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GOMX-1 Flight Experience and Air Traffic Monitoring Results

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ABSTRACT

On the 21st of November 2013 the Dnepr rocket propelled a record number of small satellites into space including the 2 kg GOMX-1 satellite with a novel miniaturized payload for air traffic monitoring from Space.

The mission of GOMX-1 is to demonstrate that ADS-B (Automatic Dependent Surveillance Broadcast) signals broadcasted by passenger aircraft can be received on a nano-satellite platform. The payload is composed of a deployable helical antenna and an ADS-B receiver module that is partly software-defined. The antenna is tuned to the 1090MHz ADS-B signal and extends 40cm when deployed compared to 2 cm in the stowed configuration.

On the first pass over the ground station in Aalborg in Denmark contact was established with the satellite and already the following day commissioning activities had advanced to deploying the ADS-B antenna and successfully receiving the first ADS-B signals.

To date, the GOMX-1 payload has collected over 3.5 million Mode S Extended Squitter Frames containing aircraft position/velocity data. It is the vision that space based ADS-B eventually can help reduce the separation between aircraft on such dense routes and thereby allow more capacity in the most fuel-efficient routes across the oceans.

The paper will describe the mission background, provide an overview of the platform parts and their in-orbit performance, provide an assessment of the payload performance and discuss the future of nano-satellites for air traffic monitoring.

INTRODUCTION

Since the launch of the first CubeSats in 2003 significant resources are now being invested worldwide in developing technologies and capabilities that allows nano-satellites to perform more meaningful functions in space other than being a great educational resource for young engineers. On this basis we are now starting to see very interesting science and technology demonstration missions based on nano-satellite platforms being launched.

The growth in the number and maturity of nano-satellite projects is well documented[1]. And a recent forecast prepared by SpaceWorks Commercial[2] shows evidence that the number of missions will continue to grow rapidly.

In the coming years we expect that commercial applications of nano-satellites will follow where niches can be found that can be well served by nano-satellites, but are too expensive to address with traditional satellite systems.

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The mission of GOMX-1 is to demonstrate that ADS-B (Automatic Dependent Surveillance Broadcast) signals broadcasted by passenger aircraft can be received on a nano-satellite platform and in future use become a tool for significant cost and emission savings in the airline industry.

The payload is composed of a deployable helical antenna and an ADS-B receiver module that is partly software-defined. The antenna is tuned to the 1090MHz ADS-B signal and extends 40cm's when deployed compared to 2 cm in the stowed configuration.

The platform hosting the payload is composed of commercial-off-the-shelf (COTS) products from GomSpace' portfolio and includes an efficient power system based on 30% efficient cells, UHF communication and a magnetically actuated 3-axis control system. A flexible and capable software framework based on the Cubesat Space Protocol controls the mission[3].

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After collecting over 3.5 million Mode S Extended Squitter Frames containing aircraft position and velocity data, the ADS-B payload mission ended on 9 May 2014 due to an SD card hardware failure. The satellite bus continues to operate efficiently with communication on all ground station passes. The downlinked payload data is currently being used for evaluation of the feasibility and expected performance of future nano-satellite constellations for global ADS-B monitoring.

The future potential uses for space based ADS-B are many and range from the optimization of air space procedures based on statistical data from a few nano-satellites to an operational real-time system (utilizing geo-stationary satellites for data relay) of 40-70 active nano-satellites. One application of a fully deployed constellation could be the reduction of required separation of trans-oceanic flight allowing up to, in theory, 16 times as many aircraft on the most fuel-efficient routes.

INTRODUCTION

The ADS-B System

The Automatic Dependent Surveillance – Broadcast (ADS-B) signal consists of a periodically transmitted set of data packages, which are broadcasted using the aircrafts Mode-S transponder at 1090 MHz, and which provides information on key data such as aircraft ID, position, altitude and intent.

The signal is received by terrestrial ground stations and used in operational air traffic control in the same manner as information from air surveillance radars; in fact, traditional radars are now being out phased and replaced with ADS-B receivers, which provide a reduced maintenance cost to operators.

The ADS-B system is today standard equipment on new commercial aircraft and it is estimated that more than 70% of the current fleet is equipped. Recent decisions taken by the various aviation authorities such as EUROCONTROL and FAA means that ADS-B will become mandatory equipment on all high performance aircraft from 2015 and 2020, respectively.

The ADS-B system is designed to provide a range of 80 NM meaning e.g. that oceanic coverage is very limited and it is also expensive to cover large land areas with poor infrastructure using terrestrial receiving stations.

Space Based ADS-B is the idea to place sensitive receivers on board satellite in (low earth) orbit, which can receive ADS-B packages and relay these to the relevant stakeholders.

Introduction of Space Based ADS-B and Business Opportunities

Space Based ADS-B is the idea to place sensitive receivers on board satellite in (low earth) orbit, which can receive ADS-B packages and relay these to the relevant stakeholders. We are working on two concepts for utilizing nano- satellites to provide space based ADS-B service;

Off-line data: A small fleet of satellites (3-6) sampling the airspaces and providing information for mainly statistical processing off-line. The data is downlinked with delay when passing by one or more ground stations.

On-line data: A larger fleet (40-70) of satellites is connected to the air traffic control infrastructure via geostationary data relay satellites in near real-time. This could be realized using e.g. the SB-SAT for the Inmarsat BGAN network, which is in development[4].

While certainly an interesting idea, Space Based ADS-B needs to bring economical benefits to the table to be viable and worthy of investment.

For the off-line concept, which is only a modest investment, value can be generated by analyzing past data providing proof-of-flight information as sampled by the satellites. This information can be used for e.g.:

- Improvement in en-route charging calculations increasing yield 1-2% over charges calculated from posted flight plans.
- Second source on plane routes and prior locations as an input to national security intelligence gathering.
- Improvement of oceanic air space operating procedures based on usage patterns documented by Space Based ADS-B to increase air space efficiency.

Clearly, as the number of satellites in the constellation increases, the better a service can be provided. For the on-line concept, requiring significant investment, offering global full-time situational awareness of the air traffic situation, additional uses cases are possible:

- Application to search and rescue situations allowing the position of air crafts in distress to be reported immediately, unlike e.g. the situation with the crashed Air France flight AF447 in 2009 for which the crash position was not known – in fact it was only when the air craft did not show up in Paris much later that air traffic controller became worried.
- Similar for the recent case of the disappearing Malaysian Airline flight MH370 Space Based ADS-B could have helped determine the route of the aircraft once outside of terrestrial radar coverage until at least the point where the transponder allegedly was turned of.
- Operational air traffic control in which air traffic controller directly manages flights based on Space Based ADS-B in areas that are today not covered by radar or ADS-B. This will allow significant reduction in the inter air craft spacing and provides benefits in terms of reduced fuel consumption (and emissions), reduced flight time and greater air space capacity. To be of full value, however, a robust radio link must be available to the cockpit for the air traffic controller to interact with the pilot.

In April 2013 DLR for the first time demonstrated Space Based ADS-B with a receiver payload on the Proba-V mission[5]. Further, Aireon, a US company founded by Iridium, is working to have a full global service in operation in 2018 based on operating hosted payloads on-board the Iridium Next satellites.

THE GOMX-1 MISSION

Mission Objectives

The GOMX-1 mission is experimental in nature with the following mission objectives relating to ADS-B:

- To be the first demonstration of space based ADS-B using a nano-satellite
- To validate and refine the established link and signal environment model, including characterization of signal collision in congested air space.
- To characterize and optimize different algorithmic approaches for decoding received data with low SNR.
- To perform evaluation of potential performance of space based ADS-B with relevant stakeholders in the loop.

Spacecraft Bus

The satellite is a 2 unit Cubesat with deployable UHF antennas for tele-commanding and telemetry, and a deployable helical antenna for reception of the ADS-B signal.

The payload antenna will be Nadir pointing at all times, with pointing being handled by the autonomous 3-axis attitude control systems that is based on magnetic actuation and attitude estimation using an Unscented Kalman Filter with inputs from sun-sensors, a magnetometer, and rate-gyros.

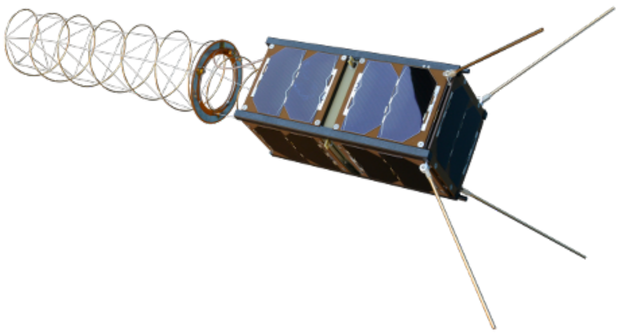

Figure 1: The GOMX-1 flight model with antennas deployed

The platform elements of the bus are taken from GomSpace's standard portfolio of products for Cubesat and Nanosats as used in many projects commercially.

At first glance the top-level bus architecture is not that different to that of AAU-Cubesat launched in 2003[6], but a lot has been learned since then and these valuable lessons learned from the early Cubesat days have been vigorously integrated into the subsystem and system design.

Payload

A top-level block diagram of the ADS-B receiver payload is provided in Figure 2 below.

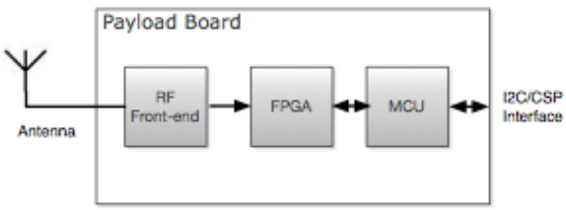

Figure 2: Top-level design of the ADS-B payload board

The antenna is the deployable helical antenna depicted on Figure 3, which provides approximately 10 dB of gain at 1090 MHz.

The RF front-end provides amplification and initial down-conversion of the signal. To compensate for the increased path-loss due to the receiver location in space in contrast to the 80 NM nominal range of the system, the RF Front End has carefully been designed to provide the required sensitivity to be able to decode the signal.

The FPGA samples the down-converted signals and run the decoding algorithms. The FPGA can be reconfigured with new bit-code during the mission and this feature will be used to improve operational performance of the payload during the mission based on the feedback gained from operating it in space.

The FPGA transfers decoded packages to the Micro-controller unit that stores the data in a (in memory) database that can be queried over the CSP network providing wide opportunities to extract ADS-B data and meta-data on system performance.

LAUNCH AND OPERATIONS

Launch and Early Operations

The satellite was launched on the 21st of November 2013 on the Dnepr rocket together with many other CubeSat and small satellites. About 1 hour after deployment the GOMX-1 beacon was picked up at the ground station in Aalborg and confirmed good basic health of the satellite.

During the first day of operations two-way communication was established, housekeeping data downlinked and the maximum power point tracking mode of the solar panels was enabled.

On the second day of operations the ADS-B antenna was deployed and aircraft position reports were immediately received thereafter. Further, the satellite was de-tumbled from a post-deployment spin-rate of 23 degrees/second using the ADCS system.

During commissioning it was found that the satellite residual dipole moment is much higher than anticipated and this provides problems for the 3-axis control modes of the spacecraft and the satellites is effectively currently only two-axis stabilized meaning that the antenna is not always downward pointing.

The root cause of this issue has been identified as magnetization of the helix antenna after last check-out. The helix antenna product is now being updated to use materials that cannot be magnetized. Investigation of improvements of the ADCS algorithms to cope with this disturbance on GOMX-1 is under investigation and will potentially be uplinked to the satellite.

Another issue affecting operations is that ADS-B data collection over the southern hemisphere under some circumstances are not correctly packed prior to downlink resulting in ambiguity for resolving the longitude on ground. This is a minor software bug in the payload that will be solved in Q2 2014 with the uplink of a new software image to the payload board.

On-Orbit Temperatures

GOMX-1 is in an SSO orbit, ensuring stable insolation and eclipse times. This, in combination with good thermal design, has allowed the spacecraft temperatures to remain in the operational "sweet spot", as shown in Figure 3 and Figure 4 below.

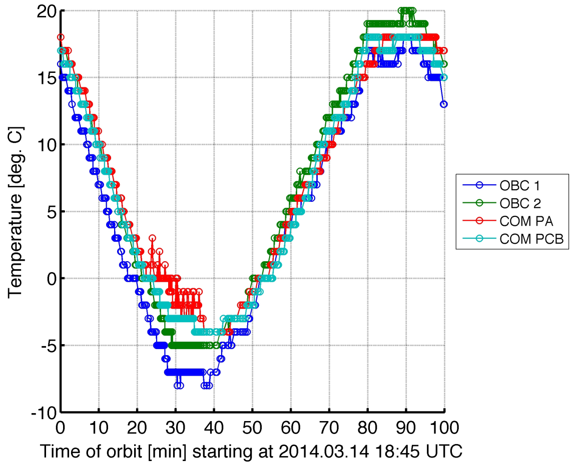

Figure 3: NanoMind A712 and NanoCom U482C Temperatures

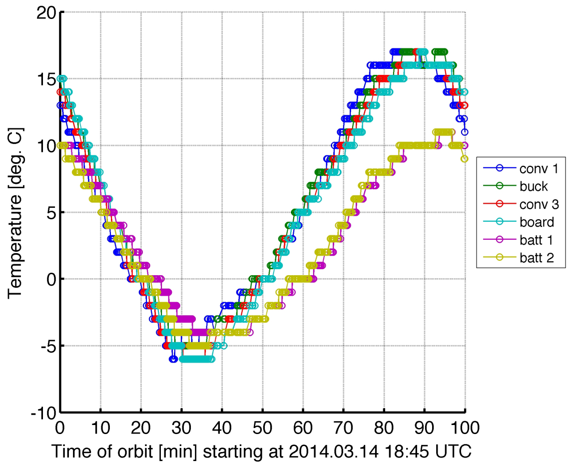

Figure 4: NanoPower P31u Temperatures

The solar panel temperatures (Figure 5) are especially interesting as they are high enough resolution to clearly see the low- and high-frequency temperature changes due to eclipse/insolation and satellite rotation, respectively.

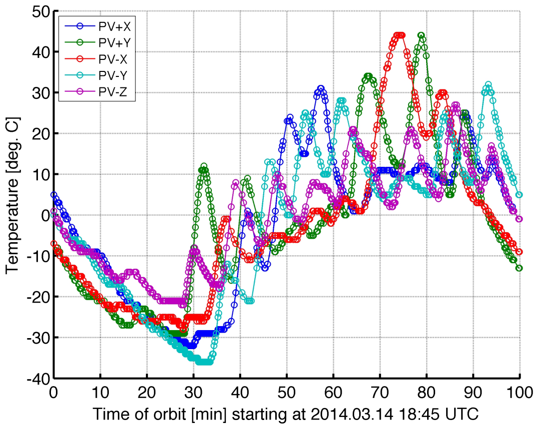

Figure 5: NanoPower P110 Solar Panel Temperatures

On-Orbit Power Budget

The GOMX-1 system has a positive power budget, as shown in Figure 6 below, which is collected during the same orbit as the temperature plots above. Transmission to the GomSpace ground station occurs from minute 25 to 35, during the transition from eclipse to sunlight. The satellite remains power positive, with a minimum battery voltage above 8.0V during a transmission in eclipse.

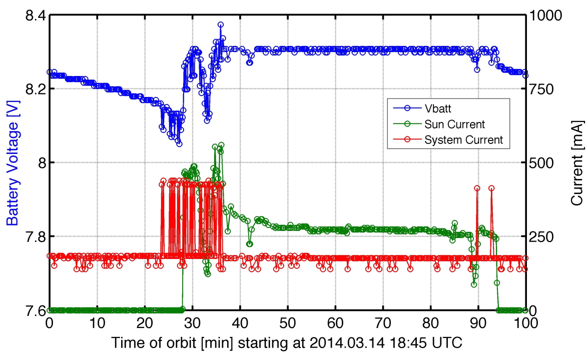

Figure 6: GOMX-1 On-Orbit Power Telemetry

SPACE BASED ADS-B RESULTS

The following subsection provides examples of space based ADS-B data acquired by the GOMX-1 payload.

Raw Samples Over Europe

Figure 7 shows 4 samples of ADS-B signals, as raw samples, acquired by GOMX-1 over Europe in November 2013.

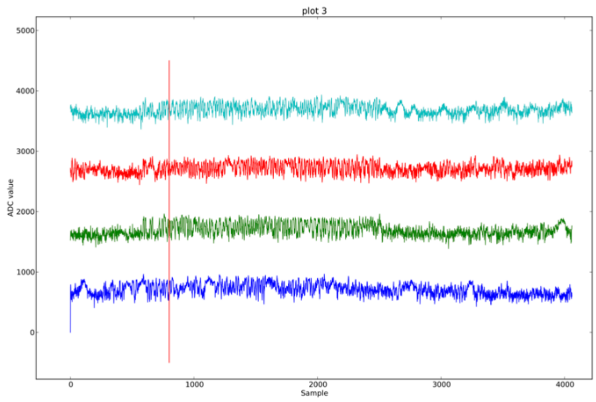

Figure 7: Raw ADS-B sampled collection over Europe

What are interesting from these graphs is not just the signals, but also the fact that disturbances from other radio emitting sources, such as DME (Distance Measuring Equipment) pulses are evident. This means the data can be used to effectively describe the quality of service metrics that can be achieved with a space based ADS-B system.

Northern Hemisphere Overview

Figure 8 shows overview data from the Northern hemisphere acquired during the first week of December 2013.

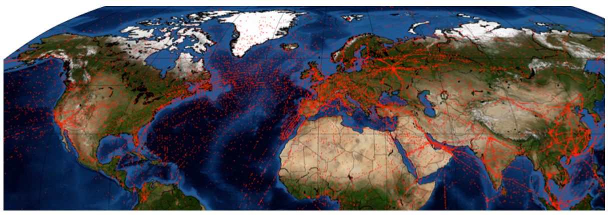

Figure 8: Overview of flights on the northern hemisphere

Such data clearly shows the patterns of the global air traffic system with clear indication of major hubs and routes. For the North-Atlantic region patterns of discrete routes at different latitudes can be seen; optimal route selection changes daily based on weather and air space congestion.

Strong traffic patterns are also evident in the South-East Asia area corresponding to the high level of economic development in this region.

ADS-B deployment on US domestic aircraft is behind ADS-B deployment rates of European aircraft and this also shows in the overview data.

The Middle East

Finally, Figure 9 below shows the air traffic situation in early January 2014 for the middle-East. It is clear from the plot that commercial air traffic avoids flying over troubled areas in Syria.

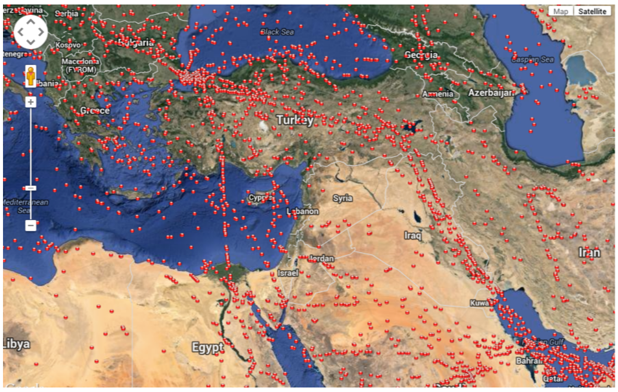

Figure 9: Air traffic in the Middle-East

Location of Flight MH370

Given the incident of the ill-fated MH370 flight from Malaysian Airlines there have been strong interest in the GOMX-1 mission and the possibility of the mission to contribute data to the investigation.

While GOMX-1 has received ADS-B data from the specific Boeing 777 airframe of the MH370 flight on many occasions then unfortunately the satellite was not over the area at the time the MH370 disappeared.

Had GOMX-1 been in the area there is a possibility at least that space based ADS-B data could have helped to understand exactly when the aircraft transponder was shut down and what the location of the aircraft was at that time.

Payload Resets

The GOMX-1 payload includes a flight-programmable FPGA. The FPGA is continuously monitored for bit flips; if one occurs, the ADS-B payload is reset to clear the reset. Over the course of the mission, 26 such power cycles occurred. Figure 10 plots the location of these resets and overlays measurements of high-energy electrons at LEO using CSSWE data[7].

The resets are grouped at locations where high-energy particles are present within LEO. This is a good indicator that the resets are due to bit flips caused by radiation interacting with the payload. However, the low-cost mitigation of these events via subsystem reset allowed the payload to continue collecting data quickly after each event.

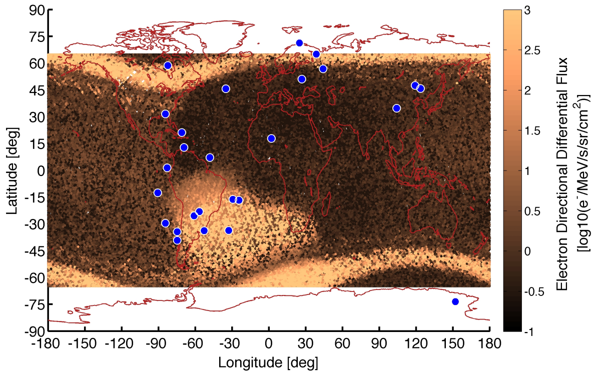

Figure 10: ADS-B payload resets overlaid with electron flux measurements at LEO

LESSONS LEARNED

Lessons learned from GOMX-1 add to the knowledge that GomSpace has accumulated over 7 years in the nanosatellite industry. There is knowledge to be gained in both good performance and unexpected performance. First of all, the satellite commissioning was automated (timed), which allowed the first ADS-B data to be received within hours of launch; this was excellent for the enthusiasm of everyone involved.

The team found that additional testing is especially useful for the communications link. HDMI cables operating at about 400 MHz were found to interfere with the ground station until they were identified as the problem. The inclusion of Forward Error Correction (FEC) has been essential for the 4800 baud link, which is decoded with errors for 90% of the packets received at Aalborg. Also, the polarization of the signal changes from LHC to linear to RHC over a ground station pass; a polarization switch during the pass is therefore used for best performance.

GOMX-1 is the first iteration of the ADS-B payload; as such, a few minor issues were discovered. As mentioned above, the ADS-B helical antenna is ferritic steel which overpowers the magnetorquers due to its large dipole moment. A focus on magnetic cleanliness would have recognized this issue early and used austenitic (non-magnetic) steel instead. Testing in both hemispheres would have shed light on the minor software bug causing the longitude to be unresolvable in the southern hemisphere.

ADS-B PAYLOAD FAULT

On 7th May 2014 the ADS-B payload showed an increased power draw during a nominal ground station pass. In response, the subsystem was power cycled from the ground via the CSP interface. After this power cycle, the subsystem booted up but was not responsive to queries. Based on the power draw of the subsystem (measured from the NanoPower EPS subsystem), the components of the ADS-B payload have successfully booted. The boot order in the software code indicates that the SD card is likely responsible for a reset loop due to a hardware failure. The ADS-B payload has a safe mode which disables the SD card, but there is no pause in the boot sequence which allows the SD card to be disabled before it is initialized. Alternatively, safe mode could be triggered when the subsystem has been rebooted a certain number of times. Either of these features could have extended the ADS-B payload mission and will be included in future versions of this payload.

Although the ADS-B payload mission has ended, the mature GOMX stack continues its stable performance. Further GOMX-1 experiments involving the NanoCam and system software are in progress.

CONCLUSION

The GOMX-1 spacecraft and mission has successfully shown that a 2 kg can contribute to development of new space based services by demonstrating the feasibility of space based air traffic monitoring.

GOMX-1 will continue to operate in the coming years and the ability to upload new software to the on-board computer and payload FPGA will be exploited to further improve the system.

The future will tell if commercial space based services can be developed from this technology using a nano-satellite approach.

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