RAPID RESULTS: THE GOMX-3 CUBESAT PATH TO ORBIT

Jesper A. Larsen(1), David Gerhardt(2), Morten Bisgaard(3), Lars Alminde(4), Roger Walker(5), Miguel Fernandez(6), Jean-Luc Issler(7)

(1)GomSpace ApS, Alfred Nobels Vej 21C, 1., 9220 Aalborg East, Denmark, jal@gomspace.com
(2)GomSpace ApS, Alfred Nobels Vej 21C, 1., 9220 Aalborg East, Denmark, dge@gomspace.com
(3)GomSpace ApS, Alfred Nobels Vej 21C, 1., 9220 Aalborg East, Denmark, bisgaard@gomspace.com
(4)GomSpace ApS, Alfred Nobels Vej 21C, 1., 9220 Aalborg East, Denmark, alminde@gomspace.com
(5)ESA/ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, Netherlands, Roger.Walker@esa.int
(6)Syrlinks, 28 Rue Robert Keller, ZAC des Champs Blancs, 35510 Cesson-Svign, France, miguel.fernandez@syrlinks.com
(7)CNES/DCT, Centre National d'Etudes Spatiales France, 18 Avenue Edouard Belin, 31401, Toulouse, France, jean-luc.issler@cnes.fr

Historically, nanosatellite developers do not have much time. Many missions must deliver with an accelerated schedule due to their status as secondary payloads driving toward fixed launch dates. Even if a launch is delayed, it is often too late for nanosatellites which have already been delivered. The short development cycles usually result in project schedules dominated by subsystem development, leaving little time for system-level testing or higher-level functionality that could be essential during operations (i.e. on-orbit reprogramming or calibration).

Danish sector leader GomSpace designed, built, and delivered the first European Space Agency In-Orbit Demonstration CubeSat in less than 1 year.

The GOMX-3 3U CubeSat deployed from the International Space Station on October 5, 2015. Just like its developers, GOMX-3 stayed busy after orbit insertion. After 24 hours on-orbit, the communication link was increased to 19.2 kbps to take advantage of the excellent communication capability. The helical ADS-B antenna was deployed on day 2 and began collecting thousands of aircraft positions each day. After 96 hours on orbit, the satellite entered 3-axis control, tracking earth nadir.

The satellite has been a success in terms of its planning, speed, and technical achievements. This paper presents a detailed review of the GOMX-3 design, development, on-orbit experiences, and lessons learnt with the European CubeSat community.

1. INTRODUCTION

Europe has come a long way in developing cubesat / nano-satellite capabilities since the launch of the first European cubesat, AAU-Cubesat, in 2003 [1]. The promise of nano-satellites is that of "faster, cheaper, and better".

Certainly there is evidence that nano-satellites have been developed faster and cheaper than traditional programs, but the "better" needs some definition of the point of view - a 3U CubeSat has not yet better astronomical imaging than the Hubble telescope, just as a 6U (even a 12U) has not yet taken on the task of radiating kW of power from GEO for TV transmission to 1/3 of the globe for 15 years.

The "better" for nano-satellites needs to be measured in Return on Invest (RoI) for the mission owner. For the institutional customers this could mean faster and cheaper cycles to test new technology or principles in space, for scientists this can come with the promise of using many nano-satellites to combine measurements from multiple points in space at the same time, and for the commercial market this could mean having the capability to deploy and scale a service quickly so the investment is not devaluated by cost of capital during the development phase.

Any of these metrics can only be met if the 'fast and cheap' spacecraft also delivers the data it is supposed to do. Simply closing the link to the ground station is no longer sufficient for mission success.

1.1. The GOMX-3 Mission Opportunity

As a consequence of the first Danish astronaut Andreas Mogensen going on a mission to the ISS in September 2015, the opportunity for GomSpace to deploy a 3U satellite from the ISS arose and was discussed with ESA. The project was defined to deliver:

- A new attitude-agile 3U platform
- Flight opportunities for novel radio payloads including a 2nd generation ADS-B receiver (GomSpace), Software Defined Radio platform for spectrum monitoring (GomSpace), and an X-band transmitter with its antenna (both Syrlinks, procured by CNES and ESA)
- Project implementation, test activities and documentation compliant to the ESA project management, engineering and product/quality assurance approach for "In Orbit Demonstration CubeSats"[2] including tailored ECSS standards

This challenging mission had the additional constraint of delivery in 12 months. This mission certainly presented a worth-while challenges to demonstrate the faster, cheaper and better promise in action!

1.2. How GOMX-3 did "better"

GomSpace met the challenge with success acting as mission prime delivering the GOMX-3 mission to ESA. Contributing factors to this, as will be described in detail, have been:

- Use of mature COTS components both in-house and some sourced from trusted partners
- Re-use of (updated) flight proven software from the GOMX-1 mission
- High degree of in-orbit reconfigurability and programmability allowing continuous in-orbit performance refinement

Further, the use of the ECSS IOD requirements provided an efficient framework for managing the project and the interaction with ESA in a constructive way. In fact, at GomSpace the IOD is now the baseline for most turn-key delivery projects based on this experience from GOMX-3.

Also very important for the project was the very efficient dialogue with both ESA and our subsystem partners (Syrlinks and Astrofein) in dealing constructively with challenges as they arose during the project implementation.

1.3. Paper Organization

The paper will at first discuss the various factors contributing to a successful project implementation in 12 months. Hereafter the mission, spacecraft design, and in-orbit results will be presented. Finally, lessons learned are presented. An image of the finalized GOMX-3 satellite in its deployed configuration can be seen in Figure 1.

2. REDUCING DEVELOPMENT TIME

The very rapid development and testing phase of GOMX-3 was successfully achieved due to a number of key factors. One element is to utilize primarily well tested in-house COTS components that each allow for a high degree of flexibility and have a low inter-system dependency level. Another element is to setup the entire satellite architecture to allow for of on-orbit adjustments of parameters, algorithms and entire software images.

2.1. COTS Components

One of the key factors to do more with less is to utilize the newer COTS components. Traditional satellites are built from special production runs of well proven and highly tested components, meaning that the technology is typically in the order of a decade old before flown. Opposite to this is the utilization of standard COTS components, which is used in most CubeSats. Component testing is usually limited to temperature, vibration, and total radiation dose of up to 20 kRad(Si), which is sufficient for a typical 2-3 years CubeSat mission in LEO.

The COTS components allows for very compact and power efficient designs, e.g. the TT&C radio system and the OBDH system in GOMX-3 are both credit card sized systems with a power consumption of less than a quarter of a watt in Rx mode and 150 mW for the OBDH running at 32 MHz.

2.2. Distributed architecture

The GOMX-3 satellite is built around a very distributed architecture, where each module is self-contained, and all communication with other modules is performed using the CSP protocol over the interfaces which the subsystem provides: I^2C, CAN or UART. This approach has two clear benefits: reduce the subsystem inter-dependency and standardize the communication ICD.

Figure 1: GOMX-3 in its fully deployed configuration.

2.2.1. Reduced subsystem inter-dependency

Each subsystem is self-contained, meaning all sub-system development and testing can be performed and validated independently of the development status of the rest of the satellites subsystems. It also has the added benefit that all processing trade-offs can be kept internally to the sub-system at hand and the external budget constraints are reduced to power, mass, and bandwidth. On a satellite level, this in turn reduces the system engineering load as there are very few inter-subsystem constraints which must be met.

2.2.2. Standardized communication ICD

All internal communication on the satellite, and between satellite and ground is performed using the Cubesat Space Protocol (CSP). CSP is a small, light-weight network-layer protocol designed with CubeSats in mind, with a very small memory footprint. The protocol has a simple Berkley sockets inspired API and supports both connection less and connection oriented operations supporting up to 32 devices with 64 ports on each device. The protocol is easily ported to different architectures, and within the GOMX-3 satellite it runs off Atmel AVR8 and Atmel AVR32 micro controllers under FreeRTOS as well as Atmel Cortex A9 processors running Linux. As CSP only specifies the network layer it can run on multiple physical layers, and within the GOMX-3 satellite it is running over CAN and I^2C. On the TT&C link the CSP packages are transmitted as well with an added encapsulation, and on the ground segment the CSP messages are distributed via TCP/IP. Hence, seen from a sub-system point of view, there is no difference if the communication is performed with the OBC, the COM-subsystem or the ground station. Here a ground station is simply a node on the network with periodic availability.

2.3. Parameter System

For any spacecraft it is important to be able to easily do in-flight configuration changes in a safe way. All GomSpace products are equipped with a method that allows the operator to adjust configuration data in orbit. For new systems this is done through a generic parameter system common to all subsystems. This system operates with a RAM and FRAM backend that allows robust non-volatile storage of parameters. This system also integrates with the watchdog system that allows for safe restoring of parameters in case of problems. The same generic system is also used for storing and downlinking of telemetry data.

2.3.1. Watch Dogs

In a GomSpace satellite, several different layers of watchdogs are implemented to safe-keep the integrity of the satellite operation. All subsystems have individual internal watchdogs to ensure their firmware is running properly. Furthermore, all critical subsystems have a configuration watchdog that is reset from ground. This ensures that if a problematic configuration has been set in a subsystem, it will automatically restore the old and trusted configuration after a certain period (typically 48 hours) without dedicated reset commands from the ground. Another layer of watchdogs are implemented in the power supply which monitors (pings) the individual subsystems over the networked communication bus and reboots them in case of problems. The power supply furthermore monitors the communication bus as a whole and if there is no activity over a length of time (10 minutes) the entire satellite is rebooted. Finally, the power supply as a critical system also has a configuration watchdog that not only will revert the power supply to a trusted configuration after 48 hours without ground contact, but will also perform a hardware reset of the entire satellite. The communications system will also revert to a low-rate, high link margin safe configuration after 48 hours without ground contact.

2.4. On-orbit Reprogramming

With the rapid development cycle testing time is often cut short which especially impacts the mission software testing as this is a major part of the final long term testing. It is therefore necessary for the satellite design to allow for mission software errors to show during the early operation phase and to have a robust setup in place to allow for upload of new firmware to advance the functionality of subsystems like the OBC and ADCS computers. This can be achieved by primarily focusing the available testing time on survival critical software elements as well as low level interfaces. With a reliable safe-mode and watch-dog system, higher level mission specific functionality can be allowed a lower testing priority as this can be adjusted in-orbit. The GomSpace software upload system is implemented with its own watch-dog system that can detect booting issued on the upload software images and default back to the launch software.

2.5. On-Orbit Calibration

An element that can take a substantial development/testing time is attitude determination and control system testing and calibration. Furthermore, to perform high-accuracy calibration of sensors and actuators on-ground often requires specialized laboratories that may not be readily available. Therefore, in order to save time in the testing phase, the ADCS for GOMX-3 was setup for easy on-orbit calibration. This allow for focusing tests on the basic hardware functionality and safe-mode ADCS (detumbling). During the LEOP phase, a number of experiments were performed to generate data for sensor calibration, actuator calibration and satellite parameter determination. For each experiment, a dataset is generated and downlinked as input to calibration and parameter estimation. On-ground and on-orbit parameters can then be adjusted accordingly.

2.6. In-the-Loop Testing

Another method for reducing testing time is extensive use of software-in-the-loop testing during system development. For example, during ADCS development all simulation is done with the flight code in-the–loop, which ensures a smooth transition from simulation to flight. Furthermore, as mentioned earlier, all GomSpace systems use a standardized command interface that is used both in subsystem checkout, satellite testing and on-orbit operations.

3. GOMX-3 SATELLITE

3.1. Mission

The GOMX-3 mission statement is as follows: "The GOMX-3 satellite will capitalize on a 2015 ISS launch opportunity by demonstrating advanced pointing while receiving both L-band and ADS-B signals." In practice, this mission was split into three key goals. First, GOMX-3 would demonstrate three-axis pointing to an accuracy of 2° or less. Second, GOMX-3 would provide aircraft position measurements via space-based ADS-B reception. Third, GOMX-3 would demonstrate new capabilities for software-defined radio payloads aboard nanosatellite platforms. During the Phase A/C study, the contract was revised to include support for a third-party X-band transmitter from Syrlinks. Taken together, these goals represent a highly advanced mission to be developed on a rapid timeline.

The achieved mission timeline is shown in Figure 2. As shown, the tested satellite was delivered about one year after the Phase A kickoff. This represents a significant reduction in satellite development time, even considering the accelerated pace of most CubeSat projects. The LEOP phase was concluded two months after deployment from the ISS with the successful completion of a In-Orbit Commissioning Review. The mission was deemed a full success after three months of full operational use. The operations continue in the extended mission of the satellite.

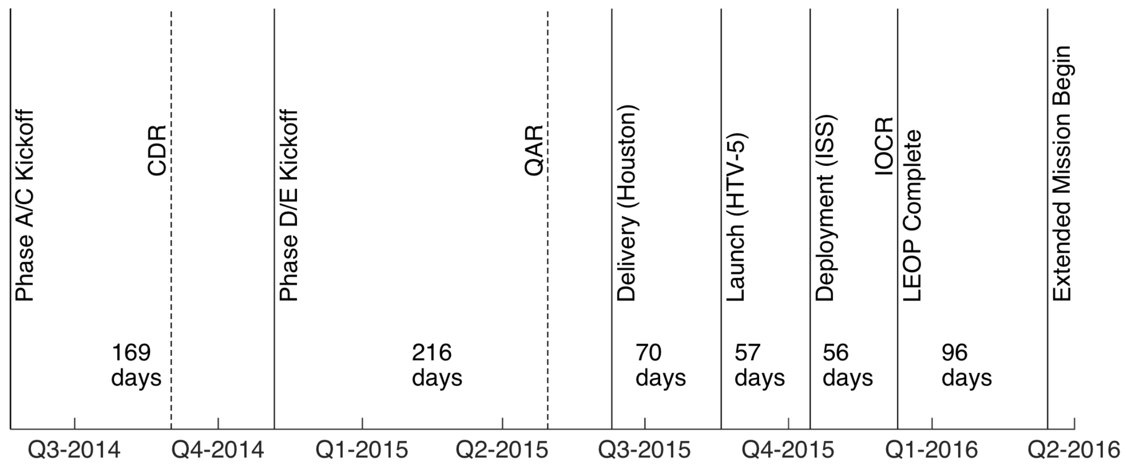

Figure 2: The GOMX-3 satellite followed an accelerated schedule, with delivery about 1 year after project kickoff.

3.2. System Design

GOMX-3 uses a 3U CubeSat form factor, which allows the use of many GomSpace COTS components designed to the PC/104 standard. This standard simplifies many of the mechanical and electrical interfaces of the satellite.

The overall satellite layout is shown in Figure 3. The bottom 1U of the satellite is dedicated to the OBC, COM, and EPS subsystems, while the middle 1U houses the ADCS, the ADS-B receiver, and the NanoCom SDR SOFT radio. The upper 1U contains the Xband transmitter and the further ADCS support hardware. Externally, the satellite uses interstage boards to mount the fine sun sensors and collect sensor data from the solar panels. Stack breakout boards are used to electrically connect the 1U stacks. Additionally, GOMX-3 uses five RF antennas mounted on various external faces.

The subsystems shown may be categorized into the bus and the payloads.

3.2.1. Bus

With reference to Figure 3 the following components are considered part of the bus (further description/datasheets are available for all GomSpace components [3]):

- **NanoPower P31us** is the EPS used on the GOMX-3 satellite. This EPS features regulated 3.3 V and 5.0 V power with 6 independently switchable latch-up protected outputs. It also provides MPPT on 3 independent input converters used by GOMX-3 to handle solar power input from 4 satellite faces. Finally, the EPS is responsible for the critical task of battery handling.
- **NanoPower BP4** is the battery pack used together with the EPS, consisting of 4 LiIon cells in series.
- **NanoMind A3200 OBC** is the OBDH, which is in charge of the flight planner and logging. The OBC also collects telemetry from the different subsystems in order to generate the house keeping beacons.
- **NanoCom AX100** is a UHF radio system used for commanding, telemetry, and payload data. It is a very flexible radio system, allowing for adjustment of frequency, bitrates and data encapsulation formats in orbit.
- **NanoDock DMC3** is a motherboard which is used to host the A3200 OBC and AX100 radio.
- **NanoMind A3200 ADCS** is an identical-hardware A3200 which is dedicated for ADCS operations. The computer is responsible for filtering the sensor data input (GOMX-3 uses magnetometers, fine & coarse sun sensors, and rate gyro), applying control laws (GOMX-3 uses a Sliding Mode Controller), and commanding actuators (GOMX-3 uses magnetorquers and 4× Astrofein RW-1 Reaction Wheels)
- **NovAtel OEM615 GNSS** is a card-sized GNSS receiver capable of determining the position of GOMX-3 using both the GPS and GALILEO constellations. Its associated antenna is located on the -Y/+Z interstage.

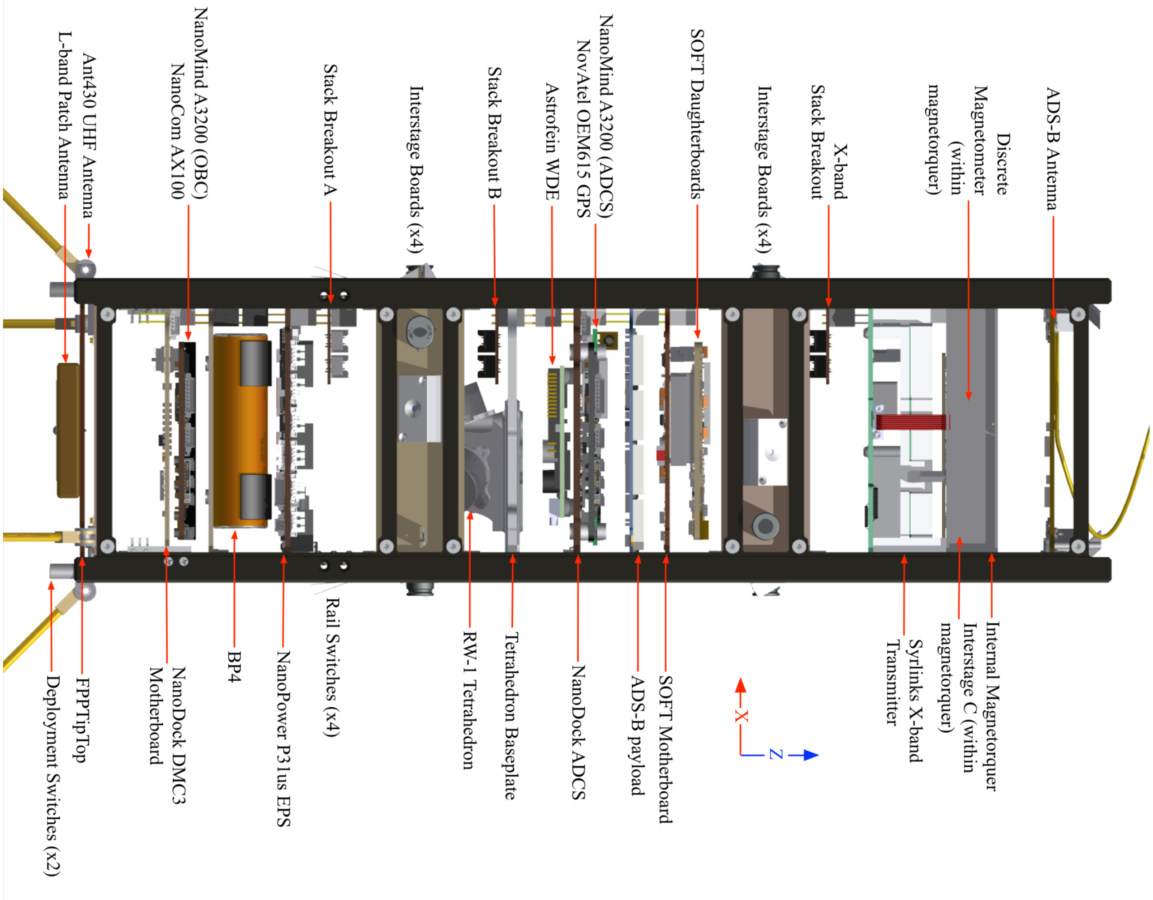

Figure 3: The GOMX-3 internal layout diagram, identifying the position of all hardware within the structure.

- **NanoDock ADCS** is a variation of the standard motherboard designed to house the OEM615 adjacent to a dedicated A3200 ADCS computer. It also provides the mechanical interface to a support board for the Astrofein RW-1 reaction wheels, as well as necessary power switches for the GPS and reaction wheels.

- **AstroFein RW-1** is ultra small reaction wheel from Astro assembled in a tetrahedron for redundancy. To drive the wheels, the Astrofein WDE driver board is used.

- **NanoCom Ant430** is the canted turnstile UHF antenna. the 4 antenna elements are in a stowed configuration during launch where they are folded down along the satellite body and restrained by a Dyneema wire.

- **NanoUtil Interstages** are small PCBs, which are mounted in the interstage area between solar panels, 8 in total. Each interstage holds Fine Sun Sensor (FSS), which provides a 2-axis sun vector measurement, and a release knife for the canted turnstile antenna elements. Each FSS is canted 30° to account for the impossibility of sensor placement on the ±Z faces.

3.2.2. Payloads

Again with reference to Figure 3, the following components are defined as payloads:

- **NanoCom ADS-B** is an update of the hardware which flew aboard GOMX-1 [4]. It has hardware and software updates designed to make it more resilient to single event upsets. GOMX-3 collects the ADS-B signals using a deployable helix antenna located on the body +Z face.

- **NanoCom SDR** (aka SOFT) is a software-defined radio built around the Xilinx Zync Z7030 FPGA. A single FPGA daughterboard may be augmented with up to 3 Front End Modules which may interface to multiple antennas each. GOMX-3 uses one Front End Module connected to an L-band patch antenna located on the -Z face of the satellite.

Figure 4: The GOMX-3 nanosatellite (center) was deployed from the ISS on 5 Oct 2015. Also visible is AAUSAT5 (bottom left) and the Nanoracks deployer assembly. Thanks to Astronaut Scott Kelly for images of the deployment event.

- **Syrlinks EWC27** is an Xband transmitter housed on GOMX-3. GOMX-3 uses this transmitter at a bitrate of 3 Mbit for its firt orbital testings, and uses a patch antenna located on the +Y face of the satellite. The NanoCom SDR provides the data interface which feeds the transmitter.

4. GOMX-3 OPERATIONS

GOMX-3 was launched from Japan aboard the HTV-5 on 19 Aug 2015; it successfully berthed to the ISS a few days later, 11 days before Andreas Mogensen arrived at the ISS. Unfortunately, Mogensen's time aboard the ISS was shortened as a consequence of a routine debris avoidance maneuver [5] and thus he did not have time to jettison GOMX-3 during his stay. Instead, GOMX-3 was deployed from the ISS on 5 Oct 2015. Astronaut Scott Kelly captured images of GOMX-3 and fellow satellite AAUSAT5 as they moved away from the ISS with a relative motion of about 1 m/s (see Figure 4). After deployment, the GOMX-3 operations phase began.

The first GOMX-3 pass proceeded as shown in Table 1. The first beacon was received just after GOMX-3 crossed the local horizon in Aalborg, Denmark; the telemetry showed a healthy satellite in all respects: strong beacons, full battery, and de-tumbled attitude. The satellite was commanded to downlink historical telemetry; after immediate reception this data also showed nominal satellite performance. The ground watchdog timers aboard EPS and COMM were reset, and the satellite clock was set via a timesync to the ground station.

Due to the near-ISS orbit of GOMX-3, its Aalborg, DK ground station has an average of 5.0 passes per day, with an average pass length of 7.4 minutes. Over the first 37 minutes of contact time, the activities described in Tables 1 and 2 were completed. The UHF antenna auto-deploy was disabled. The latest Two-Line Element (TLE) which is input to the satellite position propagator (SGP4) was uploaded to the satellite, as the satellite position is an external input to the Unscented Kalman Filter (UKF) used to determine the satellite attitude, which was also enabled during the first day. The SOFT payload was shortly checked out and found to be operational. As expected, the UHF radio link was strong, the team decided to increase the bitrate; first to 9.6 kbps then up to 19.2 kbps after receiving authorization from the International Amateur Radio Union (IARU). Finally, the satellite Bdot controller was disabled to collect free-floating data which was later used to calibrate the ADCS.

Table 1: The executed plan for the first pass of GOMX-3.

Step	Description
0	Ground station setup
1	Single beacon receive
2	Satellite telemetry health check
3	Command historical beacon downlink
4	Satellite telemetry health check
5	Reset watchdog timers
6	Timesync

Table 2: The executed plan for the remainder of the first day of GOMX-3 operations.

Step	Description
7	Disarm UHF antenna auto-deploy
8	Upload TLE
9	Enable SGP4 ephemeris mode
10	Enable UKF determination
11	Checkout SOFT payload
12	Increase COM link to 9600 bps
13	Increase COM link to 19200 bps
14	Enable ADCS free-floating mode

Thus, after the first 37 minutes of communication with the on-orbit satellite, the GOMX-3 bus was confirmed to be healthy in all aspects: power, communication, and attitude determination & control. This was made possible by designing for on-orbit operation, as well as careful planning and rehearsing of critical ground passes.

4.1. Payload Verification

The payload checkout was comprised of the same discrete steps as the bus checkout. The checkouts may be separated by the subsystem in question. The LEOP was concluded with a successful In-orbit Commissioning Review at ESA ESTEC on December 10, 2015. Further detail of the GOMX-3 LEOP phase is available in [6].

4.1.1. Advanced ADCS

Because of the advanced goals of GOMX-3, some degree of on-orbit calibration was required for the ADCS. The attitude determination (and thus also control system) relies on a variety of sensors uses as inputs: fine and coarse sun sensors, magnetometers, and a rate gyro. Each sensor was calibrated using a variety of techniques unique to each sensor [7], [8]. The satellite inertia matrix and magnetic dipole moment were also empirically determined by fitting to on-orbit data. This process took a period of about one month, as large datasets are sometimes necessary for calibration.

The UKF itself also requires tuning to ensure that its estimates of attitude uncertainty are in line with reality. This was performed using standard methods [9]. Figure 5 shows the attitude control and determination performance after calibration while flying in nadir-tracking mode. As shown, the satellite is capable of periods of 1° pointing (1-sigma), but suffers from worse performance when the orientation vectors (magnetic and sun) are close together or during eclipse, when the sun vector is lost entirely and the magnetometer and gyro are used to propagate the satellite attitude.

4.1.2. NanoCom ADS-B

After initial communication checks to the ADS-B receiver, the next step was deployment of the helix antenna designed for data collection at 1090 MHz. Immediately after antenna deployment, the satellite recorded its first ADS-B signals. To date, the ADS-B receiver has regularly collected thousands of plane positions per day and continues to operate nominally.

4.1.3. NanoCom SDR

The antenna used by the NanoCom SDR (SOFT) is designed to monitor signals in the L-band. On-orbit tests began by simply powering the device on and monitoring its behavior: temperatures remained within

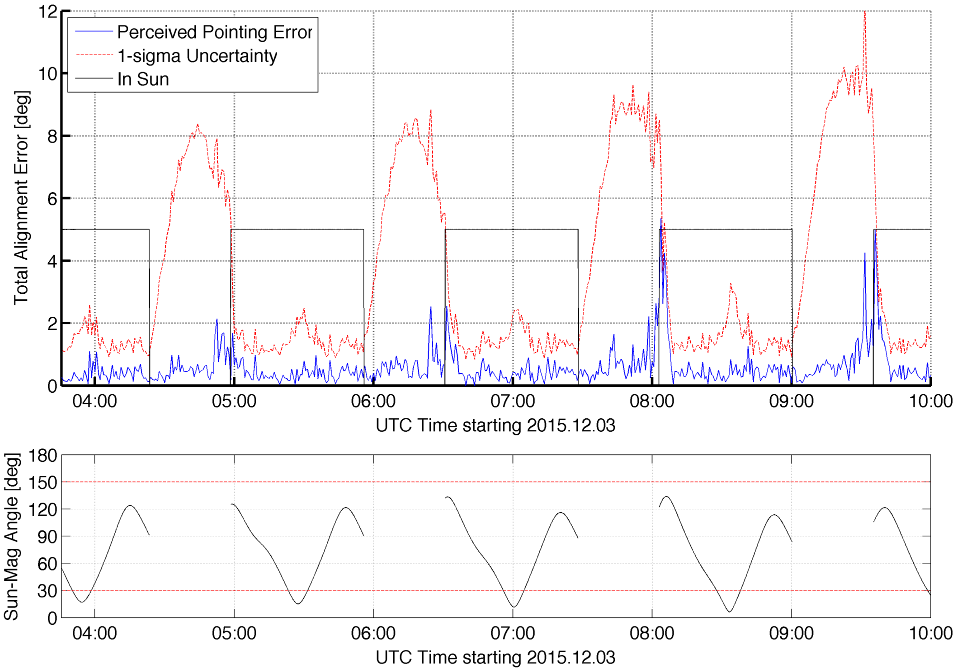

Figure 5: The GOMX-3 ADCS performance, as shown during a 6 hour dataset while operating in nadir-tracking mode. The attitude determination uncertainty bounds are 1-sigma (68%).

operational bounds. Next, the spectrum monitoring capabilities proceeded to monitor the UHF environment during GOMX-3 transmissions. With this sanity check complete, the system was proven by recording the spectrum in Lband, where signatures indicative of spot beams and global beams from communications satellites can be identified. An example of one orbit of Lband monitoring is shown in Figure 7.

4.1.4. Xband Transmitter

GOMX-3 hosts an experimental Syrlinks EWC27 Xband transmitter as a third-party payload [10]. SOFT provides the data stream which is modulated by the transmitter. The GOMX-3 Xband was tested using two CNES Xband ground stations located in Kourou, FG and Toulouse, FR. Over a period of 3 weeks, GomSpace supported 10 passes over Kourou. After a small software correction, GOMX-3 proved its ability to download multiple megabytes of onboard data during a single Xband pass over the Kourou ground station. In early 2016, GomSpace supported a second test campaign using a CNES Toulouse ground station. The Toulouse testing was aided by an increased ground station antenna beamwidth which is more forgiving of satellite position uncertainty inherent to the TLE/SGP4 combination. The Toulouse testing showed that 113 MB of verified data could be downlinked in a single 7 minute pass; this amounts to a total overhead of about 25%, which is quite acceptable considering the one-way nature of the communication.

4.2. Mission Success

Six months after the deployment from the ISS, GOMX-3 is still operational and has fulfilled all its mission requirements. Thus, it has been a complete mission success. It now continues operations in its extended mission. During this time, the satellite will be used to collect additional ADS-B data, for experimental ADCS testing, and for SOFT operations. The satellite is expected to remain in-orbit until November 2016, when atmospheric drag will bring it back to earth.

5. LESSONS LEARNED

As with any on-orbit satellite, there are a variety of lessons learned from the GOMX-3 project. These are itemized below:

- **Representative model is invaluable**: The GOMX-3 project included a qualification and test phase using an Engineering Qualification Model (EQM) of the satellite. The EQM is identical to the flight model of the satellite, which allows the flight model to undergo the (relatively) low stress of acceptance

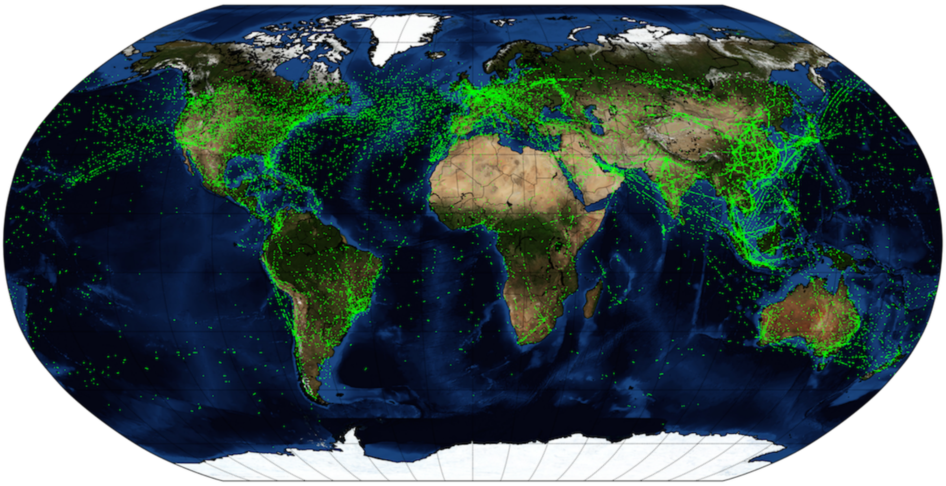

Figure 6: Global ADS-B data collected by GOMX-3. Each dot represents a plane location recorded by GOMX-3. Note that data collection is limited by the orbit inclination of about 52°.

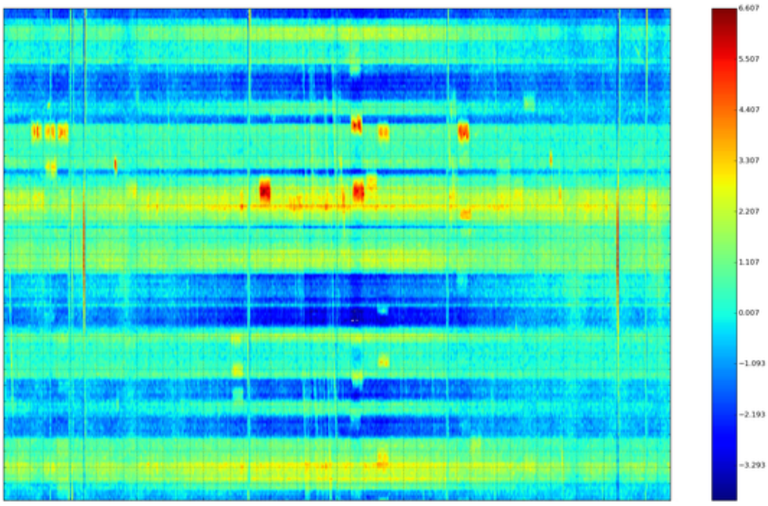

Figure 7: Single orbit L-band monitoring.

testing. However, the EQM is also useful as a software testbed before and after launch. Before delivery, the parallelized software development was especially important given the short time to delivery for the GOMX-3 project. After delivery, the EQM was used to develop the LEOP plan and quickly resolve on-orbit anomalies. Simply having hardware available greatly reduced the troubleshooting time and reduced risk to the on-orbit satellite by attempting fixes on the EQM first.

- **Easy review of telemetry is useful**: During the GOMX-3 mission, work was continued on a tool which was very helpful for operations of GOMX-1. This tool, called GSWeb, allows for automatic plotting and storage of both historic and realtime satellite telemetry. It maintains a database of all telemetry received from the satellite. Because it is browser-based, it allows multiple users to review various realtime data simultaneously. Before delivery, this tool was used to collect and review satellite housekeeping data throughout various tests. After delivery, this tool collected data from both the EQM and FM. The team has found that the easier it is to review satellite data, the quicker problems (and solutions) can be found.

- **Automatic data collection is helpful**: During the operations phase, the GomSpace ground station was augmented with a mission-specific autopilot to automatically request historical beacons from the satellite, which is helpful when considering long-term effects greater than a single 10 to 15 minute pass. The autopilot is especially useful when the passes occur outside normal work hours.

- **GomSpace methods save time**: The GOMX-3 mission proves that the time-saving methods used by GomSpace (and described in this paper) work in practice on a high-performance mission with short time to delivery. Short delivery times are a common problem in the nanosatellite world; trusted solutions to this problem are thus in high demand.

6. Acknowledgements

This work is supported by the European Space Agency under contract number RFP/NC/IPL-PTE/GLC/as/881.2014. The GOMX-3 team is grateful to our colleagues at GomSpace for their continual support and expertise in the development and operation of this nanosatellite.

[1] K. stergaard, L. Alminde, M. Bisgaard, D. Vinther, T. Viscor, The AAU-cubesat Student Satellite Project: Architectual Overview and Lessons Learnt, IFAC, 2004.

[2] IOD CubeSat Document Requirement Definition, TEC-SY/127/2013/DRD/RW.

[3] Products, `http://gomspace.com/index.php?p=products`, accessed: 2016-04-24.

[4] L. K. Alminde, K. Kaas, M. Bisgaard, J. Christiansen, D. Gerhardt, GOMX-1 Flight Experience and Air Traffic Monitoring Results, in: Small Sat Conference, 2014, pp. 1–7.

[5] Longer flight to the international space station for andreas mogensen, `http://m.esa.int/Our_Activities/Human_Spaceflight/iriss/Longer_flight_to_the_International_Space_Station_for_Andreas_Mogensen`, accessed: 2016-01-11.

[6] I. A. Portillo, D. Gerhardt, M. Bisgaard, Launch and Early Operations Phase for the GOMX-3 Mission, in: 2nd Latin American CubeSat Workshop, 2016, pp. 1–13.

[7] J. C. Springmann, J. W. Cutler, Attitude-Independent Magnetometer Calibration with Time-Varying Bias, Journal of Guidance, Control, and Dynamics 35 (4) (2012) 1080–1088. doi:10.2514/1.56726.

[8] J. C. Springmann, On-Orbit Calibration of Photodiodes for Attitude Determination, in: Small Satellite Conference, no. March, 2013, pp. SSC13–VIII–1.

[9] J. R. Wertz, Spacecraft Attitude Determination and Control, 1st Edition, D. Reidel Publishing Company, 1978.

[10] M. Fernandez, G. Guillois, Y. Richard, J.-L. Issler, P. Lafabrie, A. Gaboriaud, D. Evans, R. Walker, O. Koudelka, P. Romano, K. Hansen, D. Gerhardt, New Game-changing on cube and nano satellites radios, in: 66th International Astronautical Congress, no. October, 2015.