EXACTVIEW-9: COMMISSIONING AND ON-ORBIT OPERATION OF A HIGH PERFORMANCE AIS NANOSATELLITE

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ABSTRACT

On 28 September 2015, exactView-9 (EV9) was launched into a 650 km equatorial orbit by an Indian Polar Satellite Launch Vehicle (PSLV) from the Satish Dhawan Space Centre. Housing an advanced Automatic Identification System (AIS) receiver from Kongsberg Seatex, the primary mission of EV9 is to provide ship detection services in the shipping corridors around the equatorial regions of Earth for exactEarth Ltd., a leading provider of satellite AIS data services.

EV9 is a 5.5 kg satellite based on the Generic Nanosatellite Bus (GNB) satellite platform, and was designed, assembled, and commissioned by the Space Flight Laboratory (SFL). The satellite has a three-axis attitude determination and control system (ADCS) capable of terrestrial target tracking, making EV9 one of the smallest satellites to demonstrate this high performance capability on orbit. Coupling the attitude control system with a high data rate S-band transmitter, supporting rates up to 2048 kbps, EV9 is able to downlink over 1 GB of data per day to its ground station in Panama. Acting as a bent pipe relay, the satellite is capable of streaming AIS messages in real-time or downlinking data collected from around the globe during one pass each orbit.

1 INTRODUCTION

The exactView-9 (EV9) satellite is a high performance maritime monitoring nanosatellite built by the Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies (UTIAS) for exactEarth Ltd. Currently, exactEarth maintains a constellation comprised of eight satellites, including EV9, called the exactView constellation. EV9 however is the first equatorial satellite in the constellation, which greatly improves global revisit times at low latitudes.

Designed by SFL, EV9 incorporates high performance three-axis attitude control, an advanced Automatic Identification System (AIS) receiver for high ship detection rates, and a high speed downlink transmitter for high data volume transfers. SFL specializes in the development of micro- and nanosatellites for commercial and research applications. With the use of these small satellite buses, SFL has the ability to provide rapid and economical access to space for novel scientific and technology payloads. Since its establishment in 1998, SFL has successfully launched and operated 13 satellites, including the first satellite in the exactView constellation, called Nanosatellite Tracking of Ships (NTS) [1]. NTS captured its first AIS messages on 6 May 2008, marking the first time an AIS message was received by a nanosatellite [2].

AIS transmissions were designed for ship-to-ship and ship-to-shore reception to improve control and monitoring of maritime traffic. AIS data has several important applications, primarily being used for surveillance, vessel traffic monitoring, search and rescue, and environmental protection. The use of AIS is mandated by the International Maritime Organization aboard ships of more than 300 gross tons, and aboard all passenger ships. The AIS message content and broadcast intervals depend on dynamic conditions of the ship, such as speed and rate of turn, and include content such as position, course, speed, and ship identification information, also called the Maritime Mobile Service Identity (MMSI) number. Since the introduction of nanosatellite AIS systems in 2008, space-based AIS has evolved from being an experimental application to a fully operational service on which maritime safety authorities are reliant [3].

This paper summarizes the EV9 satellite design, followed by the on-orbit commissioning and operations of EV9.

2 EV9 SATELLITE OVERVIEW

The design of EV9 is based on the Generic Nanosatellite Bus (GNB) platform, with a 20 cm cubical form factor and an approximate mass of 5.5 kg. The spacecraft solid model of the internal layout is shown in Figure 1.

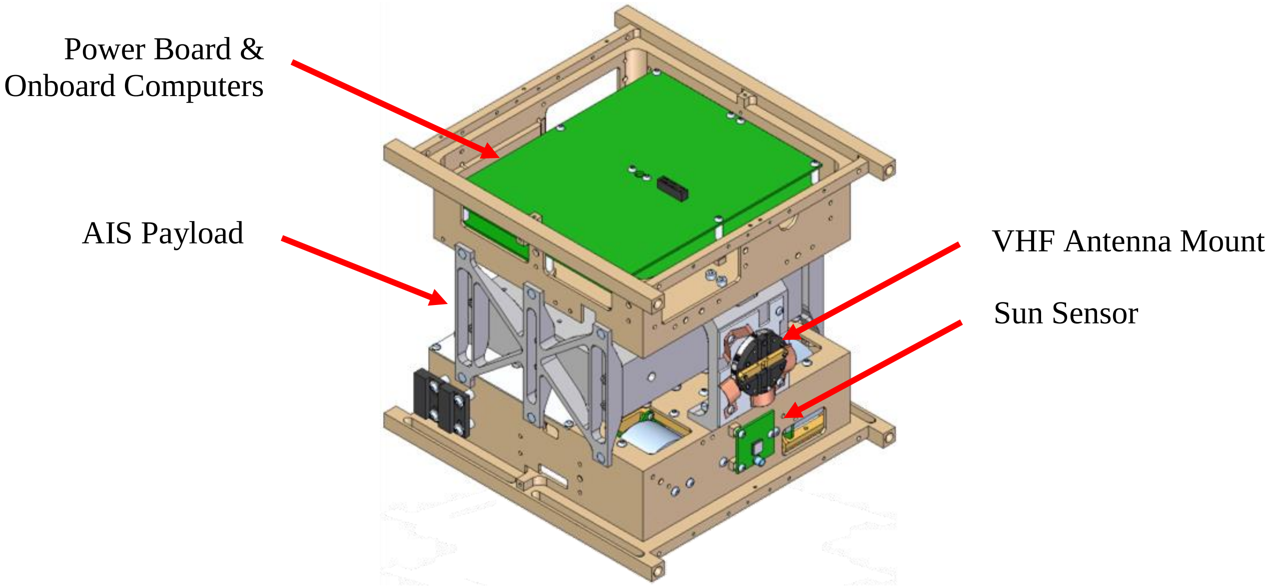

Figure 1. EV9 interior solid model.

EV9 was designed with a full complement of GNB electronics and hardware in addition to its payload. The system architecture of EV9 is shown in Figure 2, with payload elements highlighted in yellow. The onboard subsystems are described in the sections that follow.

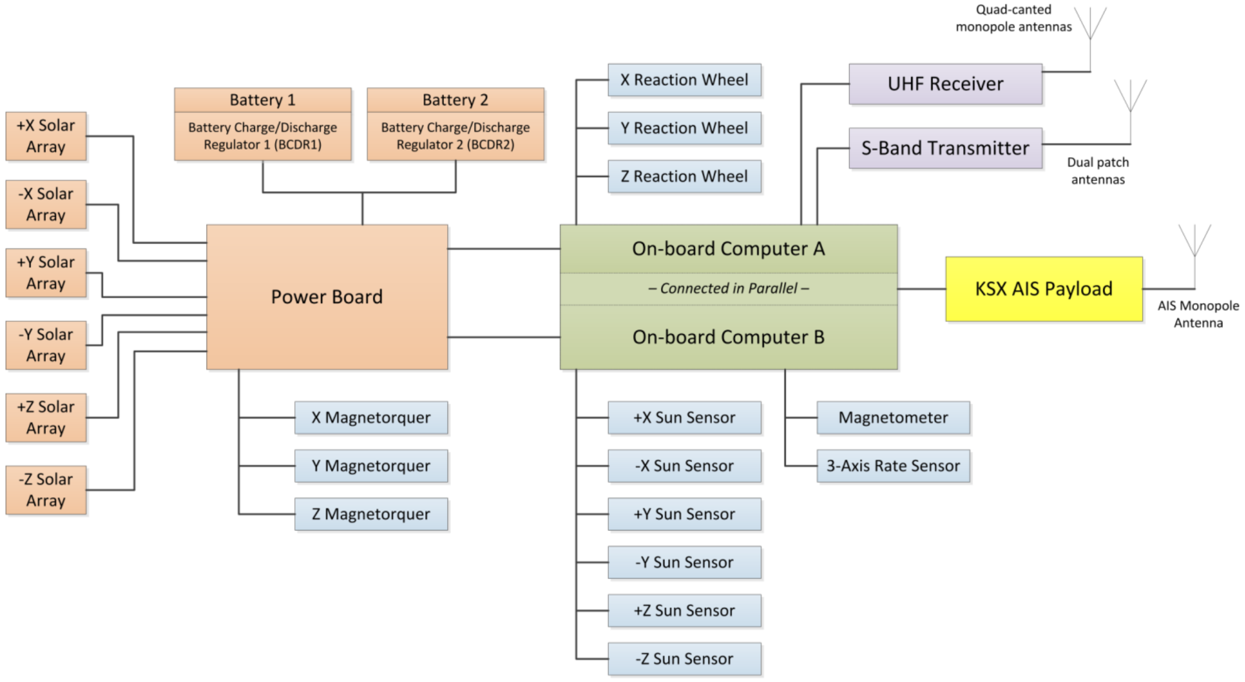

Figure 2. EV9 bus architecture.

2.1 Command and Data Handling

There are two identical onboard computers that are used for housekeeping and attitude control. One computer is nominally off as a cold spare. Each computer has 1 GB of Flash memory, which is used to store both payload data and bus telemetry.

Commands can be sent in real-time to the onboard computer during a ground station contact, or they can be time-tagged. Lists of time-tag commands can be uploaded to the computer, where they are then dispatched to the respective unit or software thread at a specified time. Responses are stored in logs onboard the computer and later downlinked during a ground station pass. This functionality supports continuous payload observations around the globe, even when real-time commanding of the payload is not possible.

2.2 Electrical Power System

The power system is a direct energy transfer topology with peak power tracking capability, consisting of 42 triple-junction GaAs solar cells and two redundant Battery Charge and Discharge Regulators (BCDR) with dedicated single-cell Lithium-ion batteries. A central power board provides switched power distribution to all subsystems, and provides voltage and current telemetry. Solar cells are evenly distributed on all sides of the spacecraft which allows for continuous payload operations in any attitude. The power generated from the satellite on-orbit ranges from approximately 6 to 14 W.

2.3 Telemetry and Command

A UHF receiver designed by SFL is used for the command uplink. This UHF receiver operates at a fixed uplink rate of 4 kbps. The uplink antenna system on EV9 is an omnidirectional pre-deployed quad-canted monopole configuration (see Figure 3). The downlink is achieved with an S-band transmitter, also designed by SFL. Its data rate and modulation can be scaled on-the-fly from 32 kbps to 2048 kbps, with typical operation at 2048 kbps. Scaling is automatically executed by ground software as the link with the Earth station improves and deteriorates throughout the pass. The antenna system used for the downlink on EV9 is an omnidirectional pair of patch antennas bonded to two opposing satellite faces (also shown in Figure 3). Radiated power is split evenly between the two antennas at all times.

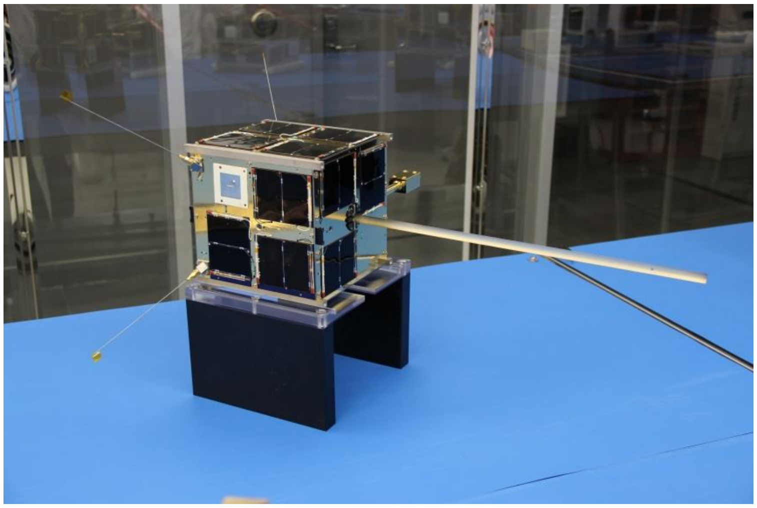

Figure 3. EV9 satellite in the SFL cleanroom facility.

2.4 Attitude Control Subsystem

The attitude determination and control algorithms are executed at a two second period on the housekeeping computer. The attitude determination sensors include a three-axis magnetometer, six fine sun sensors, and a three-axis rate gyro – all designed and built at SFL. These measurements are fused together in an extended Kalman filter to generate quaternion and angular rate estimates used by the control algorithms. Actuation is provided by three orthogonal vacuum-core magnetorquers built by SFL and three orthogonal nanosatellite reaction wheels built by Sinclair Interplanetary. The reaction wheels are used for fine pointing control while the magnetorquers are used mainly for reaction wheel desaturation. Orbit determination provided by two-line elements is used for both orbit determination and control trajectory generation.

The spacecraft operates in two main attitude control modes: nadir-tracking using an align/constrain formulation for nominal operations, and ground target tracking during passes over the ground station. At a high level, the align/constrain targeting mode allows an operator to specify a spacecraft body axis to align with a vector in the orbit frame, while simultaneously constraining a second body vector to be as close as possible to a second vector in the orbit frame. Some examples of the alignment and constraint options include nadir, along-track, and Sun vectors. In the ground target tracking mode the spacecraft tracks a static target on the ground with a specified body axis while a second body axis is constrained to a second desired axis. In this mission the constraint vector is given by orbit normal.

Spacecraft momentum management is performed in parallel with the active control tasks and can be enabled or disabled by an operator as required. Given the desired spacecraft inertial angular momentum is entered as a setpoint, the magnetorquers are actuated to regulate the wheel speeds while simultaneously holding the desired attitude.

2.5 Payload

The payload onboard EV9 is comprised of an advanced Kongsberg Seatex AIS receiver and associated VHF monopole antenna. The AIS receiver is a software defined radio operating across the maritime band from 156 MHz to 163 MHz. The VHF antenna on EV9 is a deployable tape-measure monopole design. Prior to launch, the antenna is folded around the body of the spacecraft and held in place by the separation system. After separation from the launch vehicle the antenna immediately deploys passively under its own spring energy.

3 LAUNCH AND EARLY OPERATIONS

EV9 was launched on the Polar Satellite Launch Vehicle (PSLV) C30 mission. PSLV-C30 carried Astrosat as its primary payload, with EV9 as one of its secondary payloads. PSLV-C30 took off from the Satish Dhawan Space Centre (SHAR) First Launch Pad in Andhra Pradesh, India on schedule at 04:30:00 UTC on 28 September 2015. EV9 was successfully deployed into an equatorial orbit with an altitude of 650 km and an inclination of 6°. Figure 4 shows EV9 in its final launch configuration inside the XPOD separation system mounted underneath Astrosat on the PLA of the PSLV.

Figure 4. EV9 in launch configuration aboard PSLV-C30, 19 September 2015.

Initial acquisition with EV9 was made on the first contact at 05:25 UTC. During the first good contact, application software was loaded on the onboard computer and the AIS receiver was switched on and commanded to decode messages from all four channels. During that pass, EV9 received 5035 messages from 1498 unique vessels in approximately seven minutes. Figure 5 shows a map of the messages received during the first contact that the payload was powered on.

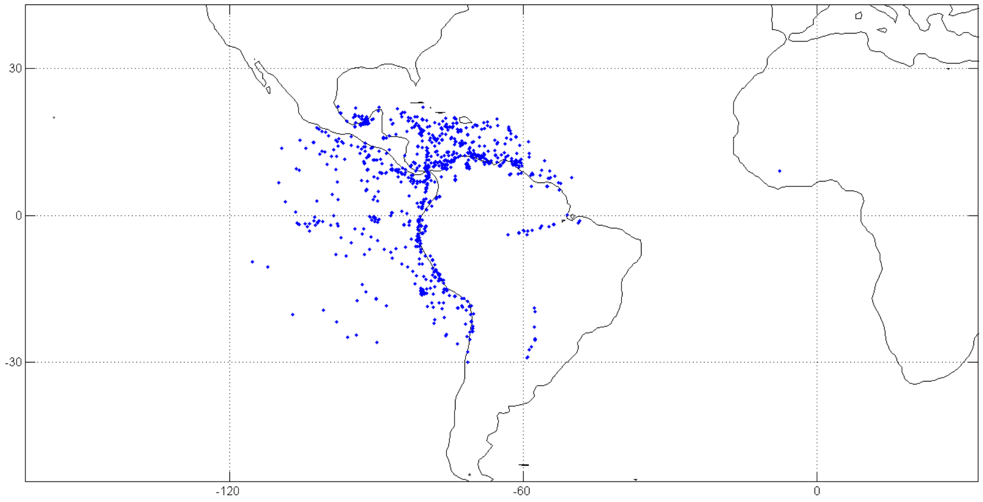

Figure 5. First payload acquisition on 28 September 2015.

3.1 Earth Station and Network Operations Centre

The Earth station for EV9 operations is located just outside of Panama City, Panama (shown in Figure 6). The Earth station consists of both a UHF station and an S-band station. The UHF station is a 4-antenna Yagi array and supporting equipment, including the polarization controller and power amplifier. The S-band used for downlink purposes consists of a 4.3 m composite prime focus antenna, with receive frequencies between 2200 and 2310 MHz. Both antennas are shielded using radome assemblies. The equatorial location of the ground station permits contact with EV9 in all of the satellite's 15 daily orbits. Expansion of the Earth station network for EV9 operations is underway, with a second site coming online in Singapore later in 2016.

Telemetry and logs downloaded from EV9 are routed from Panama to the Network Operations Centre (NOC) located at the exactEarth facilities in Cambridge, Ontario.

Figure 6. Panama Earth station used for EV9 operations.

4 ON-ORBIT PERFORMANCE

4.1 Payload

exactEarth delivers a global capability for monitoring over 200,000 AIS-equipped vessels using a strategically placed satellite constellation and global network of ground stations [4]. Given that the traditional land-based vessel tracking is limited to 50 nautical miles in most areas, there are a number of applications for global vessel tracking that require visibility well beyond the terrestrial coverage. These include national security, border protection, search and rescue, fisheries and environmental monitoring, logistical planning, commodity trading, and vessel fleet management to name a few. For all of these applications, a number of parameters are very important considerations with respect to an AIS asset or the capabilities of an entire satellite AIS constellation:

- Revisit – time interval between when the satellite is acquiring data over an area
- Latency – time duration between when a message is sent out by the ship and the when it is delivered to the customer through the exactEarth data feed
- Detection – percentage of ships detected over an Area of Interest (AOI) over a defined time period

The EV9 satellite has a unique orbit of 6° inclination. The equatorial orbit provides very frequent refresh of the maritime vessel environment in equatorial regions. The EV9 orbit also complements the detections provided by the remainder of the exactEarth satellite fleet in higher inclination (generally polar) orbits that provide more frequent revisits at the higher and lower latitudes. The addition of EV9 has made significant improvements to the global revisit values for the entire constellation.

The EV9 satellite, in conjunction with the ground segment, has been able to demonstrate latency improvement with a tactically placed ground station and custom mission management tools. In addition, it has a real-time message streaming mode, in which the messages are sent to the receiving ground station immediately upon acquiring the message from the ship. This mode allows for minimal latency of the messages, and is used over strategic ground station locations.

The EV9 AIS payload has demonstrated excellent performance characteristics. Its capability to acquire in both Onboard Processing (OBP) mode as well as raw spectrum captures for on-ground processing allow for a targeted concept of operations. Onboard processing decodes AIS messages directly on the satellite using narrow band filters, whereas the capture of the AIS RF raw spectrum requires processing on the ground using highly specialized algorithms. The equatorial orbit predominantly consists of low ship density areas, where the OBP detection mode performs very effectively. The raw spectrum mode acquisitions are then targeted over the more congested areas, and the data is routed to the exactEarth Data Processing Center, which includes much more rigorous processing that can extract an even greater number of messages from the capture. The power subsystem has been designed to support 100% payload duty cycle, which allows for maximum OBP and spectrum captures in areas of interest. High profile areas of interest can provide service that includes both real-time OBP messages and ground processed spectrum with harder to detect messages.

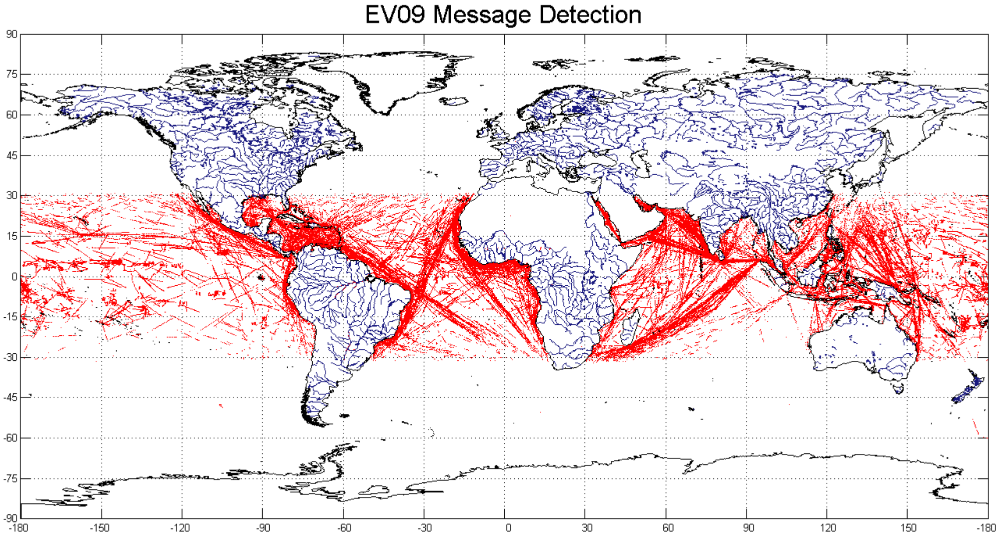

Figure 7. EV9 Ship detection over 2 days in March 2016.

The high detection rate for the EV9 AIS receiver payload is evident based on the distinct ship positional tracks as well as very clear delineation of shipping lanes illustrated in Figure 7, even within the relatively short observation time interval of two days. Moreover, the excellent sensitivity of the EV9 receiver allows for a relatively wide coverage access about +/-29 degrees of latitude about the 6° inclination equatorial orbit, as evidenced by the strong ship detection right out to the edge of coverage.

The advanced attitude control of EV9 allows for even further utilization of EV9's capabilities. The three-axis control and the evenly distributed thermal, power and communications design allows for the satellite to perform payload specific pointing and tracking of AOIs to improve detection performance. In addition, tracking the ground station using the downlink antenna maximum gain orientation allows to maximize the downlink throughput, supporting the larger data-volumes associated with the spectrum acquisition mode.

4.2 Communications

For the Panama ground station which has a 3° minimum elevation horizon mask, the average download capacity is 1.2 GB/day. This assumes the satellite's attitude control system is target tracking the ground station with the S-Band antenna to maximize gain. When EV9 target tracks the ground station it is able to achieve a 2 Mbps downlink with a 3 dB margin at worst case. The following section describes the attitude control performance necessary to achieve this level of downlink performance.

4.3 Attitude Control

The spacecraft pointing performance was analyzed during a routine downlink scenario on 10 December 2015 as shown in Figure 8. In this scenario the spacecraft starts in a nadir-tracking attitude, autonomously transitions to a ground-target tracking attitude to maximize data downlink, transitioning back to the nominal attitude at the end of the pass.

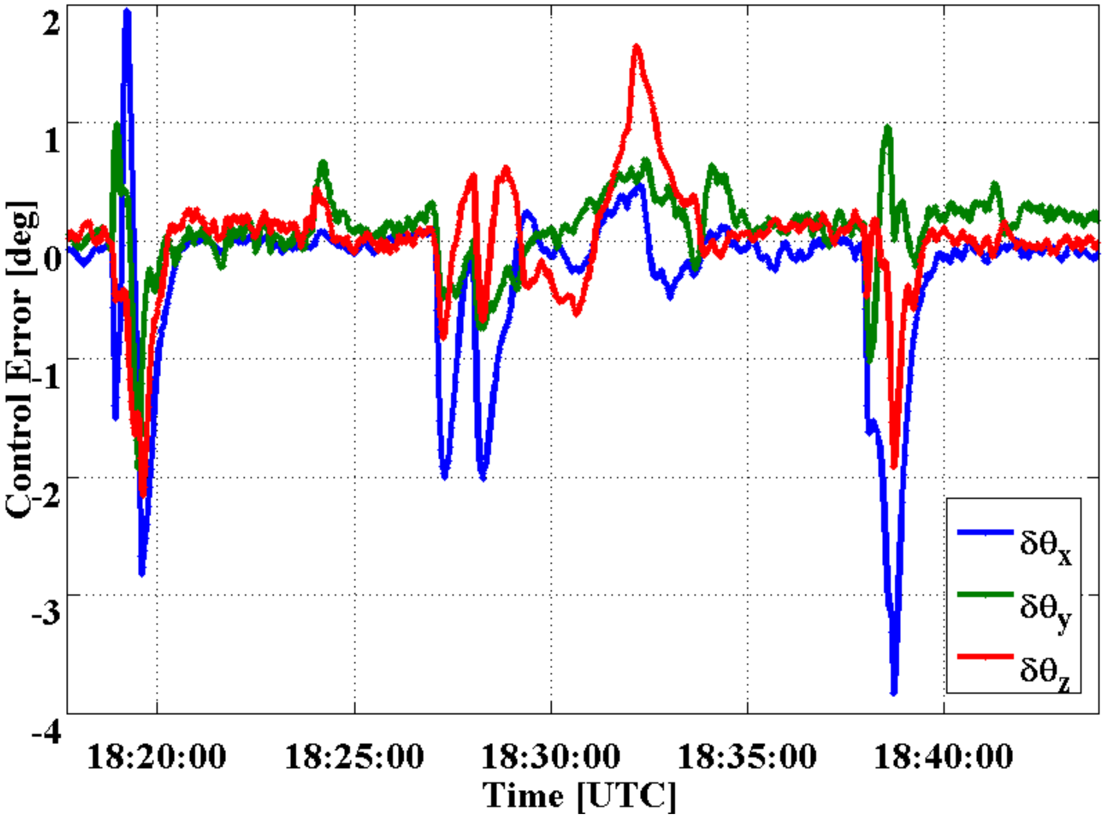

Figure 8. Pointing performance during routine ground contact on 10 December 2015.

At 18:18:53 a time-tagged command is autonomously executed onboard, beginning the transition to the target-tracking control mode. The transition begins roughly 4 minutes before the ground station is expected to come into view. The desired attitude has the –Z axis tracking the Panama ground station with the –X axis constrained to orbit normal. The reference trajectory guiding the spacecraft to its final target attitude is generated onboard in real time; the total maneuver angle is approximately 64° and the target rate is 2 °/s. At the prescribed end of the maneuver the total control error is 3°, and one minute later at 18:20:33 the control error is less than 0.3°. The small increase in control error at 18:24 is due to the commanded Y-wheel falling below the minimum threshold, and thus no torque being commanded for five control cycles. The two jumps in control error at 18:27:20 and 18:28:20 result from the sun vector passing between two adjacent sun sensors. The first jump occurs when both reported sun vectors are used in the state estimate, and the second when the system returns to using only one sun vector. It is known from unit-level calibration that the error at the edge of the 45° field of view can be up to 3°, therefore these errors are expected. These errors are acceptable from the standpoint of this mission, since no there is no observed degradation in downlink performance. The increase in pointing error about the Z axis at 18:32:16 is due to the Z reaction wheel undergoing a zero-crossing; the wheel's torque performance is significantly reduced when its speed is below 25 rad/s. The downlink performance is not affected since the error is about the antenna boresight. The final spike at 18:38:00 is a slew back to the nominal nadir-tracking attitude at the end of the pass. Again it takes approximately 90 seconds to reduce the attitude control error below 0.5° following the slew.

Overall, the RMS errors for the target tracking period (not including the initial convergence period) are 0.45°, 0.28°, and 0.40° about the X, Y, and Z axes, respectively. This high level of pointing performance meets all mission requirements, enabling the system to maximize data downloaded during ground station passes.

5 CONCLUSIONS

As of January 2016, all commissioning activities were concluded and exactEarth took over full operational responsibility of the mission. The EV9 mission has demonstrated that a high degree of operational performance and reliability can be obtained from a nanosatellite platform. The addition of this equatorial satellite to the exactView constellation has complemented the existing polar satellites by providing shorter revisit intervals to some of the densest shipping areas in the world.

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