# IN-FLIGHT RESULTS OF THE NAPA-2 TURN-KEY HIGH RESOLUTION IMAGING SYSTEM – A STEPPINGSTONE TO WORLD-LEADING EO MISSIONS

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## ABSTRACT

Earth Observation (EO) has grown to become a key-application for CubeSats enabling low-latency, global imagery to customers. With the earlier development of the 6U NAPA-1 satellite ISISPACE joined the ranks and built-up valuable experience with respect to platform performance and data processing. Confined to snapshot imaging only with NAPA-1, ISISPACE took it up a notch through the development of NAPA-2. NAPA-2 is another 6U EO satellite housing the Simera Sense MultiScape100 CIS: a 7-band multi-spectral line-scan imager. This turn-key EO system offers an impressive ground sampling distance of 5m and includes an on-ground data calibration and processing chain through FarEarth, a system developed by Pinkmatter Solutions. The attitude determination and orbital control system (AOCS), a completely new ISISPACE built, has successfully supported the imager with forward-motion-compensation (FMC) maneuvers, stable attitude control for long line-scans, and high levels of time-delay integration (TDI). Jitter and stability – both vital for imaging – and the resulting image products will be discussed and showcased. The experience gained by the development of this mission allows ISISPACE to support more demanding missions with confidence, such as the proposed ESA Scout mission TANGO, which requires Forward Motion Compensation and stable pointing, as well as higher resolution imaging missions.

## 1 THE NAPA-2 MISSION

The NAPA-2 mission is characterized by several key requirements that have driven the design and implementation of the NAPA-2 system, which includes both space and ground segment. The key requirements are as follows:

| |
|---|
| The satellite shall be able to capture Thailand and nearby area defined by latitude and longitude |
| Ground targets shall be captured by with a GSD of <5m at 500km altitude |
| All captured data shall be downlinked within 24 hours thereafter |
| The system shall support target capture planning >24 hours before |
| The operator shall be able to select and download raw, compressed, and thumbnail data |
| On ground processing of data shall be done up to level L1B |

To support these, and the remaining customer requirements, the system architecture as shown in Figure 1 was implemented. This consists of three separate segments covering the user, space, and ground segment. The user segment focusses on Thailand and its region to be monitored from space. Imaging shall occur with the Simera Sense MultiScape100 CIS camera to support reconnaissance and detection of objects (combination of the RGB bands) and vegetation detection and change thereof (near-infrared bands). The latter to support monitoring of natural disaster aftermaths.
Nominal operations are carried out through the RTAF's ground station in Thailand, which includes automatic on ground processing of image data through Pinkmatter Solutions' Far Earth application.

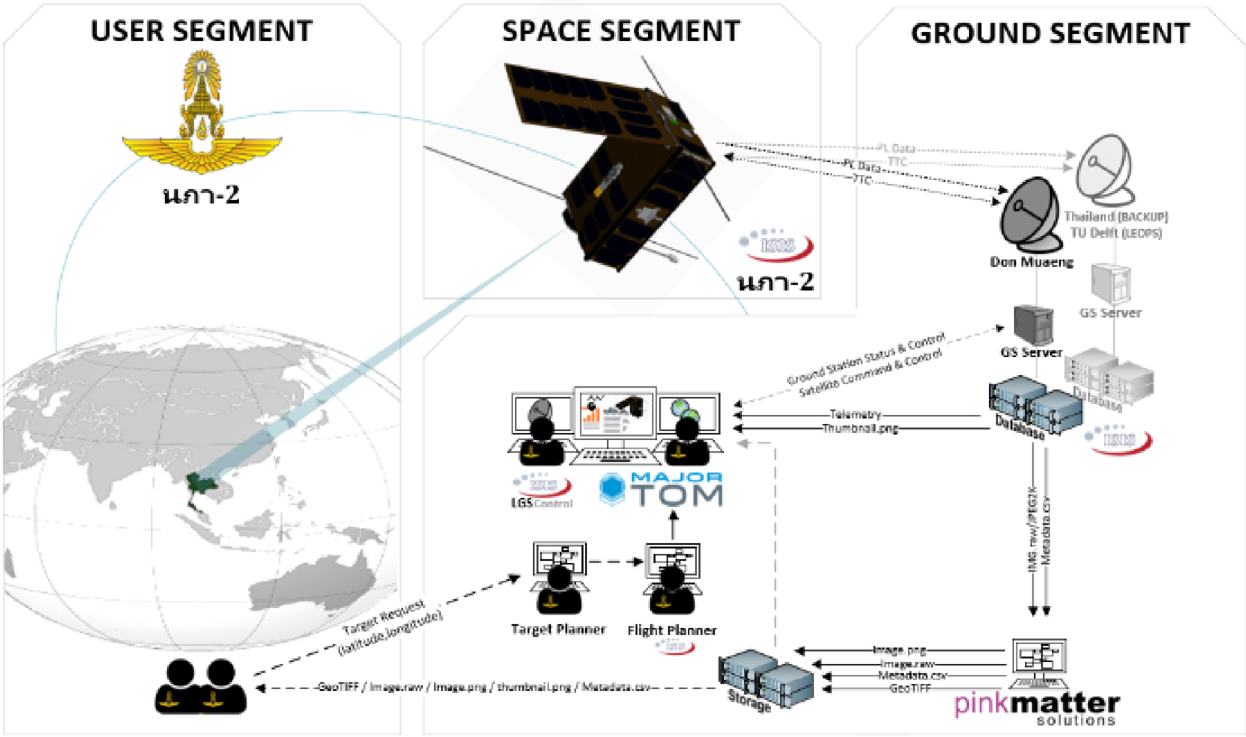



Figure 1. NAPA-2 mission and system overview.

## 2 THE NAPA-2 EARTH OBSERVATION SATELLITE

The NAPA-2 EO satellite is the successor of the Royal Thai Airforce (RTAF)'s NAPA-1 satellite. Both are 6Us designed and built to provide high-resolution imaging from low-Earth orbit. NAPA-2 consists of an ISISPACE built set of avionics covering the command- and data-handling system, the AOCS, the payload data handling system, and the power system. In addition, the Simera MultiScape100 CIS 7-band line-scan imager is included as well as the ThrustMe I2T5 propulsion system. Finally, NAPA-2 flies another payload, completely developed by ISISPACE, which is the LED-payload board. The 6U satellite external and internal are shown in Figure 2.

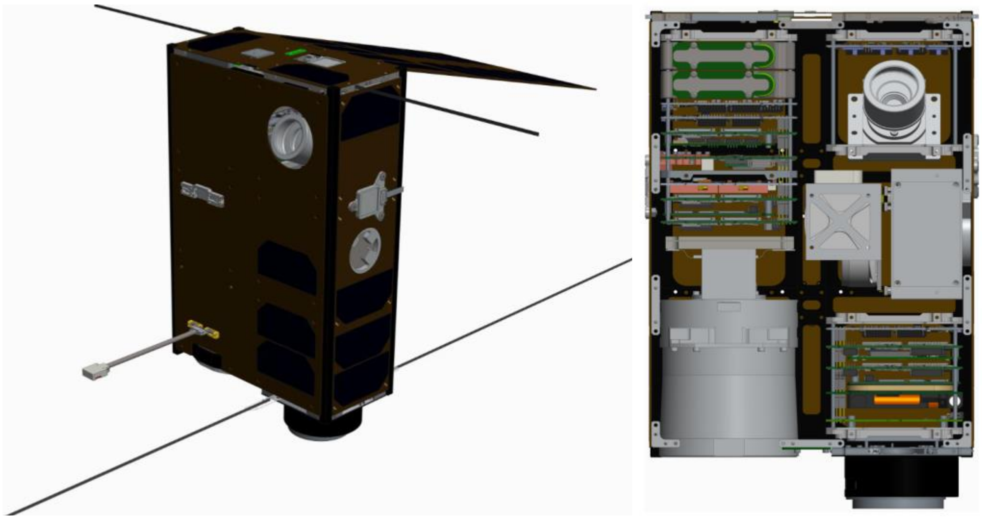
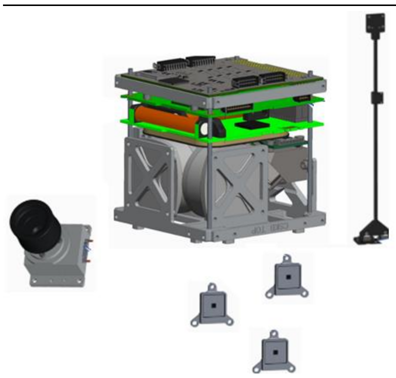


Figure 2. NAPA-2 6U satellite external and internal lay-out.

## 2.1 ISISPACE Attitude and Orbital Control System

The ISISPACE AOCS is a complete solution for attitude determination and orbital control. It consists of a collection of commercial-off-the-shelf (COTS) sensors and actuators in combination with ISISPACEs own developed magnetorquer board, command and control system, software algorithms, and deployable magnetometer. The COTS items are procured from different suppliers of which an overview is presented in Table 1.

Table 1. ISISPACE AOCS bundle and component suppliers.

| ISISPACE AOCS | System | Supplier | Pointing | Performance |
|---|---|---|---|---|
|  | AOCS OBC | ISISpace | Accuracy | 0.1° |
| | SCG Gyro Module | ISISpace | Stability | 0.05° |
| | iMTQ and MTM boom | ISISpace | Knowledge | 0.05° |
| | Photodiodes (6x) | ISISpace | Position | 2m |
| | Fine Sun sensors (3x) | Lens R&D | | |
| | OEM719 GNSS receiver | NovAtel | | |
| | RW25 30mNms RWs (3x) | Astrofein | | |
| | Auriga Star tracker | Sodern | | |

*Provisionally estimated as relative error over the duration of an FMC image acquisition from 1s control error measurements.

The system has been designed to support high-performance missions, which includes NAPA-2. In addition, the AOCS can be made compatible with COTS propulsion systems, such as the ThrustMe I2T5 flying onboard NAPA-2.

## 2.2 Simera Sense MultiScape100 CIS

The Simera Sense MultiScape100 CIS camera (Figure 3) is a multi-spectral line-scan imager designed to fit within CubeSats while giving unprecedent performance. It boasts a 5m GSD at an orbital altitude of 500km. It supports time-delayed integration to improve the camera's signal to noise ratio at the cost of straining the platform's AOCS, leading to smearing of cross-track pixels in case requirements are not met.

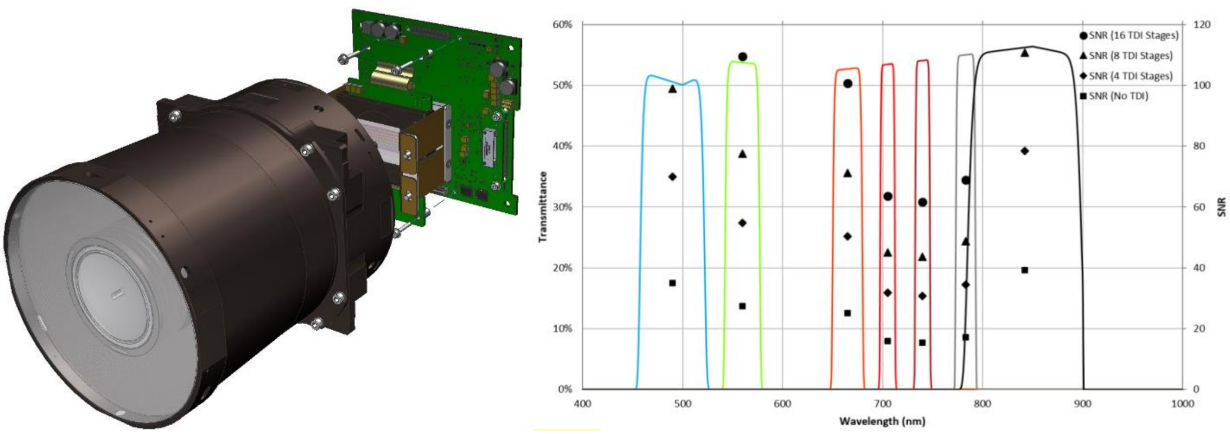



Figure 3. Simera MultiScape100 CIS exploded view and transmittance for each of the wavelengths as a function of TDI.

The full set of specifications is shown in Table 2, along with the spectral bands and wavelengths.

Table 2. Simera MultiScape100 CIS specifications and spectral bands.

| Parameter | Value | Comment | Wavelength (nm) | Band |
|---|---|---|---|---|
| Focal length | 580 ±1 mm | | 490 | Blue |
| Aperture | 95 mm | | 560 | Green |
| Full Field of View | 2.22° | Across-track | 665 | Red |
| Pixel Size | 5.5 µm | | 705 | Red(edge) |
| TDI-stages | Up to 32/band | User assigned | 740 | Red(edge) |
| Line Rate | Up to 2600 Hz | | 783 | Red(edge) |
| Image processing | Binning/thumbnails | | 842 | Near InfraRed |
| Storage | 128 Gbyte | NAND flash | | |

## 3 PLATFORM DATA AND COMISSIONING RESULTS

Since NAPA-2’s launch July 2021, ISISPACE has been actively operating the satellite successfully completing launch- and early operations as well as commissioning. Through this phase, ISISPACE has been able to measure platform performance and obtain a significant number of images. Gaining flight heritage for the very first time, the ISISPACE built AOCS has been extensively commissioned and tweaked to improve its performance for NAPA-2 and future missions.

### 3.1 Platform Data

Platform telemetry has been gathered throughout the commissioning phase. Telemetry is kept up to date by downloading the latest 24h log data daily. This allows for continuous platform monitoring and ensures that any issues arisen allow for detailed investigation due to the availability of telemetry. Common platform parameters that are collected and displayed to the operators cover currents, voltages, temperatures, up-times, modes, and subsystem specific (measurement) data.

Figure 4 shows two examples of temperature telemetry gathered from the satellite while being in its nominal nadir-pointing attitude: panel temperatures (external) and IOBC temperature (internal). These provide critical information on the safety of the systems regarding thermal environment but also, for example, give indirect insight into the attitude of the satellite.

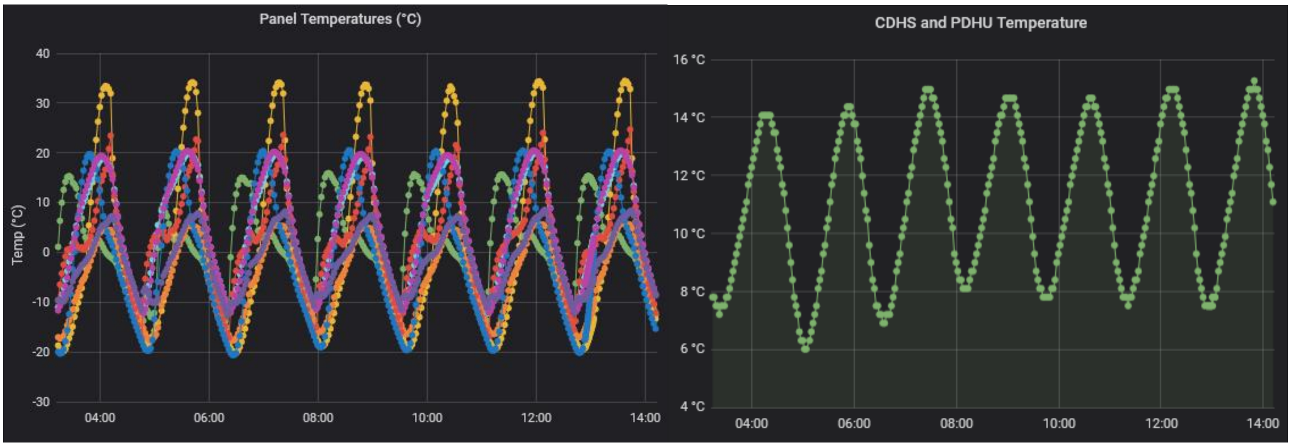



Figure 4. NAPA-2 panel- and iOBC (CDHS and PDHU) temperature data for several orbits in steady nadir-pointing attitude.

Another set of data – also temperature – was collected from the ISISPACE deployable magnetometer. This system was fully developed by ISISPACE and obtained its first flight heritage through NAPA-2. With the magnetometer being on a long boom (~20 cm) the sensor itself is significantly thermally decoupled from the satellite itself, which required a delicate thermal solution to ensure a safe temperature range. Thermal analyses carried out in the design phase led to the usage of thermal tape with specific optical properties. Subsequently, in-orbit data retrieved from NAPA-2 has shown that the implemented solution has been successful (Figure 5) as the magnetometer's temperature remains consistently between approximately -20°C and +20°C.

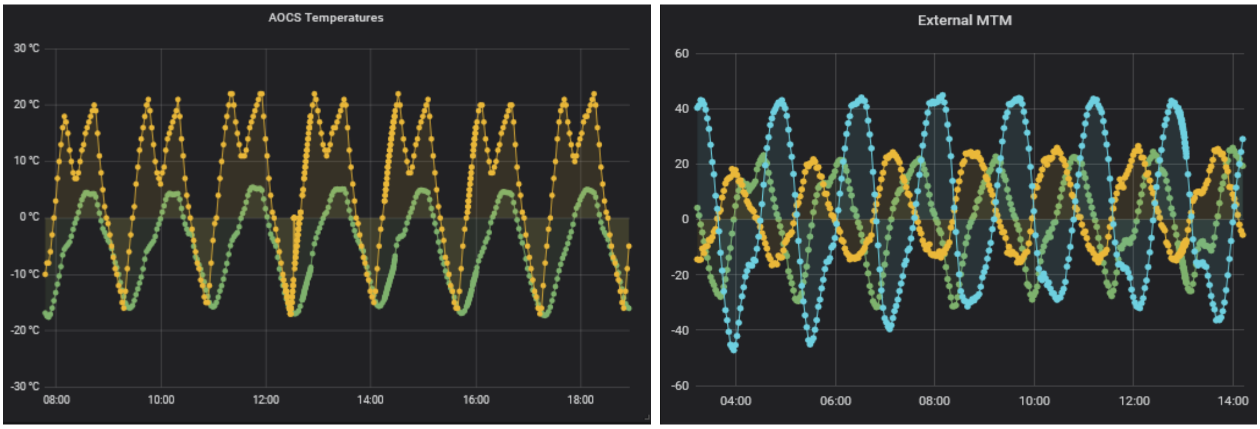



Figure 5. On the left: Y-Panel temperature (green) ranging from approximately -20°C to +5°C and the deployable magnetometer temperature (yellow) ranging from approximately -20°C to +20°C. On the right: magnetic field measurements.

Finally, power generation is computed through the measured data on the EPS' conditioning unit allowing validation of NAPA-2's power budget. The NAPA-2 generated power supports multiple image acquisitions daily including downloading of data (~250 Mbytes per image session) within the required 24 hours.

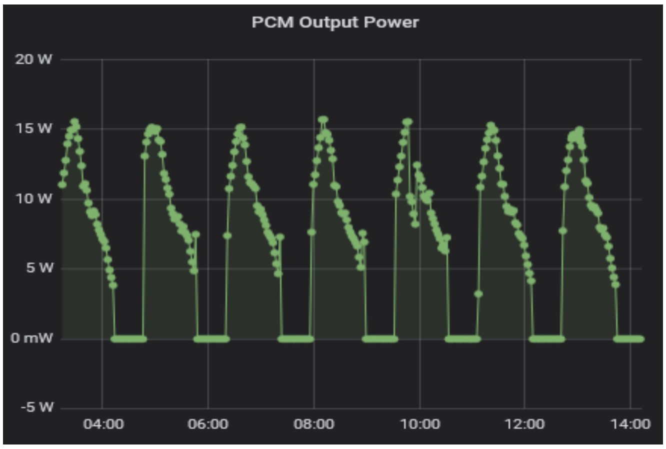



Figure 6. NAPA-2 power generation computed from the telemetry received from the conditioning unit.

### 3.2 Commissioning Results of the ISISPACE AOCS Bundle

The AOCS configuration detailed in chapter 2.1 above flew for the first time on the NAPA-2 mission. Overall, the system has proved to be very robust after its teething issues were resolved with firmware updates and has fully met its initial performance targets in the mid- and high-performance regimes, while, at the same time, remaining highly versatile and customizable, in order to facilitate experimentation with advanced pointing modes, such as FMC, which were out of scope of the mission.

After the initial commissioning that aimed to check out its individual subsystems and ensure correct inter-sensor alignment between the star tracker and the rest of the sensor suite, a system level commissioning campaign was conducted to carefully calibrate the residual system-level bias between the AOCS and the imaging camera, since there was no effort on optics-based alignment of the two systems spent on ground. Initially, a significant, but nearly constant residual bias was evident after analyzing many images, such as the ones shown below in Figure 7.

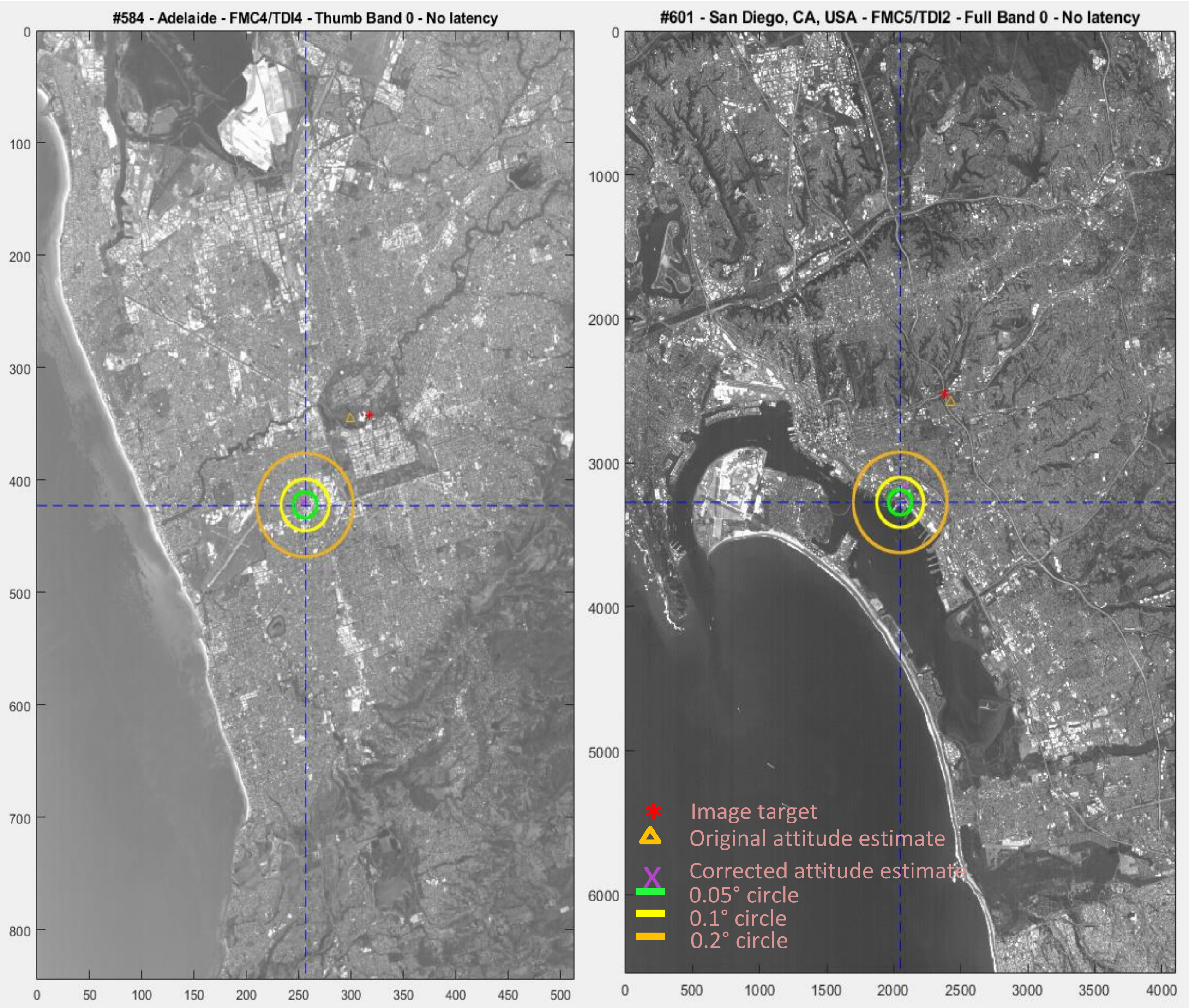



Figure 7. Example images and analysis done pre-calibration

The bias was calibrated out (although this is still work-in-progress) and the first results post-calibration show good accordance with the expectation of an absolute pointing accuracy on platform level of <0.1° and an absolute attitude knowledge error of about 0.05°, as shown in Figure 8.

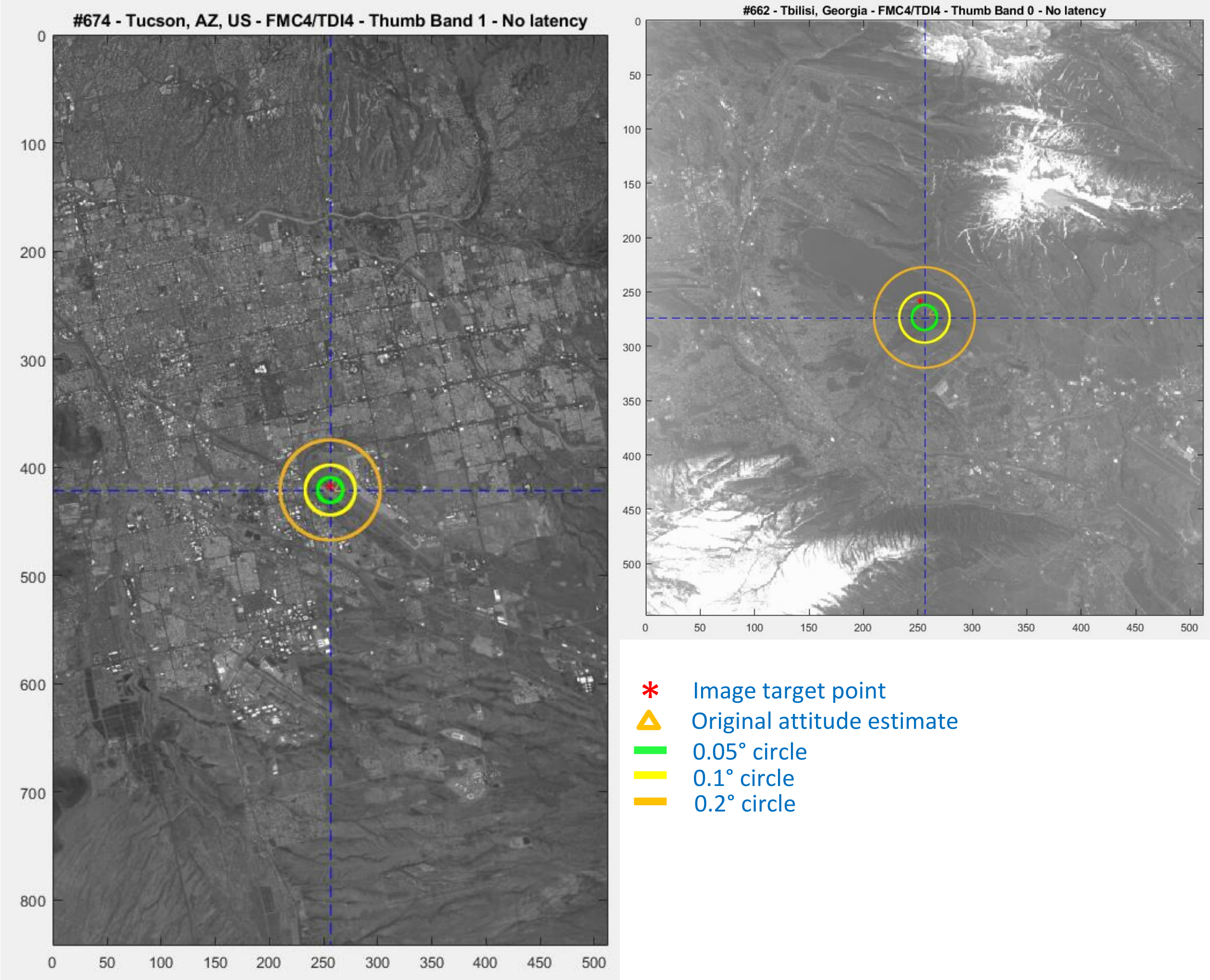



Figure 8. Example images and analysis done post-calibration

## 4 SIMERA IMAGING AND PROCESSING

After a successful platform commissioning the next step involved commissioning of the payloads. As NAPA-2 carries two payloads both have been independently commissioned. After the successful LED payload activations and tracking from ground [1] the Simera MultiScape100 CIS was commissioned. The steps executed involved validation of the communication and highspeed interfaces, health-check through telemetry, health-check through image acquisition, target acquisition planning.

### 4.1 Camera health-check and telemetry

Nominal values were obtained from the camera upon switch-on. The reported telemetry – coming from the electronics board – reported temperatures within the required operational temperature range (Figure 9). In addition, the camera being powered on for several orbits also showed that the electronics remained within a safe temperature range.

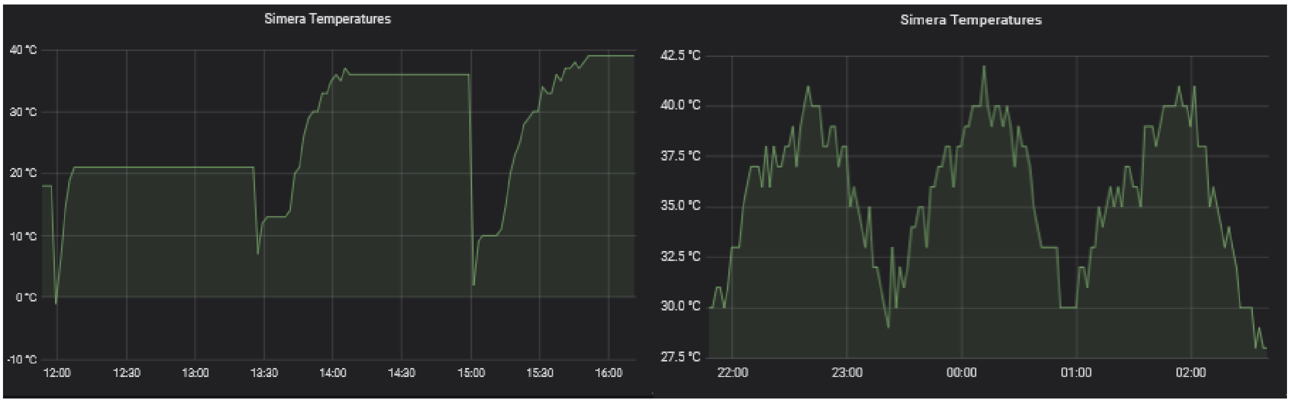



Figure 9. Simera FPGA electronics temperature during the three image acquisition periods (left) and when the camera electronics remained on over three orbits (right).

However, what has become visible is that upon powering on the camera (also confirmed through the panel temperatures and temperature sensors close by the optical part of the camera) is that the overall temperature of the optics remains on the low end and thermal gradients are expected over the camera, potentially negatively affecting the camera's performance. To minimize this effect, the camera was powered on earlier to allow for more heat being dissipated within the satellite to try and elevate and even out the temperature internally.

### 4.2 Image Planning

Image planning is critical: cloud forecast, and accurate timing is important as otherwise images will either be rendered useless (clouds) or result in different targets being captured. NAPA-2 operates through flight plans built on ground, after which they are uploaded to the satellite and executed. These flight plans contain specific commands, each executed based on its associated timestamp.
The flight plan itself is developed on ground and use is made of the Systems Tool Kit (STK) software which allows for propagating a satellite's orbit based on a known two-line element (TLE). As timing is important - the satellite has a relative surface velocity of approximately 7km/s – it is key to minimize errors in the system. This means, using an accurate TLE during planning and have sufficient knowledge of any timing errors that may linger in the system. With an accurate TLE at the ready, STK allows for setting up a sensor and targets, after which a simulation can be run to provide time of intersecting target, time directly overhead, and time of losing target. Along with these timestamps the required roll angle is computed as well. With this information, a flight plan can be built containing commands to power on the camera, set the AOCS in imaging mode along with the right roll angle, and push the image settings to the camera. The complete flow of image planning is shown in Figure 10.

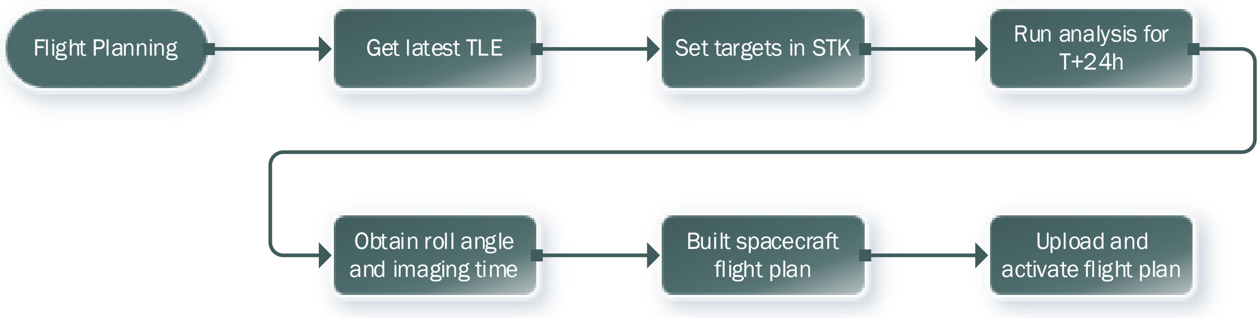



Figure 10. Image planning flow followed for accurately computing the time to start imaging and setting up the imaging control mode and roll angle of the AOCS.

### 4.3 Simera Camera Image Results

The goal of the commissioning phase of the camera onboard NAPA-2 was threefold:

1. Image targets for on ground calibration
2. Image targets for AOCS calibration and improvement
3. Image targets to show camera capabilities and performance

The first goal was supported by Pinkmatter Solutions, who's on ground image processing software was implemented in the ground segment of the NAPA-2 system. Targets involved geometric and radiometric sites (Figure 11), as well as other sites to identify the most optimal camera settings. The second goal was solely carried out by ISISPACE. With full control and insight into the AOCS (as being ISISPACE built) many maneuvers were executed to identify and improve the AOCS behavior where necessary. Images tremendously helped to discover the effect of sensor measurements, zero-wheel crossings, and control loops. Finally, the last goal was devised to showcase the camera's performance after the many improvements made (goal one and two). Images of interesting sites (harbors, forest area, agriculture) were targeted to show the camera's its capabilities for the RTAF as well as potential future customers.

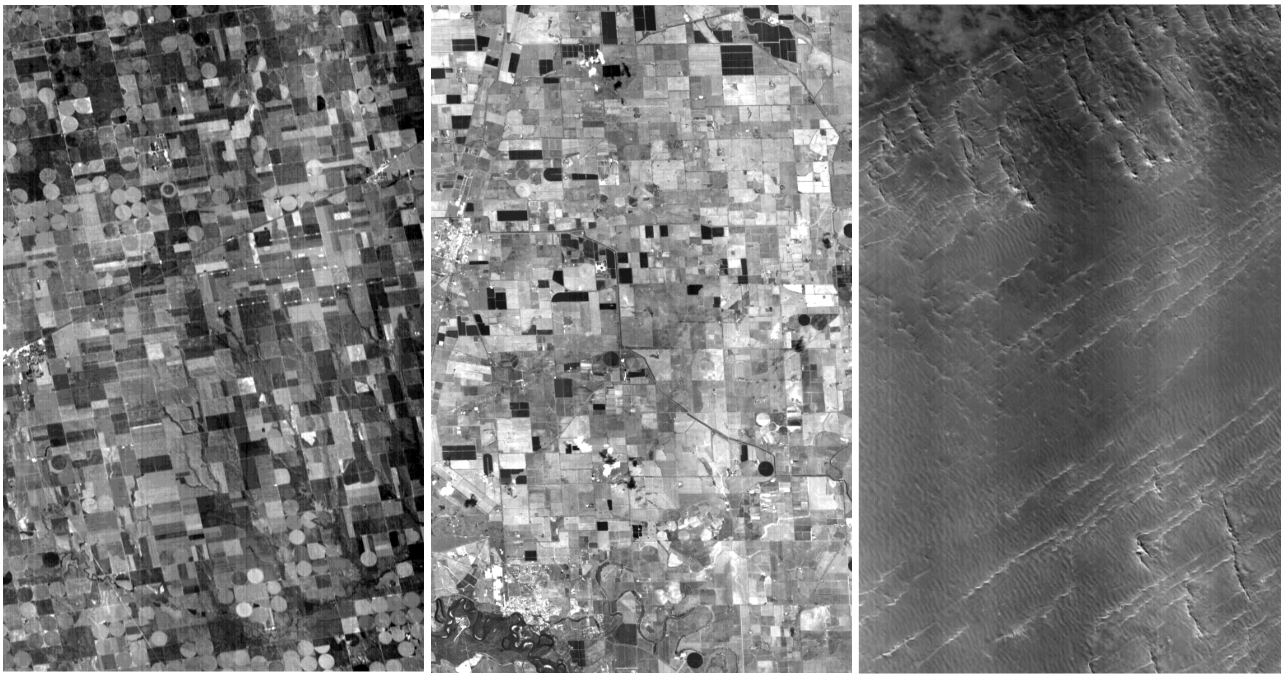


Figure 11. NAPA-2 RAW and unprocessed images (thumbnails) showing geometric and radiometric targets taken over Sioux Falls area (left), Australia (center), and Lybia (right).

The many images taken throughout the calibration phase allowed Pinkmatter Solutions to identify the correct camera settings, resulting in TDI 4 with a line period of 735µs (altitude dependent). TDI 4 led to the optimal signal-to-noise ratio for flyovers (with or without a roll angle) without straining the AOCS to the point where smearing would occur. This input was further used to achieve the second and third goals.

The capabilities of the camera and its performance was thereafter showcased through a series of images successfully taken over various sites. Harbors were successfully targeted to show capabilities of ship tracking, of which Figure 12 is a good example: San Francisco was imaged showing large ships as well as the wakes of smaller ones. **Note** the image shows a fully **unprocessed** raw image band (blue band).

Figure 12. NAPA-2 RAW and unprocessed thumbnail (left) of San Francisco and a snippet of the full RAW unprocessed blue band showing ships and wakes and the shadow of the Golden Gate Bridge.

Further examples of sites imaged, included Bangkok, Thailand with the headquarters of the RTAF (Figure 13, left), Salt Lake City area with agriculture covered in snow (Figure 13, center), and the Permian base in the United States (Figure 13, right).

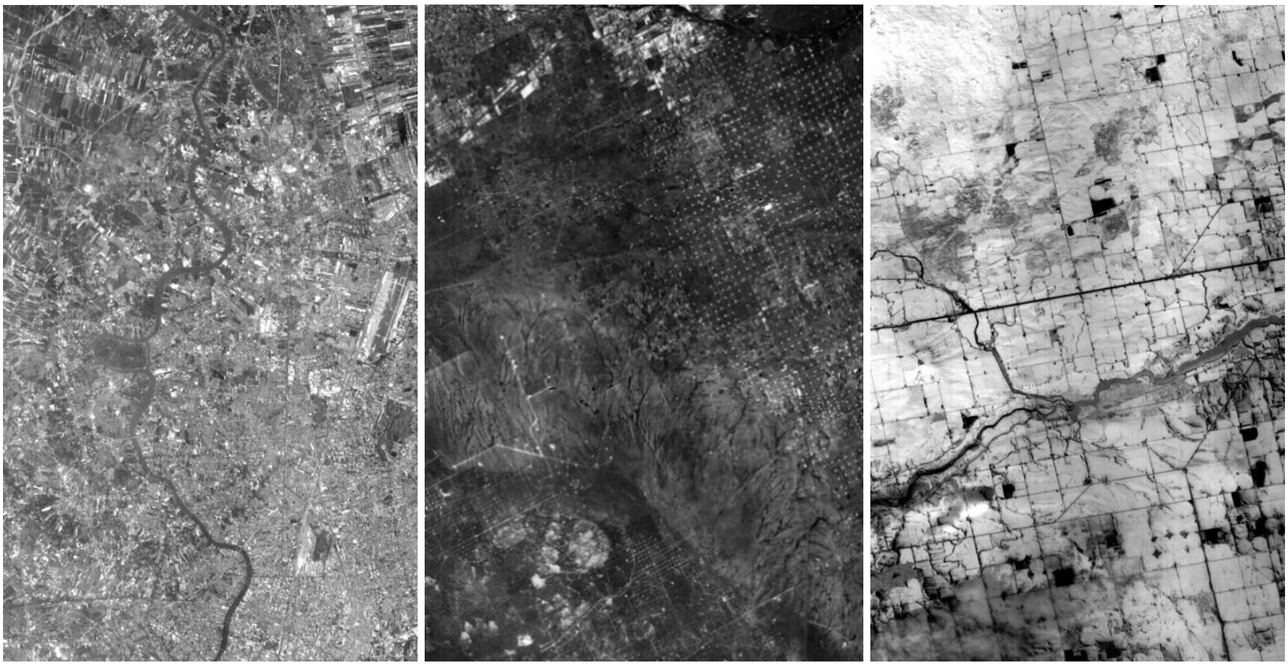


Figure 13. NAPA-2 **RAW** and **unprocessed** images (thumbnails) showing the targets Bangkok, Thailand (left), Permian Base (center), and snow-covered fields in the area of Salt Lake City (right).

## 5 ONGROUND IMAGE PROCESSING

Pinkmatter Solutions' FarEarth software suite was used for end-to-end image production for the NAPA-2 mission. This involved the systematic processing of raw mission data to a radiometrically top-of-atmospheric orthorectified product. Geometric and radiometric calibration routines, periodically performed within the processor, ensure that the best possible product can be generated throughout the lifespan of the mission. This product generation starts with mission data decoding into a Level-0 (L0) product. The L0 product is radiometrically, then geometrically corrected using the calibration parameters obtained from the calibration routines.

Radiometric calibration is performed to determine bias/gain values for each detector which translates the raw digital number (DN) values from NAPA-2 into radiance values. These bias/gain values are obtained by modelling NAPA-2's DN values to reference imagery that cover the same area and is close to the same acquisition date.
Geometric calibration involved the modelling of any rotation bias by comparing NAPA-2 pixel data to reference imagery using the spacecraft's ephemeris (EPH) and attitude (ATT) information. In addition to this, line-of-sight (LOS) polynomials are modelled in a similar fashion. The LOS polynomials model each detector to precisely project each pixel onto Earth. This allows each pixel's geodetic location to be a function of the spacecraft’s EPH, ATT, rotation bias and LOS polynomials.

Several of the taken RAW image data (more than 250 images have been taken) was pushed into the FarEarth software suite, after which L0 and L1 level data is available to be retrieved by the user. An example is shown in Figure 14, showing the resulting image product data from RAW to L1-level data. In addition, a L1-level product data result is shown in Figure 15, displaying an agricultural scene captured in Australia.

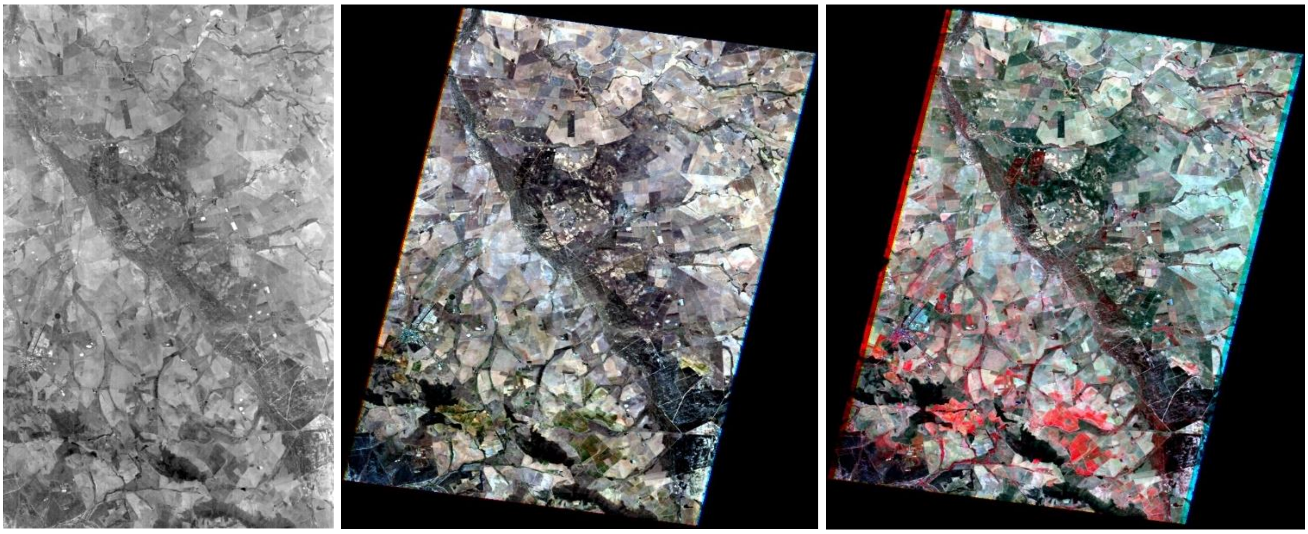


Figure 14. Agriculture north of Cape Town, South Africa in RAW (left), fully processed L1 RGB (center), and fully processed L1 NRG (right) format.

With the geometric and radiometric calibration completed for NAPA-2 some (initial) conclusions have been drawn. Using cloud-free land imagery, the geometric verification produces band aligned scenes within a pixel (with some outliers to be expected near the edge of the scene). Data has been compared with Sentinel 2, concluding that the absolute geometric accuracy, compared to the Sentinel 2 data, is around 1-2 pixels. TOA reflectance values were achieved with a mean difference of less than 1% and standard deviation within 5% when compared to its reference Sentinel 2 imagery. With many different and varying scenes captured from a reflectance point of view, a combined calibration file containing non-fixed radiometric parameters was generated. By applying this combined calibration file, the reflectance mean error was found to be within 5% and its standard deviation within 5%.

Figure 15. Full processed L1 image data from Australian agriculture.

# 6 OUTLOOK

With NAPA-2 operations ongoing ISISPACE continues to improve the platform's performance by tweaking configurations and settings (specifically on the AOCS side) and also testing various imaging maneuvers (forward motion compensation) with a varying ground speed reduction and TDI setting. The results look promising and are analyzed at this very moment. Results and findings will be shared in a future paper.

The Simera Sense xScape100 imager product range was designed for a predefined operating temperature environment which includes temperature offsets, as well as axial and transverse thermal gradients. As a dedication to continuous improvement, measured data from the NAPA-2 mission helped ISISPACE systems engineers working with Simera Sense satellite thermal and opto-mechanical engineering specialists to better understand the achieved inflight thermal environment. This mission feedback was used to further optimize and adapt the nominal proposed satellite level thermal shielding, as well as to optimize the design of future active thermal control on the imager. To this end, Simera Sense created a detailed thermal model of the imager (Figure 16) in Siemens NX Space Thermal software and investigated alternative shielding and active heating loads in the in-orbit environment.

Figure 16. Thermal model of imager

Specific areas of optimization included a reduction in traverse and axial gradients on the Optical Front-End. The imager thermal control system design was updated to include an actively controlled heater wrapped around the upper body, Figure 17 on the left. In addition, the heater's external side is covered with a low IR emissivity tape to reduce radiative transfer.

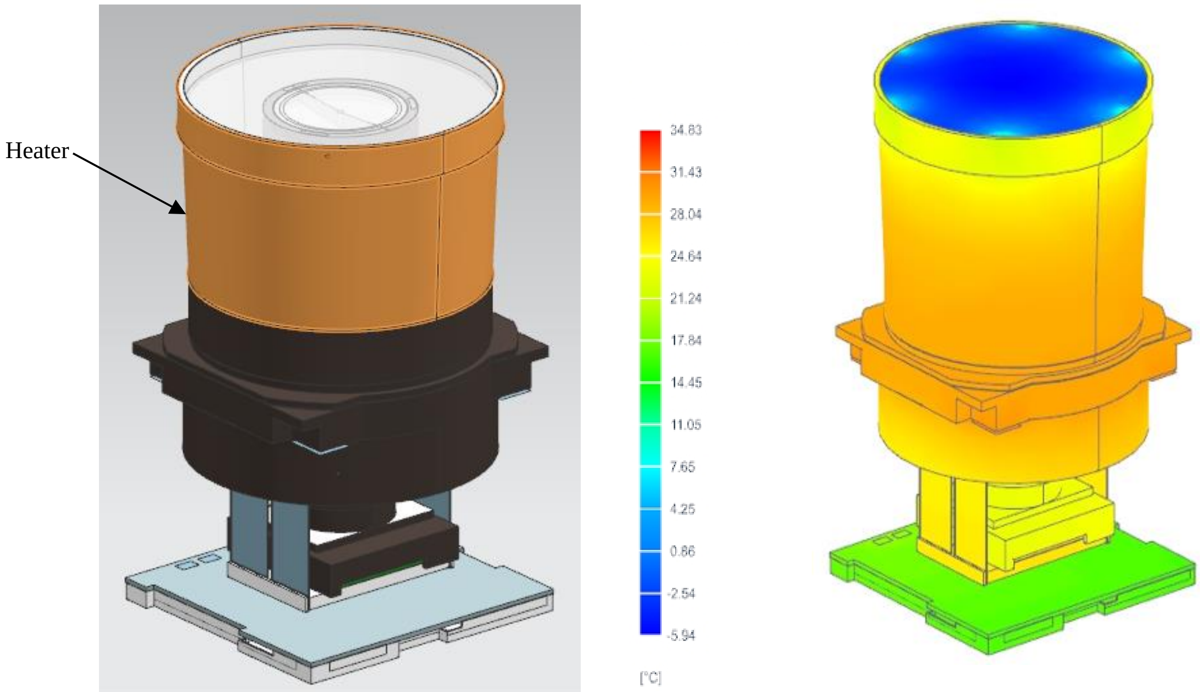



Figure 17. Heater location (in orange) (left) and temperature contour plot (imaging phase) (right).

The new design was analyzed for various mission scenarios using a simplified 6U bus to simulate industry like applications. A snapshot of the results during an imaging phase is given in Figure 8 on the right. The results shows that a uniform temperature distribution in the Optical Frond-End components can be achieved, which results in lower temperature gradients. ISISPACE and Simera Sense will continue to work collaboratively, learning from all flight missions, to render optimally configured high performance CubeSat solutions.

## 7 REFERENCES

[1] Brouwer H .S.B., et al. *High-Resolution Operational Earth Observation from a 6U Small Satellite*, 72nd International Astronautical Congress (IAC), Dubai, United Arab Emirates, 2021.