The SEAM story

Nickolay Ivchenko
Royal Institute of Technology KTH / South African National Space Agency + SEAM Team

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.
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

Deployable Boom
- SC mag (analog x 3)
- EF sense (analog x 1)
- SMILE FG mag
- Boom Star Tracker

Solid Structure
- DPU
  - Store raw science data in circular buffers
  - Generate intermediate data
- Hybrid
  - Offset magtrq.
  - SMILE Elect.
  - Boom ST Elect.
- Body Star Tracker
- GPS

Solid Structure Connections:
- UART
- SPI
- I2C bus

MM
- Store raw/intermediate/HK/status data in solid state
- Route raw data from DPU to S-band radio (by request)
- Send I2C command (by request)
- Pulse command (sat. reset)

S-band Transceiver
- RS422

NanoMind
- Scheduling
- Command interpreter
- AD&C

NanoPower
- Supply 3.3V, 5.9V & Vbatt
- Hard reset satellite
- Output switching

NanoCom UHF
Another view...

- FSS, CSS, T_SP, T_FSS Interstage board (6)
- Service Mag
- Gyro
- GSSB
- Star Tracker (2)
- Dipole Bias
- S-Band (I^2C)
- UHF
- EPS
- TCM
- DPU
- CSP

OBC
Early satellite layout
- 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 connected ones in the subsystems)

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

- **Sensors**
  - GPS
  - Star Trackers
  - FSS
  - Service Mag

  **DPU**
  - Waveform CH0...3
  - Waveform CH4...7
  - Quick Look data products

  **OBC**
  - Orbit, Attitude

Data Rates:
- 2.5 Mbit/s
- 24 kbit/s
## Quick Look Data Products

<table>
<thead>
<tr>
<th>Data product</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP1</td>
<td>Decimated DC magnetic field data (10 samples/s)</td>
</tr>
<tr>
<td>DP2</td>
<td>Mains frequency spectra (40-70 Hz)</td>
</tr>
<tr>
<td>DP3</td>
<td>Integrated spectrum</td>
</tr>
<tr>
<td>DP4</td>
<td>Overview spectrum</td>
</tr>
<tr>
<td>DP5</td>
<td>Time series of power density</td>
</tr>
</tbody>
</table>
Quick Look Data archive

Data budget:
CH0…3 requested
CH4…7 requested

One Orbit

PREPARE
DPU REQUEST
FOR NEXT UPLINK
Orbit prediction, power modeling

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

<table>
<thead>
<tr>
<th>Task Description</th>
<th>Start</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP1 Management</td>
<td>1</td>
<td>36</td>
</tr>
<tr>
<td>WP2 Preliminary design</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>T2.1 Requirement formulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2.2 Technology survey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2.3 E-M cleanliness analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2.4 Mission Analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2.5 Satellite preliminary design</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WP3 Technology development</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>T3.1 Attitude determination</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3.2 Power system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3.3 Avionics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3.4 Magnetic Sensors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3.5 Deployable boom</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3.6 Telemetry and telecommand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3.7 O/b processing &amp; op. strategy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3.9 EM testing and validation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WP4 Implementation</td>
<td>21</td>
<td>16</td>
</tr>
<tr>
<td>T4.1 Flight hardware manufacturing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4.2 Assembly and integration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4.3 Flight model testing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4.4 Launch campaign</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4.5 Operations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4.6 Flight data analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WP5 Dissemination</td>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td>T5.1 Internal communication</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T5.2 Community dissemination</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T5.3 Public outreach</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WP6 Commercial evaluation</td>
<td>1</td>
<td>36</td>
</tr>
<tr>
<td>T6.1 Market potential evaluation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T6.2 Business plan formulation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Start**: October 2013
- **PDR, April 2014**
- **CDR, May 2015**
- **FRR, September**
- **Extra review, October 2014**
- **Extra review, 151201**
- **Project restarted August 2017**
- **"not-FRR" Review, April 2016**
- **Launch**
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

- DPU
- TCM
- S-band

UART
Baseband
Data + Clk

Cortex
RAMSES
LAN
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
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)
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
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 2\textsuperscript{nd} 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...
Purpose: to qualify the EM boom after the design change with the stronger carbon fiber kick springs attached to overcome the initial friction.
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.

Table temperature was set to -50C for faster cooling.
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
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
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.
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

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>20 – 20000 Hz</td>
</tr>
<tr>
<td>Frequency response shape</td>
<td>flat</td>
</tr>
<tr>
<td>Transformation factor:</td>
<td>10 mV/nT</td>
</tr>
<tr>
<td>Noise level:</td>
<td></td>
</tr>
<tr>
<td>at 10 Hz</td>
<td>15 pT/sqrt(Hz)</td>
</tr>
<tr>
<td>at 100 Hz</td>
<td>1.5 pT/sqrt(Hz)</td>
</tr>
<tr>
<td>at 1 kHz</td>
<td>0.12 pT/sqrt(Hz)</td>
</tr>
<tr>
<td>Power consumption</td>
<td>210 mW</td>
</tr>
<tr>
<td>Voltage supply</td>
<td>± 5V</td>
</tr>
<tr>
<td>Dimensions of sensor</td>
<td>38x38x38 mm</td>
</tr>
<tr>
<td>Mass of sensor</td>
<td>72 g</td>
</tr>
</tbody>
</table>
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 Mao¹; Pier Luigi Ganga, Ph.D.²; Michele Ghizio³; 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. © 2017 American Society of Civil Engineers.

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

Huina Mao
Department of Aeronautical and Vehicle Engineering,
KTH Royal Institute of Technology,
Stockholm 100 44, Sweden
e-mail: huina@kth.se

Anton Shipsha
Department of Aeronautical and Vehicle Engineering,
KTH Royal Institute of Technology,
Stockholm 100 44, Sweden
e-mail: shipsha@kth.se

Gunnar Tibert
Department of Aeronautical and Vehicle Engineering,
KTH Royal Institute of Technology,
Stockholm 100 44, Sweden
e-mail: tibert@kth.se

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 uncoiling. 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