Launch and Early Operations Phase for the GOMX-3 Mission

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Abstract

The plan for activities to be performed immediately after a satellite orbital insertion, commonly known as the Launch and Early Operations Phase (LEOP), can be sometimes disregarded or not given enough importance until later in a project, especially by new university teams developing their first CubeSat. Besides, the execution of LEOP activities brings an additional challenge after many years of project development due to its singular criticality. These activities are required regardless of the type of launcher and include: ground station set-up, reception of first beacon, satellite de-spin, downlink and uplink tuning, power budget monitoring, time synchronization, and more. Depending on the payloads the LEOP can extend from a few days to a few weeks for an average CubeSat project.

In many cases, an additional challenge exists for small and/or new groups using a single ground station for communication. This means that only a few short passes per day may be available for performing all necessary LEOP tasks, depending on the type of orbit and the latitude of the ground station. Additionally, long breaks between pass sets may increase the effect of satellite anomalies as operators cannot respond to them quickly. Each of the above considerations increases the need for proper LEOP planning and execution.

GOMX-3, an advanced performance 3U CubeSat financed by the European Space Agency, has been designed and built by Danish sector leader GomSpace, and was deployed from the International Space Station on October 5, 2015. The LEOP execution has been a success in terms of its planning, speed, and technical achievements. Also remarkable has been the coordination of the LEOP team members during the performance of the different tasks. This paper presents a detailed review of the GOMX-3 LEOP with the aim of sharing the positive experiences and lessons learnt with the growing Latin American CubeSat community.

Keywords: CubeSat, GOMX-3, LEOP, GomSpace

1. Introduction

When designing a nanosatellite, an important (but often forgotten) element is the satellite acquisition and early operation phase. Many nanosatellites are designed as one-of-a-kind and utilize state of the art subsystems and components which, together with very rapid implementation from design to launch, provide an inherent higher level of uncertainty compared to bigger and more expensive satellites. Most of the uncertainty is focused on the early operation phase where the functionality of satellite subsystems is validated and where potential mission critical problems will reveal themselves.

This paper will detail what the LEOP phase entails for a CubeSat mission and, with a basis in the GOMX-3 satellite design (see Figure 1), show how to achieve a successful commissioning of a CubeSat.

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

1.1. LEOP Definition

In this paper the LEOP phase is defined as the interval from when the satellite leaves the launch vehicle to the point where the commissioning of the satellite is complete and it is ready to enter full operation. And the LEOP phase is indeed the critical for satellite operators: "If anything can go wrong, it's most likely to happen during LEOP" [1].

A number of goals are to be reached during the LEOP phase before the satellite can enter full operation:

- **Satellite acquisition**: First and foremost after the satellite deployment from the launch vehicle is the signal acquisition from the satellite; two-way communication must be established.
- **Satellite safekeeping**: After communication is established, the health of the satellite must be evaluated and if any problems are detected they must be swiftly acted upon.
- **Satellite checkout**: When the satellite is determined to be in a safe and healthy state, the individual subsystems should undergo checkout, calibration and in-orbit validation. Important elements in this phase are adjustment of communication systems, calibration of ADCS, validation of payloads, etc.
- **Satellite mission trial**: When all individual parts of the satellite are validated, the satellite will enter a trial operation state as a final validation before the operations phase can begin.

1.2. Common Problems

For many CubeSat missions the challenges begin at first signal acquisition. According to [2] and [3], historically there has been a failure rate of up to 50% of university built CubeSats; of these about 45% are classified as “No-Contact”. However, for satellites that achieve first contact the next challenge is to achieve tracking. Often CubeSats are deployed in large numbers from the same launch vehicle; it is sometimes difficult to determine which of the provided TLEs is applicable to the desired nanosatellite. This can make it difficult to maintain two-way communication during the initial LEOP phase. Other problems that are seen among nanosatellites are:

- Satellites launched with a power problem that yields a negative power budget and without a proper safe mode to account for this.
- Satellites launched with faults (typically sign errors) in de-tumbling systems.

For these problems it is critical that satellite operators are aware of problems as soon as possible and take corrective action. It is essential that the satellite is designed specifically to allow for such action.

2. Design for LEOP

Designing a satellite for a successful LEOP phase starts with the design of the satellite subsystems. Each subsystem must be designed with a high level of focus on basic operation reliability and resilience to unforeseen issues. Trying to design for clear interface between systems and limited inter-operability dependencies are key factors as well as using defensive measures like watchdog timers. Allowing each subsystem to be less dependent on others heightens the probability of the overall system producing the desired result. Furthermore, the individual subsystem and overall system design must assume that unforeseen in-orbit issues will occur and the design philosophy must allow for easy reconfiguration of systems.

2.1. Beacons

Allowing the satellite to autonomously transmit beacons with frequent regular intervals containing important housekeeping data is vital to the initiation of a successful LEOP phase. GomSpace has on multiple occasions successfully used the strategy of transmitting very frequent, short, low baud data beacons in the initial LEOP phase. Having the beacons frequent (≥ 0.1Hz) allows for easier tracking of the satellite in the initial phase of the orbit when information is the most uncertain. Having the beacons short ensures that fades due to tumbling of the satellite will not disrupt reception of individual packages.

2.2. Safe Modes

For the LEOP phase it is important to realize that this period of the mission is where most design and implementation problems will show up. A common method in spacecraft design for dealing with critical situations is the use of safe modes. For most CubeSats there are three elements to consider when designing safe modes, all of which often are constrained by each other: power, attitude, and communication.

Especially for mission operation scenarios where power is limited, power safe mode is vital and two different approaches can be taken: a) save power by switching off systems or b) harvesting more power by focusing attitude pointing from payloads operations to a power optimum mode. However, 3-axis pointing is often not considered “trustworthy” during LEOP as it usually requires substantial time to validate and calibrate the ADCS system to perform this complex task. Therefore, the best safe mode for power critical situations is to reduce power usage.

When the available stored power on the battery drops below a certain point, the power supply should power down non-critical systems like payloads and eventually also non-essential bus systems like advanced ADCS components. Although it is possible, conserving power by reducing the beacon transmissions is not recommended, as these are an important part of the initial phase satellite tracking.

The attitude determination and control system is often the most advanced bus system in CubeSats and it is therefore important to design it such that anomalies are handled by proper safe mode design. A faulty ADCS could lead to mission critical situations such as the spacecraft spinning out of control. Two different safe mode strategies can be taken: if an anomaly is detected either fall back into idle or fall back into a simple de-tumbling BDOT algorithm.

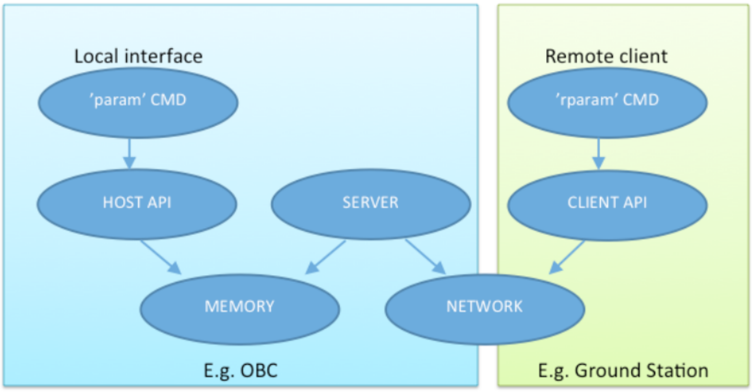

Figure 2: The GomSpace parameter system. Parameters are stored in local FRAM, but may be modified either locally or remotely via whatever physical medium connects the two (I2C, CAN, UHF, etc.).

The simplest safe mode is to switch the ADCS into idle which will result in the satellite free floating and, for most satellites, being governed by its residual magnetic field. However, for several CubeSat missions the free floating mode has resulted in uncontrollable spins, most likely caused by varying current paths in the satellite generating alternating magnetic fields. A better option can then be to use the simple BDOT algorithm for ADCS safe mode and then invest sufficient time to perform ground validation of this mode.

2.3. Watchdogs

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.

2.4. Parameter System

For any spacecraft it is important to be able to easily do in-flight configuration changes in a safe way. This is especially true during the LEOP phase where quick adjustments can be necessary

All GomSpace products are equipped with a method that allows the operator to adjust configuration data in orbit (see Figure 2). 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.

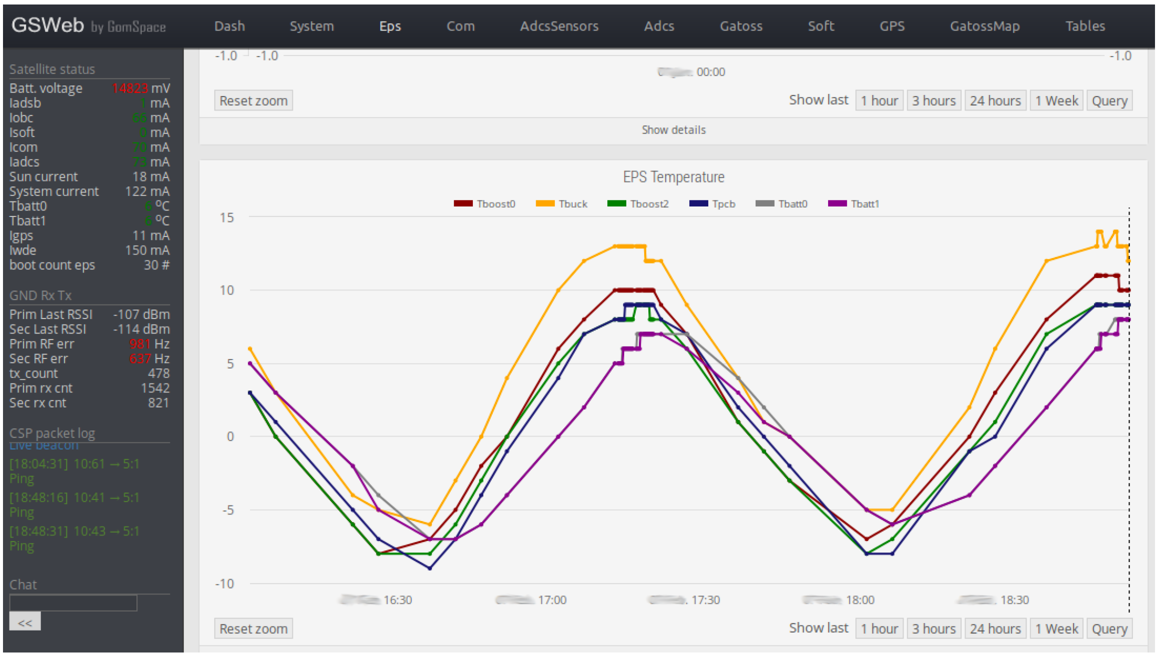

Figure 3: GSweb is used to visualize data in real time as it is collected by the ground station.

2.5. On-Orbit Upload

With the rapid development cycle called for in a Cubesat mission, 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 LEOP 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.

2.6. Telemetry Viewing System

The telemetry viewing tool is an especially important element for the satellite operator during the LEOP phase. A well designed tool can be a strong support in a LEOP phase where the operator must make quick decisions based on a wide range of telemetry such as power, voltages, temperatures, etc. The tool must allow the easy data visualization as well as data comparison.

The ground station visualization tool GSweb can be used on top of the GomSpace parameter system. GSweb allows for individual graph setup and real-time data plotting. Furthermore, data thresholds can be setup for automatic detection of anomalies (i.e. low voltage, high temperature, etc.). Additionally, GSweb is accessible using only a browser and is accessible to anyone on the local network, making it ideal for teams to view data together to focus on various subsystems simultaneously, even when physically separated. Figure 3 shows an example screen from GSweb generated using GOMX-3 data.

3. GOMX-3 Satellite

The GOMX-3 CubeSat is a 3 kg nanosatellite designed, delivered, and operated by Danish sector leader GomSpace. Notably, it has demonstrated excellent performance in all aspects of its mission goals, from three-axis attitude control to spectrum monitoring. As of this writing, it continues to operate in-orbit with no major anomalies affecting its mission operation. It serves as a model of a satellite designed for LEOP and excelling in its mission as a result.

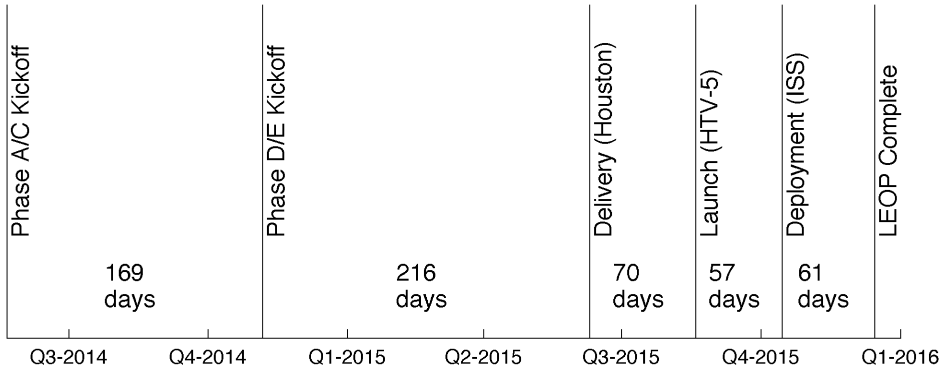

Figure 4: The GOMX-3 satellite followed an accelerated schedule, with delivery about 1 year after project kickoff.

3.1. Mission

The GOMX-3 mission was initially conceived in response to Andreas Mogensen's planned visit to the International Space station in September 2015. As the first Danish astronaut, Mogensen would release multiple Danish nanosatellites during his stay at the station. Thus, one of the main goals of the project was to develop a satellite in an extremely limited time frame (about 1 year from Phase AB kickoff to FM delivery).

GOMX-3 is the first ESA In-Orbit Demonstration (IOD) CubeSat; it is the first to use a tailoring of the full ECSS standard suitable for a CubeSat mission. This tailoring ensured that the standards applying to the development and testing of the satellite are suitable for a low-cost mission.

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

3.2. System Design

The GOMX-3 system follows the same model that GomSpace suggests to its customers: use Commercial-off-the-shelf (COTS) subsystems to reduce risk and allow for time-limited delivery schedules to focus on payload development and testing. Thus, the satellite is comprised mainly of standard components from the GomSpace product line. Some of these components are the first in a new generation which gain their flight qualification from this mission.

3.2.1. Layout

The GOMX-3 satellite layout is shown in Figure 5. 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 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.

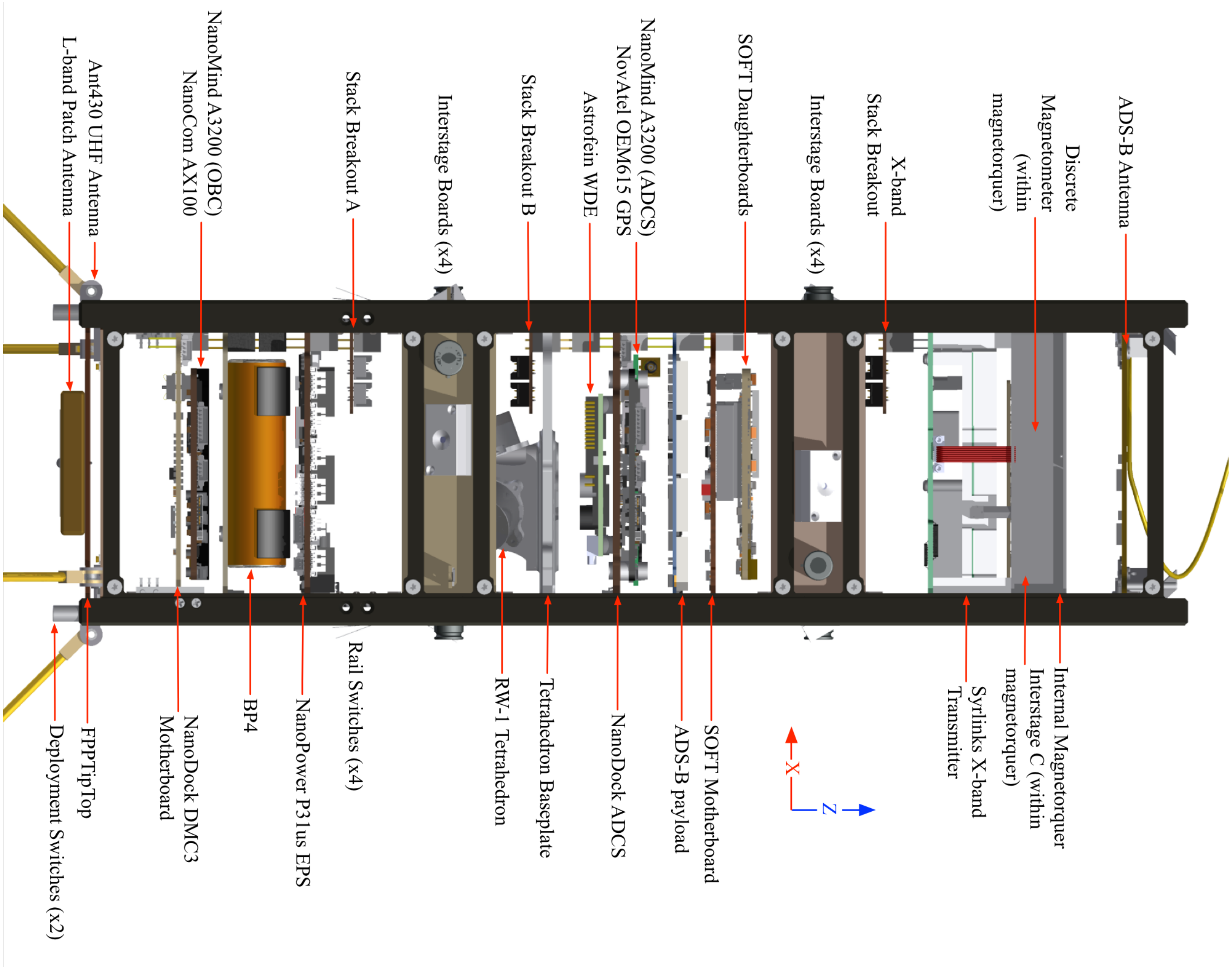

Figure 5: The GOMX-3 internal layout diagram, identifying the position of all hardware within the structure.

3.2.2. Data Architecture

As shown in Figure 6, GOMX-3 uses a variety of data connections. The majority of the bus subsystems are reconfigurable to use either CAN or I2C while implementing the CubeSat Space Protocol (CSP) [4], a protocol similar to the TCP/IP but specifically designed for low-overhead nanosatellite networks. CSP allows GomSpace satellites to follow a distributed network topology rather than the centralized topology used among larger satellites. This greatly simplifies software development for GomSpace satellites by reusing flight-proven low-level software elements. This is another instance of satellite design that allows the developer to focus on high-level design necessary to make the mission work.

GOMX-3 also uses the GomSpace Sensor Bus (GSSB), a dedicated I2C bus for ADCS sensors (coarse & fine sun sensors, magnetometers, and a rate gyro) which reduces the complexity (and thus increases reliability) of the main bus. Additionally, a variety of point-to-point data lines are used for high-rate or 3rd party payloads.

3.2.3. Telemetry

GOMX-3 uses beacons with multiple periods: 10 seconds for direct sensor measurement (temperatures, voltages, currents, etc.), 60 seconds for subsystem modes and counters (boot & watchdog). Each beacon

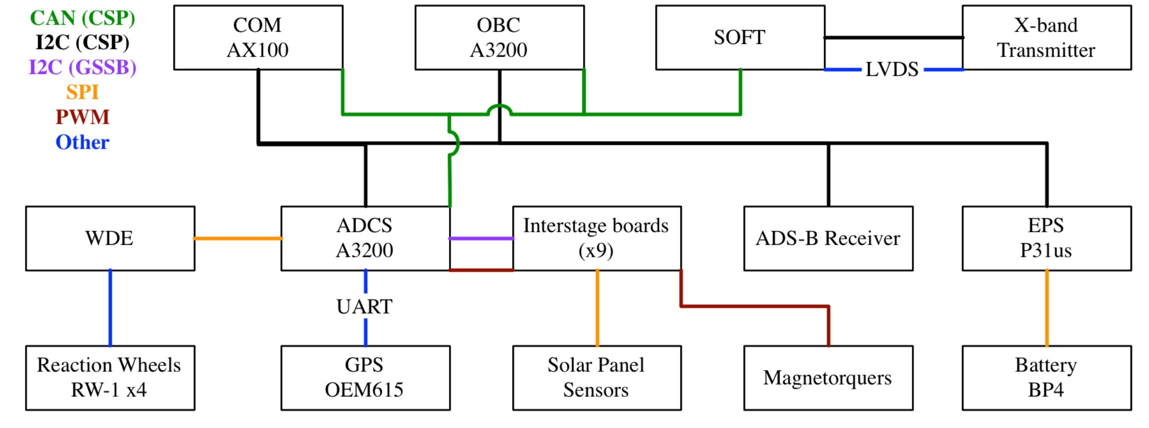

Figure 6: GOMX-3 uses a variety of data busses which mostly employ the CubeSat Space Protocol to simplify system-level software design. A secondary I2C bus, the GomSpace Sensor Bus (GSSB), is dedicated for collecting ADCS sensor data.

is also saved in non-volatile memory (GOMX-3 is set to save the last 10,000 beacons, equivalent to no less than 27 hours of data).

Specific beacons are set via firmware, but the enabling / disabling of these beacons, beacon period, and number of stored beacons are set via a parameter system which allows for reconfigurability in-orbit, allowing collection of longer-duration or high-frequency data of a specific type.

3.3. Launch & Deployment

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 at a speed of about 1 m/s (see Figure 7).

4. GOMX-3 LEOP

4.1. Planning

The early operations phase must be planned well to ensure mission success in a minimal amount of link time. Here the mission is greatly helped by a functional FlatSat (electrical / software equivalent) or Engineering Model (electrical / software / mechanical equivalent) of the on-orbit satellite. This should be used to generate a checklist of functional checks for the satellite, organized by complexity of the task: proceed from simple to complex functionality. Ideally, each task is separated into a single (or perhaps two) subsystem check. This setup allows operators to rearrange checkout "on the fly" in response to variables such as link time remaining the pass, availability of ground experts, etc.

GomSpace worked over many weeks to develop an Early Mission Operations Plan. This plan was checked against the Engineering model at all points in its development and reviewed to ensure that it was both minimal risk and a full checkout of the satellite. The plan also contained responses to various contingencies which were unlikely, but must be considered regardless. Criticalities which are especially important in the early mission include watchdog triggering, negative power budget, satellite spin-up / loss of ADCS control, and up/downlink communication blackout.

The operations team rehearsed nominal and critical satellite passes using the GOMX-3 EM in combination with a UHF ground station to ensure that all human operation was as efficient and safe as possible.

Figure 7: 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.

Once all satellite operators were comfortable with all aspects of operation, the team was ready for on-orbit satellite operation.

4.2. Pass 1

The first pass is often indicative of a satellite's success or failure as a mission, as it typically shows the issues that may plague a satellite throughout its lifetime. Thus, this pass was practiced more than all others to account for the various contingencies mentioned above. The first step in any LEOP should be a thorough check of all ground station setup, ideally through the use of a ground-based clone of the satellite. With all checks successful, the team was ready for the first pass.

The pass proceeded as outlined 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: power, communication, and attitude control. 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 local ground station.

4.3. Day 1

Due to the orbit of GOMX-3 (almost identical to the International Space Station orbit), the GomSpace 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 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

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 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

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 complete the COM link update the first day; 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.

Thus, after the first 37 minutes of communication with the on-orbit satellite, we had confirmed that the GOMX-3 was 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 ground passes.

4.4. On-Orbit Calibration

Because of the advanced goals of GOMX-3, some degree of on-orbit calibration was required, especially among 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 [6],[7]. 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 necessary to calibrate some sensors.

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 [8]. Figure 8 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.

4.5. Payload Checkout

The payload checkout was comprised of the same discrete steps as the bus checkout. The checkouts may be separated by the subsystem in question.

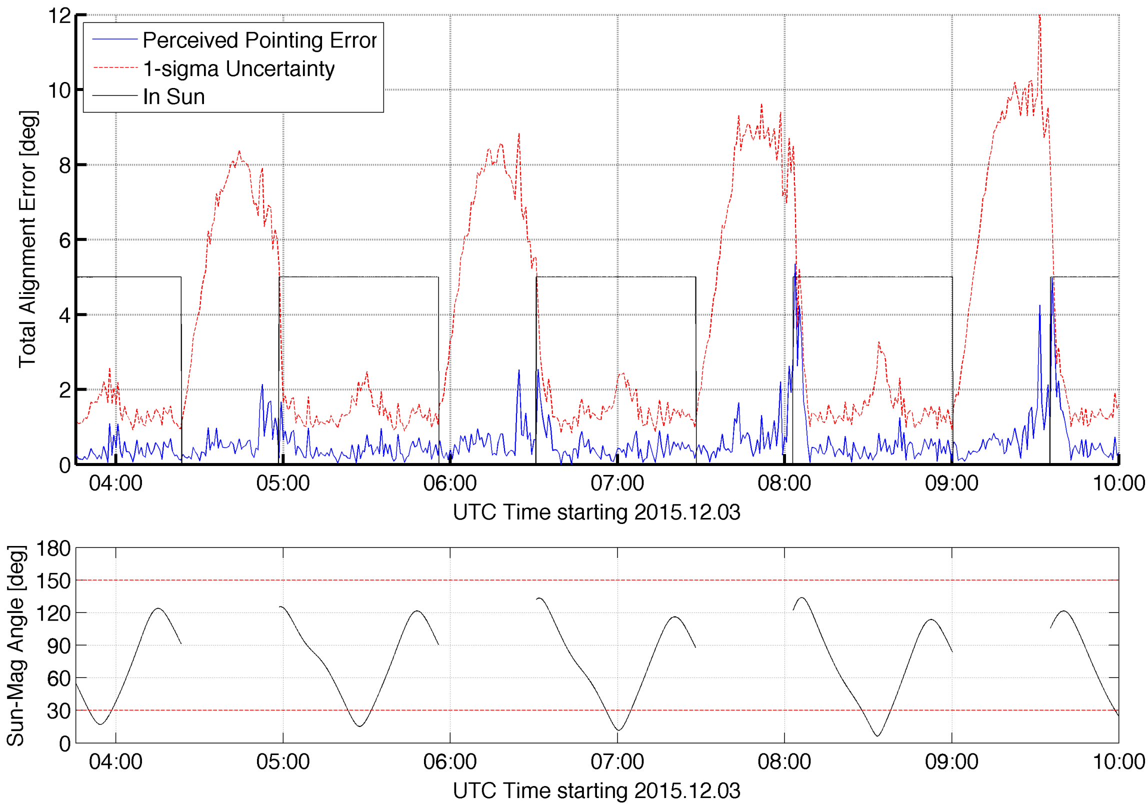

Figure 8: The GOMX-3 ADCS performance, as shown during a 6 hour dataset while operating in nadir-tracking mode. The attitude determination uncertainty bounds are 1-sigma (68%).

4.5.1. 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. The satellite was programmed to deploy the antenna upon reception of a specific sequence of ground commands. This too had been practiced on both the EM and FM satellites during ground testing. Immediately after antenna deployment, the satellite recorded its first ADS-B signals (see Figure 9). To date, the ADS-B receiver has regularly collected thousands of plane positions per day and continues to operate nominally.

4.5.2. SOFT

The SOFT radio is a powerful FPGA module with Front-End modules customizable to a specific mission application. For GOMX-3, SOFT was designed to monitor signals in Lband. On-orbit tests began by simply powering the device on and monitoring its behavior: temperatures remained within operational bounds. Next, the spectrum capturing capabilities were proven by monitoring the UHF environment for the GOMX-3 transmission signal. Finally, the system was proven by recording the spectrum within Lband, where signatures indicative of spot beams and global beams from communications satellites could be seen.

4.5.3. Xband Transmitter

GOMX-3 hosts an experimental Syrlinks EWC27 Xband transmitter as a third-party payload [9]. SOFT provides the data stream which is modulated by the transmitter. GOMX-3 used a CNES ground station located in Kourou to test the Xband transmitter. Over a period of 3 weeks, GomSpace supported 10 passes over Kourou to ensure that the Xband transmitter was properly tested. After a small software correction,

Figure 9: Immediately after GOMX-3 deployed its ADS-B antenna, it began receiving ADS-B beacons. Each red dot represents a plane location recorded by GOMX-3 during its first pass with a deployed helix antenna.

GOMX-3 proved its ability to download multiple megabytes of onboard data during a single Xband pass over the Kourou ground station.

5. Lessons Learned

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

- **Representative model is invaluable**: The GOMX-3 EM was critical to the development of the LEOP plan and quick resolution of 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 EM first.
- **Reconfigurability is key**: GOMX-3 was developed and delivered in an extremely tight schedule. In these conditions, even using COTS components may not be sufficient to allow enough time for testing. One way to further reduce risk is to ensure the subsystems used are able to be reconfigured in-orbit. This was very helpful for GOMX-3, and helped to ensure mission success during on-orbit calibration of the ADCS and problem solving for the Xband downlink.
- **Automatic data collection is helpful**: The GomSpace ground station may be augmented with a mission-specific autopilot to automatically request historical beacons from the satellite, which is necessary for viewing long term effects greater than a single 10 to 15 minute pass. The autopilot is especially helpful when the passes occur outside normal work hours.

6. Looking Forward

State of the art technology and very rapid development cycles will continue to be a crucial part of the nanosatellite market. However, with product maturation happing through fully operational missions like GOMX-3, the push towards larger nanosatellite constellations has been going on for some time in the industry. Deploying constellations of a large number of satellites brings a new level of complexity to the LEOP phase. A large number of nanosatellites (2 to 50) can be deployed from a single launch; in such cases the importance of satellites designed for LEOP is even more important. Furthermore, running a large number of satellite through LEOP efficiently and safely calls for a larger level of automation to be used.

GomSpace is a participant in the FP7 project Sensation where one focus point has been on optimization and planning of satellite operations to allow for more efficient utilization of spacecraft flight time. A spacecraft operator is faced with a highly complex task when having to plan and command in-orbit operations constantly balancing power and data budgets. The Sensation project has, among other things, investigated using networks of priced timed automata together with cost-optimal reachability analysis to generate power and data optimal operation plans that stay within safe constraints of the satellite (for a similar system see [10]).

Integrating these methods from the Department of Computer Science at Saarland University with tools like the GomSpace POWERsim and ADCSsim toolboxes and utilizing stochastic validation techniques allow for complete validation of inflight operation scenarios. The methods and models are based on experience from GOMX-1 and have been successfully tested on the GOMX-3 mission allowing for compact operation schedules while staying within safe power operation limits.

This approach will in the future be researched further for use, not only in the operation phase but also in the LEOP phase. Through modeling of LEOP scenarios and identification of allowable safe constraints will yield a number advantages. As the methods allow for actual validation of complex stochastic state machines it can provide the probability of entering specific states. This information can in turn allow, not only for better early LEOP planning, but also for validation of automated LEOP operations.

7. Acknowledgements

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