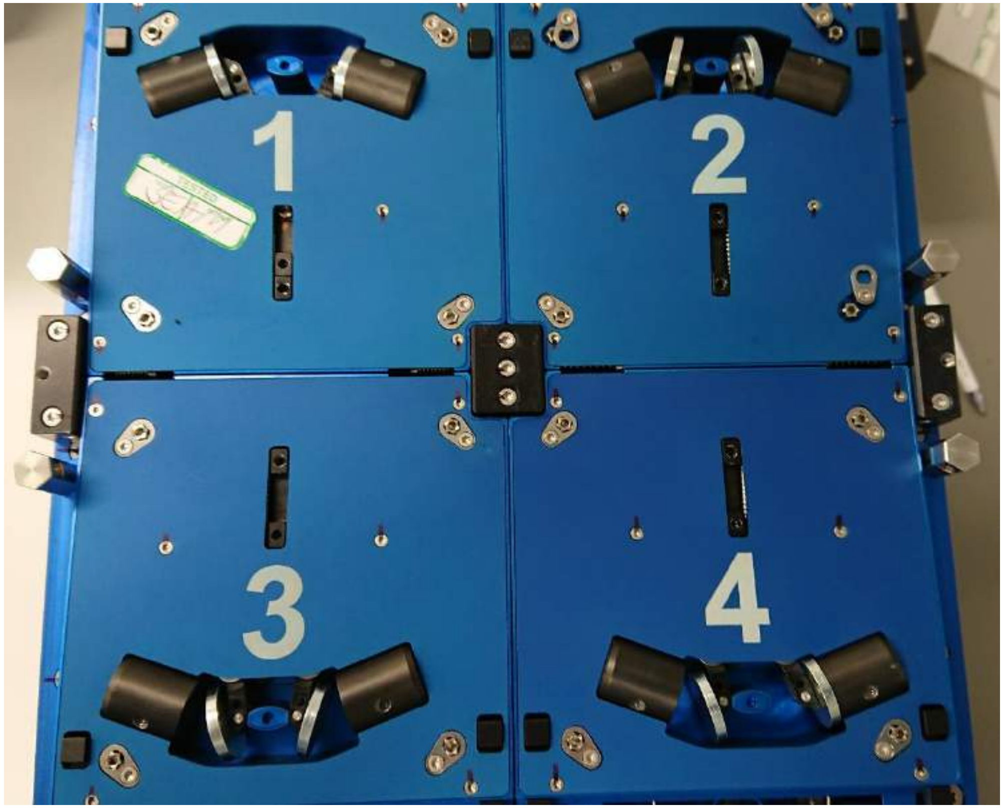
- An accurate template was quickly manufactured to continuously check the rail width during assembly.
- SEAM FM was disassembled and rail widths corrected at KTH.



Fit check test of SEAM FM 2017-09-29

- Successful final integration in ejection dispenser!



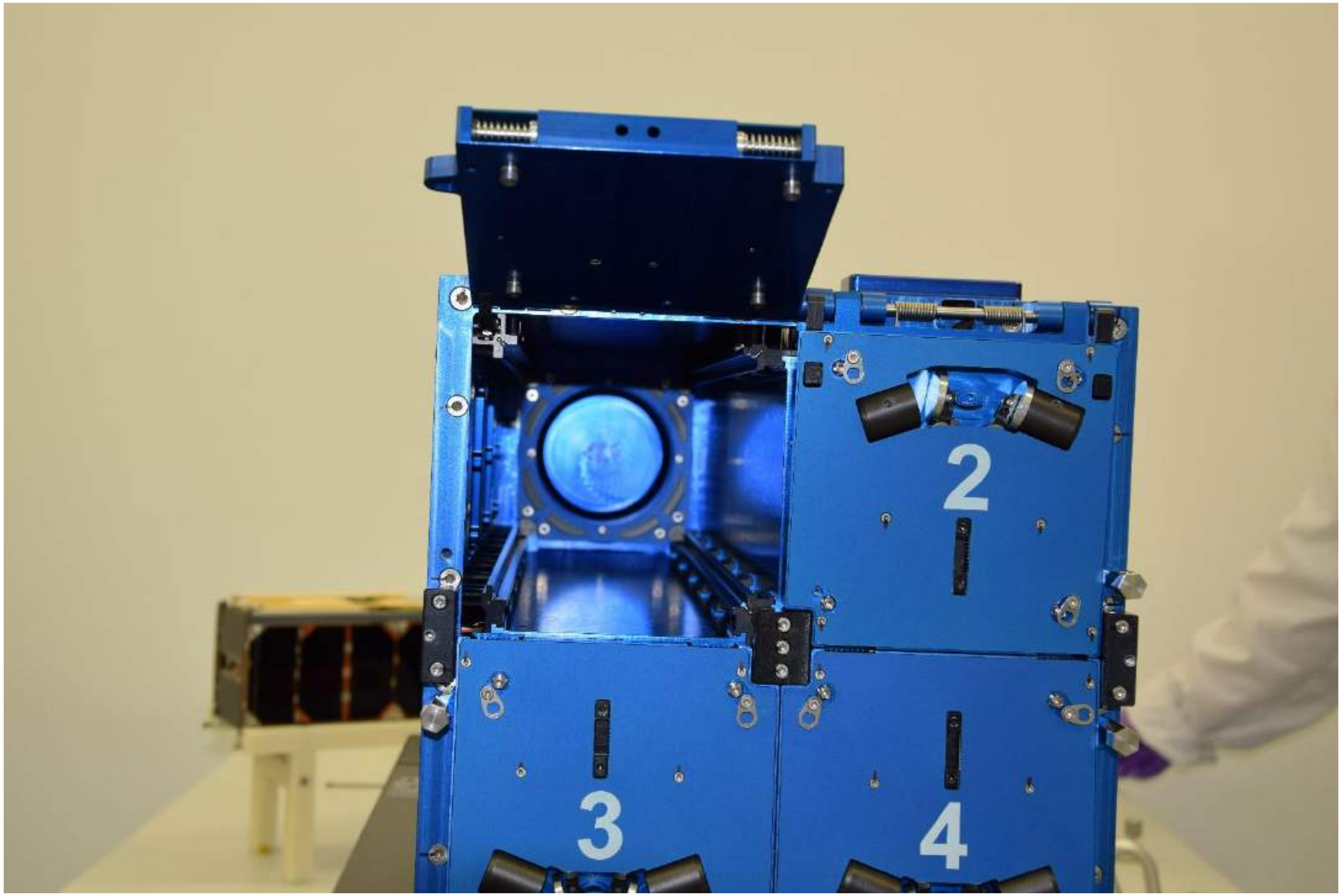


Integration of the FM SEAM in Berlin

- FM was transferred to ECM facilities middle of September 2017

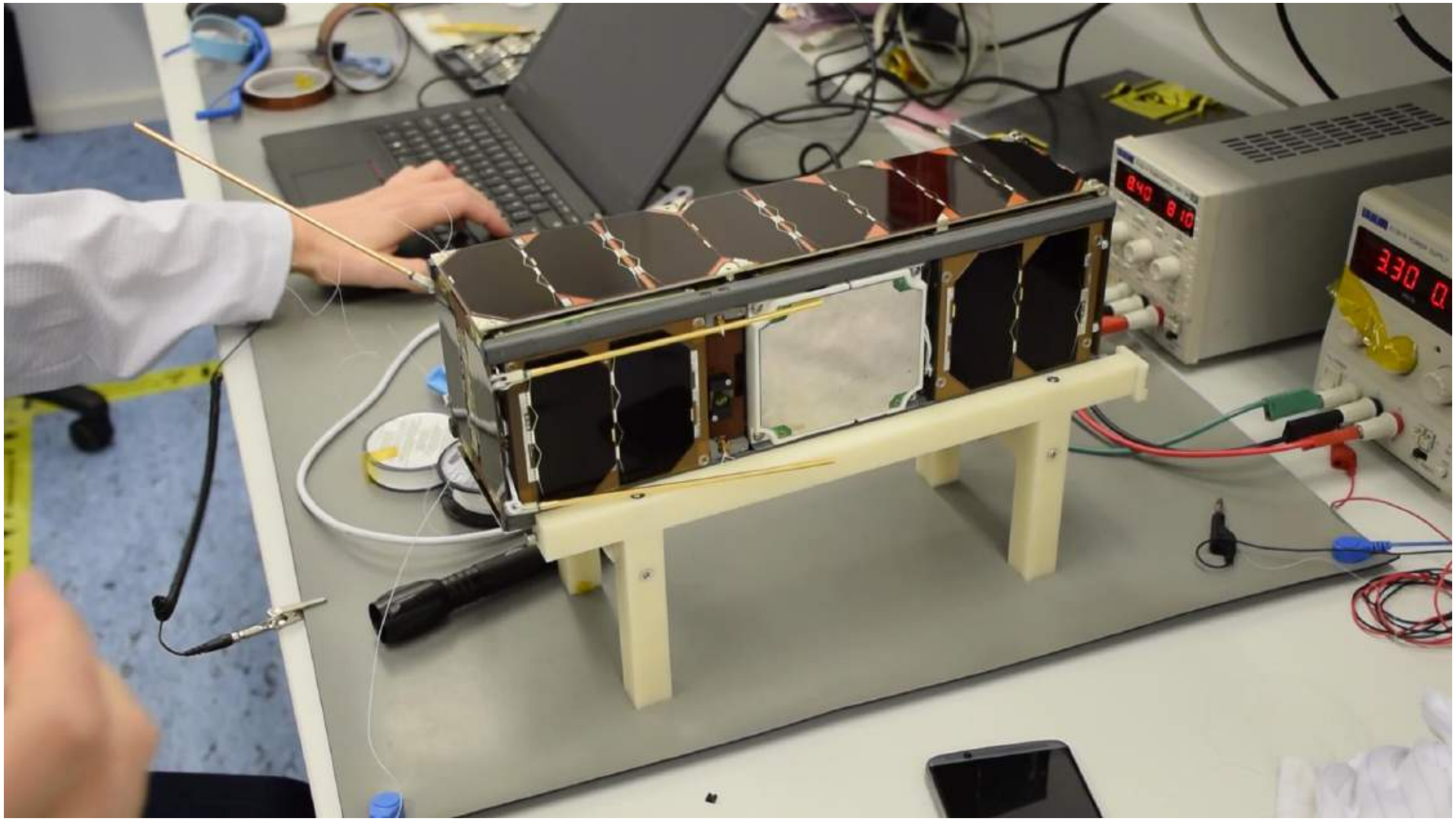
- Final check out operations and the integration of the FM into the ECM Dispenser was fulfilled in the beginning of October 2017

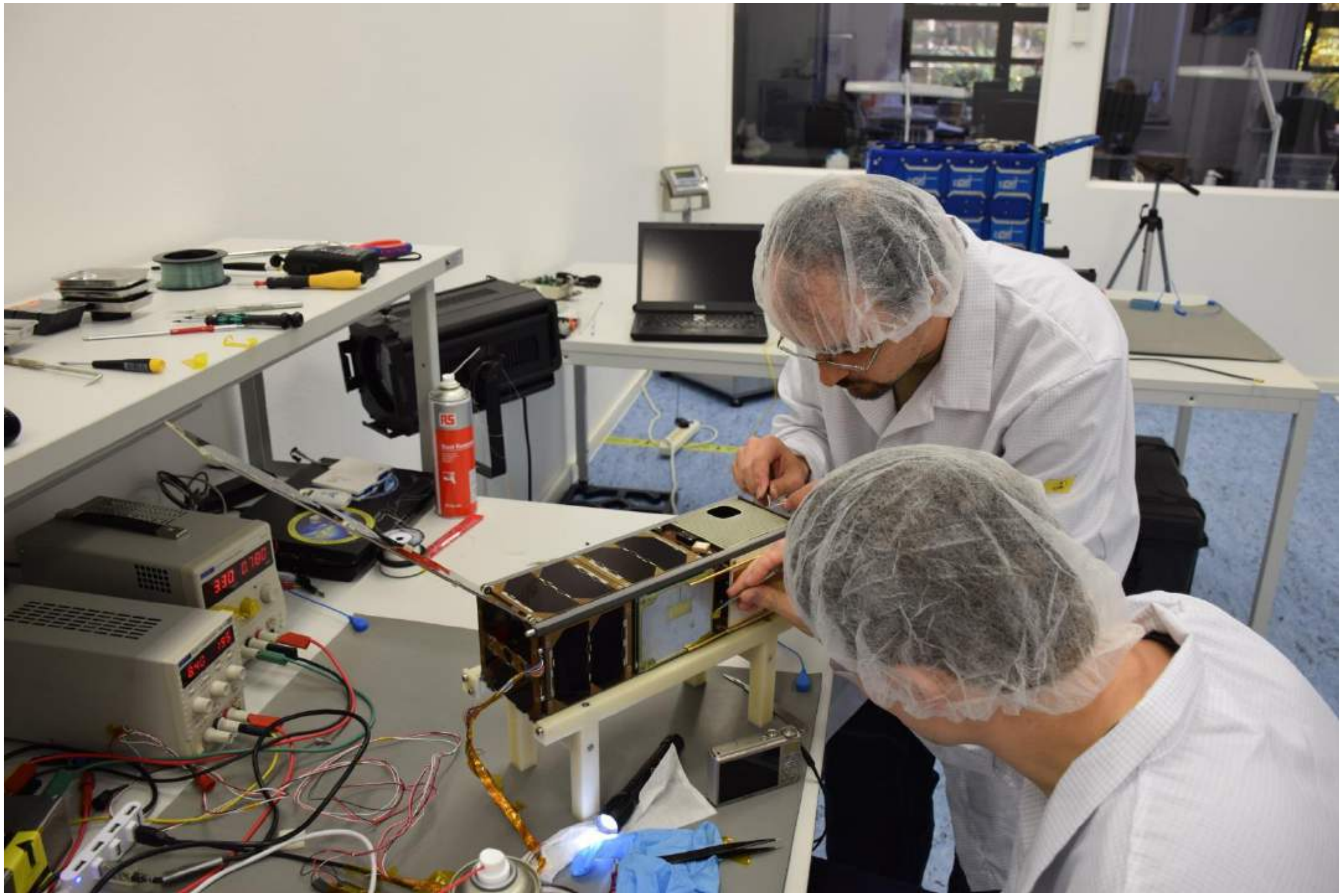
- After the integration the whole assembly was shipped to the Space Center Vostochny by ECM in cooperation with it's contract partner Glavkosmos

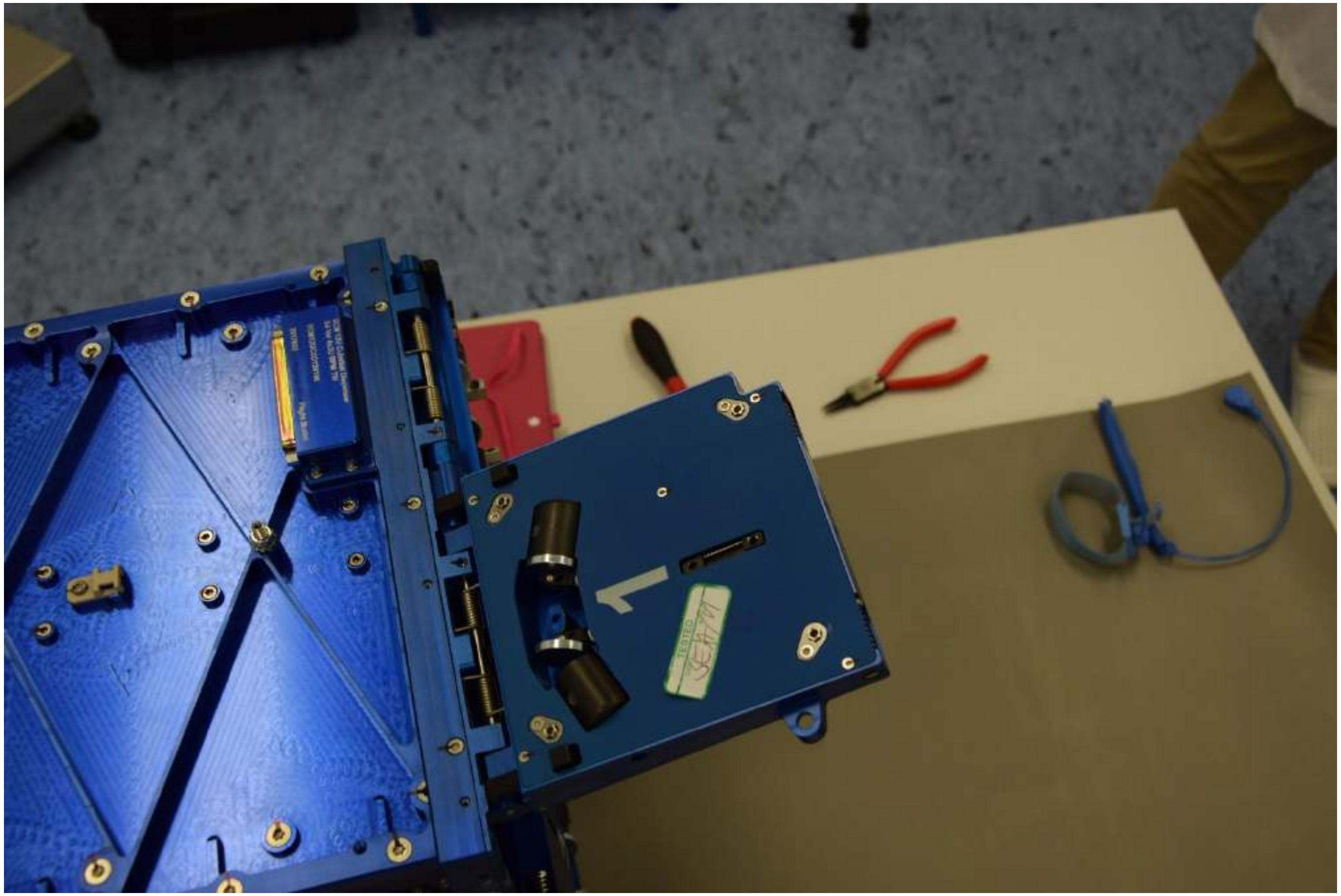

2
3
4

KTH VETENSKAP OCH KONST

ECM LAUNCH SERVICES www.ecm-space.de







KTH VETENSKAP OCH KONST

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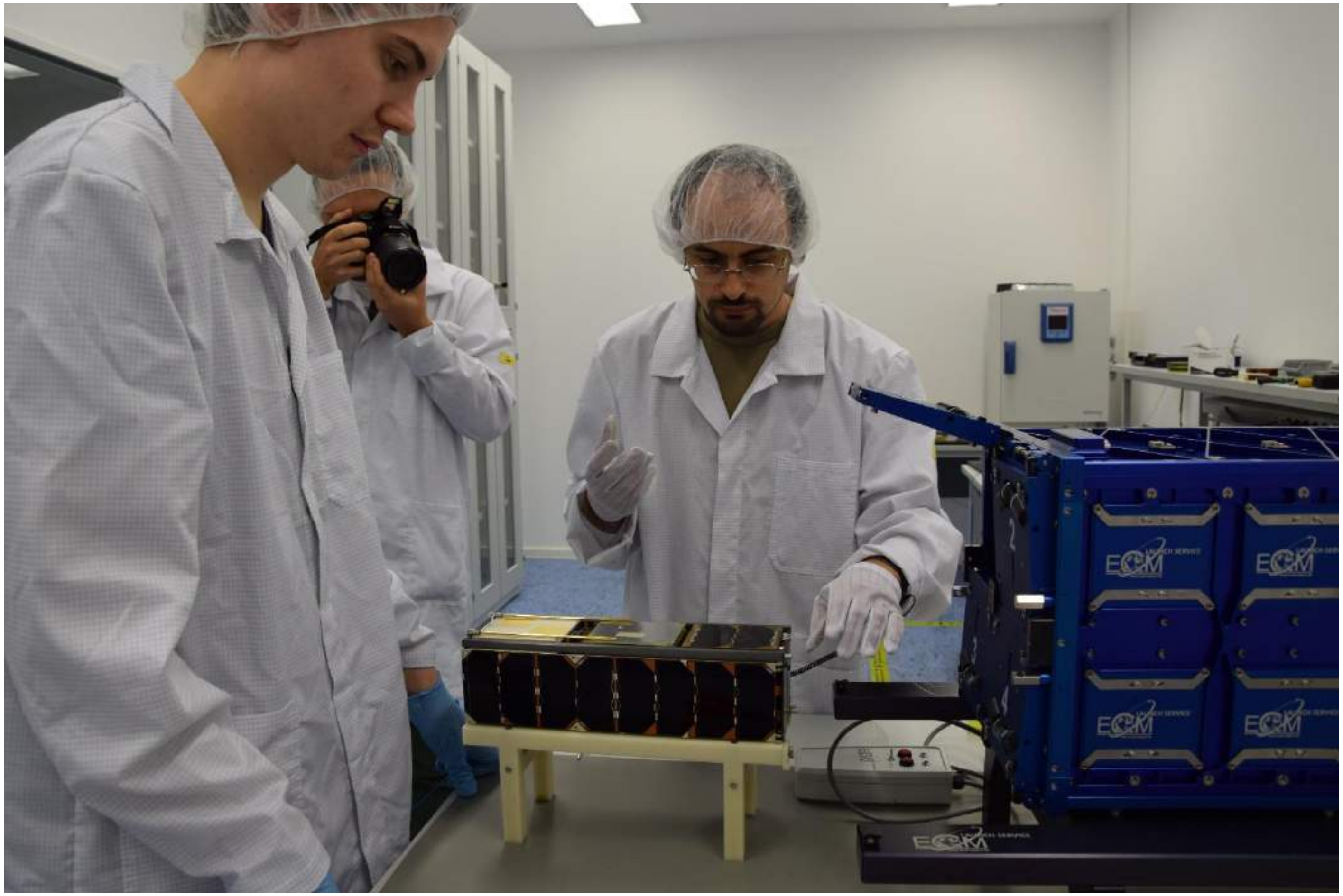
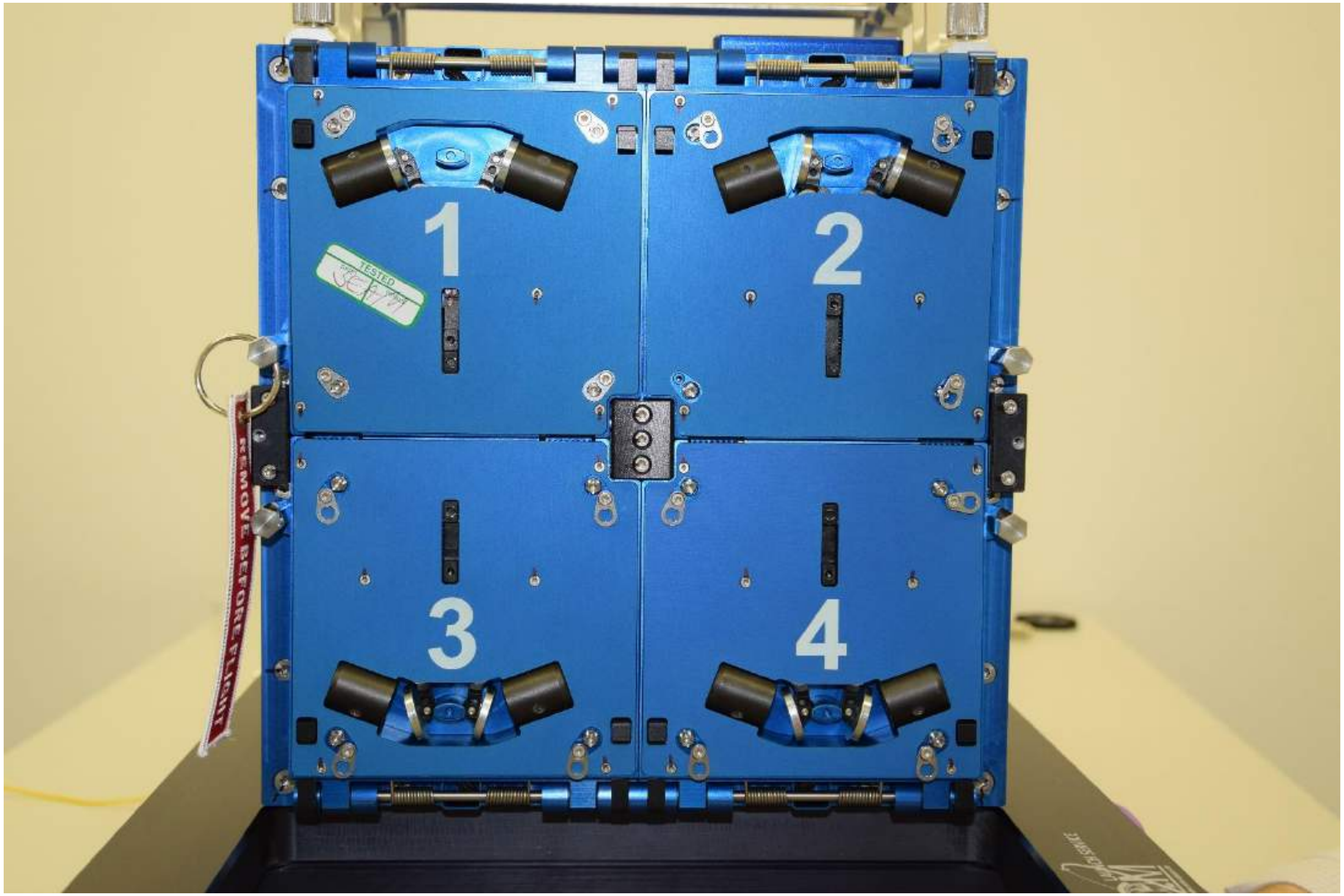
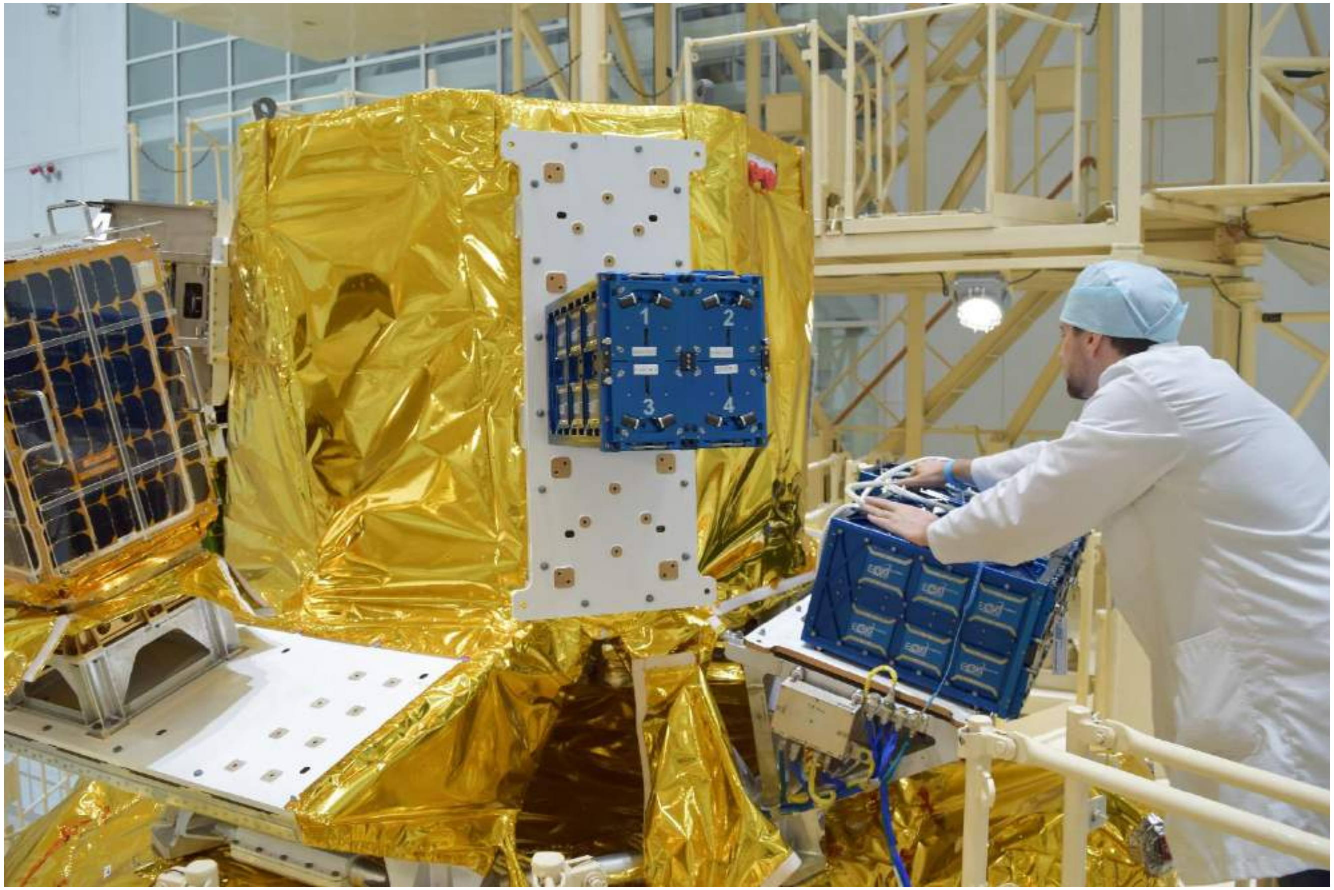



1
2
3
4
TESTED
REMOVE BEFORE FLIGHT

KTH VETENSKAP OCH KONST

LAUNCH SERVICES ECM www.ecm-space.de



KTH VETENSKAP OCH KONST

LAUNCH SERVICES ECM www.ecm-space.de

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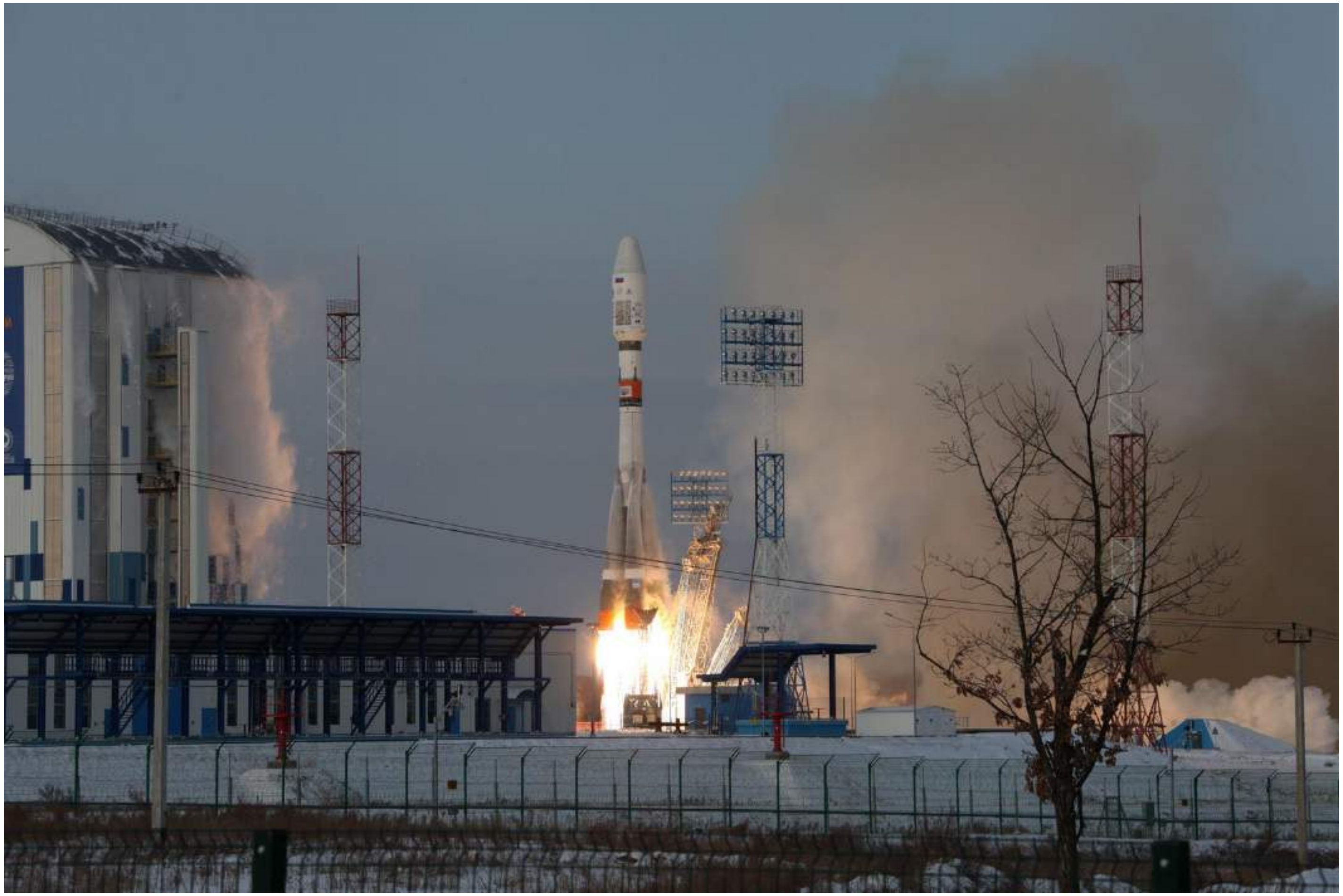
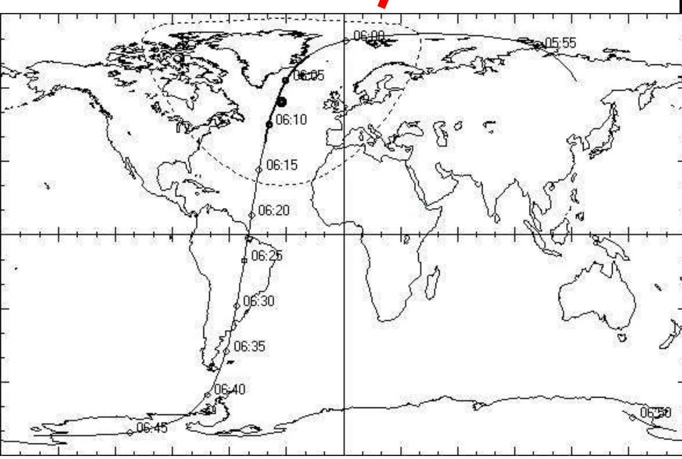


Failure of the Meteor-M #2.1 Mission

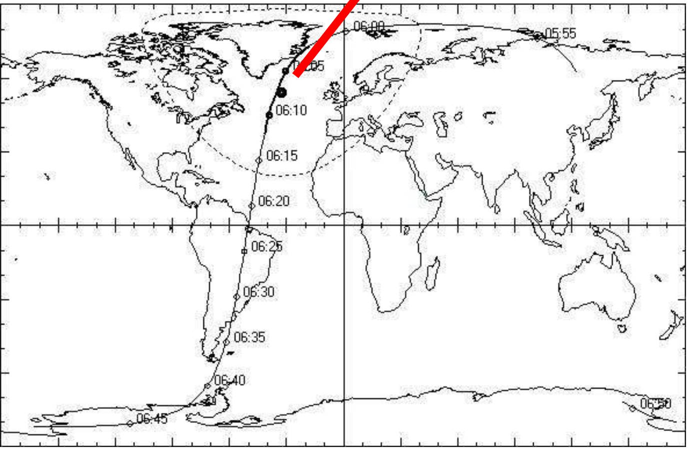
- The Investigation commission of the launch Failure has concluded that the failure resulted from a latent problem in the algorithm of the control system of the Fregat Upper Stage
- The Soyuz-2.1b launcher operated nominally and inserted the Space head Module into the expected orbital point
- It has been initiated to correct the algorithm of the Fregat‘s control system and existing procedures

The correction actions were successful and could be seen on the successful launch of the Kanopus-3,4 mission from Vostochny Space Center on 01.02.2018

Longyearbyen, Svalbard



Atlantic ocean, south-west of Iceland

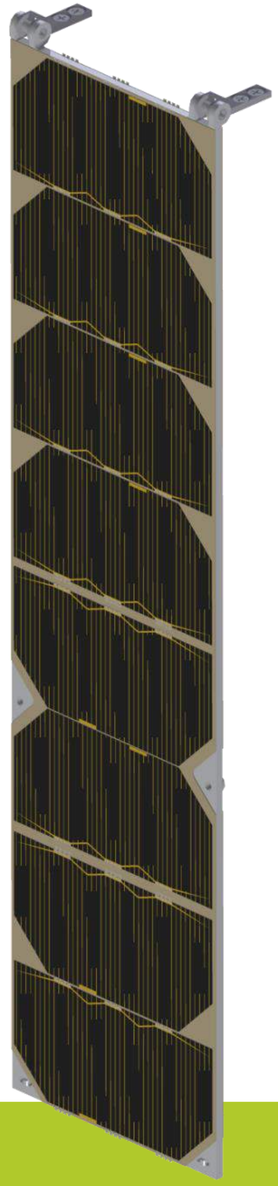


Overview of achievements in the SEAM project

Solar Panels

GomSpace Custom Deployable 3U Solar Panels

- Eight 3G30A cells arranged in a 4S2P configuration
- Both sides of the deployable panel house 8 cells
- Increase from 6 to 8 cells results in 20% increase in orbit average power (up to 10.2W): large impact on power budget and thus satellite operations

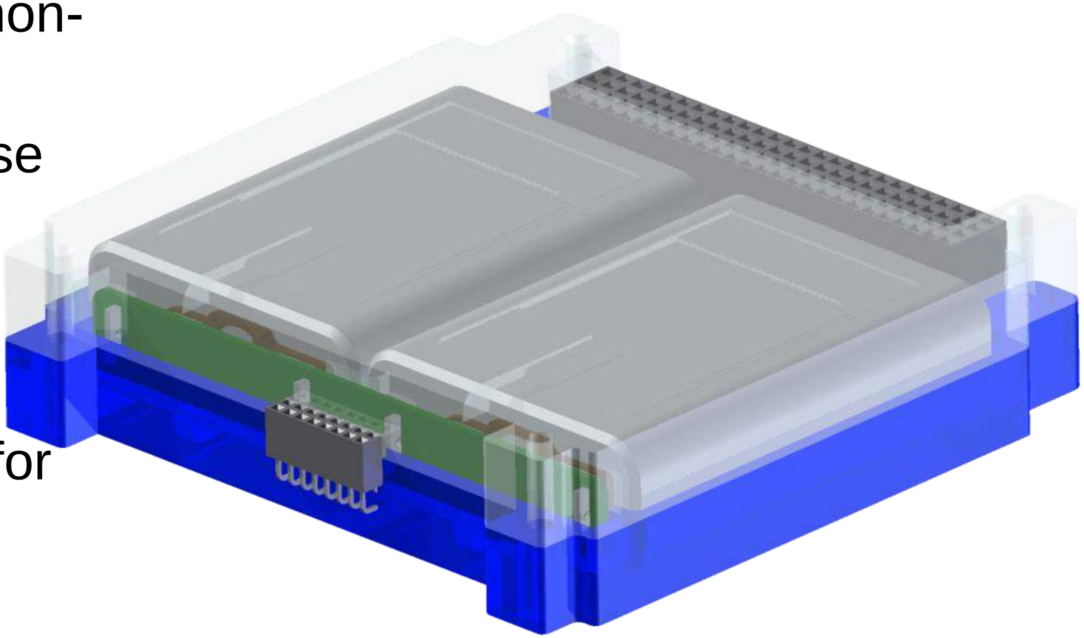


Battery Pack

PEEK case houses 2 SAFT non-magnetic aluminum batteries

Perpendicular PCB within case

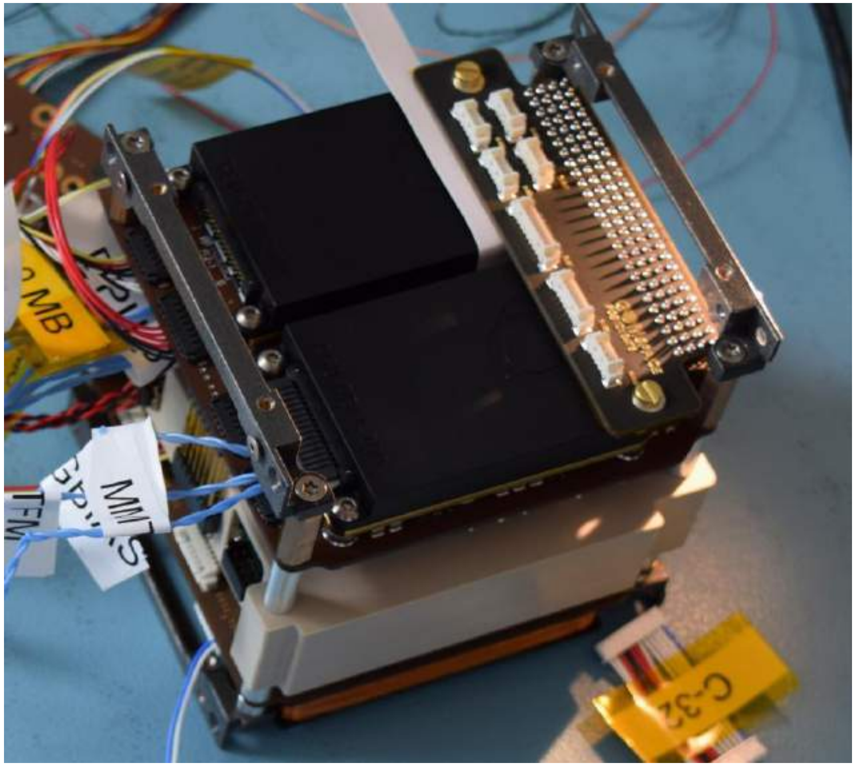
- Heater interface
- Temperature Sensor
- 2S1P connection
- 16 pin Samtec connector for P60



Power Supply

Next-generation P60 power supply

- Motherboard / daughterboard design to minimize stack height
- 1 input module + 2 output modules
- 1 daughterboard space for dedicated ADCS A3200 (if deemed necessary late in development)



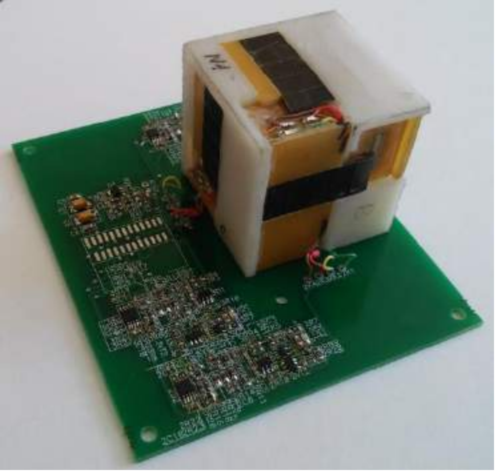
SEAM TCM development

- SEAM TCM
  - Seam TCM was built on the previous ÅAC Rapid Integration Architecture (18 MHz, 16GB, TMTC CCSDS, S-BAND and serial interfaces)
    - From start usage of a mass memory covered the storage needs for the mission.
    - Part of the SEAM project included development of the combined TMTC CCSDS stack and mass memory on the same board for rapid download of live and stored data.
    - The CCSDS IP was developed in a separate project and merged into the SEAM TCM system on chip.

ÅAC Microtec™

SIRIUS TCM development

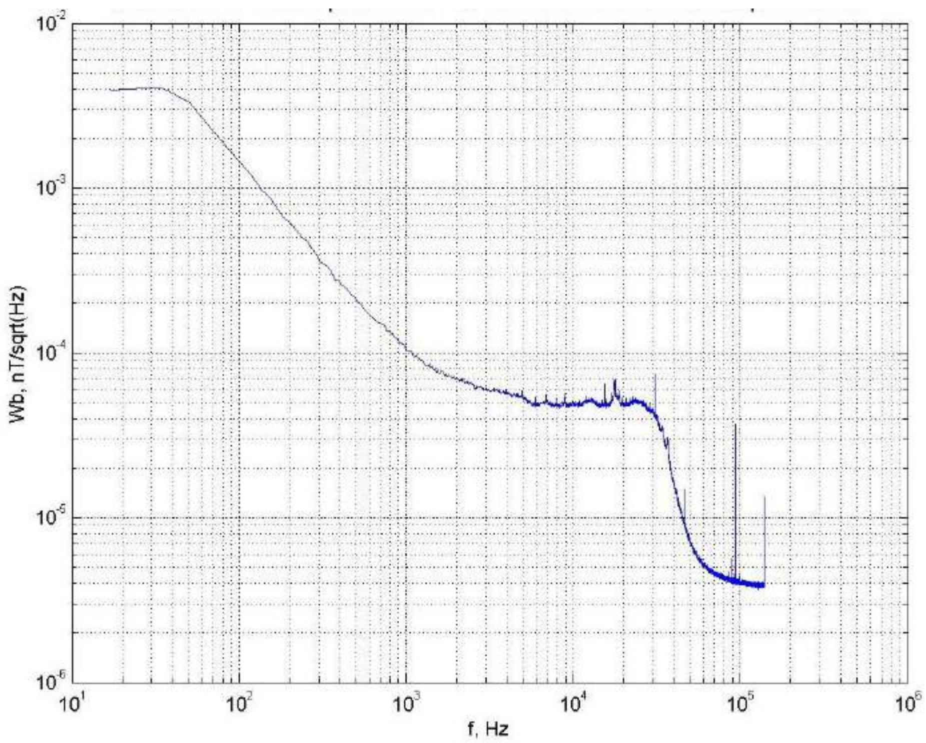
- Part of ÅAC Data Handling Products
  - The Sirius TCM was further developed from the SEAM TCM. For higher bandwidth an X-band interface was added. Spacewire was introduced and more functions were moved from software into hardware on the SoC. The Sirius TCM has system freq of 50 MHz, 16GB-32GB, TMTC CCSDS, PUS ECSS, SpW).
- Sirius Data Handling Subsystems
  - Consists of OBC and TCM and is the baseline for the Swedish InnoSat platform.

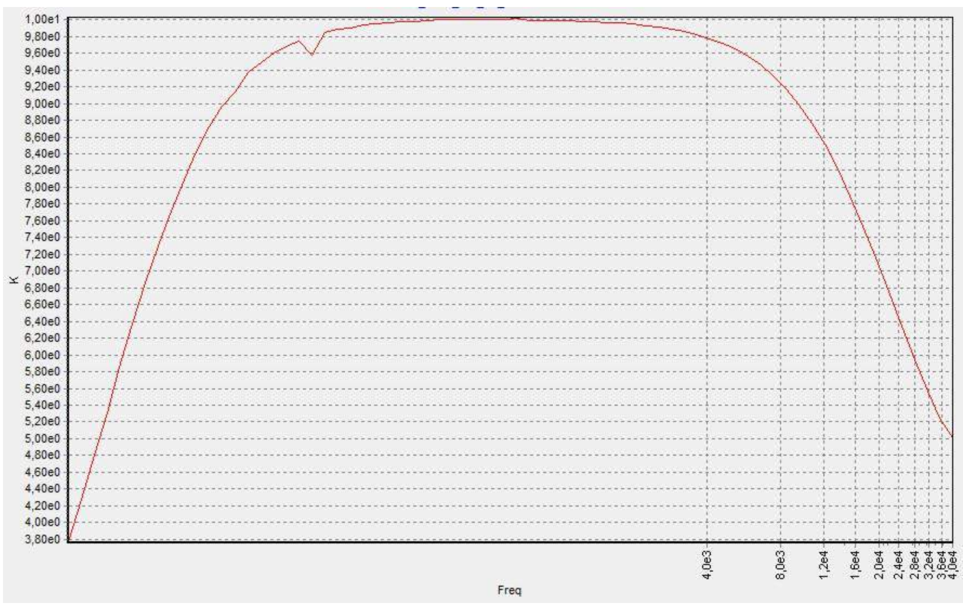


INDUCTION MAGNETOMETER LEMI-151

Frequency range	20 – 20000 Hz
Frequency response shape	flat
Transformation factor:	10 mV/nT
Noise level:	
at 10 Hz	15 pT/sqrt(Hz)
at 100 Hz	1,5 pT/sqrt(Hz)
at 1 kHz	0,12 pT/sqrt(Hz)
Power consumption	210 mW
Voltage supply	± 5V
Dimensions of sensor	38x38x38 mm
Mass of sensor	72 g

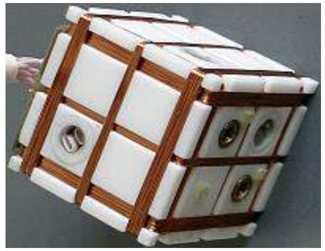
The results of the induction magnetometer tests





Induction Magnetometer noise level

Induction Magnetometer transfer function

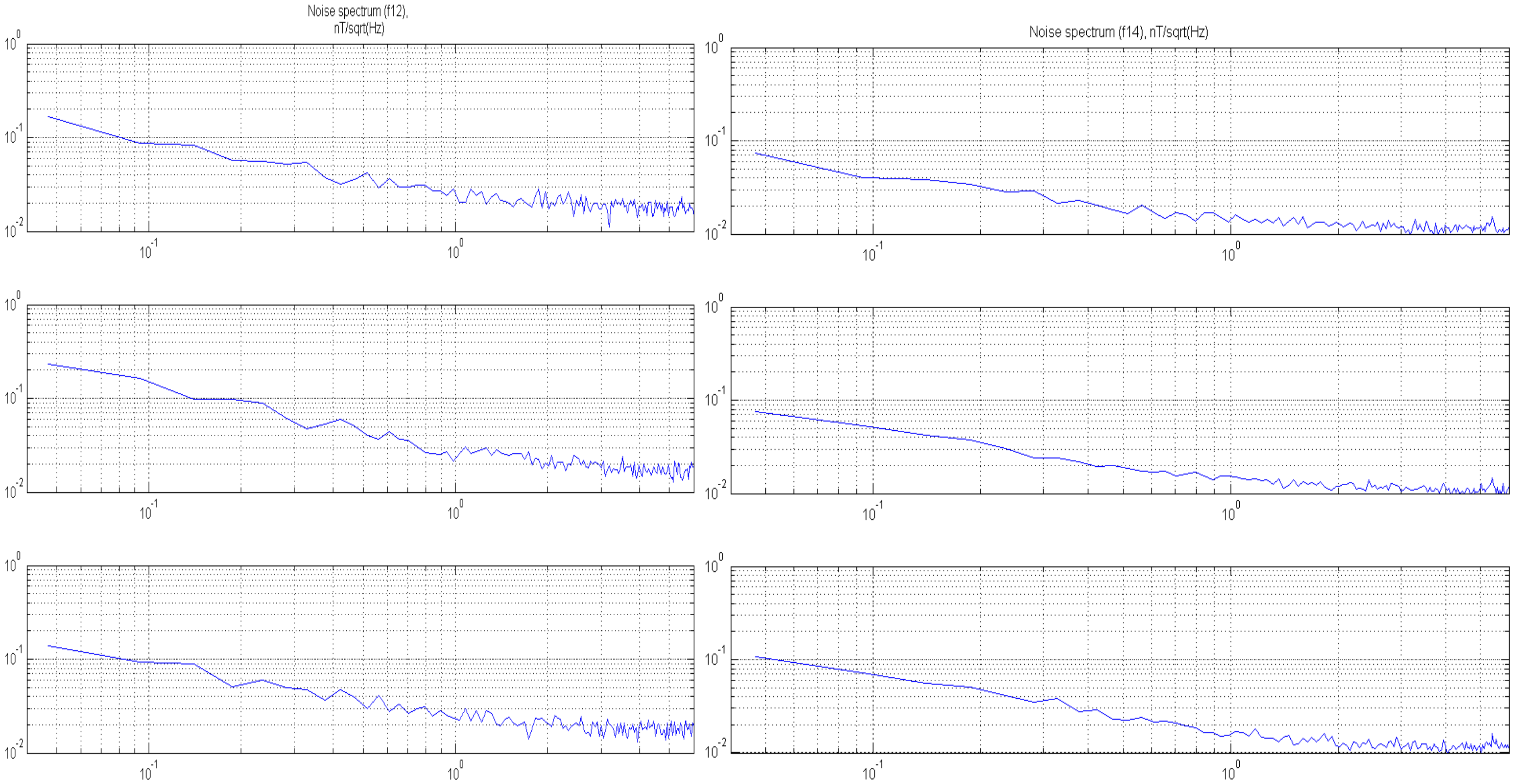


FLUX-GATE MAGNETOMETER LEMI-020

Measuring ranges of total magnetic field	± 64 000 nT
Frequency range	DC…100 Hz
Sample rate of measurements	250 Hz
Noise level at 1 Hz	< 20 pT/sqrt(Hz)
Resolution	20 bits
Components initial orthogonality	< 20 min of arc
Operating temperature range	minus 40…+ 60° C
Power supply voltage	5 ± 0.2 V
Power consumption	0.35 W
Weight:	
sensor	21 g
electronic unit PCB	80 g
Dimensions:	
sensor	20 x 20 x 21 mm
electronic unit PCB	72 x 77 x 1.6 mm

Noise tests of a prototype of the sensor and an improved sensors for SEAM project

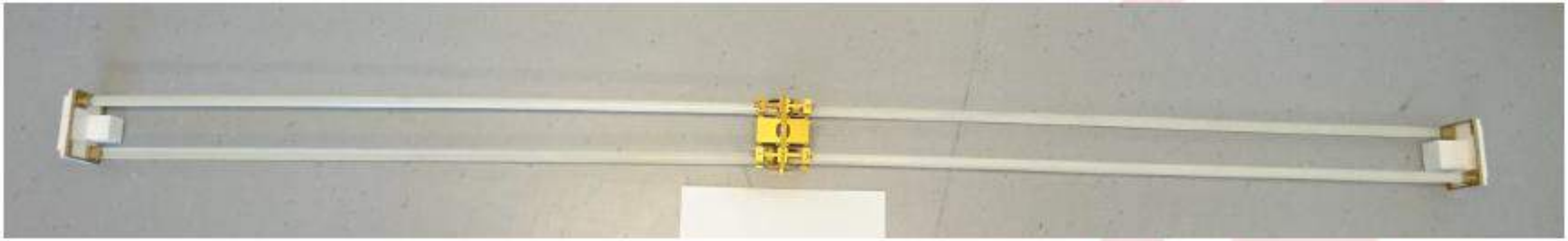
Changes of core parameters and annealing mode allow decreasing sensor own noise by 1.4…1.6 times comparing to the sensor prototype

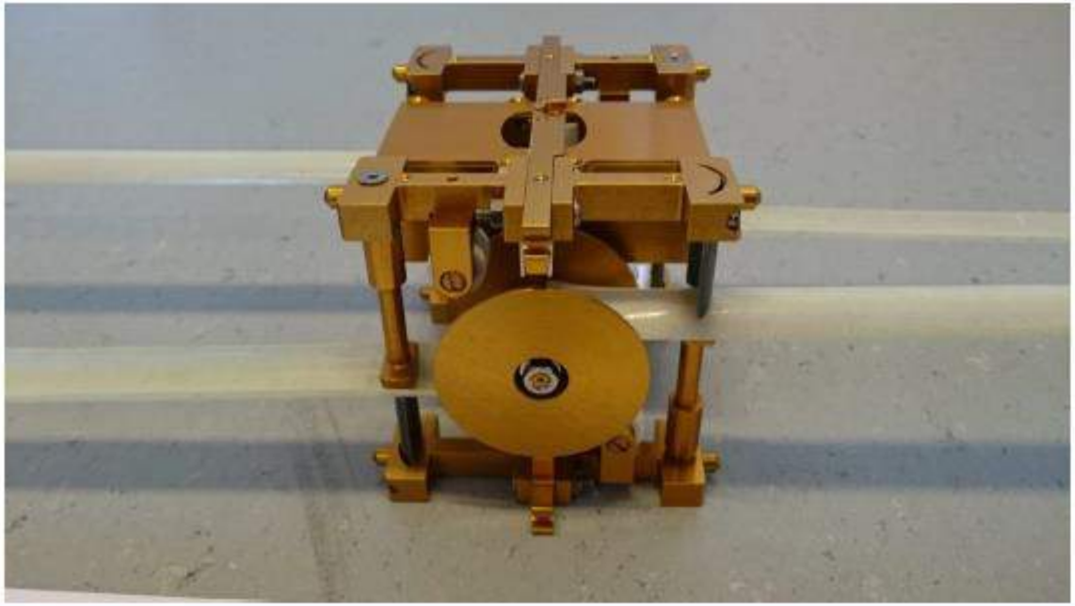


Noise level at 1 Hz is confirmed to be < 20 pT/sqrt(Hz)

SEAM Deployable Boom

- An assembly (the "SEAM boom") that simultaneously self-deploys two 1 m long tips
- Inspired by the AFRL SIMPLE boom





Main lessons learned from the boom development in the SEAM project

- Think about friction problems earlier in the design phase to avoid severe problems later

Deployment of Bistable Self-Deployable Tape Spring Booms Using a Gravity Offloading System

Huina Mao[1]; Pier Luigi Ganga, Ph.D.[2]; Michele Ghiozzi[3]; Nickolay Ivchenko, Ph.D.[4]; and Gunnar Tibert, Ph.D.[5]

Abstract: Bistable tape springs are suitable as deployable structures thanks to their high packaging ratio, self-deployment ability, low cost, light weight, and stiffness. A deployable booms assembly composed of four 1-m long bistable glass fiber tape springs was designed for the electromagnetically clean 3U CubeSat Small Explorer for Advanced Missions (SEAM). The aim of the present study was to investigate the deployment dynamics and reliability of the SEAM boom design after long-term stowage using onground experiments and simulations. A gravity offloading system (GOLS) was built and used for the onground deployment experiments. Two booms assemblies were produced and tested: a prototype and an engineering qualification model (EQM). The prototype assembly was deployed in a GOLS with small height, whereas the EQM was deployed in a GOLS with tall height to minimize the effects of the GOLS. A simple analytical model was developed to predict the deployment dynamics and to assess the effects of the GOLS and the combined effects of friction, viscoelastic relaxation, and other factors that act to decrease the deployment force. Experiments and simulations of the deployment dynamics indicate significant viscoelastic energy relaxation phenomena, which depend on the coiled radius and stowage time. In combination with friction effects, these viscoelastic effects decreased the deployment speed and the end-of-deployment shock vibrations. **DOI:** 10.1061/(ASCE)AS.1943-5525.0000709.

Author keywords: Tape spring; Bistable; Deployment boom; CubeSat; Viscoelastic effect; Energy relaxation.

Main lessons learned from the boom development in the SEAM project

- Tape springs suffer from visco-elastic effects, which we now understand much better and have developed a design method.

Design and Analysis of Laminates for Self-Deployment of Viscoelastic Bistable Tape Springs After Long-Term Stowage

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Bistable tape springs are ultrathin fiber-reinforced polymer composites, which could self-deploy through releasing stored strain energy. Strain energy relaxation is observed after long-term stowage of bistable tape springs due to viscoelastic effects and the tape springs might lose their self-deployment abilities. In order to mitigate the viscoelastic effects and thus ensure self-deployment, different tape springs were designed, manufactured, and tested. Deployment experiments show that a four-layer, [−45/0/90/45], plain weave glass fiber tape spring has a high capability to mitigate the strain energy relaxation effects to ensure self-deployment after long-term stowage in a coiled configuration. The two inner layers increase the deployment force and the outer layers are used to generate the bistability. The presented four-layer tape spring can self-deploy after more than six months of stowage at room temperature. A numerical model was used to assess the long-term stowage effects on the deployment capability of bistable tape springs. The experiments and modeling results show that the viscoelastic strain energy relaxation starts after only a few minutes after coiling. The relaxation shear stiffness decreases as the shear strain increases and is further reduced by strain energy relaxation when a constant shear strain is applied. The numerical model and experiments could be applied in design to predict the deployment force of other types of tape springs with viscoelastic and friction effects included. [DOI: 10.1115/1.4036672]

Lessons learned – technical

- System Engineering is critical for success. Initial effort was very useful! (D. Gerhardt of GomSpace)
- Development of new systems at different places poses high risk at integration
- Interface definitions are not the whole story…
- Early FlatSat test is critical
- Subsystems must be reprogrammable in the assembled state

Lessons learned – management

- Qualification testing scope and effort heavily underestimated at the state of the project

- Software development not sufficiently well defined in the original plan

- Continuity of staff is critical for the project, as is the commitment of the executives

- Managing the documentation is important