GOMX-4, the most advance nanosatellite mission for IOD purposes

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After the success of GOMX-3[1][2], GomSpace has developed the next generation of nanosatellite platforms. The demonstration mission for these advanced nanosatellites is GOMX-4 and it includes two satellites, GOMX-4A and GOMX-4B.
GOMX-4B is funded by ESA to be the most advanced CubeSat for IOD purposes demonstrating the 5 payloads on-board: the 6U propulsion module from NanoSpace; the innovative Inter-Satellite Link (ISL) from GomSpace; the Chimera board developed by ESA; the HyperScout Hyperspectral Camera from Cosine and the Star Tracker from ISIS.
GOMX-4A is a satellite to monitor Greenland and the artic region by capturing ADS-B, AIS and images for the Danish Defence Acquisition and Logistics Organization (DALO).
The numerous in-orbit experiments included in GOMX-4 mission are possible thanks to the high performance and flexible 6U platform from GomSpace flying in this mission for first time.
The two satellites were launched on the 2nd of February 2018 on a LM-2D. The in-orbit results presented here after a success LEOP and commissioning phase, shows the extensive capabilities of these innovative nanosatellites and opens the road for scaling to larger platforms and advanced constellations with compact communication and optical payloads.

1 GOMX-4 MISSION INTRODUCTION

After nanosatellites have showed their utility during the last decade as low cost platforms for the space sector, a new generation of nanosatellites with more complex functionality, performance and applications is welling up. In this context, the GOMX-4 mission has been developed during the last 2 years and half to be a pioneering European demonstration mission for future constellations.

Figure 1. Illustration of the GOMX-4 mission.

The GOMX-4 mission consists in two 6U nanosatellites with similar platform and different payloads which must perform Inter-Satellite Link operations and orbit control between them. The two satellites are called GOMX-4A and GOMX-4B and they are respectively funded for data collection for the DALO (The Danish Defence Acquisition and Logistics Organization) and for in-orbit demonstration for the European Space Agency (ESA).

Both satellites are flying in Sun Synchronous Orbit (SSO) at around 500 Km of altitude to ensure that both satellites have daily coverage passing by the primary ground station located in Aalborg (Denmark) and GOMX-4A covers the Artic Area for monitoring and data collection. This inclination also allows coverage of the entire globe for different applications using the on-board optical payloads.

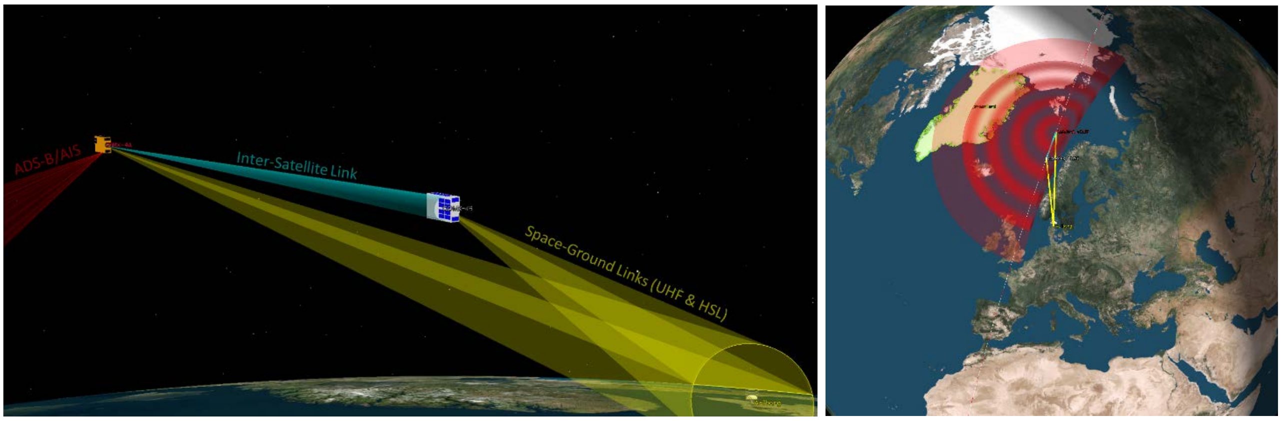

Figure 2. STK links simulation for the GOMX-4 mission demonstrating constellation capabilities.

One of the main objectives of GOMX-4 is to test the Inter-Satellite Link (ISL) in distances from 300 up to 4500 Km, demonstrating low-latency capabilities for communications and observations applications, which is the key functionality for future constellations. For this purpose, the satellites must fly in tandem and control their separation distance using drag management and ground-commanded propulsion manoeuvres. GOMX-4A includes only ADCS capabilities but GOMX-4B also accommodates the NanoSpace 6U propulsion module for additional orbit control.
In first place, propulsion manoeuvres are applied before concluding the LEOP phase to equal the orbit altitude of both satellites and stabilize them at around 300 Km of separation distance. Then, the Inter-Satellite Link communications shall be characterized while performing station keeping and varying the inter-satellite distances. This step drives to the operation phases where these main constellation capabilities are tested in combination with the different payloads experiments and data collection.

In the following sections, the system design of the satellites and in-orbit results obtained until now are presented.

2 GOMSPACE 6U PLATFORM

Both GOMX-4 satellites implement the same architecture based on the GomSpace 6U platform which supports a variety of advanced payloads.

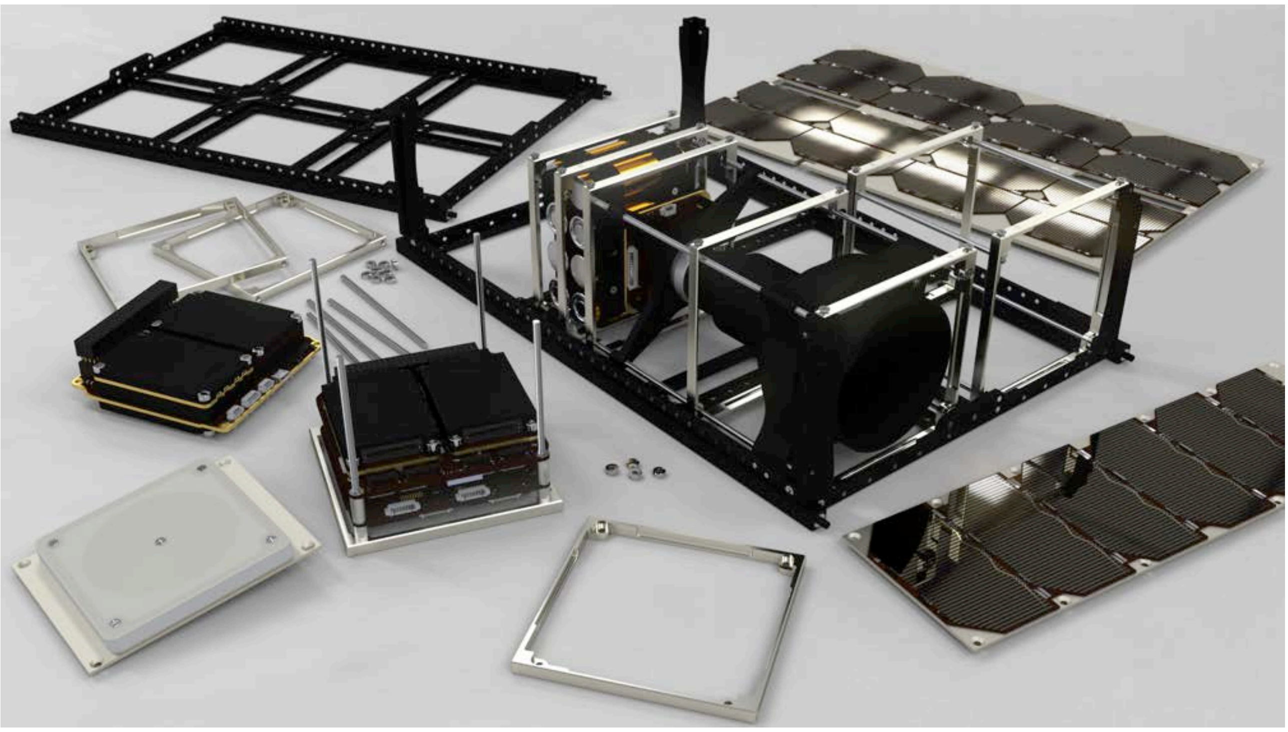

Figure 3. GomSpace 6U platform showing some of the advanced avionics systems and modular structure and solar panels.

The GomSpace 6U platform uses modular components into an innovative 6U structure allowing standard systems flexibility in placement and satisfying multiple mission requirements.
It can accommodate new payload designs that would be difficult to integrate in most of the current CubeSat buses and, at the same time, it is also fully compatible with current standard CubeSat components. This system is designed to integrate new system architectures with higher reliability, faster interconnect speeds, and easier integration.

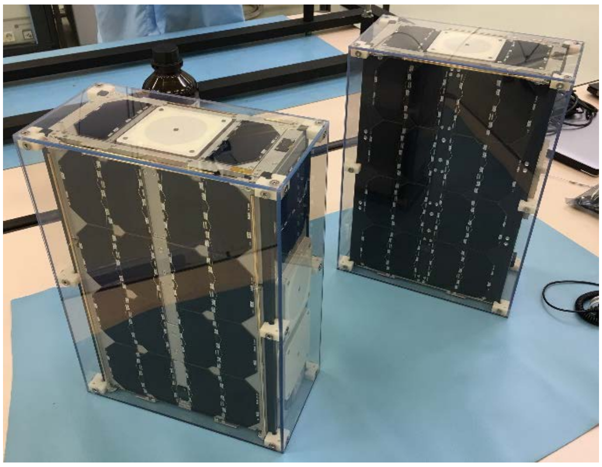

Figure 4. Photos of the external layout of GOMX-4A (left) and GOMX-4B (right).

Regarding to the external components, this platform allows a wide variety of antennas, sensors, solar panels, radiation shields and radiative surfaces. The new GomSpace modular solar panel architecture, developed for this platform, provides a less expensive and faster design on new customized panels, reducing risk to larger nanosatellite missions which frequently require customized solar arrays. These external components architecture is also directly applicable to larger nanosatellite sizes. Therefore, the same configuration can be used with any customized mechanical interface.

For the platform avionics, GomSpace has developed new modular and flexible subsystems supporting multitude payloads and requirements. One of the key elements is the innovative and high-power EPS, NanoPower P60, composed by independent input and output modules connected to a dock which allows as many inputs and outputs channels as the mission requires with protective and configurable voltage supply channels for payloads.

The 6U ADCS subsystem also includes new features like the variety of sensors and actuators allowed under plug-and-play philosophy. It includes electrical and software interfaces for powerful magnetorquers, up to 4 independently controlled reaction wheels, sun sensors, magnetometer, GPS, star tracker and propulsion module.

This new platform architecture is debuting on both satellites GOMX-4A and GOMX-4B, leveraging its strengths to develop two highly specialized missions in a common platform with maximum flexibility and design reuse.

3 GOMX-4A SATELLITE DESIGN

The GOMX-4A satellite is a 6U satellite mainly intended to collect ADS-B and AIS data above the Artic Area with minimum latency for a lifetime of 3 years. To reach this goal, it is equipped by flight proven ADS-B and AIS receivers, cohabiting with the Inter-Satellite Link payload and the NanoCam. In addition to achieve the GOMX-4A goals, these fours payloads will work together to optimize operations planning capabilities and data delivery to customers for next constellations.

As brief overview of the GOMX-4A system design, this satellite includes the GomSpace 6U avionics driven by the NanoMind A3200 as OBC, the NanoCom AX100 as the main UHF radio link to ground and the NanoPower P60 as advanced EPS with an input module (ACU) and two protective input modules (PDU). For energy store, it accommodates the NanoPower BPX with 8 cells battery pack connected as 4s2p. Finally, it also contains the NanoADCS 6U system composed by a dedicated ADCS computer, the Novatel OEM615 GNSS receiver, coarse and fine sun sensors in every external surface, the NanoTorque GST-600 and the NanoTorque GSW-600 with 4 reaction wheels distributed in pyramidal configuration.
The payloads are the ADS-B and AIS dedicated receivers, NanoCom ADS-B and QubeAIS, two independent Software Defined Radio for S-band links and advanced radio experiments, the NanoCom SDR, and the NanoCam camera.

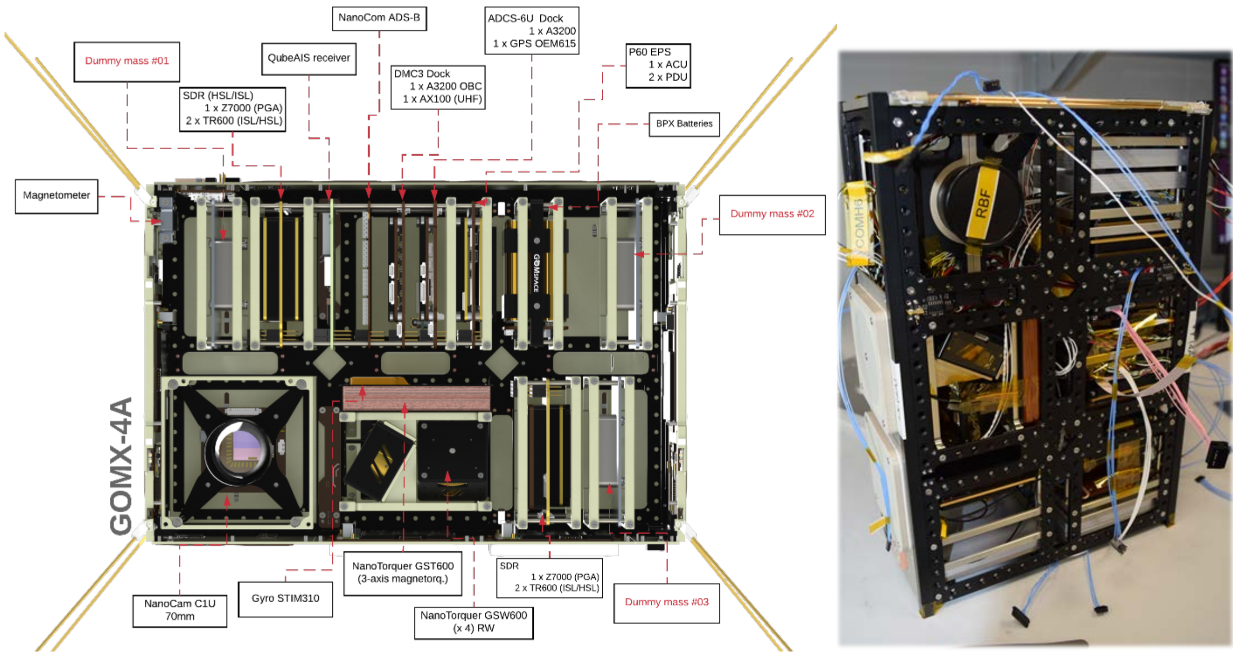

Figure 5. GOMX-4A system design: internal components layout.

Externally, the satellite is equipped with several patch antennas for S-band Inter-Satellite Link, High-Speed Link (HSL) and ADS-B data acquisition, together with deployable VHF and UHF antennas

for AIS data collection and main telemetry-telecommand space-ground link respectively. All the remaining external surfaces have been filled with body mounted solar panels capturing an average input power in the nominal attitude of around 9 W.
GOMX-4A is intended to act as a passive control satellite in the constellation operations due to its lack of active orbital control system. By this reason, its mass has been compensated with dummy masses to reach a similar mass than GOMX-4B and to orbit in similar conditions in terms of orbit decay and velocity. Therefore, the constellation maintenance is optimized reducing the number of active maneuvers along the lifetime.

4 GOMX-4B SATELLITE DESIGN

GOMX-4B is the second ESA in-orbit demonstration nanosatellite for miniaturized technologies combined with the orbit control utilization to be extended to larger constellations.

To fulfill its main mission goal, GOMX-4B includes the 6U cold-gas propulsion module developed by NanoSpace and the Inter-Satellite Link system to perform bi-directional communication with GOMX-4A from 300 up to 4500 Km of separation distance. These combined capabilities demonstrate the constellation features for communication applications where the latency is minimized without impacting the number of Ground Stations.
The avionics and ADCS subsystems onboard GOMX-4B are identical to the ones used in GOMX-4A, while implementing a more complex power and data interface configuration to supply the larger number of advanced payloads. As a secondary goal, GOMX-4B includes three additional payloads for in-orbit demonstration. They are the Hyperscout hyperspectral camera developed by Cosine, the CHIMERA payload testing the radiation hardness of different memories in LEO by ESA, and a Star Tracker for nanosatellites from ISIS.

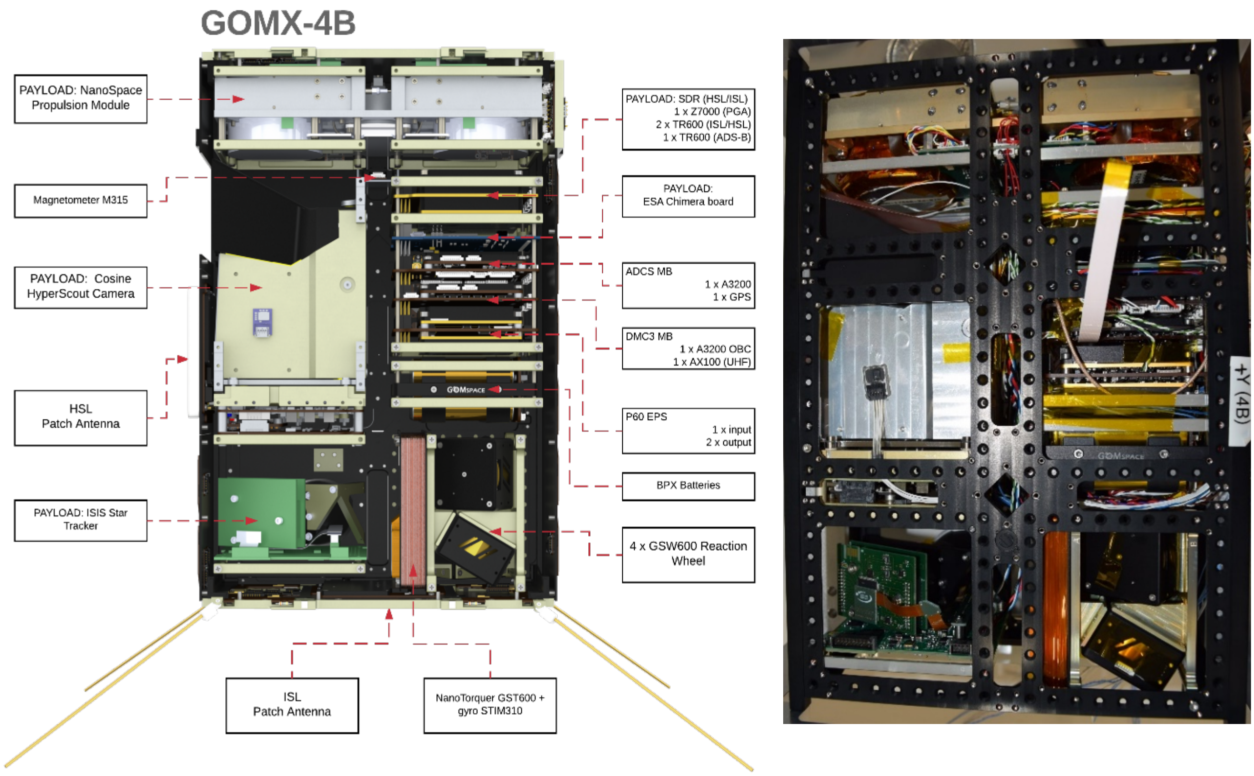

Figure 6. GOMX-4B system design: internal components layout.

The external configuration of the GOMX-4B satellite is similar to GOMX-4A, excepting the different patch antenna locations, the opening for the optics components, and the 4 thrusters. The 4 external surfaces with major solar radiation incident keep the same number of solar cells in both satellites and, therefore, the average input power is similar.

5 GOMX-4 LEOP

5.1 Launch

Figure 7. GOMX-4 team in JSLC with the satellite ready to be launched.

GOMX-4A and GOMX-4B were launched on February 2nd 2018 from the Jiuquan Satellite Launch Centre (JSLC) in the Long March 2D-Y13.
They were assembled in a single pico-satellite deployer, the Astrofein PSL-P for 6U.

The satellites were successfully inserted in orbit according to expectations at 503 Km of altitude and a Local Time of Ascending Node of 14:10, releasing GOMX-4A in the first group of secondary payloads and GOMX-4B 28 seconds later. The deployment from the launcher drove a difference in the altitude of GOMX-4B by 320 meters below GOMX-4A as it was expected.

5.2 Platform commissioning

Within the first 3 weeks after launch the different subsystems of platforms of both satellites were successfully commissioned.
In first place, the two satellites were successfully released from the launcher and activated by the kill switches. The first contact from the Aalborg Ground Station with the satellites happened 6 hours and 18 minutes after the launch showing healthy and responsive satellites. Within the first 3 passes, the release of the deployable UHF antennas were checked together with the proper automatic activation of detumbling. The GPS was activated to estimate the initial TLE more accurately and improve ground station contact.

Then, during the next 3 weeks the different platform subsystems were commissioned and tracked ensuring their proper behaviour.

The main telemetry-telecommand link was successfully established in both directions and different transmission powers were tested in the space segment to verify the expected link budget.
The performance of the On-Board computer was nominal, and no mission software updates or debugging were needed.

As mentioned, one of the key new subsystems in this platform is the advanced EPS flying for first time in GOMX-4. For this reason, its behaviour has been closely tracked and the different features were activated and verified before any payload activation.

The input modules, or ACUs, it shows an adequate level of input voltage and input current in all its 6 channels matching the sun angle given by the coarse sun sensor telemetry. Additionally, the Maximum Power Point Tracking (MPPT) mode was also activated increasing the input power as expected.
The battery voltage and current discharge validated the estimated power budget of the mission and they have kept very stable and within the expected ranges.
The two output modules, or PDUs, also indicated good functionality of the system. All the independent protected output channels were tested with good responsive results. The PDU power channel latch-up protection was validated during the ADCS reaction wheel commissioning, where a planned sequence of events would exceed the current limit on the PDU power channel supplying the reactions wheels.

Both external and internal temperatures in the different components of the satellites kept within expected ranges.
The internal temperatures oscillate between -8°C and +26°C in average keeping the components in the bus (OBC, UHF radio, ADCS computer, batteries and EPS modules) at very similar temperature between +14°C and +25°C and having the bigger temperature range for the sensors and actuators.
The external temperatures oscillate between -30°C and +40°C within the range of the solar panels, coarse sun sensors and fine sun sensors.
During the operations phase, the temperature shall be monitored for the different payload operational modes paying special attention to the HyperScout operational mode which is the scenario with biggest amount of released heat.

5.3 ADCS commissioning

For the GOMX-4 mission, the following ADCS features have been implemented and in-orbit verified:

- **Detumbling**: Immediately following the satellites release from the launcher, the detumbling mode was automatically activated, decreasing the spin rate in every axis to less than 1 deg/s within the first 4 orbits.
- **3-axis pointing commissioning**: With the satellite detumbled, the 4 reaction wheels were activated in both satellites performing 3-axis pointing. In this configuration using the ground calibration, different telemetry over few days was collected to evaluate the performance versus the final in-orbit calibration configuration.
- **Drag management commissioning**: The difference in altitude from both satellites drove an initial drift of around 50 Km of separation increase per day in the along-track direction. This effect was decelerated by using drag management to apply maximum drag pointing in GOMX-4A versus minimum drag pointing in GOMX-4B to equilibrate as fast as possible the orbit altitude between both satellites. Further explanation and details are provided in section 6.
- **In-orbit ADCS calibration**: To improve the ADCS performance for the specific orbit environment, GomSpace applies a variety of techniques[3][4][5] to calibrate the in-orbit response of the sensors in terms of temperature, scale and offset noises and correct the albedo effect empirically from analysis of extensive telemetry sampling. Additionally, the inertia matrix and magnetic dipole are also recalculated in-orbit to adapt the response of the system.
- **Calibrated 3-axis pointing commissioning**: After calibrating and adjusting the response of the sensors and actuators in the satellites reducing the noise in their signals, the 3-axis pointing modes have been tested and its performance analysed.
- **Nominal ADCS commissioning**: The final step in the ADCS commissioning of the GOMX-4 mission is to activate the autonomous software which executes detumbling and pointing modes based on the sensor inputs or the operations under execution. Therefore, the satellites

are fully capable to migrate from detumbling to nominal pointing and also to initiate the ground station tracking for HSL operation or specific payload pointing.

After the GOMX-4 ADCS full commissioning, the obtained telemetry shows an average determination error AKE (1 sigma) of 0.5 degrees in Sun and 3 degrees in total orbit which is the expected performance without the use of the star tracker as part of the nominal ADCS. The 3-axis pointing mode shows maximum Absolute Knowledge Error (AKE) of 1 degree in Sun and around 3 degrees in average within the orbit. The absolute performance error (APE) 1 sigma is estimated as 0.3 degrees in average.

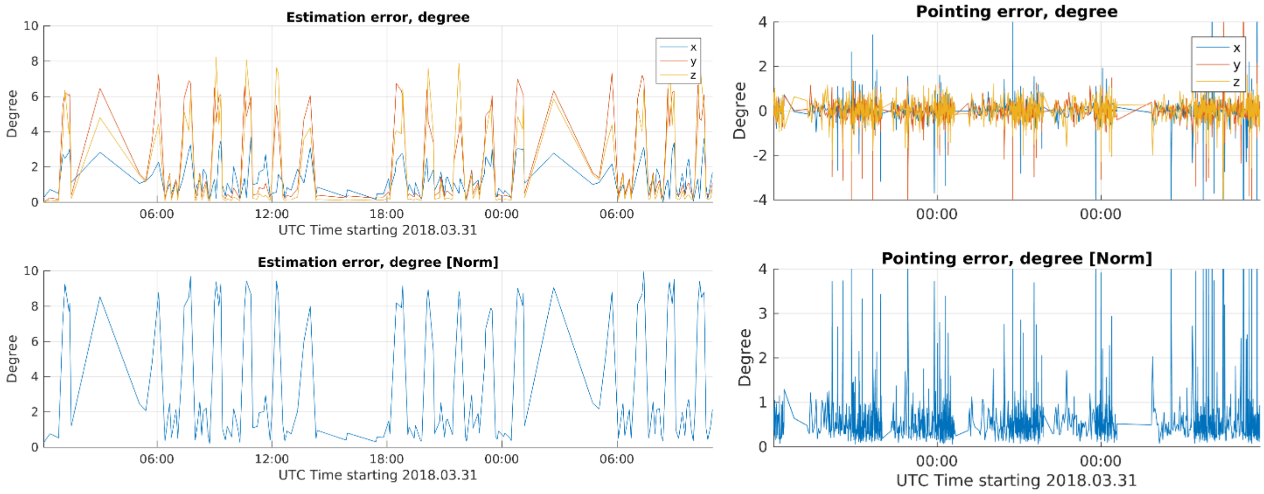

Figure 8. Representative plots of the GOMX-4 ADCS performance during LEOP phase: AKE (on the left) and APE (on the right).

6 ORBIT CONTROL

As it has been mentioned, the satellite GOMX-4B was released from the launcher 28 seconds after GOMX-4A with an insertion orbit altitude 320 meters lower than the first satellite. This caused a drift in both satellites of around 50 Km of separation distance per day.
This separation trend was decelerated by drag management on 25th February when GOMX-4B was around 350 meters below GOMX-4A. Then, GOMX-4A was changed to high drag attitude facing ram at around 900 cm^2 surface area and GOMX-4B was kept flying in low drag or ram attitude with 250 cm^2 surface area in the velocity direction. This configuration introduced a slow trend to equal the orbit altitude in both satellites decelerating the separation drift but several months would have been required to equal the orbit altitude, without using the propulsion system.

This scenario was kept until 13th March when GOMX-4A and GOMX-4B reached a maximum separation distance of around 2000 Km. Then, a propulsion maneuver was performed using the NanoSpace 6U propulsion module where it is proven in Space for first time.

On 13th March, the propulsion module was commissioned checking its health and performing an initial burn of 1 minute using all 4 thrusters to check the adequate response analysing the orbit altitude increase from the GPS telemetry and the TLE update.
After a successful result from the first short burn, the prograde manoeuvre was completed firing the 4 thrusters at 4 mN for 9 minutes and 40 seconds as simulations predicted using GMAT. This drove

GOMX-4B to an orbit with a Semi-Major Axis (SMA) around 350 meters above GOMX-4A with a behaviour similar to the predictions.

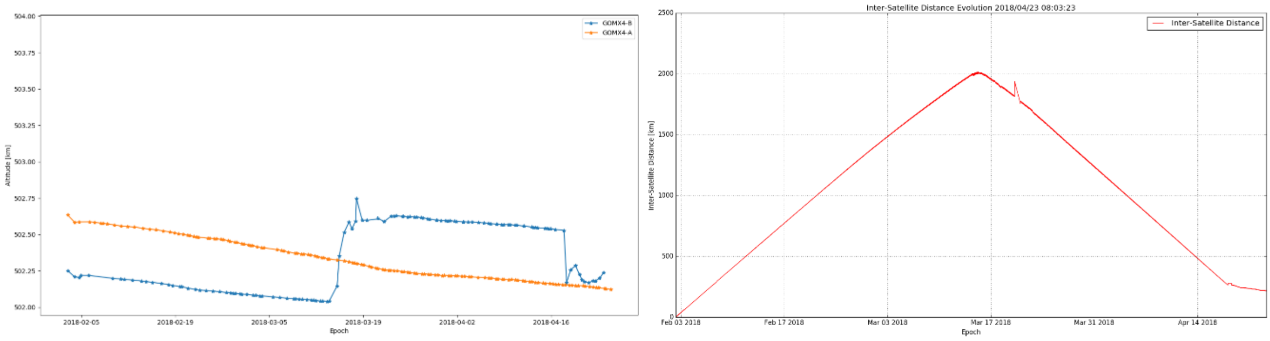

Figure 9. Graphics of the orbit altitude for GOMX-4A and GOMX-4B (on the left) and separation distance evolution by TLE data (on the right) during the first 2 months in-orbit.

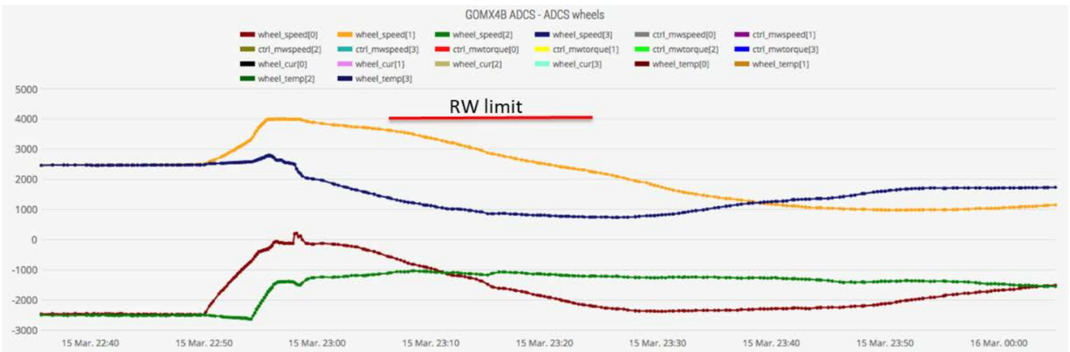

Figure 10. Telemetry from the GOMX-4B reaction wheels during the fourth burning.

It must be noticed than the total propulsion manoeuvre of 10 minutes and 40 seconds was split in 4 different burns. The first one of 1 minute of duration was intended to commission the 4 thrusters checking its in-orbit effectiveness. The other 3 burning steps were sequenced to avoid possible saturation of the reaction wheels, split in 2 burns of 3 minutes and a fourth one of 3 minutes and 40 seconds of duration.

The ADCS implements a mechanism of counteract the disturbances caused by the propulsion module using the reaction wheels and this ensures the satellite is under control even under an undesired torque. The limit of the reaction wheels before saturation is 4000 RPM and, as it is showed in figure 10, one of the wheels reached this limit during the last burning step. As conclusion, the safety limit identified to avoid this effect of saturation is burning for no longer than 3 minutes and the firings shall be split in several steps producing the same orbit change as a similar single burn with minor risk in the satellite control.

During the passes on 17th April 2018 when the satellites were separated approximately around 250 Km, the corresponding retrograde manoeuvre was performed burning the 4 thrusters during around 7 minutes. The results are showed in the figure 9 where it is possible to check how both satellites finished with same altitude orbit and around 250 Km of separation distance.

7 PAYLOAD COMMISSIONING

7.1 S-band radio for High Speed Link and Inter-Satellite Link

Both GOMX-4 satellites include S-band capabilities based on the GomSpace Software Defined Radio to perform High Speed Link (HSL) communications with ground and Inter-Satellite Link (ISL) communications.
After 3 weeks in-orbit, the HSL was successfully commissioned showing a minimum elevation to close the link budget between 10 to 17 degrees depending on the direction of the communication window to the GomSpace ground station in Aalborg. The transmission power used until now is 0.7W and datarate 1Mbps increasing the data download capacities in the satellites and serving the payloads in their commissioning.
Regarding the ISL, its commissioning took place after 2 months, once the satellites were under orbit control and separated by 750 Km. The transmission power and datarate used for the first ISL test were similar to the HSL.

During the operation phase of the present mission, a variety of datarate, transmission power and separation distances of the satellite shall be tested characterizing the link and the capabilities to form a constellation, minimizing the latency of data acquisition.

7.2 NanoCam (GOMX-4A)

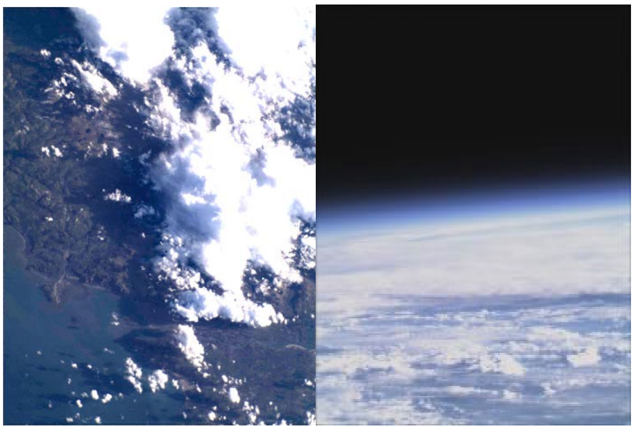

Figure 11. Photos taken from the NanoCam in GOMX-4A during its commissioning.

GOMX-4A includes on-board the miniaturized imaging system NanoCam providing photos of 2048 x 1536 pixels.

The camera was commissioned after 3 weeks from the launch date showing a positive response, healthy behavior and good quality images.

This camera shall be further used to characterize its performance at day and night and to support the monitoring of the artic area.

7.3 ADS-B receiver payload (GOMX-4A)

GOMX-4A includes the same ADS-B receiver already successfully proven in GOMX-3 as one of the primary payloads, the NanoCom ADS-B. The ADS-B antenna is a new patch element developed and proven during this mission to optimize the data capturing with low pointing requirements.

This ADS-B receiver payload was successfully commissioned on 28th February, activating the system in a communication window above Aalborg Ground Station. During the 2 minutes it was active, the payload captured 772529 valid frames and 309 planes were detected.

Figure 12. Graphic representation of the first 14 planes tracked by GOMX-4A during its commissioning.

7.4 AIS receiver payload (GOMX-4A)

The other primary payload in GOMX-4A is the AIS receiver intended to monitor shipborne tracking signals around the artic. It uses the flight proven QubeAIS system from Satlab together with a new VHF deployable antenna design optimized for 6U or larger platforms.

The AIS receiver was commissioned on 1st March collecting data during 1 orbit, approximately 1,5 hours. It captured 3100 valid AIS messages in the low populated areas identifying a large number of ships.

The AIS data collection, together with the ADS-B data, are the key element in the monitoring of the artic region where the density of ground tracking stations is low.

Figure 13. Graphic representation of 41 of the ships identified by the AIS receiver in GOMX-4A during its commissioning.

7.5 Chimera board payload (GOMX-4B)

The Chimera board is an experimental board where several ceramic memories are accommodated and monitored to address their behavior in space radiative environment measuring single events and possible anomalies.

This payload was commissioned on 10th February for 1 orbit and on 2nd April for 6 orbits showing a good nominal behavior and sending the corresponding status and data packages to the OBC for its transfer to ground.

During its first commissioning, a latch event was detected on the two output lines, 3v3 and 5v, and an underestimation of the in-orbit residual current of the line concluded the protection current limits of both channels must be increased. In the second test, the 5V output line presented a new latch-up event during its powered on probably due to the uncertainties in the peak current consumption when all the memories included in the board are activated simultaneously.

Figure 14. Photography of the FM Chimera board included in GOMX-4B.

This event will be further tracked and analyzed during the mission to ensure no inconveniences in its normal operations.

7.6 Hyperscout camera payload (GOMX-4B)

The HyperScout camera payload is a hyperspectral camera developed by Cosine to be in-orbit demonstrated in the present mission.

The HyperScout payload commissioning was performed on 20th March capturing a photo above Scotland and download it a small part of the photo fitting within a pass with a size smaller than 2 MB.
The results were good, but the downloaded part was offset from the target one and, by this reason, the same test was performed with a correction of the images parameters capturing a second photo above Cuba.
Nominal behavior and telemetry as expected, and the offset was confirmed to be corrected.

7.7 Star tracker payload (GOMX-4B)

The Star Tracker payload is an attitude determination sensor developed by ISIS to be in-orbit demonstrated and used for the first time for high accuracy pointing in nanosatellites during this mission.
Its commissioning took place divided in three steps:

- First step performing the brief hardware health check.
- Second step monitoring telemetry and parameters during 1 orbit.
- Third step capturing a photo of the stars checking the functionality of the optical parts.

The steps were performed successfully, and the payload was found healthy and ready to start its operations.

8 OPERATIONS PHASE

After concluding the LEOP phase of both satellites, the operations phase takes place with the exploitation of the payloads and the constellation maintenance.

During that, GOMX-4A is operated from the operations control centre testing the ADS-B and AIS data capture and customer deliver. In addition, several pictures shall be scheduled and taken around the globe optimizing the image capturing of the on-board camera.

Regarding to GOMX-4B, the operations phase includes 6 months splits in several time slots where every payload shall be used to perform calibration, experiments and analyse its performance in-orbit. In first phase, the Inter-Satellite Link (ISL) experiments shall be carried out at intervals in separation distances between 300 Km up to 2000 Km using the propulsion for relative orbit control. Then, the different secondary payload shall be operated within around 2 months and half to conclude the long-distance use of ISL and relative orbit control and allowing extra margin for combined tests with several payloads or further experiments.
As exceptional case, the Chimera payload which is intended to be constantly powered on collecting and transmitting data to the Ground unless an unexpected situation is found.

9 CHALLENGUES AND CONCLUSIONS

The GOMX-4 mission is a pioneer in Europe to de-risk miniaturized technologies and deployment/maintenance of future operational constellation systems based on nanosatellites.

The successful results presented here from the LEOP and commissioning phase has demonstrated the feasibility of advanced nanosatellites platform to fly in constellation geometries and accommodate complex payloads at the same time.
The main highlights of the present mission are based on the use of the GomSpace 6U platform for first time, specially the new EPS NanoPower P60 and the complex AOCS system showing an excellent performance. This is a big achievement in the nanosatellites sector where the same platform

can be used for constellations, communication or Earth observation applications with minor customization reducing the cost of a mission.

On the other hand, the Software Defined Radio technology is demonstrating in this mission further capabilities and the opportunities it can provide for advanced communications.

The LEOP and operations are challenging the capabilities and need of nanosatellites operations since high coordination between the two satellites and the dedicated experiments in each one is required. In addition, the access time is also limited during short separation distance test due to the constraint of sharing the same main ground station located in Aalborg for both satellites.

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