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NAVIS: PERFORMANCE EVALUATION OF THE AAUSAT3 CUBESAT USING STRATOSPHERIC BALLOON FLIGHT

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This paper documents the usage of a stratospheric balloon flight to evaluate the AAUSAT3 student satellite prototype, called NAVIS (North Atlantic Vessel Identification System). The Balloon EXperiment for University Students (BEXUS) provided a 3 hour long flight in October 2009, and reached a floating altitude of 24 km. This presented a unique opportunity to perform a realistic test of the satellite, including radio communication system and the main payload; Two radio receivers designed to receive live position and identification signals from ships in open seas and around Greenland by monitoring signals from the Automatic Identification System (AIS). Hence, AAUSAT3 is a proof-of-concept, to show that a 1 kg CubeSat is sufficient to monitor AIS from space, when the area of interest is the open sea and around Greenland. The aim of space based AIS monitoring is to extend the limited field of view from ground station based monitoring. The prototype performed as expected for the entire flight, and collected valuable sampled AIS data. More than 25000 AIS messages were successfully received from ships in the northern Scandinavia, and the communication system performed well.

I. Introduction

A student CubeSat project is often characterized by cheap standard components, little or no redundancy, highly experimental design, and only fast and unstructured testing. Missions often fails due to small errors, that can be reproduced on earth and should have been detected before launch. For the design of AAUSAT3, a balloon flight has been chosen for system evaluation one and a half year before planned launch.

The NAVIS project (North Atlantic Vessel Identification System) is the name given the prototype of AAUSAT3, the third CubeSat satellite developed by students from Aalborg University. The satellite is the successor to AAUSAT-II which was launched in 2008 and has now been operational for more than two years – longer than any other Danish student satellite. The AAUSAT3 project was initiated in the fall of 2007 and the satellite is expected to be launched in the first half of 2011. The primary payload of AAUSAT3 is two Au-

tomatic Identification Systems (AIS [1]) receivers designed to study the quality of AIS reception from a Low Earth Orbit (LEO) satellite. AAUSAT3 is a one unit CubeSat, i.e. approximately one kilogram of mass and one decimeter of volume. AAUSAT3 will be the first CubeSat designed to monitor AIS, and to publicly reveal design details and results.

The satellite prototype was tested on a stratospheric balloon flight in October 2009 as part the BEXUS (Balloon Experiments for University Students) programme, which allows European students to test scientific experiments in high altitude conditions. The balloon test served as an excellent opportunity to test the AIS receivers with an extended field of view (FOV) and to acquire realistic samples for further development of the final payload receivers. The NAVIS project also included a test of the main satellite systems: Power supply, batteries, radio link, and ground segment.

The paper is structured as follows. The following section contains a short introduction to AIS. Section II. describes the satellite design, while Section III. is dedicated to present the obtained results.

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I.I Automatic Identification System

AIS is a data exchange protocol standardized by the International Telecommunication Union (ITU), designed to enhance safety at sea by automatic exchange of ship identification and positioning data. All ships with a gross tonnage of more than 300 tons and all ships carrying passengers are required by law to have an AIS transponder on board. For all other ships it is an optional safety feature. At regular intervals, AIS transponders broadcasts information such as their Maritime Mobile Service Identity (MMSI) number, position, speed, and name, to nearby ships as well as shore based stations.

Recently, investigations on the possibility of receiving AIS signals in space has received much attention, since a satellite based receiver will be able to cover a much wider area than conventional ground station networks. AIS was originally designed as a completely ground-based system, and reception of AIS signals in space thus impose a number of challenges that must be addressed, such as reduced signal strength and increased packet collisions.

II. Method

AAUSAT3 is designed to be a highly modular and distributed design, with strictly defined subsystem interfaces and tasks. Compared to the satellites predecessor AAUSAT-II, which is a monolithic system based on a centralized On-Board Computer (OBC), this presents a number of advantages, most importantly the parallelized development and testing.

This section describes the AAUSAT3 prototype subsystems. The experiment consisted of a subset of the AAUSAT3 subsystems, illustrated in Figure I. The main payload is two AIS receivers based on two different receiver structures and demodulation methods. These are used for testing how different solutions will react to the extended FOV and to evaluate the two solutions for further development of AIS receives for the final satellite. The AIS1 subsystem performs demodulation of the signals with a commercial radio front-end and processes a serial output to decode the AIS messages. AIS2 is a software based receiver, that samples a down converted intermediate frequency output and stores it for later processing. Because the two AIS receivers are completely independent, the probability of success is increased even if one of the subsystems should malfunction during the flight. However, they share a common VHF antenna and Low Noise Amplifier (LNA).
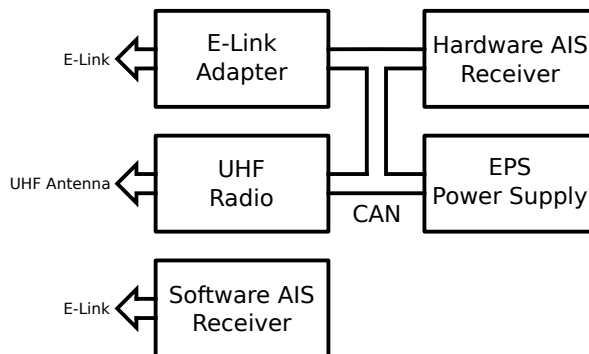

Figure I: Subsystem structure and communication interfaces.

In order to keep the system as modular as possible, the internal communication between subsystem is handled on a CAN-bus (Controller Area Network) using the network-layer CubeSat Space Protocol (CSP). CSP was originally developed for use in AAUSAT3, but is now jointly maintained by the AAUSAT3 students and involved persons from the open source community[2]. The protocol allows subsystem programmers to use socket-like communication between subsystems by assigning addresses to subsystems and ports to available services, hence hosting services to reply to requests. All subsystems except AIS2 are based on Atmel AVR8 micro controllers. The AIS2 receiver has high requirements for processing power and therefore uses the ADSP-BF537 digital signal processor from Analog Devices, which also is experimental to fly in LEO. AIS2 is equipped with a dedicated E-Link connection to allow transfer of large AIS samples to ground. The ELA (E-Link Adapter) is developed specifically for use on the BEXUS flight to bridge the internal CAN-bus network with the BEXUS provided E-Link, as a redundant communication channel from the ground segment to the experiment. The E-Link is an Ethernet connection provided to all on-board experiments, used for telemetry and telecommands.

II.I AIS1

AIS1 is a hardware receiver based on the Analog Devices ADF7021 radio transceiver. The transceiver demodulates the radio signals from one of the two AIS channels to a 9.6 kb/s data stream. This is connected using a Serial Peripheral Interface (SPI) to an Atmel AVR micro controller that processes and decodes the

data. The received AIS messages are decoded and messages with both correct and incorrect Frame Check Sequence (FCS) and stored on permanent storage for later analysis. Messages and reception statistics were downlinked during the flight, using both the UHF of ELA. The power consumption of AIS1 peaks at 300 mW[3].

II.II AIS2

AIS2 is an Software Defined Radio (SDR) prototype. The subsystem samples the raw Intermediate Frequency (IF) output of a hardware down conversion of the AIS radio signals. A 200 kHz wide frequency spectrum covering both AIS channels around 162 MHz, is down converted to a 200 kHz IF and is sampled with 1 MSPS simultaneously on the Inphase and Quadrature output. A Digital Signal Processor (DSP) is used for filtering and demodulation of the data[4]. Each sample is 8 MB in size and contains 2.175 seconds of sampled data. The size of a continuous sample is limited by the size of high speed memory on AIS2. The raw sample files were saved on permanent storage during the BEXUS flight, so that demodulating algorithms can be optimized before the launch of AAUSAT3. AIS2 is equipped with a dedicated E-link connection, and raw samples were downlinked to ground during the flight. AIS2 has a peak power consumption at 924 mW.

II.III EPS

The main task of the Electronic Power Supply (EPS) is to monitor the batteries and to supply regulated voltages to the individual subsystems. The EPS has one dedicated power channel per subsystem and is able to turn these on and off individually, and to monitor the power consumption of each subsystem. The EPS is also in charge of monitoring housekeeping data, to verify that subsystems are running nominally or if a subsystem fails to respond on the internal communication interface. As a fault recovery mechanism in case of software failure, the EPS reboots all of the experiment subsystems, including the EPS itself, if an internal timer is not manually reset from the ground station every 20 min. This resets the ELA and UHF to their default settings and prevents the subsystems from staying in a locked-up state for the entire balloon flight. For the BEXUS flight, the EPS was equipped with three times the battery capacity of AAUSAT3 because all subsystems were powered on during the entire flight, and the prototype did not carry any solar panels for recharging the batteries. Furthermore, the EPS was connected

to 10 temperature sensors in the satellite and an 8 W regulated heating system, in order to heat up the experiment box if needed.

II.IV UHF

The UHF radio is novel design developed for AAUSAT3 and is based primarily on the work in [5]. The thesis focus on the development of a new radio system for amateur spacecrafts and uses a commercial off-the-shelf radio transceiver. The coding and space link protocol design is based on the CCSDS standard, and uses a concatenation of convolutional and Reed-Solomon error correction codes. This is a large improvement over traditional AX.25 based CubeSat radio systems, that only uses error detection. Flying the UHF radio on the high altitude balloon will influence the system in ways similar to that of a LEO satellite, and provides a unique possibility for a long range test not otherwise possible. The goal of the test is to predict and model the effect of these influences and to test the ability to maintain a reliable data-link for telemetry. The UHF radio operates on an allocated channel at 437.475 MHz in the amateur satellite frequency band.

II.V ELA

The E-Link Adapter (ELA) acts as a gateway between the BEXUS provided E-Link, and the internal CAN-bus by encapsulating CSP packets in UDP datagrams and forwarding them to ground. By using both E-Link and the AAUSAT3 UHF subsystems, the experiment subsystems had completely transparent and redundant communication channels.

III. Results

The BEXUS balloon flight took place on October 11th 2009, from Esrange Space Center in northern Sweden. The total flight had a duration of more than 3 hours, and had a float period in a constant altitude of 24 km for 2 hours. The AAUSAT3 prototype was working during the flight with all systems running operational. Monitoring and control was done from the NAVIS ground station placed at Esrange, Northern Sweden, using both the E-Link and the UHF radio.

In total AIS1 received 25196 AIS messages with correct FCS, of which 17000 were received in the float period. Furthermore 70000 AIS messages were detected with correct length and start/stop flag, but with invalid FCS. AIS2 saved 200 sample files each containing 8 MB

of raw data each, corresponding to 200 times 2.175 sec of traffic.

This section further explains the results from all the subsystems.

III.I AIS1

The AIS1 data has been subject to a post-flight analysis, which is explained in detail in [6]. A total of 25196 AIS messages with valid FCS were received and stored during the flight. The messages have been decoded and analysed with a custom developed MATLAB tool. AIS messages of type 1, 2 and 3 contains position reports from ships carrying Class A transponders. These contain the MMSI number, position, speed, and course over ground.

The received data set has been compared with reference data from the coverage area provided by the Danish Maritime Safety Administration (DaMSA). Table I identifies the number of messages received by AIS1 and the messages received by the reference ground stations in the same time window. Of the unique MMSIs received by AIS1 and the reference data, 151 were located in both data sets. AIS1 received in average 69 AIS messages per MMSI, while the reference data from DaMSA on average contained 9 AIS messages per ship, which is due to the message filtering used in the reference database.

Description	AIS1 Data	Ref. Data
Total messages	25196	2833
Ships	339	309
Ground Stations	24	-

Table I: Number of decoded AIS1 messages and reference data.

A subset of AIS position reports also contains the number of other ships within range of the transmitting ship. These numbers can be exploited to estimate the average size of the TDMA zones by calculating the average number of ships within range. The average number of ships within range of another ship was found to be 12. In comparison, each ground station in FOV synchronized its transmission with 21 transponders in average. The histogram in Figure II illustrates the number of ships within range of each ship, as reported in the AIS messages.

The histogram shows that there is a large amount of ships with only few ships within range. This can be explained by ships located inside the fjords of Norway, where mountains block the signals from ships that would otherwise be within range. Larger zones with many ships indicate that the size of a TDMA zone vary a lot from ship to ship and area to area.
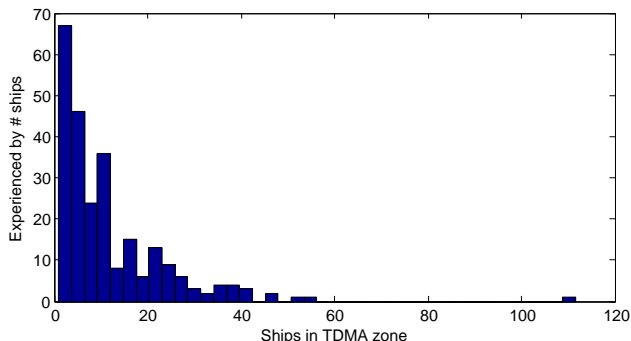

Figure II: Number of ships within range of each ship.

Figure III shows the theoretical coverage area around the balloon flight and a plot of the received position reports. The balloon trajectory is illustrated by the black line, and line of sight from the balloon gondola is indicated by a circle of 550 km in radius. The AIS1 data is plotted with circles illustrating ground stations and crosses indicating a received position report from a ship.

The theoretical FOV is limited by the curvature of the earth and the antenna configurations for both AIS1 and the transponders. The estimated coverage area appears to agree well with the received position reports. A number of messages were received from a Finnish ground station 70 km outside the expected coverage area, which is believed to be explained by a high position of the antenna at the ground station.

The received data shows that the most common dynamic condition was ships sailing at 0-14 knots. This was observed in 72 % of the cases and yields a reporting interval of 6 s. The second most common dynamic condition was ships sailing at 0-14 knots while changing course, which was the case for 20 %, corresponding to a reporting interval of $3^{1/3}$ s. It is noted that only few messages were received from ships at anchor, which is due to the low reporting interval of 3 minutes.

The 158 ships detected in the reference data set, but not by AIS1, can be partially explained by 20 ships located outside the theoretical FOV. Also, four ships had Class B transponders and 14 Class A transponders were at anchor resulting in a high reporting interval.
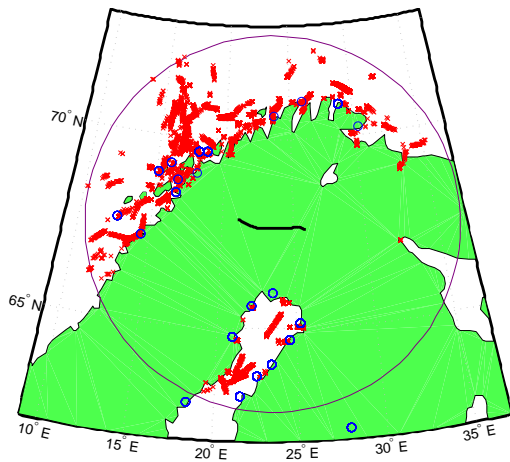
Figure III: Balloon flight trajectory, AIS1 data and theoretical coverage area. Circles show ground station positions and crosses illustrates messages from ships.

The rest can not be sufficiently explained by these reasons. From DaMSA's database is not possible to decide whether these were Class A or B transponders. However, this still indicates that not all ships within the FOV were detected by AIS1.

The reference data can not be used to estimate the detection ratio, since the reference data was not limited to ships within FOV nor did it cover the entire FOV.

The ships detected by AIS1 that were not in the reference data, were mostly outside the range of the ground stations, because the reference data did not cover the far north of Norway, nor the Finnish coast. However, the AIS1 receiver did detect ships within the area of the reference data that were not detected by other ground stations. This indicates that the landscape might have caused problems both for the ground stations and the experiment, and this is also indicated by the closely placed AIS ground stations in the northern fjords of Norway.

A method for evaluating the quality of AIS reception has been developed. Based on the highly predictable transmission interval of AIS transponders, that is depending on the dynamic conditions of the ship, the number of lost transmission per ship is estimated. This data interpolation is based solely on the data received by AIS1 during the float period. For ships, the data interpolation extended the AIS1 data set from approximately 17000 to 106000 AIS messages, meaning that 15.9 % of the messages available were received. For more information on this method, please refer to IAC-10.B4.2.11.

III.II AIS2

AIS2 was working as expected during the balloon flight. More that 200 raw samples were saved, with each sample containing 2.175 s of data. Of approximately 1.6 GB of data sampled during the flight, around 350 MB was downloaded in flight using E-Link. All samples were stored on permanent storage for post flight analysis.

The first AIS message was received in 4.3 km altitude from a ground station located 180 km from the gondola. Figure IV shows the frequency content as a Fast-Fourier Transform (FFT) waterfall plot of one of the 200 sample files that AIS2 saved during the flight. The two AIS channels are clearly seen at the two frequencies 161.975 and 162.025 MHz. During the balloon flight AIS2 detected 27 AIS messages in average on each channel in the 2.175 s. With a channel capacity of 37.5 messages pr. second pr. channel, this gives an estimated channel usage of 33.1 %.
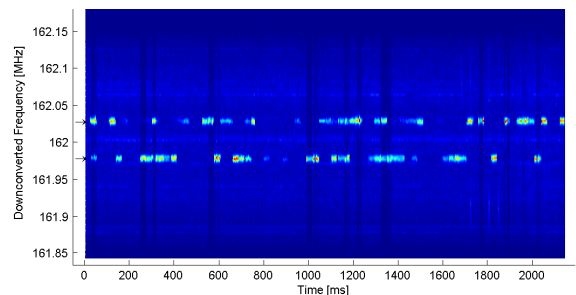

Figure IV: Frequency analysis of a raw sample file from AIS2 in 24 km altitude.

The structure of the demodulator is fairly simple. A 5th order Butterworth filter is used to filter out the two AIS channels, and a matched quadrature FIR filter is used to demodulate the GMSK modulated signal. An example of the soft output of the demodulator is shown in Figure V, where the preamble of an AIS message is detected. The crosses indicates the clock recovery (bit placement) of the 9.6 kb/s AIS data transmission. By evaluating the sign of the soft demodulator output in these points, the transmitted data can be recovered. The figure shows an NRZI encoded training sequence of alternating ones and zeros and followed by a HDLC start flag of 0x7E.
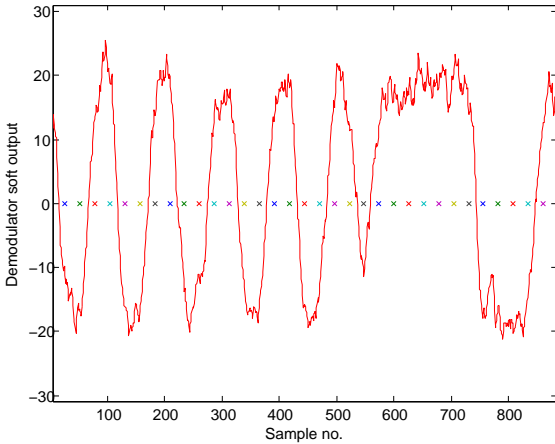
Figure V: Start of AIS package, demodulated by AIS2.

Figure VI: UHF RSSI (Received Signal Strength Indicator).

III.III UHF

The radio equipment on both ground station and the experiment were similar except for the antenna configuration. A half-wave omnidirectional monopole antenna was hanging beneath the balloon gondola, while a 15 element Yagi-Uda antenna was used on the ground station. A transmission power of 30 dBm was used for both the experiment and ground station, with a 2FSK modulation scheme and adjustable data rate, modulation index and error correction. The default data rate was 9.6 kb/s with both convolutional and Reed-Solomon encoding enabled. The link was tested at speeds ranging from 1.2 to 19.2 kb/s. Even at the maximum range between balloon and ground station of 200 km, a telemetry data rate of 19.2 kb/s was maintained without problems. The UHF ground station was placed at Esrange, and a total of 10.400 packages were transmitted through the link. Figure VI shows the Received Signal Strenght Indicator (RSSI) for the UHF datalink. The silent period in the middle was due to a time windows allocated to receive AIS without possible interference from the radio link to verify that the EMC design and shielding was sufficient for the UHF subsystem not to disturb the AIS receivers. The lower period from 4000 to 5000 s after launch can possibly be explained by the UHF ground station antenna pointing close to the E-BASS antenna setup.

III.IV Electronic Power Supply

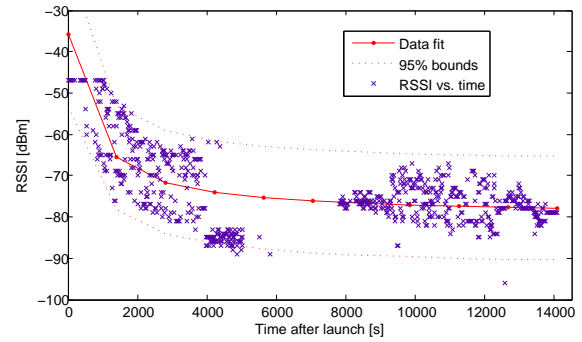The EPS monitored healthy batteries during the entire flight and registered enough spare capacity after the flight for at least 5 additional hours of full operation. No subsystems exceeded their power limit and all regulated voltages were stable during the flight. The internal temperature sensors measured values in the range from 9°C to 26°C, with the warmest being the UHF power amplifier and the coolest being the batteries. The high internal temperatures compared to the ambient temperature of less than -40°C, was achieved with 5 cm insulation and active heating on the batteries. The heating was automatically enabled when the internal temperature dropped below 10°C, but was only briefly used near the end of the balloon float stage even though the whole experiment dissipated less than 2 W. During the flight, the EPS was used to shut down subsystems temporarily, mostly for subsystems containing radio receivers when measuring the noise floor and to compare the AIS quality with the UHF powered on and off.

III.V E-link Adapter

The ELA was responsible for converting the internal CAN-based CSP traffic to Ethernet UDP datagrams for communication through the E-link provided by the launch provider. The ELA generally performed as expected and routed 36522 packets between the experiment and the ground segment. The subsystem did have three temporary failures due to wrong error handling. The ELA watchdog timer was however able to perform a reboot to recover nominal functionality. During normal operation, no packet loss was experienced. As the subsystem was only designed to be used for the balloon experiment, and will not be used in the final satellite, no further investigation of the cause of the errors have been carried out.

IV.   Conclusion

The satellite prototype was working as planned and the only problems were small and manageable. The quality and quantity of AIS data exceeded the expectations prior to the flight and supported the possibility that AAUSAT3 will be able to receive AIS messages in LEO when launched.

The NAVIS experiment has taken the development of AAUSAT3 through a key iteration, both regarding hardware and software prototyping. All key subsystems for the satellite were prototyped and tested for the balloon flight and a list of design improvements has been specified after the NAVIS experiment, including missing features and new requirement revealed by the balloon test. Furthermore, it has been a valuable opportunity for the students to gain experience in design and production of high quality hardware and software, with a broad aspect from RF circuits to high speed digital signal processing. In software design, prototyping and testing, fault tolerant principles were used to increase the chances of success and to confine errors within each subsystem.

The extent and size of this project has been a unique experience in project planning for all involved students, that will help in the final phase of the AAUSAT3 project.

Additional work is needed on the Attitude Determination and Control System (ADCS), and the antenna deployment before launch in 2011.

More information can be found on the AAUSAT3 website at http://aausat3.space.aau.dk/.

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