GOMX-4 – the twin European mission for IOD purposes

Laura León Pérez, Per Koch
GOMSpace A/S
GomSpace Headquarters, Langagervej 6, 9220 – Aalborg East, Denmark; T +45 2391 8498
llp@gomspace.com

Roger Walker
EUROPEAN SPACE AGENCY (ESA)
ESTEC, Keplerlaan 1, NL-2200 AG Noordwijk, The Netherlands; T +31 71 565 3349
roger.walker@esa.int

ABSTRACT

The next generation of nanosatellites in GomSpace has been developed after the success of GOMX-3 in aircraft traffic monitoring and L-band communications. GOMX-4 is the demonstration mission of this new 6U platform including two satellites; GOMX-4A and GOMX-4B, which are mainly intended to test constellation capabilities for orbital control and inter-satellite communications together with additional innovative technologies.

GOMX-4B is funded by ESA for In-Orbit Demonstration (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 Defense Acquisition and Logistics Organization (DALO).

The numerous in-orbit experiments and various payloads included in the GOMX-4 mission show the high performance and flexibility of the GomSpace 6U platform, flying its advanced EPS and its AOCS for the first time.

The two satellites were launched on the 2nd of February 2018 on a LM-2D. The in-orbit results presented here show the extensive capabilities of these innovative nanosatellites, and opens the path for scaling to larger platforms and advanced constellations with compact communication and optical payloads.

INTRODUCTION

With an exponential increase of the interest in nanosatellite mission from the space community and potential users, the requested capabilities for CubeSat platforms are naturally growing. In this context, the market is trending to offer services covering the globe with minimum data latency.

For this purpose, nanosatellite constellations are highly demanded together with advanced capacities for power supply, orbit control and communication schemes.

GOMX-4 mission is the constellation precursor project for further Inter-Satellite Link (ISL) and orbit control operations between several satellites.

GOMX-4 MISSION GOALS

The GOMX-4 mission consists in two nanosatellites flying in Sun Synchronous Orbit at around 500 Km of altitude during a lifetime between 3 and 5 years. They will perform several experiments and images/data collection around the globe, streaming them daily to the primary ground station located in Aalborg.

Figure 1: Inter-Satellite Link communication and constellation architecture demonstrated in GOMX-4.

Figure 2: GOMX-4 mission simulation for data collection above the Artic region and ISL transmission.

As primary capacity to be demonstrated, one satellite captures data from a certain targeted region and it is transmitted to the second satellite while it is under ground station coverage using the ISL. The ISL shall be
characterized in inter-satellite distances from approximately 200 km up to line of sight, around 4500 km, using different data rates and transmission power.

During these operations, the relative separation and station keeping between the two satellites in-orbit is controlled by propulsive maneuvers from one of the satellites, GOMX-4B.

The concept of the coordinated operations between the two GOMX-4 satellites is directly extrapolated to constellations with satellites distributed in same and different planes to collect or transmit data with minimum latency between space and ground segments.

GOMX-4 SATELLITES DESIGN

The GOMX-4 satellites are 6U standard CubeSats with the same platform components and different payload technologies. The satellites, called GOMX-4A and GOMX-4B, are intended respectively for data and images collection for the DALO (The Danish Defence Acquisition and Logistics Organization) and for technology demonstration for the European Space Agency (ESA).

Both satellites apply the same architecture based on the GomSpace 6U platform with only different hardware configuration. One of the main new subsystems is the NanoPower P60, a modular EPS with independent input and output modules connected to a dock allowing various input and output channels with protected and configurable power channels. On the other hand, the ADCS subsystem on-board is an upgraded version for large cubesat sizes using powerful reaction wheels, external gyro sensor and adapted to integrate different star tracker technologies, in addition to the magnetorquer, sun sensors and magnetometer successfully used in previous missions. The space-ground communication capacity of both satellites are improved by the use of High Speed Link in S-band which supports the nominal UHF communication link for uplink and downlink.

On top of these highly capable internal subsystems, this platform allows different external configurations including various antennas, sensors, solar panels, radiation shields and radiative surfaces customized to the satellite only changing the mounting plate. In this way, the external components of the 6U platform are directly scalable to even larger platform or different structures by only mechanical customization.

GOMX-4A layout

The GOMX-4A satellite accommodates the AIS and ADS-B flight proven receivers together with the 3 Mpx camera. These instruments operate to monitor regions of interest, like the Arctic area, where the ships and planes information is scarce, commonly determined by estimations about the captured data in populated regions.

For the ISL operations, the satellite includes two patch antennas in every 2U end and the GomSpace Software Defined Radio (SDR) implementing two innovative modulation skills for short and long distances. Under large distances, the required transmission power to close the link budget exceed the maximum Power Flux Density (PFD) allowed by ITU regulations. By this reason, for inter-satellite distances above 600 Km, the Direct Spread Spectrum architecture is used in the satellites reducing the power transmitted measured in a 4 kHz bandwidth in which the PFD is defined.

The GOMX-4A satellite includes three stacks of dummy masses to compensate for the mass different regarding to GOMX-4B, facilitating the similar dynamics and deorbit behavior for longer operations.
**GOMX-4B layout**

GOMX-4B is the demonstrator satellite for orbit control maneuver based on the cold-gas 6U propulsion module from NanoSpace. The propellant is sized with around 120 grams of butane, intended to compensate differences in orbit altitude from the launch, to control the inter-satellite distances in short time, to perform station keeping and to avoid potential risk collision if needed.

The ISL payload is identical than the GOMX-4A one except in the use of only one patch antenna in the opposite 2U end of the propulsion module.

![GOMX-4B internal layout](image)

**Figure 5: GOMX-4B internal layout.**

Additionally, this satellite also includes three payloads for technology demonstration: the Chimera board by ESA to analyze COTS memory behavior under radiative space environment, the HyperScout camera from Cosine for hyperspectral images and the Star Tracker from ISIS for high accuracy attitude determination.

Since the technology demonstration phase of GOMX-4B is planned for 6 months, an extra transceiver in the Software Defined Radio for ISL operations is included to extend the lifetime of this satellite by ADS-B data acquisition for commercial purposes.

**Platform commissioning**

![Photo of the GomSpace 6U platform and payloads during the GOMX-4A integration](image)

**Figure 6: Photo of the GomSpace 6U platform and payloads during the GOMX-4A integration.**

All platform subsystems of GOMX-4A and GOMX-4B were commissioned during the first 3 weeks of operations. There, the on-board computer (NanoMind A3200), the two ground communication links for UHF and S-band (NanoCom AX100 and NanoCom SR2000) and the power subsystem (NanoPower P60) were tracked while performing optimum behavior in any of their different modes and software features.

In the same way, every component of the attitude determination and control subsystem was activated and characterized to proceed with the in-orbit calibration and pointing accuracy determination during the 4 weeks after.

Between the main achievements from the 6U platform components commissioning, it is possible to highlight the optimum Maximum Power Point Tracking mode of the NanoPower P60 which allows to gain around 20% of the input power optimizing the peak voltage and the S-band link with ground station which is successfully established even in elevations below 20 degrees.

**LAUNCH AND EARLY ORBIT PHASE (LEOP)**

The two satellites were successfully contacted from the ground station for first time 6 h and 18 minutes after the launch. This corresponded with the second pass above the ground station since communication could not be established during the first pass due to a combination of very low inclination and inaccurate TLE.

During the first days of in-orbit operations, the main functionalities of both satellites were checked, alternating every step from one satellite to the other one. This ensured the control and health of both simultaneously, but it penalized the progress in the commissioning phase which shall be improved for future constellations by ground station redundancy.
ATTITUDE & ORBIT CONTROL

After 6 weeks of commissioning operations and with the ADCS in-orbit calibrated, the propulsion payload was commissioned to perform orbit control of the GOMX-4B satellite.

![Figure 7: GOMX-4 satellites altitude and distance evolution from TLE within the first 4 month of operations.](image)

The figure 7 shows the orbit altitude and inter-satellite distance of the two GOMX-4 satellites identifying the following relevant changes:

Step 0.- Initial deployment of the two satellites from the launcher, releasing GOMX-4B 30 seconds after GOMX-4A. This sequence placed GOMX-4B in an orbit 340 meters below GOMX-4A causing a fast drift between the satellites of around 60 Km separation increase per day.

Step 1.- The Propulsion module commissioning and the first maneuver to correct the initial drift was split in three steps. Firstly, the system health was checked by activation and telemetry tracking and, then, first short prograde burning of all the thrusters during 1 minute of duration evaluating the orbit change. Once the satellite raised its orbit altitude as expected, the thrusters were burnt for the rest of 9 minutes and 10 seconds until the satellite reached an altitude 350 meters above GOMX-4A. This reversed the drift of the satellites targeting between 250 and 300 Km of separation distance in 1-month timeframe for the operations phase. During this month, payloads were commissioned, and the In-Orbit Commissioning Review was performed for the operations kick-off.

Step 2.- The corresponding retrograde burning was performed burning the thrusters during 7 minutes until GOMX-4B reached similar altitude than GOMX-4A within an accuracy between 150 and 50 meters according to the TLEs.

Step 3.- The altitude difference within the achieved accuracy of the maneuver caused a slow drift of the satellites towards one other. At this point, the satellites decreased their separation distance until GOMX-4A passed GOMX-4B allowing the use of ISL without changing the nominal RAM attitude due to the advantage of 2 ISL patch antennas included in GOMX-4A.

Step 4.- After reaching the minimum inter-satellite distance, a new prograde maneuver was performed burning for 3 minutes and 24 seconds to raise GOMX-4B around 300 meters above GOMX-4A. This maneuver was planned to set the initial separation distance and drift for the ISL experiments in the first phase of payloads operations.

Step 5.- The mission operations phase starts with a separation rate of around 35 Km per day to perform the first phase of ISL tests, evaluating the link from 250 Km up to 1500 Km within 1-month timeframe.

The use of this 6U propulsion module for first time has showed very successful results with a good orbit control and high accuracy in the reached total thrust. The satellite behavior shows very similar response than the simulations performed with GMAT.

One of the main lessons learned about these propulsion maneuvers is the saturation of the reaction wheels at 4000 rpm which has been reached during firing longer than 3.5 minutes. Therefore, all the burning performed in this mission has been split in several consecutive steps of less than that duration until the desired total burning time and targeted orbit is reached.

On the other hand, the accuracy of more than 50 meters for the propulsion maneuvers could be improved using the GPS signal, which was used only during the first prograde maneuver (step 1) for payload evaluation. After the competition of the first phase of ISL testing, the propulsion module will be used for station keeping with higher accuracy requirements where the GPS data will be added in the AOCS for a more accurate control.
PAYLOADS OPERATION RESULTS

Inter-Satellite Link operations

In coordination of the propulsion maneuvers for orbit control, the two satellites perform S-band communications between them as the main mission operation, to characterize the link within a variety of distances, data rates and transmission power. These results are directly applicable for constellation application where the minimum latency without increase in the number of ground station is the driving element.

The link budget depends on the pointing error reached which, for this mission, should be below 19 degrees which is the worst case scenario with both satellites pointing NADIR and not tracking to each other. The figure 8 shows the link margin within the targeted inter-satellite distances range establishing the link in the maximum targeted distance of 4500 Km with 2.4 kbit and a margin of 1.8 dB. Changing the pointing to ideal pointing (pointing error = 0) the calculation of the link margin for the same case show an increase to 3.3 dB which should ensure the success of the communication.

For this limitation, the ISL experiment is divided in two different phases: the short distance where the nominal QPSK modulation is used and the long distances above 600 Km where the Direct Spread Spectrum (DSS) modulation scheme is implemented reducing the impact of the RF power in the Earth surface.

During this first month of operations in the GOMX-4 mission, the short distance ISL payload had been tested using the nominal 0.5 W transmission power and varying the datarate from 100kBd up to 1250kBd under 500 Km of inter-satellite distances. Results are represented in the figure 10 showing the obtained Bit Error Rate (BER) in the various datarates used.

![Figure 10. In-orbit results from the ISL test at 500 Km showing the Bit Error Rate (BER) under the several datarates tested.](image)

This in-orbit experience and knowledge gained from the GOMX-4 mission address the link characterization and potential improvements for scaling to more advanced communication schemes and larger nanosatellite constellations.

Maritime and air traffic monitoring

As it was previously described, GOMX-4A includes ADS-B and AIS data collection capabilities based on the flight proven receivers, the NanoCom ADS-B and the QubeAIS. Both payloads are operating in a coordinating way to monitor planes and ships in remote areas where the current infrastructure does not allow to capture data and trajectories are only estimated.

The ADS-B payload was successfully commissioned on 28th February capturing 772529 valid frames and 309 detected planes during 2 minutes in a communication window above Aalborg Ground Station. Regarding to the AIS system, it was commissioned on 1st March collecting 3100 valid AIS messages and identifying several ships data during 1 orbit in low populated areas in South America. The identified planes and ships were correlated with the public databases, validating the information.
As it is showed in the figure 11, the GOMX-4A payloads are currently in full operational phase collecting data continuously in different predefined areas. In addition to the obtained data, the main added value of this demonstration is the in-orbit validation of operation automatization as well as the establishment of customer interface to adapt the operations and deliver the data satisfying the needs of clients.

**RGB Images**

The RGB camera on-board of GOMX-4A, the NanoCam 70mm, was commissioned 3 weeks after launch providing good quality images.

Once the full ADCS calibration was performed, the camera took several frames of different part of Denmark to verify its functionality and optimize the parameter selection. The camera can take pictures under different color values, brightness and exposure times depending on the conditions and purposes of the images.

**Radiation harness experiment**

One of the secondary payloads of GOMX-4B is a radiation harnessing board, called Chimera, developed by the European Space Agency. This payload is an electronics board following the PC104 standard employed in CubeSats with 12 computer flash memories from 4 different COTS types.

The board is continuously in operation mode during all the duty cycle, recording and transmitting the performance of those memories under space radiation. During its first two months of operations, no failures of the memories have been identified.

**Hyperspectral images**

GOMX-4B includes the first ever hyperspectral image capturing capabilities using the the HyperScout camera from Cosine in the Netherlands.

The camera was commissioned on 20th March by commanding an image captured above Scotland. The image was successfully captured but only a small part of it was downloaded to occupy less than 2 MB. The downloaded part was offset from the target one and, by this reason, a second similar test was performed above Cuba with a full image size to download.

The instrument shows nominal behavior and the images downloaded to date show a high quality of the instrument whose operation phase is on-going.
During the operations, the HyperScout camera is intended to demonstrate its full capacity of frames acquisition as well as perform several software compression and features to optimize its operations.

**Star Tracker characterization**

The Star Tracker secondary payload developed by Innovative Solutions In Space (ISIS) is being in-orbit demonstrated for first time during the GOMX-4B operations phase. This satellite is also ready to utilize this attitude determination sensor to improve the Absolute Knowledge Error (AKE) to around 30 arcseconds, and Absolute Performance Error (APE) to approximately 0.1 degrees of accuracy (1-sigma).

The payload was subjected to an early commissioning phase, checking the telemetry and health status during short and long period and capturing a photo of the stars. The results were successful, and the payload is now scheduled for further in-orbit operations which will characterize the attitude determination accuracy, the optical capacities to capture the dark sky and the sensor utilization under different spin rates.

**ADDITIONAL EXPERIMENTS**

For maximum advantage of the mission demonstration, additional experiments with secondary priority have been included in the GOMX-4 mission for direct application in coming missions.

**Validation of the new generation of GNSS receiver**

The GOMX-4A includes an extra GNSS receiver, the new OEM719 from Novatel, which is going to replace the flight proven previous version, the Novatel OEM615 also on-board the same satellite. Every of these GNSS on-board receivers has independent antenna and connection to the attitude control computer decoupling the responses of both devices.

The new GNSS receiver is verified in this mission by comparing its response versus the nominal receiver flying in nanosatellites missions for several years. The results would ensure the proper behavior of the device for use in future missions or it would raise the need of considering alternative solutions to the out of production device in case of not provided the desired performance.

This verification was performed on 6th March 2018 by data collection of the nominal OEM615 for an orbit before a communication pass, changing the active GNSS receiver during the pass to the new OEM719 and collecting same data from the new receiver also during an orbit.

The correlated data is showed in figure 15, representing the position error in meters of the two GPS signals regarding the TLE during those consecutives orbits separator by the communication pass above the ground station. During this test, a major number of points was collected for the OEM719 than the OEM615 for further evaluation of the new device and, by this reason, the density of both curves is different. The results show perfect continuity between the position error curves from the two devices, confirming similar behavior.

It should be noticed in the previous plot that the error value can not be taken to evaluate the performance of the receiver since the propagation of the TLE introduce different error values every orbit and only the smooth continuation of both curves with similar error trend can be considered for this validation.

After this validation, this new OEM719 is considered a redundant sensor for the nominal functionality of the satellite and it is ready to be used replacing the nominal one in case of need.

**External treatment impact in thermal behavior**

The growth of the capabilities of nanosatellites is causing an increase of the required power and, naturally, it also drives to increase the released heat to dissipate to space.
A good example of this situation is GOMX-4B which includes an operational mode to transfer data from the HyperScout payload to the S-band radio whose duty cycle must be limited by the amount of released heat to not exceed the temperature range of these components.

This is the motivation to perform an indirect experiment in this mission analyzing the different thermal response of two different coatings applied in external mechanical parts with diverse optical properties. Therefore, external mechanical components of GOMX-4A were chromate conversion coated and most of the corresponding ones in GOMX-4B were black anodized, giving different color to the satellites. Since both satellites are in similar orbit and they include same components for the 6U platform, it would be possible along the mission to operate them simultaneously with same dissipated heat by activating only the platform components and the corresponding temperature evolution would offer direct feedback about the effect of external treatment.

![Figure 16. Photo of the GOMX-4A (left) externally chromate conversion coated and GOMX-4B (right) externally black anodized.](image)

The two different coatings were thermally characterized by optical test. The results show values for absorptance and emissivity of 0.71 and 0.84 respectively for the black anodization applied in GOMX-4B while the chromate conversion coated in GOMX-4A shows 0.46 and 0.25.

![Figure 17. GOMX-4B external temperature distribution during no payload operational mode.](image)

Currently, the early results from external temperatures distribution measured in the coarse and fine sun sensors shows an average temperature difference of GOMX-4B around 10 degrees colder than GOMX-4A. However, further analysis must be performed for detailed conclusions since, due to main operations constraints, the temperatures are measured under same operational mode but different attitude, with GOMX-4B in RAM attitude and GOMX-4A in 30 degrees canted RAM.

In any case, it is clear that the externally black anodized satellite trends to a few degrees colder average temperature as it was predicted by thermal simulations.

**CHALLENGES AND CONCLUSIONS**

The in-orbit results and experience from the GOMX-4 mission are a very relevant driver to increase maturity of miniaturized space technologies and to run future nanosatellite constellations in Europe.

This experience is also showing the complexity and challenges to solve for up-scaled missions coordinating a large number of satellites. In this regard, some of the main lessons under learning and improving process are:

- **Optimization of the verification processes** is one of the biggest challenges found in nanosatellites missions. For GOMX-4, the Proto-Flight Model approach introduced an additional complexity and risk for environmental and functional test campaigns, but it also reduced cost and time to develop the mission. This approach was possible by identifying good balance in testing and levels to minimize the risks ensuring the proper and safe quality for the flight. At the same time, the availability of a flatsat with the core platform components and payload models allows to test software and updates during development and in-orbit operations in parallel. This subject is an open process subjected to improvement from the missions.
and adding the main identified tests which could have helped and accelerated the AIV phase and operations.

- First days after launch involve high complexity due to lack of accurate TLE until a later stage and the criticality of the activities to carry out. This is driving to the more extensive use of the GPS device in an autonomous way to implement TLE computations for the space and ground segment. This solution involves higher complexity of the first passes management, increasing the initial power consumption of the system and the complexity of the autonomous satellite in-orbit deployment phase.

- Sharing a ground station for both satellites under same frequencies challenged the utilization of the passes, especially during the LEOP when contacting with both satellites as simultaneous as possible was a key factor to minimize the waiting time for operations. This challenge can be addressed in the next missions by automating the main initial functions and the change of the satellite operations to communicate reducing the needed time for manual actions or by use different frequencies for consecutive satellites adapting the ground station for this use.

- The schedule for communication windows can drive operation difficulties often coinciding with inconvenient night passes and, since it is determined by the launch conditions, they cannot always be selected for a convenient smooth mission. This was exactly the case of GOMX-4 mission experiencing the communication passes above the main ground station in Aalborg during afternoon and very late night due to the final launch parameters fixed for piggy-back satellites. For this case, the automatization of non-critical activities from the launch could help, for example, downloading autonomously during those inconvenient late passes the telemetry or data for ADCS in-orbit calibration or payload operations. In this direction, further optimization for day and night passes supported by automated functions from the ground station are under study and development.

- Operations procedures and training are being settled from this mission experience covering from the telecommands and telemetry actions up to the client interface for data delivery, which will give an important advantage especially in missions involving several satellites. This is one of the most relevant values for future commercial missions since it enables the full exploitation of nanosatellite services and constellations applications.

These on-going improvements and acquired knowledge during the GOMX-4 mission demonstrate its relevance in the nanosatellite sector in Europe. On the other hand, it also shows the importance of the in-orbit demonstration projects to establish by experience the required bases for commercial exploitation and professional use of CubeSats. They do not only show the feasibility of challenging technologies on-board these reduced-size satellites, they also allow to include additional secondary investigations to solve potential problems for the forthcoming nanosatellite generation.

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