IAC-13-B4.3.1

IN-FLIGHT OPERATIONS OF A HIGH-AVAILABILITY NANOSATELLITE CONSTELLATION FOR MARITIME OBSERVATION

Alexander M. Beattie
University of Toronto Institute for Aerospace Studies-Space Flight Laboratory, Canada, abeattie@utias-sfl.net

Øystein Helleren
Forsvarets Forskningsinstitutt, Norway, Oystein.Helleren@ffi.no

Robert E. Zee
University of Toronto Institute for Aerospace Studies, Space Flight Laboratory, Canada, rzee@utias-sfl.net

The Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies (UTIAS) in Toronto, Canada has been a pioneer in nano- and microsatellite technologies since the launch of its first satellites in 2003. Since then, UTIAS/SFL has launched five more nanosatellites, ranging in size from 3 to 7 kg and spanning several different generations of technology and mission profiles. This makes UTIAS/SFL one of the largest and most experienced nanosatellite builders and operators in the world.

The Automatic Identification System Satellite no. 1 (AISSat-1) was launched on July 12, 2010 into a 635 km sun synchronous orbit by an Indian PSLV rocket from Satish Dhawan Space Centre in Andhra Pradesh, India. AISSat-1 is a six kilogram nanosatellite based on the Generic Nanosatellite Bus (GNB) satellite platform, and was designed, built, and commissioned in orbit by UTIAS/SFL The second satellite in this series, AISSat-2, has been completed and will be launched in 2013. The third satellite, AISSat-3, is under construction and will be launched in late 2014 or early 2015.

The primary mission of the AISSat-series of satellites is to receive maritime Automatic Identification System (AIS) message traffic within the primary observational area over Norwegian territorial waters, especially in the High North. Each satellite operates at a high duty cycle, with most of the coverage area revisited every orbit. Data is received, decoded, downloaded, and distributed into the Norwegian Coastal Authority's live ground network to end users in real time. The program is funded by the Norwegian Space Centre, and managed and operated by the Norwegian Defence Research Establishment (FFI).

The AISSat constellation provides a high degree of observational and monitoring capability assurance to the Norwegian maritime authority. Using a highly capable nanosatellite platform, this has been achieved at very low cost relative to other approaches to such a capability. This paper will discuss the in-flight operational experience and performance of the AISSat-1 satellite, and the combined constellation of all three satellites. In particular, the observational availability of the system based on in-flight experience will be highlighted.

I. INTRODUCTION

In recent years, nanosatellite technology has matured to the point where it can now be used to enable aggressive, timely, and relevant missions for users whose only options previously were larger, more expensive satellites, or a non-satellite solution with much greater cost or lower coverage and flexibility. The Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies (UTIAS) has been a pioneer in nanosatellite technologies since the first 1-kg CubeSat satellites were conceived and designed, and launched its first nanosatellite as part of the first CubeSat cluster launch in 2003. Since then, five more nanosatellites have been launched by SFL as summarized in Table 1.

Table 1: SFL Nanosatellite Launch History

Satellite	Launch Date	Mission
CanX-1	June 30, 2003	Technology Demo
CanX-2	April 28, 2008	Technology Demo, Atmospheric Science
NTS	April 28, 2008	Space AIS Demo
AISSat-1	July 12, 2010	Space AIS Operational Demo
UniBRITE	February 25, 2013	Space Astronomy
BRITE-Austria	February 25, 2013	Space Astronomy

Each mission has not only raised the bar in terms of technological maturity and performance, but also in the aggressiveness and import of the mission. Early nanosatellites, both from SFL and other organizations around the world, were primarily technology demonstrations. With AISSat-1, and the first deployment of the Generic Nanosatellite Bus (GNB) platform, near-operational real-world problems have now been demonstrably tackled by a nanosatellite platform.

This paper summarizes both the GNB platform in general and its tailoring and implementation in the currently operating AISSat-1 mission. The introduction of a second and third satellite, AISSat-2 and AISSat-3, into the Norwegian maritime observation system is also discussed along with a summary of the effect of the additional satellite on the overall system reliability and availability.

II. THE GENERIC NANOSATELLITE BUS

The Generic Nanosatellite Bus is an advanced nanosatellite platform that was developed by SFL as an evolution of the older CubeSat-based missions. In addition to the satellite bus itself, the GNB platform also includes a baseline supporting ground segment implementation in order to provide a reliable, complete end-to-end system.

Knowledge and flight experience gained from the earlier programs, along with important input from users regarding what scope of platform would be useful for more demanding missions, was used to define the next-generation nanosatellite platform. The GNB was originally co-designed by two SFL programs with very different mission requirements:

- The Bright Target Explorer (BRITE)[1]. BRITE is a six-satellite optical space astronomy constellation formed by an international collaboration of Canadian, Austrian, and Polish teams each building two complete satellites.
- The CanX-4 and CanX-5[2] dual-satellite mission, which is an enabling technology demonstration performing autonomous precision formation flying.

As a result, the GNB platform can easily accommodate a wide variety of payloads and operational profiles with minimal modification to the core satellite bus. AISSat-1 is a very good example of this capability, as the mission was defined and implemented long after the GNB platform design was complete. Several other missions, such as the Antarctic Broadband demonstrator[3], have also used the GNB platform as a basis.

The GNB platform is a complete satellite system that can be tailored as needed to mission needs. The tailoring process is a combination of tailor-by-omission tailor-by-modification approaches, with an emphasis on keeping design modifications to a minimum. This reduces overall schedule and cost, and minimizes the risks associated with design modifications to flight-qualified systems while maintaining the flexibility to address differing mission requirements.

The GNB is an advanced ~6 kg nanosatellite platform in a 20-cm cubic form factor. It is designed such that the bulk of the bus electronics are generic, and their accommodation in the satellite does not change from mission to mission. An example of two fully assembled GNB satellites, AISSat-1 and the first BRITE, is shown in Figure 1.

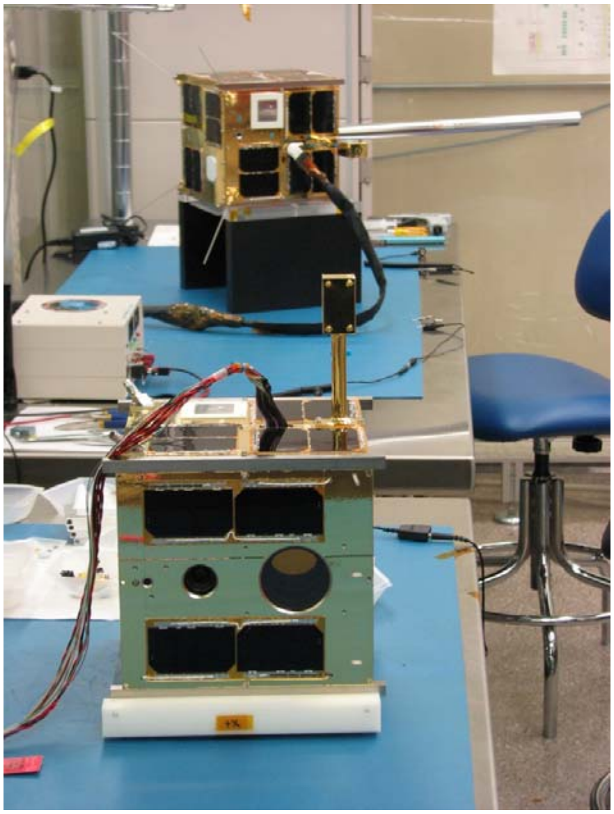

Figure 1: AISSat-1 (background) and UniBRITE (foreground)

The internal structural concept is shown in Figure 2. The platform is designed around two structural trays that house the majority of the satellite electronics, including all of the generic bus systems, around which are attached panels housing additional functionality. In addition to bus systems, additional space in these trays is available for payload support electronics (e.g. a dedicated payload computer) as needed on a mission-by-mission basis. Only minimal modification of the structure is typically necessary for different missions.

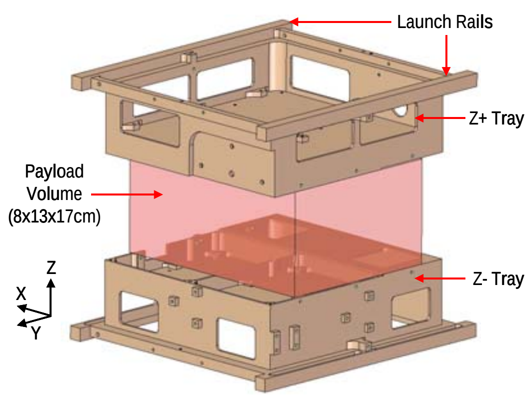

Figure 2: GNB Structural Concept

The main payload area is located in the centre volume of the satellite. A large proportion of the satellite's volume is available for use by the payload, and it is constrained only in a simple shape and mounting method. This allows great flexibility in accommodating different payloads. Locating the payload in the centre of the satellite also provides a very stable thermal environment, and access to four different surfaces for payload elements that must protrude through or have visibility beyond the outer structure of the satellite, such as antennas and instrument apertures.

The platform contains all the elements necessary for a wide variety of missions, including:

- Dual, redundant 5.2 A-hr batteries with independent charge/discharge regulation
- Body-mounted solar arrays providing power generation in all attitudes
- Dual parallel and interchangeable 60 MHz on-board computers, normally dedicated to housekeeping and attitude control duties, respectively
- Customizable payload control and data processing computer, up to 1 GB of storage
- Omnidirectional 4 Kbps UHF command uplink
- Omnidirectional S-band telemetry and payload data downlink (up to 1 Mbps, commandable)
- Hemispherical coverage GPS receiver for positioning and timing
- Full attitude determination and control system, based on a customizable suite of sensors (sun sensors, rate sensors, magnetometer, star tracker) and actuators (reaction wheels, magnetorquers). Multiple control modes are available (e.g. inertial, nadir-tracking).

Functionality that is not needed for a given mission can be omitted. For example, if a mission does not require high precision attitude control the star tracker may be omitted.

The GNB platform is designed to allow a high degree of operations flexibility and autonomy. A typical GNB mission will require much less than one full time operator to task, monitor, and maintain the system. Payload operations are typically scheduled either by an on-board scheduling mechanism or via time tagged scripts that are pre-generated by a ground tasking system and uploaded to the satellite in advance. The on-board time-tagging system allows a high degree of control and can support easy insertion of new commands at any time to allow emergency or limited-opportunity activities on short notice.

III. AISSAT-1

AISSat-1[4-6] is a Norwegian nanosatellite, funded by the Norwegian Space Centre and managed by the Norwegian Defence Research Establishment (Forsvarets Forskningsinstitutt, FFI). FFI also maintains the Mission Control Centre (MCC) for the satellite and performs all mission operations. The satellite bus was designed and manufactured by SFL, and all satellite assembly, launch, and commissioning activities were conducted by SFL with support from FFI for payload activities. The payload electronics module was designed and built by Kongsberg Seatex in Norway.

AISSat-1's original mission was to investigate the ability of a satellite platform to receive data from the maritime Automatic Identification System (AIS) and to demonstrate how this data can be disseminated and used by end-users in an operational system. The primary area of interest is the Norwegian coastal waters and areas of the High North under Norwegian authority. These are large areas of open ocean, as shown in Figure 3, much of which was previously not actively monitored on a regular basis.

The mission operations architecture is summarized in Figure 4. All operational elements are located in Norway. The main Mission Control Centre is located in the outskirts of Oslo, at the FFI campus, where all tasking and mission operations are performed. Commands, telemetry, and payload data are routed between FFI and the satellite via a secure ground network, and the satellite's primary Earth station facilities are located at the Kongsberg Satellite Services facility on the island of Spitsbergen in the High North. From this vantage point, real-time observations over the primary coverage area can be performed on every orbit. From the MCC, payload data is distributed in real-time to the Norwegian Coastal Administration's data centre and its live data network.

Figure 3: AISSat-1 Primary Coverage Areas (Courtesy FFI)

The satellite observes in one of two fashions: firstly, due to the location of the Earth station facilities the majority of the Norwegian area of interest can be observed in real time during Earth station contacts. In this mode, AIS messages are received by the satellite and immediately sent to the ground as high-priority traffic; an automated distribution system forwards live traffic on to the Norwegian Coastal Administration (NCA) with a typical latency of <1 second. Secondly, AIS messages can be stored on board and later retrieved by the ground. The ground can request stored data in several forms, including all messages observed by the satellite regardless of status, or a reduced set of filtered and sorted data. This mode allows the satellite to observe anywhere in the world and return the data to the ground at the next opportunity.

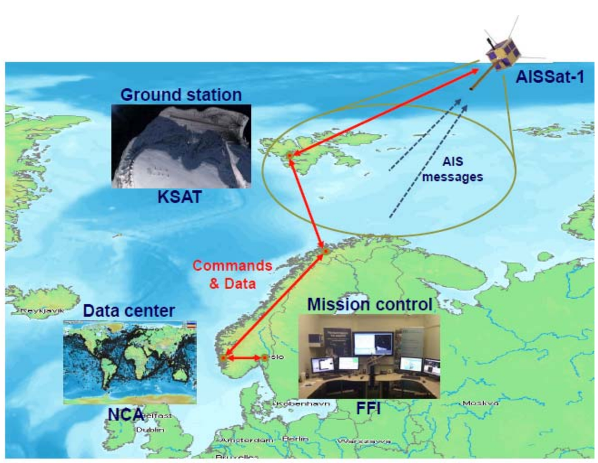

Figure 4: AISSat-1 Operations Architecture (Courtesy FFI)

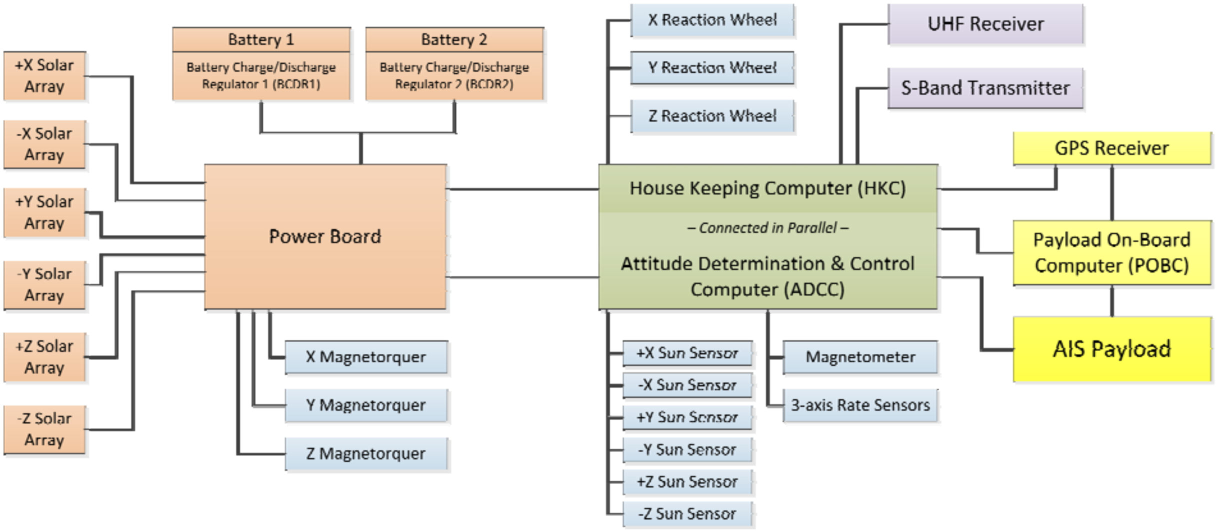

Figure 5: AISSat-1 Electrical Architecture

AISSat-1 was designed with a full complement of GNB hardware and software in addition to its payload elements, with the exception of a star tracker which was not required. In addition to supporting the AISSat-1 mission, the nearly-complete complement of GNB options allowed flight heritage to be gained on the very first mission. The electrical architecture is shown in Figure 5, with payload elements shown in yellow; the remainder are generic GNB components. The external features of the satellite are shown in Figure 6.

AISSat-1 carries two dedicated payload elements in support of its mission:

- A dual-channel high sensitivity AIS receiver, designed and manufactured in Norway
- A monopole VHF antenna, providing wide area ground coverage, designed and manufactured by SFL

In addition, two additional GNB equipment options are carried as payload support elements:

- A payload operations computer, handling data routing, payload management, payload data storage, and payload data product generation
- A GPS receiver to provide orbital position knowledge and precise timing

The VHF payload elements were a particular design challenge for this mission to accommodate and ensure optimum AIS message detection performance.

Demonstrating the advantages of the GNB design approaches, AISSat-1 was completed in a truncated satellite development program with the preliminary design phase omitted and the critical design phase highly accelerated.

AISSat-1 was successfully launched on July 12, 2010 and has recently completed its third year of successful operations. The satellite continues to operate well.

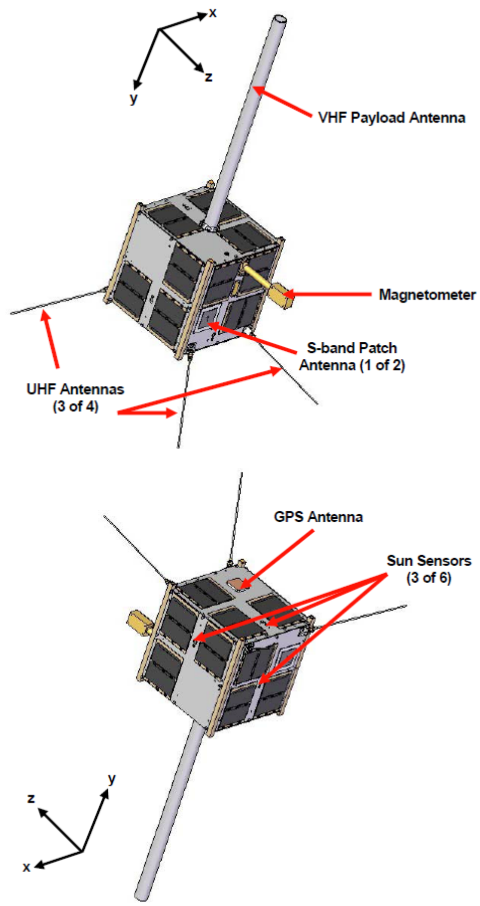

Figure 6: External Layout of AISSat-1

IV. THE AISSAT CONSTELLATION

Following the success of AISSat-1, the Norwegian authorities decided that the AIS-from-space capability had proven to be extremely valuable and the usage of its data in the operational AIS network was of long-term strategic interest.

In order to maintain the capability, a second satellite, AISSat-2, was ordered in early 2011. AISSat-2 is a build-to-print copy of AISSat-1 and is expected to be launched in late 2013. As of the time of writing, the satellite has been fully acceptance for flight and is in storage awaiting launch. The completed satellite is shown in Figure 7.

A third satellite, AISSat-3, was purchased in the summer of 2013 and is now under construction. This satellite is expected to be launched in late 2014 or early 2015.

The presence of AISSat-2, and eventually AISSat-3, in orbit along with AISSat-1 results in a system with increased capability over a single satellite. There are three areas in which the system is improved: reliability against critical hardware faults, reduced operating area revisit time, and increased overall observational availability.

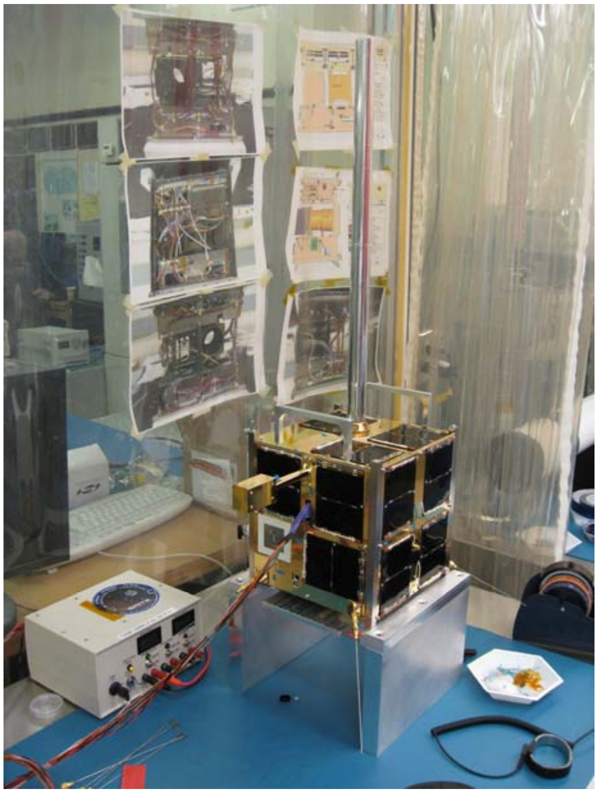

Figure 7: The flight-ready AISSat-2

IV.I Critical Fault Tolerance

AISSat-1 was original designed assuming a three-year mission, which has since passed although it continues to operate well. However, SFL's experience is that in the absence of well-defined consumables on-board (e.g. fuel), the design mission life is really only a guideline, and significantly extended missions typically result. For example, the MOST[7] microsatellite, designed and built in part by SFL and utilizing the same philosophies, is now in its eleventh year of continuous operations. The CanX-2[8] and NTS[9] nanosatellites, both designed for a one year mission, are now in their sixth year of continuous operations.

The primary purpose of AISSat-2 and AISSat-3 is to provide a higher level of capability assurance. Specifically, it is to be considered an in-orbit backup to AISSat-1 to avoid a loss of AIS-from-space capability should there be an on-board failure that results in a loss of AIS data capture capability. In this sense, the two satellites will be backups for each other and provide the overall system with a full single fault tolerance capability. Through this redundancy, Norway's AIS-from-space capability has a higher degree of assurance of continuity.

IV.II Reduced Revisit Time

AISSat-1 is in a 635 km altitude sun-synchronous orbit with an ascending node of approximately 22:00. Due to the location of the Earth station, within the primary area of interest, real-time observations occur on every orbit, and recorded observations are typically downloaded within one orbit. Thus the primary areas in the High North have a worst-case revisit time of one orbital period (approximately 97 minutes), and the entire globe is mapped at least twice per day.

A second satellite will decrease the revisit time, depending on the orbit and its phasing with AISSat-1. The orbital parameters for AISSat-2 are not yet finalized and will not be controlled following deployment from the launch vehicle. Thus, the phasing with respect to AISSat-1 will vary over time. As such, the revisit time will vary over time from being equal to the single satellite case, to a best case of half of the single satellite case (44 minutes in the High North, and at least four times per day globally). In addition to the potential reduction in revisit time, the added observation time over any particular point on the globe will increase the vessel detection rate, especially in areas of higher traffic.

IV.III Increased Availability

An additional benefit to operating multiple AISSat-series satellites together in orbit is that it allows a greater degree of availability of AIS-from-space data should there be an interruption in operations of one of the satellites. Although it was not designed with a specific availability requirement in place, the GNB platform was nevertheless designed to maximize its ability to support reliable operations within the overall design philosophy and program constraints. Additionally, it has been designed to maximize the degree of automation for normal mission operations, minimizing the costs associated with spacecraft operations.

However, there are occasional functional interrupts in the space segment that result in a loss of availability. In this instance, availability is defined as the capacity of the system to support AIS data collection at an arbitrary point in time, most critically at any time when the satellite is in view of the Norwegian areas of interest. In general, however, AIS data collection occurs continuously, thus availability requires that the satellite be fully operational at any moment in time. Most importantly this includes full operations during real-time observations in the high north, where live AIS data is forwarded to the end users by the satellite, via the mission control centre, in less than one second from the time it is sent by the vessel. Based on accumulated in-orbit operations data from AISSat-1 from January 2011 through to July 2013, the overall space segment availability has been observed to be 97.37%.

To a significant extent, this availability is driven by the level of operator support provided to the satellite's operations. Given the demonstration nature of the mission, there is limited operator support provided for the space segment. Operations are largely automated and in normal operations operator support is only required for the once-weekly satellite tasking, during which time the next weeks' worth of operations are uploaded to the spacecraft. At all other times, operators monitor the state of the system on a 8-hours-a-day, 5-days-a-week basis primarily through review of the status emails generated by the ground segment, which provide a complete picture of both space and ground segment status and performance. Thus, in normal operations very little operator time is required to maintain the complete system and is achieved with very low operational cost.

The achieved availability is limited primarily by the response time of an operator to address a functional interrupt, and not the frequency, severity, or type of interrupt. All of the observed interrupts could be addressed by a single operator within a single contact period of identification, meaning that on average each interrupt could be mitigated within half an orbit if 24-7 operator support were available. Alternately, as the characteristics and response to these events is well defined, ground-based automation could be implemented to affect a recovery. The upper limit of system availability through these methods is around 99.86%, at a substantial cost of requiring full time operator support or implementation of complex event detection and recovery software. As an alternative, preventative maintenance measures have been identified that could result in a relatively small increase in weekly operator workload, but a proportionally large increase in overall availability to approximately 99.49%.

With two satellites in orbit a boost in overall system availability can also be achieved. The functional interrupts on AISSat-1 follow a Poisson process with a mean time between interrupts of approximately 1.21 months. The interrupts are not correlated to any external, time-varying phenomena (e.g. solar activity). As such, functional interrupts on AISSat-1 and AISSat-2 would not be correlated with each other. The combined availability is then simply the parallel combination of the two individual availabilities. It is expected that the combined system would achieve an overall availability of AIS-from-space capability of 98.68% following the existing operational philosophy. Should improvements to the response time to on-board functional interrupts be improved, the availability could be as high as 99.93%. The various configurations are summarized in Table 2.

Table 2: AISSat Constellation Space Segment Availability

Satellites	Measure	Availability	Yearly Downtime (Hours)	Downtime Reduction
1	None	97.37%	230	-
	Preventative maintenance	99.49%	45	80.61%
	Full operator support	99.86%	12	94.68%
2	None	98.68%	116	49.81%
	Preventative maintenance	99.75%	22	90.49%
	Full operator support	99.93%	6	97.34%

The presence of a third satellite in the constellation will ensure continued high availability operations in the case of a failure of one. In this way, a robust space-based AIS capability will be maintained. With all three satellites operating, the availability would be incrementally higher. Additional AISSat-series satellites may be built and launched to maintain and replenish the constellation, or AIS capabilities may be installed on other platforms.

V. CONCLUSIONS

The benefits of nano- and micro-satellites in building reliable and available systems has long been discussed. The Norwegian AIS-from-space system, utilizing SFL's Generic Nanosatellite Bus technologies, has shown the potential of these technologies to allow a truly operationally useful system to be constructed at relatively low cost using AISSat-1 as an initial demonstration. The addition of additional satellites to the system will allow demonstration of a high availability capability for maritime observation.

As of July 12, 2013, AISSat-1 reached and passed its three-year operational goal. To date, it has continued to operate well and is hoped to continue operating for many years to come. AISSat-2, has been completed and is awaiting launch on board a Soyuz rocket in late 2013. A third satellite, AISSat-3, is now under construction and is expected to launch in late 2014 or 2015. This third satellite will further expand the constellation and provide additional coverage and assurance of the Norwegian space-based AIS capability.

VII. REFERENCES

1. Schwarzenberg-Czerny, A., Weiss, W., Moffat, A., Zee, R., Rucinski, S., Mochnacki, S., Matthews, J., Breger, M., Kuschnig, R., Koudelka, O., Orleanski, P., Pamyatnykh, A., Pigulski, A., and Grant, C., "The BRITE Nanosatellite Constellation Mission", *38th COSPAR Scientific Assembly*, Bremen, Germany, 2010
2. Orr, N., Eyer, J., Larouche, B., Zee, R. E., "Precision Formation Flight: The CanX-4 and CanX-5 Dual Nanosatellite Mission", *21st Annual AIAA/USU Conference on Small Satellites*, Logan, Utah, August 2007
3. Bonin, G., Zee, R., Brett, M., King, J., "The Antarctic Broadband Demonstration Nanosatellite: Fast Internet for the Bottom of the Earth", *25th Annual AIAA/USU Conference on Small Satellites*, Logan, Utah, August 2011
4. Narheim, B., Olsen, O., Helleren, O., et al., "A Norwegian Satellite for Space-Based Observation of AIS in the High North", *22ndAnnual AIAA/USU Conference on Small Satellites*, Logan, Utah, August 2008
5. Narheim, B., Helleren, O., Olsen, O., et al., "AISSat-1 Early Results", *25th Annual AIAA/USU Conference on Small Satellite*, Logan, Utah, August 2011
6. Helleren, Ø., Olsen, Ø., Narheim, B., Skauen, A., Olsen, R., "AISSat-1 – 2 Years of Service", *European Space Agency Small Satellite Systems and Services Symposium*, Portorož, Slovenia, June 2012
7. Walker, G., Matthews, J., Kuschnig, R., Johnson, R., Rucinski, S., Pazder, J., Burley, G., Walker, A., Skaret, K., Zee, R., Grocott, S., Carroll, K., Harron, J., Sinclair, P., Sturgeon, D., and Harron, J., "The MOST Asteroseismology Mission: Ultraprecise Photometry from Space", *Publications of the Astronomical Society of the Pacific*, Volume 115, No. 811, University of Chicago, September 2003
8. Sarda, K., Grant, C.C., Eagleson, S., Kekez, D.D., Zee, R.E., "Canadian Advanced Nanospace Experiment 2 Orbit Operations: Two Years of Pushing the Nanosatellite Performance Envelope", *European Space Agency Small Satellite Systems and Services Symposium*, Funchal, Madeira, Portugal, August 2010
9. Pranajaya, F.M., Zee, R.E., Cain, J., and Kolacz, R., "Nanosatellite Tracking Ships: From Concept to Launch in 7 Months", *23rd AIAA/USU Conference on Small Satellites*, Logan, USA, 2009