M3MSat – First Year Operations Update

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Abstract

The Maritime Monitoring and Messaging Microsatellite (M3MSat) is a microsatellite built by Honeywell (formerly COM DEV Ltd) for the Canadian Department of National Defence (DND). M3MSat carries an AIS primary payload, the Low Data Rate (LDR) secondary payload, and the Dielectric Deep Charge Monitor (DDCM). M3MSat was launched on 21 June 2016 on an ISRO PSLV launch along with 19 other satellites and is now an operational asset. At just over one year on orbit, M3MSat is healthy and exceeding performance expectations.

This paper gives a mission update following the first year of operation of M3MSat. A mission overview is given, describing the spacecraft, payloads, users, and operations. Major events, challenges, and performance over the first year's operations are also described.

M3MSat is operated from the Multi-Mission Operations Centre (MOC) at CSA. A series of anomalies were overcome during LEOP and commissioning. These included an initial power-negative state and eventual loadshed resulting from a problem in the Battery Charge Regulator (BCR). The resources of the multi-mission environment permitted rapid utilization of qualified personnel and external ground stations to support recovery from this critical anomaly. ADCS tuning and flight software upgrades were also performed during later commissioning.

The spacecraft entered routine operations in December 2016, at which point it began providing continuous AIS data to the Payload Operations Centre (POC) managed by exactEarth and DDCM data to DPL Science. M3MSat is also known as EV-7 within the constellation of AIS payloads operated by exactEarth. AIS detection performance exceeds expectations and the original requirements. All three payloads (AIS, LDR, & DDCM) have met or exceeded their original requirements and are operating normally.

1. Introduction

M3MSat was developed as a joint project between the Canadian Space Agency (CSA) and the Canadian Department of National Defence (DND), specifically Defence Research and Development Canada (DRDC). Following its June 2016 launch, the spacecraft began routine operations in December 2016 and has now passed one year in primary operations. A mission update is provided along with on-orbit results.

2. Mission Overview

M3MSat is a microsatellite developed with three technology demonstration objectives – collection of Automatic Identification System (AIS) signals, demonstration of a Low Data Rate (LDR) messaging payload, and demonstration of a Deep Dielectric Discharge Monitor (DDCM).

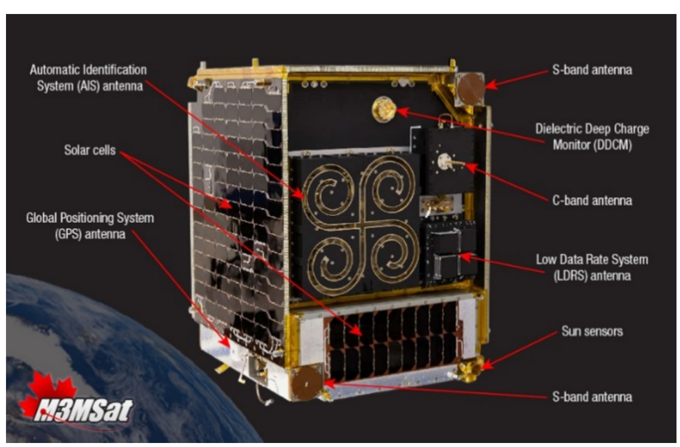

Figure 1: M3MSat Spacecraft

AIS data collection is the primary objective of the mission, and provides a contribution to Canada's existing maritime surveillance capabilities. The experience gained in the AIS payload demonstration also supports risk reduction for AIS secondary payloads that are included in the Radarsat Constellation Mission (RCM). The primary area of interest for the mission is Canadian maritime zones, however M3MSat can (and does) provide global coverage subject to data volume and power constraints.

The satellite is owned by DND and operated by CSA, with AIS payload tasking and processing performed by exactEarth.

M3MSat was launched in June 2016 into a 505 km altitude circular orbit at 97^o inclination and 9:30 LTDN. After a commissioning period, the primary operational lifetime requirement of M3MSat is 1 year, with a design goal of 2 years. The spacecraft is expected to have a 5 year lifetime, however this is not a requirement.

2.1. Spacecraft

M3MSat is based on Honeywell's AIM (Advanced Integrated Microsatellite) satellite bus. The AIM bus was developed through a collaboration between Honeywell Aerospace (then COM DEV Ltd.) and University of Toronto Institute of Aerospace Studies/Space Flight Laboratory (UTIAS/SFL), as an initiative that meets the CSA's multi-mission microsatellite bus (MMMB) requirements. This approach was intended to provide a bus platform that could serve various missions and applications in the 100 kg class.

The development of the AIM bus as well as a description of the design has been detailed in [1]. Key spacecraft performance parameters and characteristics are summarized in Table 1.

Table 1 M3MSat Key Spacecraft Performance Parameters

Orbit	Altitude: 505 km Inclination: 97.42° LDTN: 09:30 Orbital Period: 94.7 min Eclipse durations: 33 min	**Power Generation**	150 W peak, 80 W average Body-mounted solar panels on each of the 6 faces 17.4 Ah Li-Ion Battery
Attitude Determination and Control	Three-axis stabilized - Nadir pointing (nominal) - Inertial pointing capability Sensors: - Sun sensors - Magnetometer - Rate Sensors Actuators: - Magnetorquers - Reaction wheels Knowledge $\leq$ 2.42 deg (3σ) Control $\leq$ 4.9 deg (3σ)	**C&DH**	Dual (redundant) OBCs 2 GB flash memory (per OBC) CAN bus - Augmented with ECSS packet transmission over multiple CAN frames
Communications	S-Band, CCSDS and ECSS compatible AIS & LDR payload downlink via C-Band	**Structure**	Aluminum honeycomb panel construction
Spacecraft Mass	92 kg	**Thermal Control**	Passive, except battery heaters
AIS Storage	12 GB capacity	**Propulsion**	None
Dimensions	610 mm x 610 mm x 850 mm	**Deployables**	None
Availability	90 %	**Design Life (goal)**	2 years

The platform includes redundant A-side/B-side configuration providing a single-fault tolerant architecture. A simplified spacecraft block diagram is shown in Figure 2.

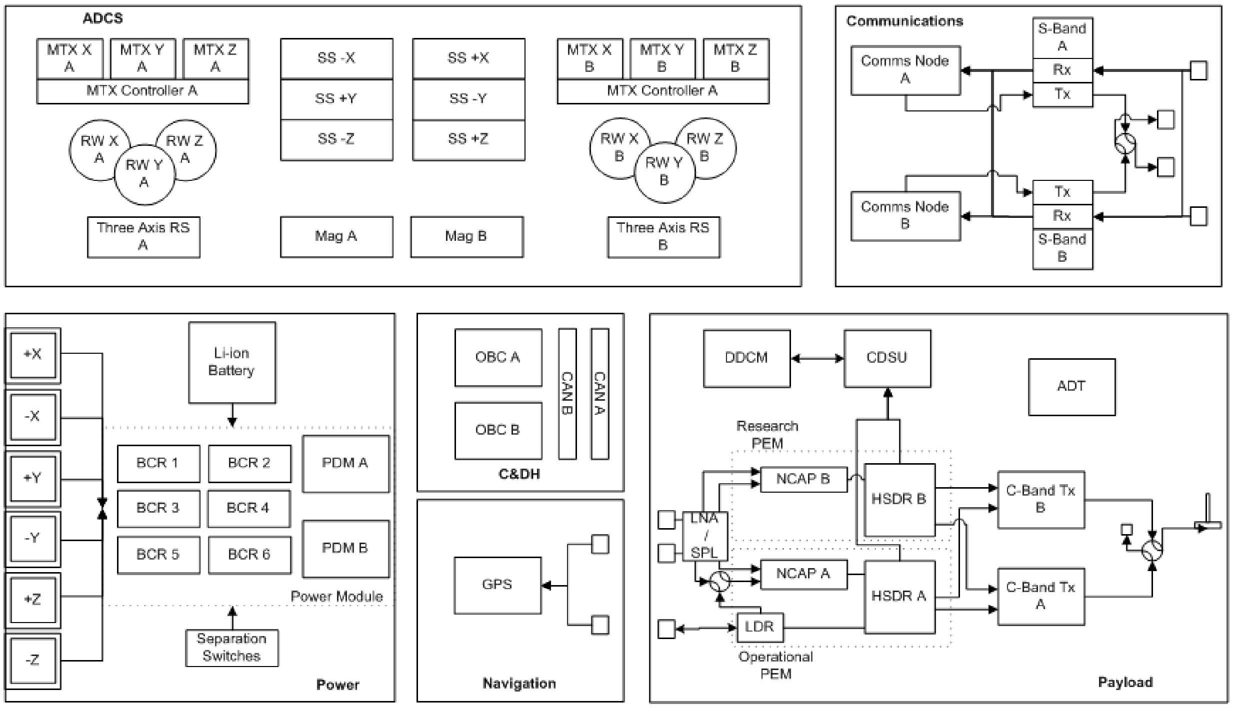

Figure 2: M3MSat Simplified Spacecraft Block Diagram

The device acronyms are as follows: MTX: Magnetorquer, SS: Sun sensor, RW: Reaction wheel, RS: Rate sensor, MAG: Magnetometer, Rx: Receiver, TX: Transmitter, BCR: Battery charge regulator, PDM: Power distribution module, ADT: Advanced deployment terminal (demo only), LNA/SPL: Low noise amplifier/splitter, NCAP: AIS receiver

2.2. Payloads

2.2.1. AIS Payload

The Automatic Information System (AIS) is an existing maritime system designed for ship-to-ship and ship-to-shore communication for collision avoidance and vessel traffic management. The use of AIS is mandated by the International Maritime Organization aboard ships of more than 300 gross tons as well as aboard all passenger ships. AIS messages include ship identification information as well as position, course, and speed. In 2008, the NTS nanosatellite demonstrated that these signals could be received in orbit.

AIS messages provide *identification* data that can be coupled with other space-based maritime products, such as ship *detection* capabilities provided by SAR platforms such as the RADARSAT missions. [2]

The M3MSat AIS payload consists of a custom-designed VHF antenna developed by the University of Waterloo and Honeywell Aerospace to meet the gain and mechanical volume requirements of the mission. The signal is passed through Honeywell VHF receivers and recorded by high speed data recorders (HSDR) for eventual downlink over a dedicated C-band data link. The AIS payload provides research and operational data to DRDC and exactEarth.

2.2.2. LDR System

M3MSat is also used as a demonstration platform for a low data rate (LDR) transponder. The LDR system operates at 400 MHz and is intended to provide two-way communications at a low data rate. This could support a range of services such as sensor data collection, machine-to-machine communications, and other packet based messaging services.

2.2.3. Dielectric Deep Charge Monitor (DDCM)

The DDCM is also technology demonstration payload, designed and built by DPL Science. The DDCM was specifically developed to improve spacecraft health and safety by addressing the hazards of internal charging. As well as demonstrating the instrument performance in-orbit, the behavior of charge accumulation and decay are being studied.

The DDCM instrument monitors the electrical potential of a dielectric sample due to internal charging by the energetic space environment. For the M3MSat DDCM, a typical printed circuit board material of 62mil thick polyimide was selected as the dielectric sample. The polyimide sample is configured to simulate a printed circuit board within a payload unit.

The instrument is equipped with two channels: high gain and low gain. The high gain channel is used to measure the dielectric sample voltage up to 4kV and the low gain channel measures the dielectric sample voltage up to 60kV. An onboard calibration system accounts for the offset voltage of electronic components as well as ageing and radiation effects on the electronics. Dielectric sample voltage and instrument temperature are measured and trended over time, and the health of the instrument is monitored via the DC power consumption and calibration factor.

The instrument provides the satellite operator with real-time information on the voltage accumulated on the dielectric which can be compared to the material breakdown voltage, thus providing advance warning of a possible material breakdown. Protective measures can then be implemented by the satellite operator. In MEO and GEO, the flux can be two orders of magnitude higher than LEO thus potentially leading to voltages of several kV and approaching breakdown. The DDCM can be a valuable instrument for the satellite operator in safe-guarding the spacecraft against internal charging hazards.

The demonstration of the DDCM on M3MSat aims to space qualify and establish flight heritage of the DDCM instrument. The DDCM is operated continuously while the spacecraft is in normal operations.

2.3. Operations

M3MSat is operated from the Multi-Mission Operations Center (MOC) at CSA headquarters. The center currently operates Radarsat-2, Scisat-1, and NEOSSat in addition to M3MSat, and is expanding for future operation of the Radarsat Constellation Mission (RCM). The MOC is operated 24/7 using on-site and on-call support personnel. The MOC makes use of 5 ground stations listed in Table 2, and can access additional ground stations run by international partners in critical situations. Each MOC ground station is operated by CSA or CCMEO (Canada Center for Mapping and Earth Observation) as listed in the table.

Table 2: M3MSat TTC Ground Network

St-Hubert (SHUB)	CSA	45.5º N, -73.4º W
Saskatoon (SASK)	CSA	52.1º N, -106.6º W
Inuvik (ICAN)	CCMEO	68.3º N, 133.6º W
Prince-Albert (PASS)	CCMEO	53.2º N, -105.9º W
Gatineau (GAT)	CCMEO	45.6º N, -75.8 º W

A separate Payload Operations Center (POC) is run by exactEarth at their Ontario facility. The POC plans the AIS payload taskings, which are uploaded to the spacecraft via the MOC. AIS data downlinks are scheduled in the AIS payload tasking, and occur via a 20 Mbps C-Band connection to a separate network of ground stations in Svalbard in Norway, Fairbanks in Alaska, and Troll in Antarctica. The AIS data is transferred directly to exactEarth for AIS message extraction and product generation.

3. Year One Operations

3.1. Launch

Originally, a 2014 launch aboard a Soyuz rocket from Baikonur had been planned; however, the launch was cancelled as a result of sanctions against Russia at the time. The launch was replanned and M3MSat was eventually launched by ISRO aboard a PSLV rocket (flight PSLV-C34) on June 22, 2016. M3MSat was one of 20 satellites deployed the launcher, which was a record number of deployments for ISRO at the time. The launch injection and initial acquisitions were nominal.

3.2. Commissioning

Commissioning was performed by an integrated team led by Honeywell Aerospace and included CSA MOC operations staff (CSA and SED personnel) as well as off-site support from Honeywell and UTIAS/SFL sub-system specialists. The commissioning plan consisted of 4 major parts:

1. initial contact and validation of the power and communication systems health (LEOP),
2. bus power on and health check,
    - This phase included gradual power up and checkout of the ACS sensors, actuators and ACS Computer
3. payload power on and health check, and
4. long term trending and data analysis.

Commissioning was completed successfully and M3MSat transitioned into routine operations, providing continuous AIS and DDCM data to users, in December 2016. During the commissioning process, the team resolved a number of anomalies and performed ADCS performance tuning. Major events of this process are described at a high level below. A more detailed description of M3MSat operations and the anomalies encountered is provided in [3]. Bus commissioning activities were followed by AIS payload commissioning, led by exactEarth, during which time detailed payload characterization and tuning was completed.

3.2.1. LEOP, Commissioning, & Anomalies

The spacecraft was successfully acquired on first contact at the Saskatoon ground station with nominal tumbling rates. 12 successful passes were completed over the first 24 hours, during which initial equipment power on and check-out sequences were completed for the communication system and housekeeping computer, enabling regular telemetry flow.

During this first 24 hour period, telemetry showed that the battery was not charging effectively. The spacecraft is designed with solar arrays on all faces to ensure that some power is generated regardless of the attitude, however current outputs from the battery charge regulators were sporadic. At this stage the ADCS subsystem was still off and attitude motion data was not available, creating difficulty in evaluating the current profiles and troubleshooting the issue. Over the next several days, intense investigation activities were conducted. Commissioning continued with the early ADCS initiation procedures to provide additional attitude data and attempt to improve charging performance by detumbling. Spacecraft power continued to decrease and resulted in level-1 (high power switches powered off) and level-2 (low power switches powered off, including the housekeeping and ADC computer). The ADCS was powered on and initialized in passive mode, enabling data collection, however the loadsheds occurred prior to attempting to detumble the spacecraft.

Through low-level telemetry requests and ground equipment testing, the problem was isolated to the battery charge regulators (BCRs). The root cause was identified to be a circuit vulnerability to dynamic illumination causing an under-voltage condition and the switching circuit to stop. A software patch was designed and 5 of the 6 BCRs were recovered. BCR-6 was unrecoverable and is considered to have experienced a permanent failure during launch or shortly after. The loss of BCR-6 has resulted in a partial loss of power generation capability from +Z and –Z (nadir, included for safety) panels. The power reduction is less than the margin provided in the system, so mission performance has been unaffected.

After resolution of the BCR issue, commissioning proceeded normally without further critical anomalies. The GPS unit did not initialize correctly and recovery attempts were unsuccessful. The unit is considered failed. The mission requirements are met without the GPS using the HKC self-running clock with spacecraft time adjustments performed from the ground as needed and orbit knowledge derived from JSPOC TLEs.

All other units were activated successfully.

3.2.2. Performance Tuning

In later stages of commissioning, performance tuning was performed on the ADCS. Attitude disturbances were noted in nadir pointing mode, which were caused by spurious sun vector solutions caused by the sun sensors generating a valid vector from Earth albedo illumination. These disturbances were resolved by tuning the exposure thresholds for the sensors. In addition to various parameter updates for optimal turning, handling of reaction wheel zero-crossings was revised with a FSW update. Following all updates, control error was measured to be 2.26 deg (3σ).

3.3. Routine Operation

The first year of operations has now passed and the primary mission requirements have been met. The AIS and DDCM payloads are tasked continuously, and the LDR payload has successfully performed it is technology demonstration mission.

Spacecraft equipment has been operating nominally with no observed degradation. Occasional anomalies and temporary interruptions occur as expected due to SEUs and other effects, and these outages are within the mission budget.

3.4. Payload Results

3.4.1. AIS Performance

exactEarth is performing AIS payload scheduling at a typical duty cycle of 70%, scheduled in coordination with other AIS assets operated by exactEarth. M3MSat detects more than 1.7 million AIS messages per day from approximately 55,000 unique vessels. In peak seasons, the vessel count can reach 60,000. This represents the highest detection rate in exactEarth’s current constellation.

Figure 3 shows the message detection rate for M3MSat in messages per second from February 15 to 21, 2018. Blank zones across the lower southern hemisphere indicate where the AIS payload is OFF to manage the duty cycle (the mission focus is on major shipping lanes).

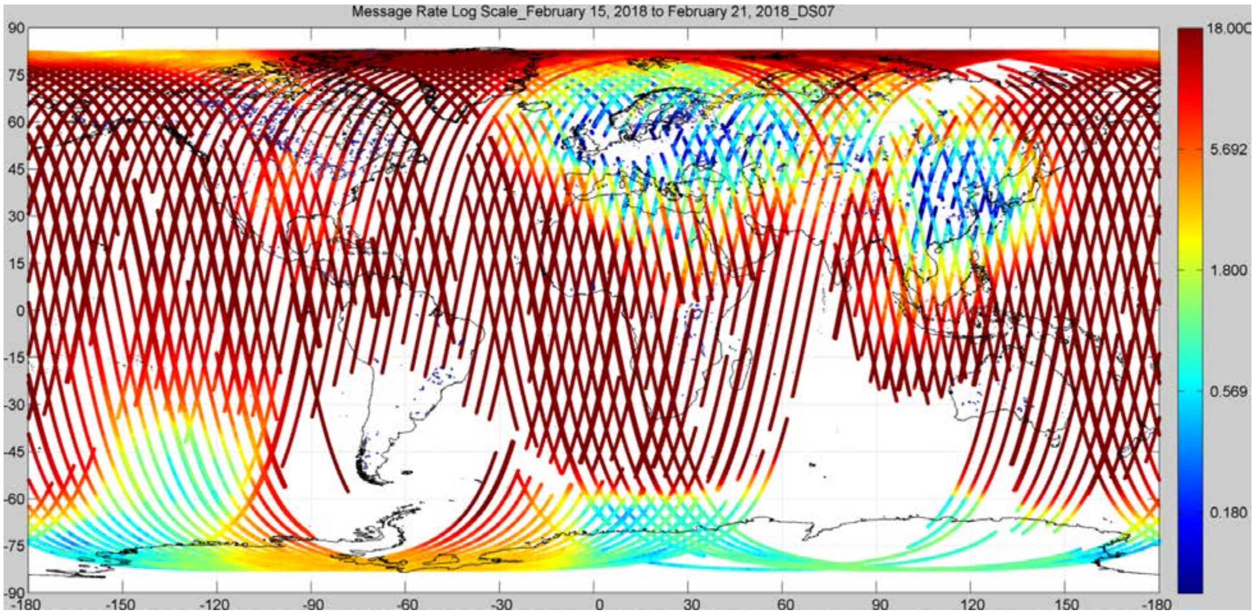

Figure 3: Messages per Second detected by M3MSat from February 15 to 21, 2018

Figure 4 shows the percentage of ships detected by M3MSat. The number of known ships (100%) is estimated based on data from coastal (terrestrial) data sources and other satellite assets. The detection rate is reduced in high traffic density areas, but is still best-in-class. Figure 4 also shows a reduced detection rate in the South America, related to the lower duty cycle coverage. The figure indicates that M3MSat detects nearly every vessel in the open sea. Coastal AIS stations are only effective to approximately 50 nautical miles from shore.

Note that M3MSat is also designated EV7 in the context of the exactEarth AIS constellation.

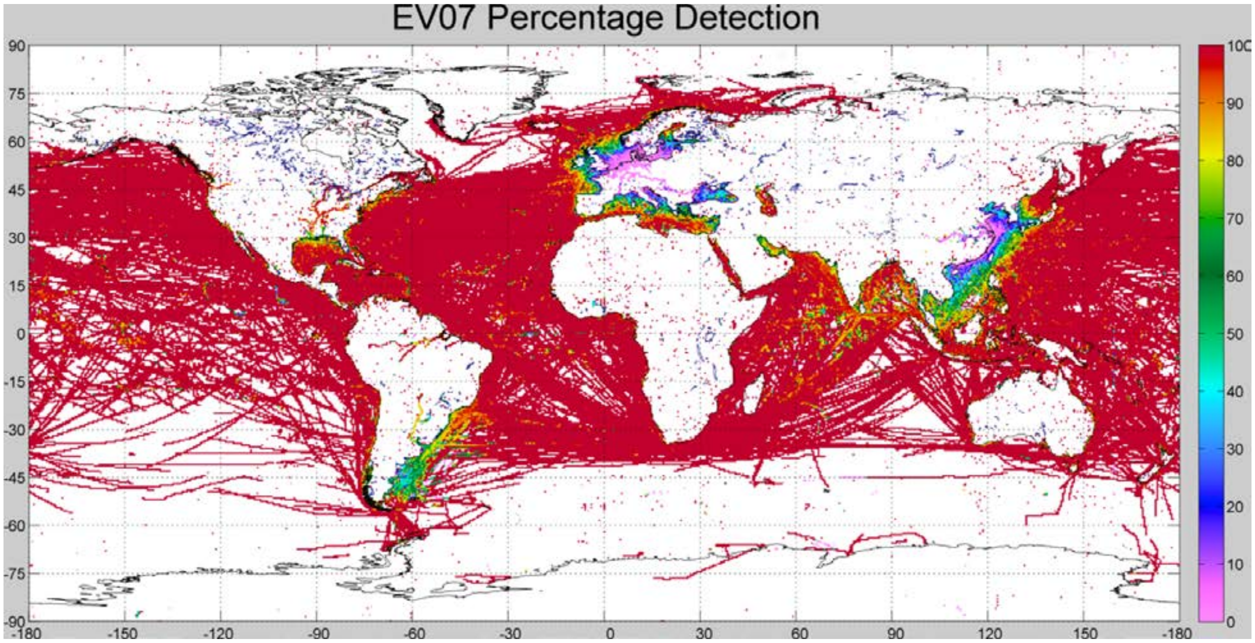

Figure 4: Estimated Vessel Detection Rate (Percentage) for M3MSat (EV07)

Data latency, measured from time of recording on M3M to the time the AIS message is delivered to the customer on exactEarth's data feed, has a median time of 40-45 minutes.

3.4.2. LDR Demonstration

An LDR demonstration was performed during commissioning. Transmit and receive performance were each measured throughout a complete pass of a Honeywell test facility in Cambridge, ON. Data was collected for RF performance characterization, which satisfied design predictions. The unit has now been successfully demonstrated in space and has completed its technology demonstration. A number of operational concepts have been proposed to make use of the LDR, however none have currently been implemented.

3.4.3. DDCM Demonstration

The DDCM has operated continuously for over one year, providing significant space heritage. No spacecraft anomalies or interruptions have been associated with the DDCM. Data is being collected continually and is relayed to DPL Science Inc.

As part of the study performed by DPL Science Inc., correlations between the dielectric sample voltage and occurrences in the space weather are investigated using flux data provided by the POES NOAA-19 satellite. The POES orbit (850km altitude, 98deg inclination, period 102 min) is a close match to the M3MSat orbit (550km, 97deg, 95min). Data collected by the POES Medium Energy Proton and Electron Detector (MEPED), one of two instruments that make up the Space Environment Monitor (SEM) suite, are used. Specifically, flux data collected by the two telescopes SEM Channel E1 – 0° and Channel E1 – 90° are used. The two telescopes capture 30 – 2500 keV electrons. The M3MSat DDCM dielectric sample captures 50 – 600keV electrons.

Figure 5 shows flight data from the DDCM over a year of operation. Daily average voltage of the dielectric sample is shown (blue curve). On the same graph is the daily average omnidirectional electron flux (brown curve) as measured by NOAA-19. As expected, the electron flux in LEO is low. However, a gradual charging of the dielectric sample is observed over time as well as an increase in voltage shortly after the solar storm of early September 2017.

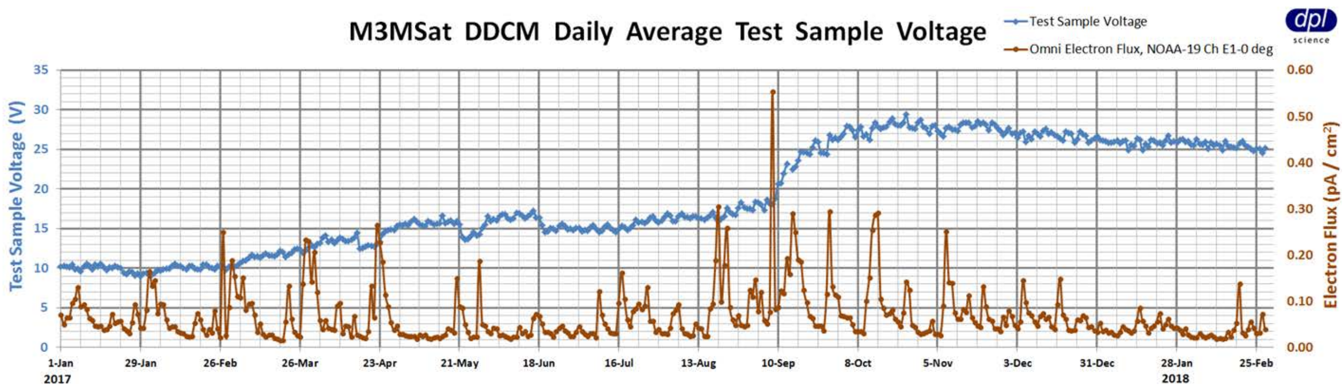

Figure 5: DDCM Daily Average Test Sample Voltage (courtesy DPL Science Inc.)

4. Conclusion

M3MSat was commissioned and has completed its first year of primary operations successfully. Each payload objective has been met and the satellite remains in a good state of health. The AIS payload has exceeded the mission performance requirements. The LDR and DDCM have each established flight heritage.

Acknowledgments

The Authors thank the contributions of SED Systems, the joint CSA/DRDC Project Team, DND, Honeywell, University of Toronto Institute for Aerospace Studies (UTIAS), exactEarth, and DPL Science.

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