

**GOMX-3: Mission Results from the Inaugural ESA In-Orbit Demonstration CubeSat**

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**ABSTRACT**

The first European Space Agency In-Orbit Demonstration CubeSat was designed, integrated and launched in less than 1 year by GomSpace. The satellite was designed according to a CubeSat-specific tailoring of the ESA ECSS Engineering standards. This tailored standard, in parallel with next-generation COTS subsystems, allowed GomSpace to achieve this compressed schedule without compromising the technical scope of the mission.

The GOMX-3 3U CubeSat deployed from the International Space Station on October 5, 2015 and immediately started a compressed commissioning schedule for its bus and advanced payloads. After 24 hours on-orbit, the downlink was increased to 19.2 kbps to take advantage of the excellent communication capability. Its helical ADS-B antenna was deployed on day 2 of on-orbit operations and began collecting thousands of aircraft positions each day. After 96 hours on orbit, the satellite entered 3-axis control. In the weeks that followed, GOMX-3 used its 1 degree pointing capability to track nadir, ram, ground stations, and geostationary satellites. In addition, it successfully demonstrated its high-speed X-band downlink capability (based on a transmitter & antenna from Syrlinks and funded by CNES) using a CNES ground station located in Kourou, FG. Finally, GOMX-3 successfully demonstrated its powerful software-defined radio via a spectrum analysis of L-band signals in its ISS-like orbit.

The satellite continues to operate with no loss of functionality. It is a success because of the vast reconfigurability of its subsystems, which use a variety of tools (parameter system, on-orbit image upload, watchdogs, distributed network topology) to ensure mission success given tight schedule constraints. The satellite has remained active enough to necessitate the development of an optimization tool to best determine payload scheduling given geometric and target constraints, which are realized via rapid attitude maneuvering (up to 7 target changes per orbit). This paper presents a detailed review of the GOMX-3 mission, on-orbit experiences, and lessons learnt with the SmallSat community.

**INTRODUCTION**

Sometimes the best solution is to try it in space. Most components that have not achieved flight heritage add risks to a mission, the sum of which may not be acceptable for certain projects. Thus, the European Space Agency (ESA) maintains an In-Orbit Demonstration (IOD) element of its technology

program, which “finds flight opportunities for innovative technologies”.<sup>1</sup> In this way, ESA reduces risk stepwise, allowing advanced technologies to trickle up (into larger programs which have a lower risk ceiling) or across (into other demonstration missions which rely on them to test more advanced technologies).

Nanosatellites are an ideal platform for these technology demonstration missions. Their small form-factor allows them to piggyback on larger missions at low cost. Additionally, as the basic functionality of nanosatellite technology matures, more missions have a stable platform on which to test advanced technologies. The Danish company GomSpace is a leader in the development and maturation of technologies necessary for nanosatellites, and has previously demonstrated their finesse with the GOMX-1 satellite<sup>2</sup>, the first CubeSat to acquire ADS-B signals in-orbit.

The first Danish astronaut, Andreas Mogensen was scheduled to visit the International Space Station in September 2015. In early 2014, ESA proposed an IOD CubeSat development, to be led by GomSpace and to be deployed from the ISS during Mogensen's stay. Thus, one of the main constraints of the project was to deliver a satellite in an extremely limited time frame: about 1 year from Phase A/B kickoff to FM delivery.

Both GomSpace and ESA are interested in maximizing the functionality of their nanosatellite missions. As such, the development platform, named GOMX-3, was focused on a variety of technical challenges. It would demonstrate 3-axis pointing of 2 degrees or less, thus augmenting the functionality of its payloads by adding the ability to track their associated targets. The RF payloads vary from ADS-B commercial aircraft tracking to high-speed X-band downlink. Of special note is spectrum monitoring in L-band using a powerful software-defined radio aboard the satellite.

## RAPID DEVELOPMENT

In order to achieve the lofty goals set forth within the limited time frame, GomSpace and ESA worked together to focus on key areas of development. ESA developed a tailored ECSS specific to a short duration IOD CubeSat mission in Low Earth Orbit (LEO), and GomSpace augmented with a variety of methods to allow focus on payload and system-level development and testing.

## *IOD CubeSat Tailoring of ECSS*

The IOD CubeSat Tailoring was created to apply an appropriate level of ESA requirements to the more general CubeSat standard. The full ECSS standard is out of scope for low-cost CubeSat missions; the CubeSat IOD standard is tailored to apply a subset of the full requirements. Thus, each ECSS Engineering standard is classified as “applicable”, “guideline”, or “not applicable”. Within standards classified as applicable, there is a line-by-line tailoring of each requirement’s applicability to IOD CubeSat projects. In excluding standards (or specific requirements within a standard), a higher level of risk is accepted for these

small missions. The tailored ECSS Engineering standards are supplemented by “light” Product and Quality Assurance requirements developed specifically for IOD CubeSat projects, where higher risk tolerance and extensive use of COTS components is commonplace.

The IOD CubeSat tailoring represents the expertise that ESA brings to the table when working on nanosatellite missions. It has been refined through a variety of nanosatellite projects, including GOMX-3. The refinement aims to be helpful for developers, with the goal of increasing the robustness, quality and reliability of CubeSats without excessive overhead. The tailoring is available to partners when collaborating on ESA CubeSats. For further information about the IOD CubeSat ECSS tailoring, please contact the ESA Directorate of Technical and Quality Management.

## *GomSpace Methods to Reduce Development Time*

The GomSpace method builds on previous experience to reduce risk to the mission. Many design decisions and technologies are selected to reduce implementation time for the satellite bus. This allows developers to focus pre-delivery resources on the critical areas of payload and system functionality. The methods used are outlined in Table 1 below; descriptions of each method in further detail are available<sup>3</sup>.

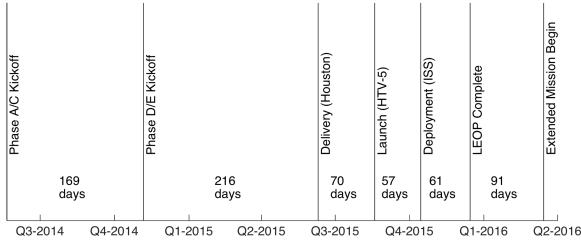
**Table 1: GomSpace methods of reducing development time before delivery**

Method	Description
COTS Components	Using COTS components allows newer, more efficient technology to be used in space (after proper qualification)
Distributed Architecture	A distributed spacecraft has reduced system interdependency (simplifying test campaigns) and a standardized communication (reducing development time through reuse of this code).
Parameter System	FRAM-based non-volatile storage allows configurations, calibrations, and more to be modified easily without a lengthy software upload.
Watchdogs	These mitigate the risk of single-event upsets by resetting parameters, subsystems, or the entire system in the case of anomalous behavior.
In-the-loop Software Testing	The mission AODCS software may be tested in-the-loop with a Simulink model, which simulates sensor output and accepts software-calculated actuator input.
On-orbit Reprogramming	This critical functionality can save a mission if the software is not perfect at orbital insertion. Smart protections allow the software to revert to default after X reboots of the new image.
On-orbit Calibration	Many AODCS sensors may be adequately calibrated in-orbit, which can reduce tedious AODCS ground testing.

## GOMX-3 SATELLITE

### Mission

The GOMX-3 mission statement states: “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 degrees 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.



**Figure 1: Mission timeline**

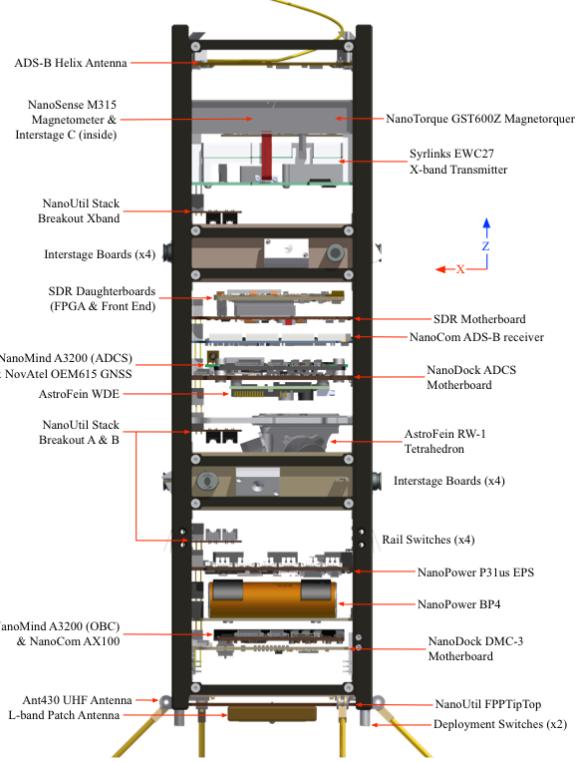
The achieved mission timeline is shown in Figure 1; the tested satellite was delivered about one year after the Phase A kickoff. This represents a significant reduction in satellite development time, even considering the accelerated pace of most CubeSat projects. The LEOP phase was concluded two months after deployment from the ISS with the successful completion of an 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.

### 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 2. 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 SOFT radio. The upper 1U contains the X-band 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.



**Figure 2: GOMX-3 internal layout**

The system design is further categorized into the bus, payloads, and data interface.

### Bus

With reference to Figure 2, the following components are considered part of the bus. Unless otherwise noted, all components are COTS solutions offered by GomSpace; further description and datasheets are available.<sup>4</sup>

*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 independent switchable latch-up protected outputs. It also provides Maximum Power Point Tracking (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. The 38 Wh of stored energy ensures the Depth of Discharge (DoD) does not exceed 10% during nominal operations.

*NanoMind A3200 OBC* is the mission computer, which stores mission-specific commands. The OBC also collects telemetry from non-ADCS subsystems in order to generate the housekeeping beacons. It stores these beacons on its flash memory to allow for historical data download.

*NanoCom AX100* is a UHF radio system used as the primary RF communications method. It is both flexible and robust, allowing for adjustment of frequency, bitrates and data encapsulation formats in orbit.

*NanoDock DMC3* is a motherboard used to host the A3200 OBC and AX100 radio.

*NanoMind A3200 ADCS* is a hardware-identical A3200 dedicated to ADCS operations. This computer is responsible for filtering the sensor data input (GOMX-3 uses magnetometers, fine & coarse sun sensors, and a rate gyro), applying control laws (GOMX-3 uses a Sliding Mode Controller), and commanding actuators (GOMX-3 uses magnetorquers and four 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 housed on the -Y/+Z interstage.

*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 nanosatellite reaction wheel assembled in a tetrahedron configuration aboard GOMX-3. The AstroFein WDE driver board is used to control four of these wheels.

*NanoUtil Interstages* are small PCBs that collect ADCS sensor data and control antenna deployment. Eight of them are mounted in the interstage area between solar panels. Each of these houses a Fine Sun Sensor (FSS), which provides a 2-axis sun vector measurement; each is canted 30 degrees to allow for near-complete sun coverage without using the  $\pm Z$  faces. Four interstages control electronic knives which release the canted turnstile antenna elements. A ninth interstage is mounted within the internal magnetorquer; it controls the ADS-B helix antenna deployment.

*NanoCom Ant430* is the canted turnstile UHF antenna. The 4 antenna elements are in a stowed configuration at launch; they are folded down along the satellite body and restrained to four Interstage boards using Dyneema

wire. After deployment, the antenna provides an omnidirectional gain pattern that allows for attitude-independent communication.

## Payloads

Again with reference to Figure 2, the following components are defined as payloads:

*NanoCom ADS-B* is an update of the hardware which flew aboard GOMX-1.<sup>2</sup> Hardware and software updates 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 Zynq 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.

*Syrlinks EWC27* is an X-band transmitter designed and manufactured by Syrlinks and housed on GOMX-3. The transmitter is capable of up to 100 Mbit bitrate, but GOMX-3 used a set bitrate of 3 Mbit for its first on-orbit test. The X-band patch antenna was also provided by Syrlinks and is located on the +Y face of the satellite. The NanoCom SDR provides the CCSDS data stream to the transmitter.

## Data Interface

CubeSat Space Protocol (CSP) is defined for a variety of physical buses; some subsystems support redundant buses and may be switched on-orbit. Figure 3 shows the data interfaces used aboard GOMX-3. CSP is the core of these interfaces and is responsible for the majority of the core subsystem communication. The ADCS sensors rely on the GomSpace Sensor Bus (GSSB), allowing interstage boards to act as intermediaries between sensors and the ADCS computer. Additionally, serial communication is used for some specialized payloads.

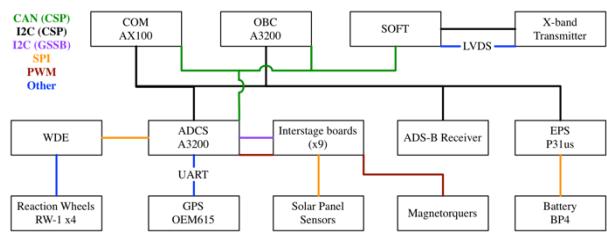


Figure 3: GOMX-3 data interfaces

## 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<sup>5</sup> and thus he did not have time to jettison GOMX-3 during his stay. Instead, GOMX-3 was deployed from the ISS (using the Nanoracks deployer) on 5 Oct 2015. Figure 4 shows the image Astronaut Scott Kelly captured of GOMX-3 (center 3U CubeSat) and fellow satellite AAUSAT5 (bottom left 1U CubeSat) as they moved away from the ISS with a relative motion of about 1 m/s. After deployment, the GOMX-3 operations phase began.



**Figure 4: GOMX-3 deployment from the ISS**

### *Operations Day 1*

The first GOMX-3 pass proceeded as shown in Table 2. 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.

**Table 2: Timeline of the first GOMX-3 pass over GomSpace ground station**

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

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 Table 2 and Table 3 were completed. The UHF antenna auto-deploy was disabled to save power. 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. Because 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; this is key for the calibration of multiple ADCS components.

**Table 3: Timeline of the first GOMX-3 pass over GomSpace ground station**

Step	Description
7	Disarm UHF antenna auto-deploy
8	Upload TLE
9	Enable SGP4 ephemeris mode
10	Enable UHF attitude determination
11	Checkout SDR payload
12	Increase AX100 bitrate to 9600 bps
13	Increase AX100 bitrate to 19200 bps
14	Enable ADCS free-float mode (for calibration)

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.

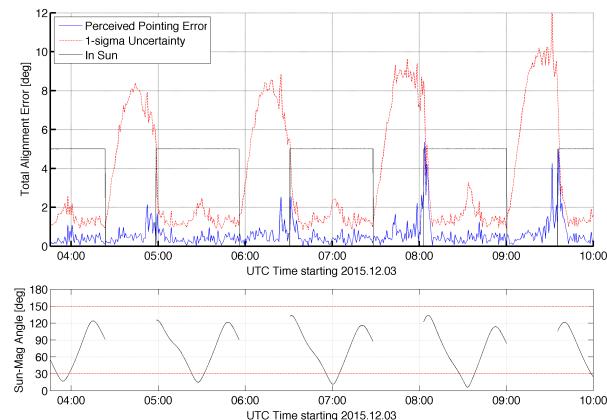
## Payload Verification

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.<sup>6</sup>

## Advanced ADCS

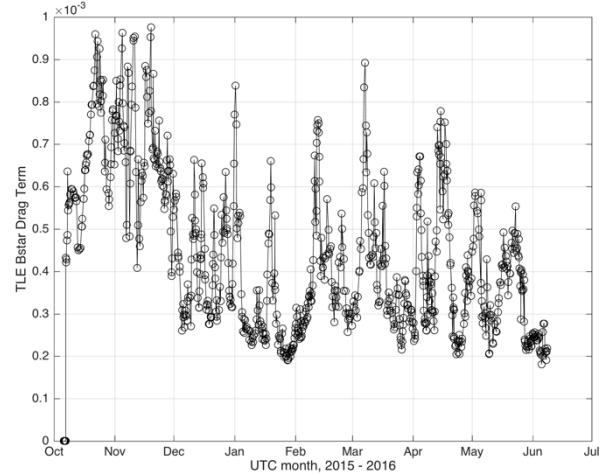
Because of the advanced goals of GOMX-3, some degree of on-orbit calibration was required for the ADCS. The attitude determination (and thus also control system) relies on a variety of sensors uses as inputs: fine and coarse sun sensors, magnetometers, and a rate gyro. Each sensor was calibrated using a variety of techniques unique to each sensor.<sup>7,8</sup> 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.<sup>9</sup> 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 degree 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.



**Figure 5: GOMX-3 ADCS performance over a 6-hour dataset while tracking the nadir direction with the ADS-B antenna. The attitude uncertainty bounds are 1-sigma (68%)**

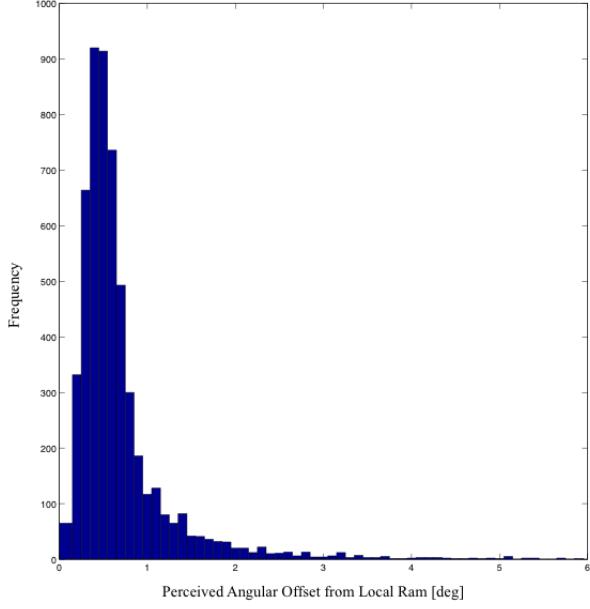
The stability of the ADCS system is also of note. After proving momentum dumping via the magnetorquers, the GOMX-3 was set to nominally point its 1U face toward the local ram vector, a minimum drag configuration. The consistency of the ADCS in maintaining this attitude has extended the expected orbit lifetime from 6 months to well over 1 year, providing much more utility from the ISS orbit.



**Figure 6: GOMX-3 historical Bstar drag term, showing the effect of its primarily ram-pointing attitude after commissioning is complete in Dec 2015**

This ADCS consistency is shown in Figure 6, which shows the satellite's historical Bstar drag term, an estimate of the satellite ballistic coefficient normalized for altitude. After the satellite is set for ram pointing in early December 2015, the Bstar drag is significantly lowered. Note that the attitude is sometimes varied to allow for mission operations such as earth object tracking or nadir-pointing.

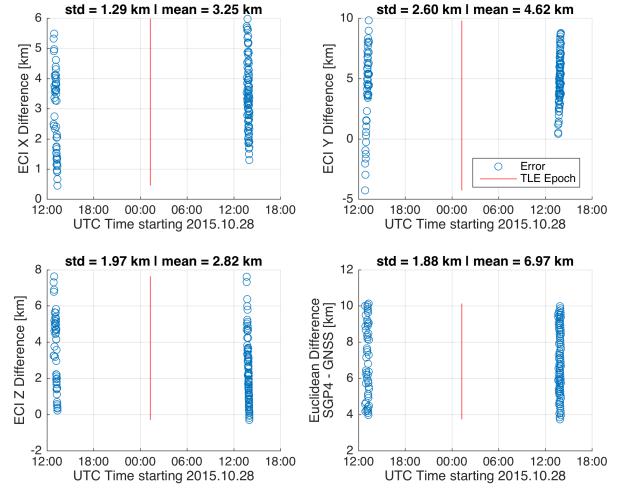
Figure 7 shows a three-week period (May to June 2016) of uninterrupted ram pointing. The onboard ADCS filters the onboard sensors to determine the perceived angular offset from the local ram vector. The mean perceived error is just 0.69 degrees over this period.



**Figure 7: GOMX-3 Perceived angular offset over a 3-week period; the mean offset is 0.69 degrees**

Figure 9 shows the results of a verification of the NovAtel GNSS receiver aboard GOMX-3. In both tests, the receiver maintained lock for a period of 20 to 30 minutes. Each of these attempts was about 12 hours away from a TLE epoch which was used to determine a relative position error between the SGP4-based position and the receiver's reported position. As shown, the Euclidean difference between the SGP4- and GNSS-reported positions varies from 4 to 10 km with an

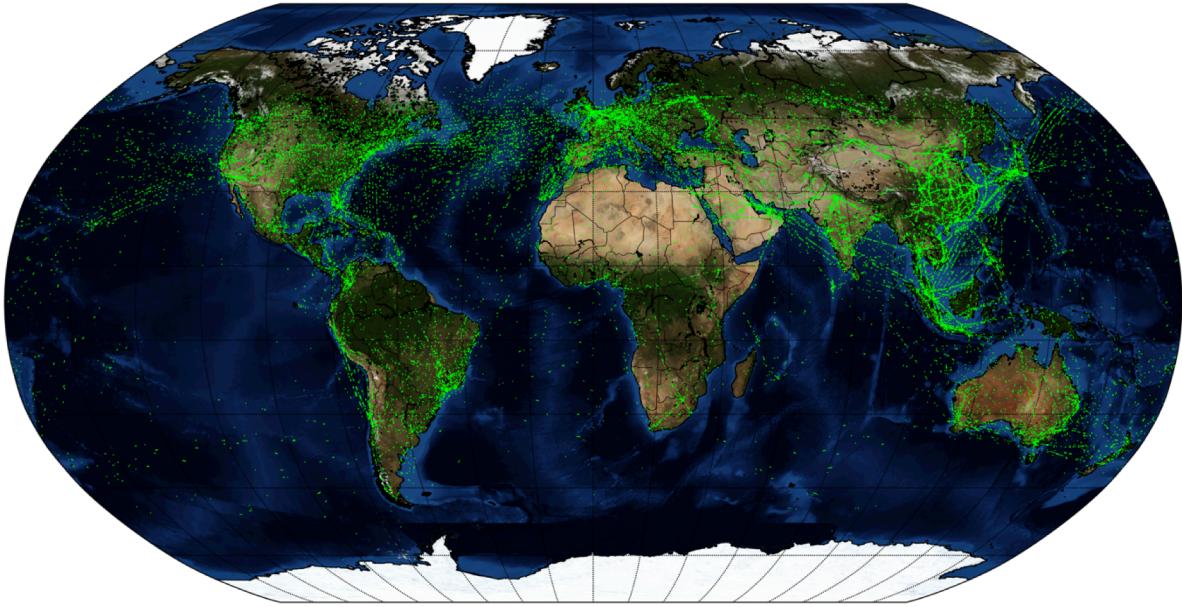
average of 7 km. This is in good agreement with previous nanosatellites comparing TLE-to-GPS position errors.<sup>10</sup>



**Figure 9: The GNSS receiver position estimation as compared with the TLE/SGP4 estimation**

#### ADS-B Receiver

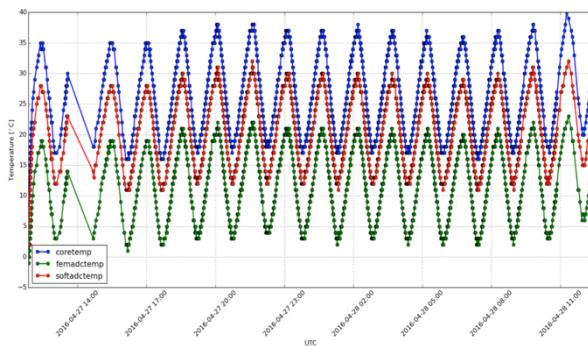
After initial communication checks to the ADS-B receiver, the next step was deployment of the helix antenna designed for data collection at 1090 MHz. Immediately after antenna deployment, the satellite recorded its first ADS-B signals. To date, the ADS-B receiver has regularly collected thousands of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



**Figure 8: Global ADS-B data collected by GOMX-3. Each dot represents a plane location recorded and downlinked by GOMX-3. Note that data collection is limited by the orbit inclination of about 52 degrees**

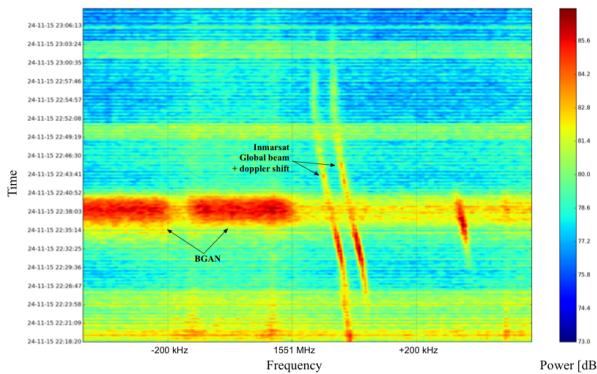
## NanoCom SDR

On-orbit tests began by simply powering the device on and monitoring its behavior. As shown in Figure 10, the highly capable SDR maintains temperatures within operational bounds, even over long timespans. Next, the spectrum monitoring capabilities proceeded to monitor the UHF environment during GOMX-3 transmissions. With this sanity check complete, the system was used to record the spectrum in L-band while tracking specific geostationary satellites. The patch antenna used by the GOMX-3 SDR is centered at 1592 MHz with a VSWR  $\leq 3$  bandwidth of 175 MHz.



**Figure 10: On-orbit active-SDR temperatures over a 24-hour period**

Figure 11 shows the spectrum recorded by the GOMX-3 SDR over a period of 50 minutes with a bandwidth of 750 kHz centered at 1551 MHz. The spectrum shows signals indicative of BGAN and Inmarsat global beams. Satellite-based signal monitoring at LEO allows estimation of the global coverage of these services. Due to the highly adaptable nature of the SDR, many other investigations may be performed with the on-orbit hardware.



**Figure 11: Spectrum measurements recorded by the GOMX-3 SDR. Approximately 50 minutes of monitoring is shown over a 750 kHz bandwidth**

## EWC27 X-band Transmitter

GOMX-3 hosts the Syrlinks EWC27 X-band transmitter as a third-party payload.<sup>11</sup> SOFT provides the data stream which is modulated by the transmitter. The X-band downlink was tested using two CNES 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 X-band pass over the Kourou ground station.

The passes over Toulouse were more successful, demonstrating 115.5 Mb of data transfer in 5.77 minutes of pass time; this represents an overall transmission overhead of less than 7%. As compared to Kourou, the Toulouse ground station uses a much smaller diameter antenna which is more robust to pointing error introduced by the GOMX-3 TLE.

## Mission Success

Over eight months after the deployment from the ISS, GOMX-3 is still fully operational and has fulfilled all its mission requirements. It has been a complete mission success. In fact, the operations of the satellite have been consistent enough to allow for the development of an automated experiment scheduling tool.<sup>12</sup> This tool maximizes the utility of the payloads while maintaining the battery charge-level above a critical threshold.

The satellite now continues operations in its extended mission.

## 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 testing. However, the EQM is also useful as a software test bed 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.

*Reconfigurability is key.* GOMX-3 was developed and delivered in an extremely tight schedule. In these conditions, even using pre-qualified COTS components may not be sufficient to allow enough time for testing. One way to further reduce risk is to ensure all subsystems are able to be reconfigured in-orbit (i.e. parameter system & ability to upload a new software image). This was very helpful for GOMX-3, and ensured mission success during on-orbit calibration of the ADCS and software debugging for the X-band downlink.

*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 real-time 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 real-time 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.

## ACKNOWLEDGEMENTS

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