SSC17-X-10

The Development of "nSight-1" - Earth Observation and Science in 2U

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ABSTRACT

nSight-1 (QB50 AZ02) is a 2U size satellite developed in South Africa as part of the international EU-funded QB50 project. The satellite carries two main payloads: an atmospheric science instrument and an imager for Earth observation. Mission-specific challenges included integrating our imaging hardware into the severely space-and-power constrained 2U form factor enforced by the QB50 mission. Additionally, the available UHF data link needs to simultaneously serve the atmospheric science payload as well as the intended imaging mission. nSight-1 serves as a benchmark for CubeSat programmes, having been completed in full compliance with the QB50 project and launch requirements in a mere 6 months.

Deployment into orbit was achieved on 25 May 2017. We present our programme's development and early commissioning results, paying specific attention to nSight-1's role as Earth Observation technology demonstrator.

INTRODUCTION

nSight-1 is the first privately funded, commercially developed, South African satellite. It was developed by SCS Space[1] to demonstrate capability and to obtain flight heritage on subsystems that include a novel multispectral imager. The nSight-1 satellite is a 2U CubeSat that is part of the QB50 constellation[2] that was launched and deployed from the International Space Station (ISS) in the second quarter of 2017.

QB50 is a constellation of 2U (10cm x 10cm x 20cm) and 3U (10cm x 10cm x 30cm) CubeSats that is coordinated and partially sponsored by the European Union (EU). Initially intended to consist of 50 satellites (hence the name), QB50 has finally resulted in 36 satellites being selected and delivered for launch. These satellites were built by as many institutions and groups across 21 countries[3]. Twenty-eight of QB50's satellites were launched aboard an Atlas V rocket on the OA-7 "John Glenn" resupply mission to the International Space Station (ISS). OA-7 was successfully captured and docked to the ISS on 22 April 2017.

Deployment of the 28 ISS-bound QB50 satellites into orbit was performed by NanoRacks[4] in several batches over a period spanning 16 to 25 May 2017.

The second part of the QB50 constellation consists of eight satellites that are scheduled for launch aboard a PSLV into a 500km Sun synchronous polar orbit.

As a member of the QB50 constellation, nSight-1 carries a scientific payload for measuring the lower thermosphere – a region of the Earth's atmosphere that is currently not very well characterized.

DESIGN

nSight-1 makes use of the 2U CubeSat standard. Figure 1 shows a rendering of the satellites layout and main components.

Many of the platform requirements are driven by the QB50 project[5]. One such design constraint is the inclusion of the FIPEX (Flux-Φ-Probe Experiment) science payload that collects information about atmospheric oxygen in the lower thermosphere.

A custom-built break-out board was developed to take care of specific interfacing elements, where components do not all conform to "standard" CubeSat electrical interfaces.

The Gecko Imager, VHF/UHF transceiver, OBC and ADCS module and Break-out Board were all designed and assembled locally in South Africa.

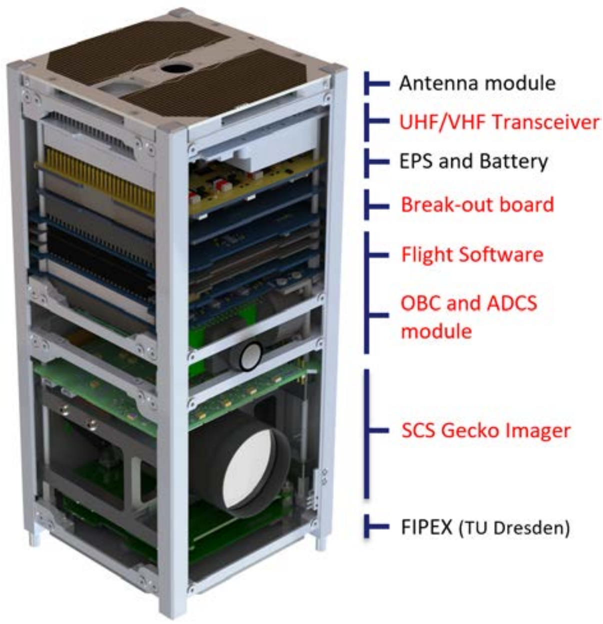

Figure 1: nSight-1's Major Components (South-African developed components shown in red)

Radio Transceiver

The satellite communicates with the ground station using a VHF uplink and UHF downlink with 9600 bps maximum data rate. The constraint of a relatively low data rate drives the need for efficient bandwidth unitization for earth observation operations. This need is addressed by several on-board image processing options as described later in this paper.

The satellite uses a deployable crossed dipole type antenna supplied by ISISpace B.V.

Power System

nSight-1 makes use of body-fixed as well as deployable solar panels covering a total area of 20cm x 30cm to maximize power generation in the nominal flying orientation.

The power sub-system is comprised of a commercial EPS module that includes the power conditioning, charging electronics and batteries. The EPS faced scrutiny from reviewers because of the risk that malfunctioning batteries would pose to the ISS.

FIPEX experiment

The Flux-ϕ Probe EXperiment (FIPEX) was developed by the Technical University of Dresden, Germany and supplied as part of the QB50 programme agreement. Its goal is to measure the time resolved behaviour of atomic oxygen flux in the upper atmosphere and lower thermosphere. This flux is of general importance in spaceflight as it interacts with spacecraft surface materials, e.g. causing erosion.

The FIPEX instrument is equipped with solid oxide electrolyte micro-sensors[6] that are able to distinguish atomic and molecular oxygen at very low ambient pressures down to 10^{-10} mbar. The sensor utilizes the amperometric three electrode principle where electrical current is measured a noble metal ceramic compound heated to approximately 660°C.

Under low-pressure conditions, e.g. in low-Earth orbit (LEO) the oxygen molecule flux is naturally limited by effusion laws. In order to distinguish the atomic oxygen (AO) from the molecular oxygen (O_2) different cathode materials are used.

Atomic oxygen flux in the lower thermosphere is not yet well characterized, and it is here that the FIPEX instrument will make its contribution. The lack of prior research in this area is partly due to the low orbital lifetime associated with satellites orbiting at low altitudes. A CubeSat constellation such as QB50 with its relatively low unit cost is therefore well suited for this scientific application.

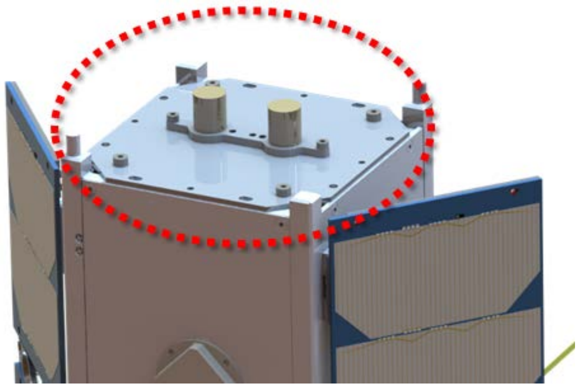

Figure 2: The FIPEX atmospheric probe is located on nSight-1's forward facing (+X) panel

Gecko imager payload

As its main payload, nSight-1 carries an SCS Gecko imager[7]. The Gecko Imager consists of a Sensor Unit (SU), Control Unit (CU), Optics and mechanical support structure.

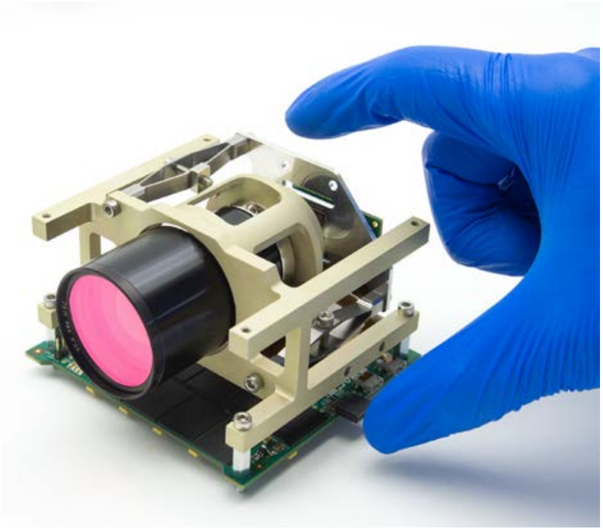

Figure 3: Imaging Payload: The “Gecko” Imager

Core design features of this imager include its modular design, integrated high-speed flash memory and FPGA processor.

The imager’s data rate and storage capabilities can be scaled to accommodate an extensive array of imaging requirements, optics and focal plane assemblies.

Figure 4: Sensor Unit for the Gecko Imager

The 2-megapixel RGB SU and optics combine to give nSight-1 a 32m Ground Sampling Distance (GSD) and 64km swath from the ISS deployment altitude of 400 km. The sensor features a Bayer-pattern filter, allowing photorealistic colour images to be captured.

The CU on nSight-1 was configured to include 128 Gigabytes of high speed flash memory. Together with its integrated FPGA processor this enables the CU to capture images at up to 300 frames per second. Its modularity and processing power allows the CU to be adaptable to larger satellite payloads that will in future support a wider range of spectral bands and more powerful optics. The CU’s flash memory controller includes automatic wear levelling and error correction functionality.

Figure 5: Control Unit for the Gecko Imager

On-board Image processing

Raw images are captured from the matrix sensor at a fidelity of 12 bits in snapshot (global shutter) mode, resulting in raw data files of approximately 3 megabytes per image frame. Raw image data is written directly to the integrated mass storage.

Although it is possible to download uncompressed full frames to ground, this may not be desirable. Assuming an average overpass duration of 5 minutes, it will take at least 9 overpasses to download one complete uncompressed image frame using the 9600 bps UHF downlink. This does not yet take into account the protocol overhead, or the fact that both housekeeping and science data should be downloaded using the same link. Optionally-activated processing options were therefore implemented on the FPGA and on-board computer (OBC), including i) JPEG image compression and ii) thumbnail generation.

Future versions of the CU will include both lossless and lossy JPEG2000 compression implemented natively on the FPGA. On nSight-1 we instead implemented the standard discrete cosine transform 8-bit lossy RGB JPEG compression with adjustable quality factor.[8]

Bayer pattern demosaicing, RGB colour space conversion, chroma subsampling and thumbnail downsampling take place in real time on the on-board CU FPGA processor. The pre-processed image data is then downloaded to the OBC, where the JPEG compression process takes place.

Due to OBC and satellite power constraints the JPEG engine was highly optimized for this platform, and supports both 4:4:4 and 4:2:2 colour subsampling for enhanced compression ratios. Using 4:2:2 sub-sampled JPEG, image frames can easily be compressed to less than 15% of their equivalent 8-bit raw file sizes, depending on image content.

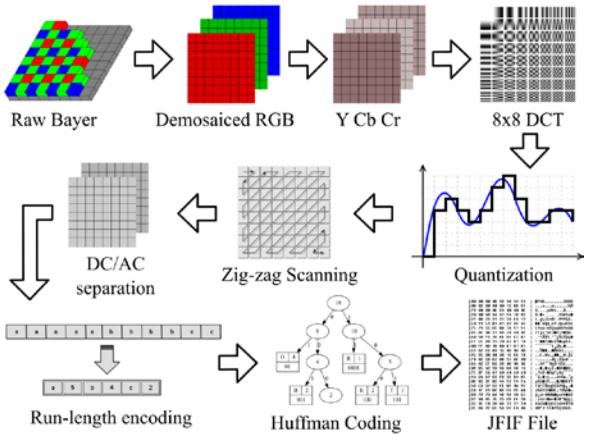

Figure 6: JPEG compression imaging pipeline

Image thumbnails are downsampled by a factor 8 and then aggressively compressed as 8-bit colour JPEGs, resulting in thumbnail files that are typically between 4KB and 7 KB each. This allows multiple thumbnails to be downloaded in a single overpass. From these, frames can be selected for high-resolution download on subsequent overpasses, as the large amount of on-board flash storage makes long-term retention a practical option. This prevents the unnecessary download of images obscured by clouds or images captured with inappropriate imaging settings (e.g. incorrect gain or exposure).

Control System

The attitude control system (designed and built by CubeSpace[9]) is similar to the ADCS that flew successfully on the QB50 precursor P1 and P2 satellites. A Y-axis momentum wheel was combined with magnetorquers in such a way that attitude is controlled while simultaneously managing wheel momentum and damping nutation.

This allows the imaging payload to remain pointing towards nadir and the FIPEX sensor pointing along the velocity vector to within 10 degrees to satisfy the QB50 requirement. This configuration will also result in minimal drag, thereby prolonging the satellite's life in orbit.

Attitude sensing is performed using a combination of a 3-axis magnetic field sensor, a fine sun sensor and nadir sensor. The fine sun and nadir sensors are also cameras with wide field of view that perform image processing to detect the sun and nadir vectors relative to the satellite body.

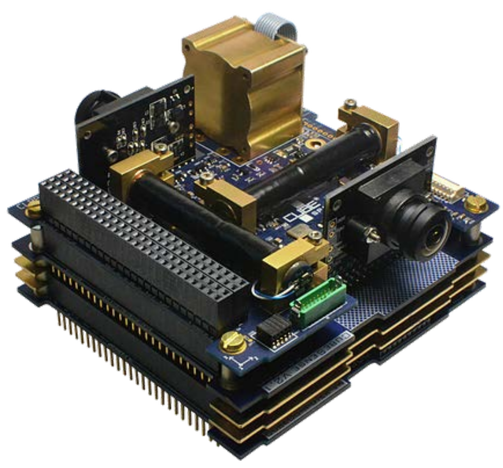

Figure 7: CubeSpace Y-Momentum ADCS stack

The ADCS unit contains a CubeComputer[9] as the satellite's OBC, it is a single radiation tolerant microprocessor board that performs both attitude control and house-keeping tasks. The attitude control system contains various controllers, state estimators, orbit, magnetic field and sensor models to do satellite detumbling, Y-momentum 3-axis stabilization and nutation damping. External to the ADCS stack is a deployable 3-axis magnetometer to assist with magnetic detumbling and to be the only attitude sensor during eclipse.

ASSEMBLY, INTEGRATION AND TESTING

Generally speaking, teams participating in the QB50 project were involved for all of the three years leading up to launch. The nSight-1 project was started in April 2016 and finally delivered for launch integration in October 2016. This very short 6-month timeframe necessitated several design choices, such as the inclusion of COTS (Commercial-Of-The-Shelf) components as opposed to new developments. Another hallmark of the project is the inclusion of largely South-African produced components, such as the ADCS module, the imaging payload and the VHF/UHF transceiver.

As with the design, the testing of the CubeSat was also greatly prescribed by the QB50 project coordinator, to make sure project and launcher requirements were adhered to. The satellite had to undergo vibration, thermal and vacuum testing. In addition to the environmental tests, it was also crucial to demonstrate the end-to-end functioning of the science and imager payloads. This includes over-the-air commanding, telemetry download and payload data downloading using the actual ground station equipment. The entire testing campaign was completed in one month.

Electronic components, including the Gecko imager's SU and CU, were tested to survive 30 kilorad of total ionizing dose (TID).

Acceptance vibration testing was performed at a local South African test facility according to launch profiles supplied by the QB50 program requirements. Following a test-as-you-fly principle the satellite was integrated in a representative launch pod mechanical structure for the testing.

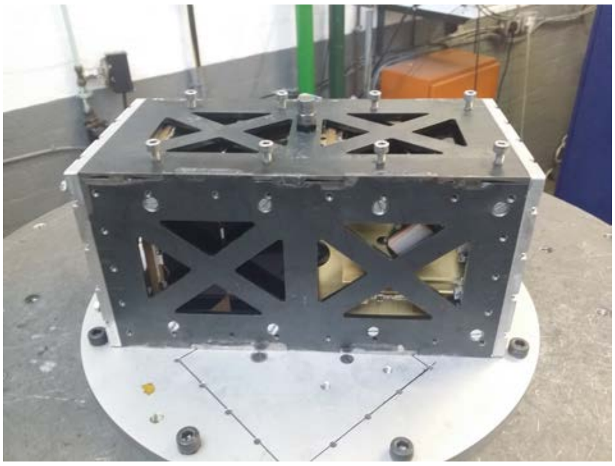

Figure 8: nSight-1 undergoing vibration testing

Thermal vacuum testing was performed at local Stellenbosch University facilities and created the necessary confidence that the satellite will survive and perform as expected in the space environment.

GROUND STATION

A dedicated ground station was set up on South African soil to service nSight-1's daily data downlink needs. The location was chosen for its radio silence and very favourable horizon elevation profile.

The ground station equipment consists of Yagi antennas on tracking mechanisms and an IC-9100 radio. The mission control system (MCS) of a South African based company, Spaceteq, is utilized in conjunction with the CubeSupport software that serves as supporting ground software for CubeSpace products. The ground station has been in contact with the satellite since the first beacon after release into orbit.

Figure 9: SCS Space Ground Station located near Grabouw, South Africa

LAUNCH AND DEPLOYMENT INTO ORBIT

On 18 April 2017, an Atlas V rocket carried the OA-7 "John Glenn" resupply mission into orbit. In addition to supplies for the ISS, OA-7 carried the full complement of 28 ISS-bound QB50 satellites, including nSight-1. OA-7 was successfully captured and docked to the ISS on 22 April.

On 25 May 2017 nSight-1 was released into a 51.6° inclination 400 km orbit using the NanoRacks deployment system[4], as part of the second airlock cycle servicing QB50.

Based on its orbital parameters and ballistic coefficient, we expect nSight-1 to have an orbital life time of between 12 and 18 months.

COMMISSIONING AND EARLY OPERATIONS

After release from the International Space Station (ISS) the satellite was spinning mainly around its lowest moment of inertia X-axis at approximately 5 deg/s. Due to a configuration mistake in the magnetometer mounting the initial magnetic detumbling controller actually increased the X-axis spin rate to around 60 deg/s. Fortunately, the error was quickly corrected and a fast Bdot detumbling controller dumped the angular body rates within an orbit. Figure 9 shows the Y-axis angular rate as measured by a solid-state MEMS rate sensor as the body spin is damped within 60 minutes.

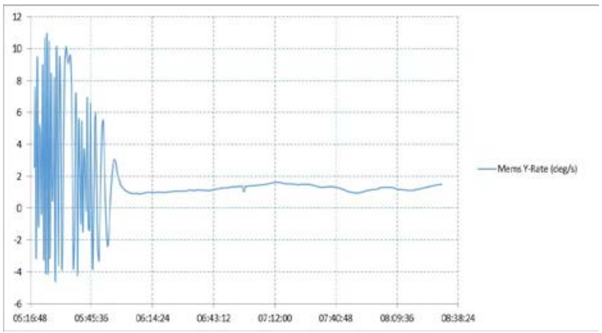

Figure 10: Detumbling result as measured by the Y-axis rate sensor

Once the body was successfully detumbled a Y-Thomson magnetic controller was enabled to bring the satellite to a controlled Y-spin rate normal to the orbit plane (the body pitch rotates with small roll and yaw angles within the orbit plane). Figure 10 shows the magnetometer measurement and Figure 11 the Y-rate measured during Y-Thomson control to a -2.5 deg/s reference body rate.

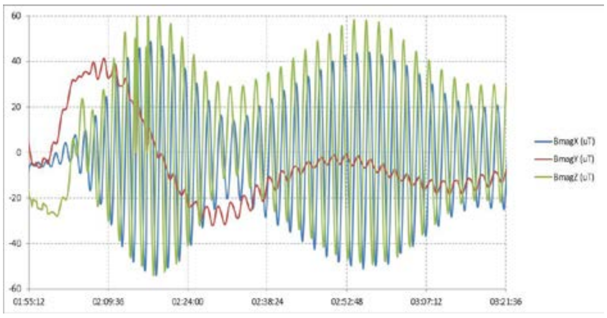

Figure 11: The magnetometer measured body vector towards an accurate Y-Thomson spin

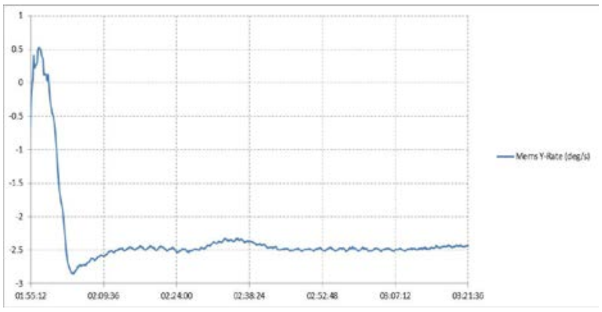

Figure 12: The MEMS sensor measured Y-rate during Y-Thomson control

The next step was to calibrate the magnetometer in-orbit for orthogonality, gain and bias. This was done by measuring the magnetic field vector for an orbit during a slow body spin. The whole orbit data (WOD) of these measurements was then downloaded and the magnetometer vector magnitude compared with an IGRF model's magnitude at the same orbit location. An attitude independent calibration procedure[10] was used to obtain the magnetometer calibration sensitivity matrix (gain and orthogonality) and offset (bias) vector. See Figure 12 and Figure 13 for the pre- and post-calibration results.

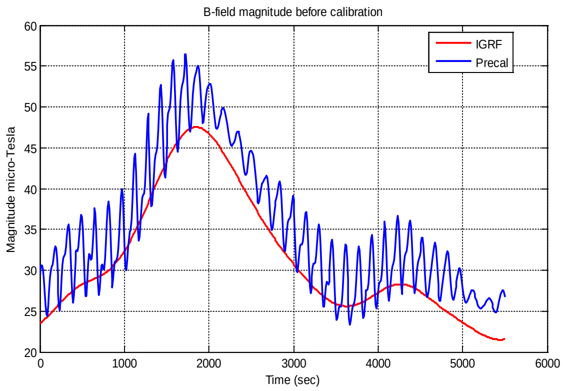

Figure 13: Magnetometer magnitude comparison before calibration (Std dev = 2.848 µT)

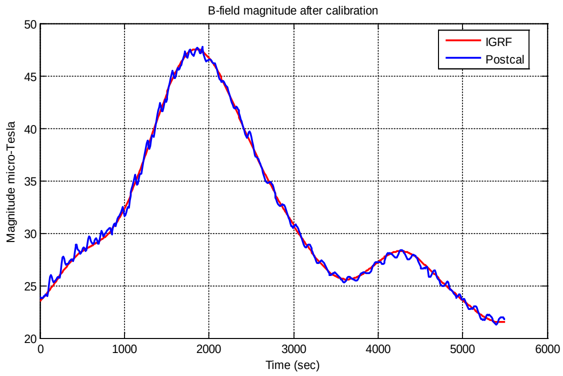

Figure 14: Magnetometer magnitude comparison after calibration (Std dev = 0.365 µT)

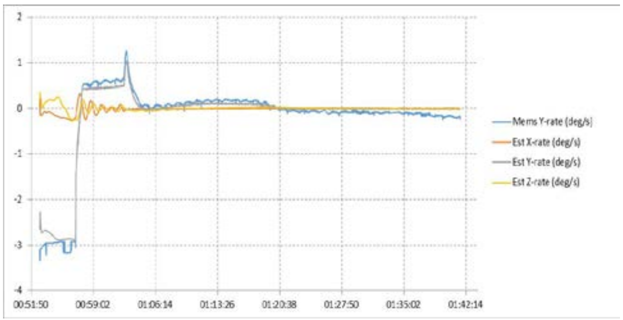

Figure 15: Estimated and measured body rates from Y-Thomson spin to Y-momentum 3-axis control

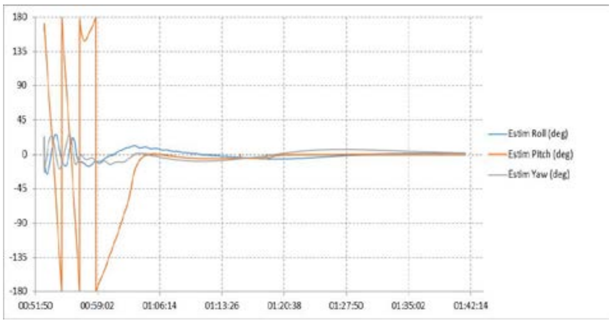

Figure 16: RPY attitude angles from Y-Thomson to Y-Momentum control

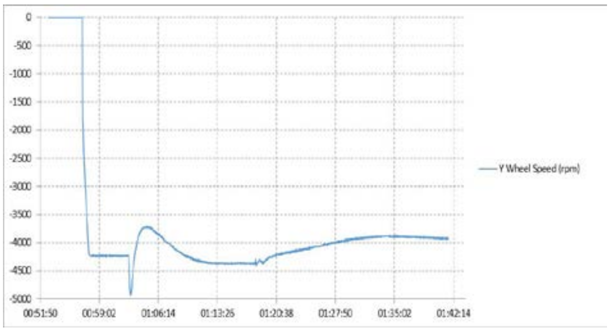

Figure 17: Y-wheel speed from Y-Thomson to Y-Momentum control

The final step was to stabilize the satellite 3-axis at zero roll, pitch and yaw angles (nadir and FIPEX pointing toward the velocity vector). From Figure 14 it can be seen that the satellite was initially in a -3 deg/s Y-Thomson spin, the Y-momentum wheel was then ramped to -4200 rpm to absorb most of the body angular momentum (see Figure 16). The wheel speed was then maintained until the pitch angle became within 45 deg from zero (see Figure 15). The pitch wheel controller was then enabled to maintain a zero-pitch angle and a magnetic nutation damping controller to damp any roll and yaw oscillations and to maintain the Y-wheel speed close to -4000 rpm (manage the Y-wheel angular momentum). The estimated roll, pitch and roll angles were quickly controlled to within a 2-degree range, easily satisfying the QB50 requirement over the full orbit.

CONCLUSION

At the time of writing nSight-1 is being commissioned, with all systems functioning as expected.

The nSight-1 project is a benchmark for CubeSat programmes worldwide, since it was completed in only 6 months, in full compliance with the QB50 project and launch requirements.

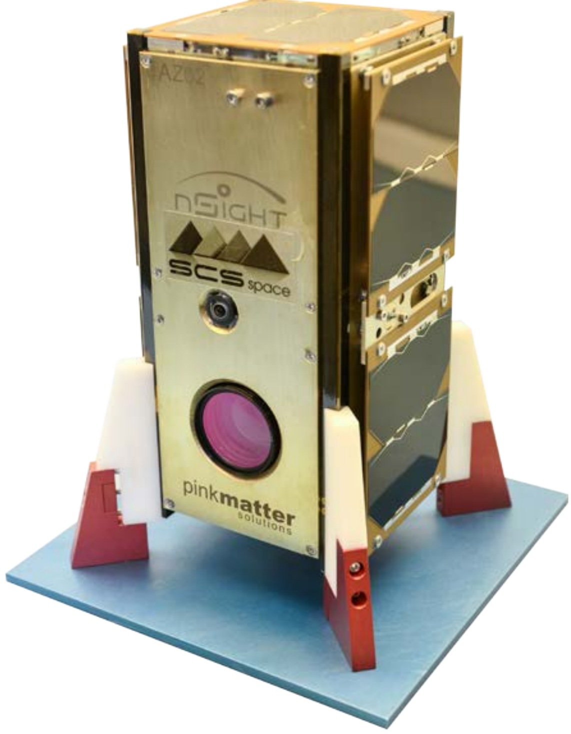

Figure 18: Completed nSight-1 Satellite (mounted on support brackets and base plate)

The heritage gained by launching and operating the Gecko Imager will be invaluable to SCS Space since it will allow the company to further market world-class Earth observation products.

The Gecko Imager, and other locally produced components showcases South African industry and universities' ability to compete in a global marketplace.

Acknowledgments

The authors are grateful for financial support, material and facilities made available by the South African Aerospace Industry Support Initiative, PinkMatter Solutions, Simera Technology Group, NewSpace Systems, CubeSpace, University of Stellenbosch and Nelson Mandela Metropolitan University.

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