NAPA-2 TURN-KEY MISSION: HIGH-RESOLUTION IMAGES AND DATA FROM LEO

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Abstract

NAPA-2 is a 6U Earth observation satellite flying the Simera Sense MultiScape 100CIS: a 7-band multi-spectral line-scan imager. Together with the on-ground calibration and processing chain from Pinkmatter Solutions, the NAPA-2 system can deliver stunning multi-spectral line scan images at an impressive ground sampling distance of 5m. After its launch and deployment in July 2021, hundreds of line scan images have been taken and valuable (and critical) data was obtained from the spacecraft platform related to attitude and control and timing. The attitude and orbital control system, a newly built ISISPACE product, has successfully supported the acquisition of all these images. Line scan images were acquired under different conditions, such as simple flyovers, target pointing, and while executing forward-motion compensation manoeuvres. The latter included imaging while the ground speed was reduced up to 50 times! In addition, time-delayed integration was applied in various levels to find the optimal signal-to-noise ratio. With the demand for hyper-spectral imaging from CubeSats, ISISPACE believes that the operational experience gained with multi-spectral imaging in combination with the attitude and orbital control system is vital to be able to educate future customers on the optical performance they can expect.

Keywords: Earth Observation, ISISPACE, CubeSat, Forward-Motion-Compensation, Simera, NAPA-2

1. NAPA-2 System Description

After a successful launch of NAPA-1 in 2020 [1], the Royal Thai Airforce (RTAF) sought to extend and improve their satellite operations capabilities and requested ISISPACE to develop a successor. With operational experience gained in the domain of snapshot imaging, the next logical step was to move towards multi-spectral imaging. This, to enhance RTAF’s survey and monitoring capabilities. While exploiting the operational experience gained, RTAF further proposed the (sub)set of user requirements for the NAPA-2 mission as listed in Table 1.

Table 1: NAPA-2 user requirements.

User Requirements
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

In addition to these, other technical requirements governed the use of a multi-spectral camera and an in-space telescope calibration source in the form of an LED.

Thanks to the NAPA-1 project the RTAF already had a fully operational system in place, including a locally installed ISISPACE ground station and back-end. This thus formed the basis for the NAPA-2 system. With a multi-spectral imager and RTAF’s desire to enhance their Earth observation capabilities, on-ground image processing was added. The full system in place to support NAPA-2 (and NAPA-1) is shown through Figure 1.

Operations is executed using KUBOS’ Major TOM, while flight planning and mission analyses is to be performed by RTAF with separate means. Data flows from satellite to ground where telemetry is split from payload data (image data) which goes through the image processing chain. This data can be picked up in raw format by the operators before processing and afterwards in both processed (L0 and L1) geotiff and unprocessed raw format.

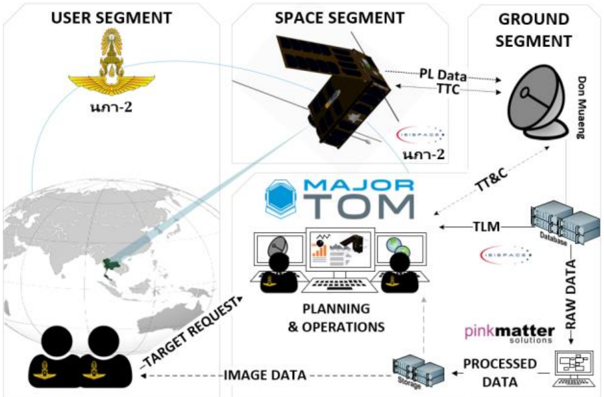

Figure 1: NAPA-2 system design compliant to the user requirements.

1.1 Platform Description

To platform design has been tailored to meet the requirements of the payloads that were requested to fly onboard the satellite. With the extensive flight heritage gained on many of ISISPACE's subsystems the focus shifted towards the Attitude Determination and Control System (ADCS) as the attitude and control performance requested demanded a high-performance system. Previously flown ADCS' either fell short in terms of performance or were lacking flight heritage and together with ISISPACE's desire to further built its subsystem portfolio led to the development of ISISPACE's own ADCS.


Figure 2: ISISPACE developed ADCS bundle.

The ISISPACE ADCS is a collection of space-proven hardware developed by either ISISPACE or third-party. It comprises of an in-house developed onboard computer, self-calibrating gyro, and deployable magnetometer. It also includes the well-proven iMTQ. In addition, Astrofein reaction wheels, Lens R&D fine Sun sensors, NovAtel GNSS receiver, and the Auriga star tracker (Figure 2). With inhouse written drivers and software the system is tailored to meet NAPA-2's performance.

Further subsystems include the well-proven modular power system (IMEPS), onboard computer for command and payload data handling (iOBC), high-rate S-band transmitter (TXS), and the vhf/uhf radio for tele commanding (TRXVU) as shown in Figure 3.


Figure 3: NAPA-2 Core avionics subsystems.

The design of NAPA-2 resulted in the key performance parameters as listed in Table 2.

Table 2: NAPA-2 key performance parameters.

Parameter	Value	Comment
Generated Power	25 W	Peak
	8.0 W	Orbit-average
Consumed Power	7.8 W	Use-case based
CDHS Storage	2.0 GB	Redundant
PDHU Storage	2.0 GB	Redundant
Data Downlink	4.3 Mbps	Throughput
TTC Up/Downlink	9.6 kbps	
Mass	7.6 kg	
Pointing Knowledge	<0.1° RMS	3-Axis control
Pointing Accuracy	<0.1° RMS	3-Axis control
Agility	8°/s	Peak

1.2 Payloads Description

For the NAPA-2 mission ISISPACE developed a LED payload board serving as an in-orbit demonstrator for on-ground telescope calibration and satellite optical tracking. The design was driven by the requirement stating a necessary light emission of minimum 180 candelas.

Figure 4: LED payload board developed by ISISPACE which is mounted on the nadir-looking Z-panel side.

Since the system can draw a significant amount of current and will generate quite some heat during its operation, the design includes several failure detection, isolation, and recovery mechanisms, including current limiting, temperature monitoring, and maximum on-time.

A successful capture was taken from ground while the LED payload was switched on (alternating between the on and off state) (see Figure 5). The endeavour of this successful capture of the LED payload in-flight are described in detail in [2,3].

Figure 5: NAPA-2 LED payload captured in on-state from ground during the commissioning phase [3].

The primary payload of NAPA-2 is the Simera Sense MultiScape100 CIS camera. It's a multi-spectral line-scan imager designed to provide a 5m GSD at an orbital altitude of 500km (see Figure 6). It has a field of view of 2.22° across-track with a 95mm aperture.

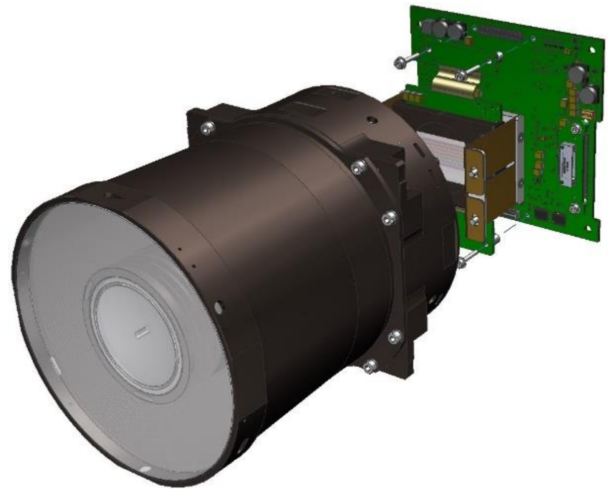

Figure 6: Simera MultiScape100 CIS camera flying as primary payload on NAPA-2.

The MultiScape100 CIS images in 7 bands (blue, green, red, red-edge (3x), near infrared). In addition, the camera supports time-delayed integration (TDI) to increase the camera's signal-to-noise ratio at the expense of an increase in required platform stability. The increase in signal for higher TDI-levels is shown in Figure 7.

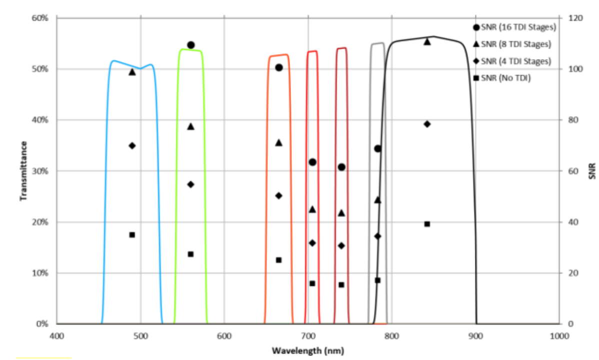

Figure 7: Transmittance for each of the wavelengths as a function of time-delayed integration.

Extensive on-ground testing, including optical functional verification has been done during the SAIT phase [2].

2. Imaging operations and results

The commissioning phase of NAPA-2 had its primary focus on three aspects:

1. Operational architecture
2. Platform performance
3. Imager performance

2.1 Operational architecture

With the system design in place, in-orbit validation of the operational architecture has been one of the key aspects to focus on as nominal operations is to be carried out by the customer. This also meant introducing an operational flow and interfaces that are easy to understand and transfer from ISISPACE to RTAF. With this in mind, three operational elements were made key for successful operations: on-ground planning, satellite commanding, and on-ground validation.

On-ground planning comprises of defining an area of interest and simulating the intersection between the area of interest and the satellite's field of regard. An area of interest is defined by its latitude and longitude, while the field of regard of the satellite (or rather camera) is the camera's field of view plus a 20° roll-angle (negative and positive). The planning is done through the Systems Tool Kit (STK) which allows for setting targets and defining satellites and sensors. By using the latest known two-line-element (TLE) one can simulate and compute the times of acquisition of the area and satellite roll angle (Figure 8).

Figure 8: NAPA-2 field of view and field of regard (top) and target acquisition (bottom) in STK.

From the simulation the times of acquisition start, mid-point, and end are obtained along with the satellite roll angle. These are to be taken and used during the creation of the satellite flight plan (which allows for autonomous satellite operation).

Special care must be taken when timestamps are obtained since the imager is a line-scan imager, meaning that if an area of interest needs to be centred, imaging needs to start earlier. This is primarily driven by the number of lines to be captured, which defines the total imaging time (Figure 9). In addition, time-errors induced by the TLE-age and the CDHS when the camera is commanded to image on the next Pulse-Per-Second (PPS) coming from the GNSS, need to be considered too. Although, for longer line-scans and without a strict requirement on whether the target is centred in the image, timing errors become less impactful.

Finally, the weather forecast needs to be considered as clouds will obviously ruin any image taken (although small, localized clouds can create amazing shadows on the ground!).

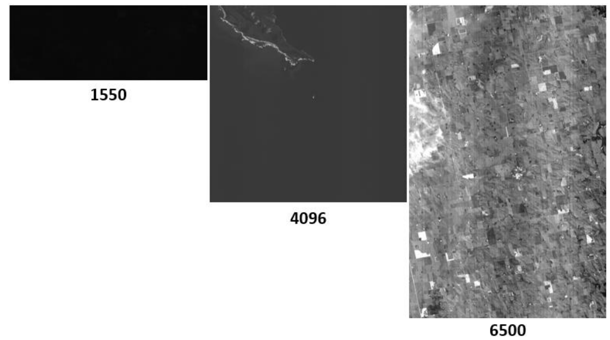

Figure 9: Number of lines and resulting image length.

With the right information gathered, flight plans are created and uplinked to the satellite by the operators. These flight plans contain instructions for the CDHS, the ADCS, and the camera, such that the satellite operates autonomously outside ground station passes.

When image captures are performed, image data is created, which is in the order of 40MB per raw image band for an image with 6500 lines. Hence, to optimize for bandwidth use, thumbnail data was created that could be downloaded and inspected on-ground to verify the target was captured, cloud-free, and optically sound. As thumbnail data is in the order of 500KB, it is a quick way of identifying whether the captured data is of use or not.

When full image data is downlinked, selectable by the operators, the image data is pushed into FarEarth, the image processing software application developed by Pinkmatter Solutions. The image processing is conducted automatically, outputting different data product levels for any user to pick up. The processing system performs the following image corrections: flat field correction, radiometric response, pixel uniformity, detector geometry, and optical distortions.

Figure 10: FarEarth impression showing data captured over The Netherlands.

2.2 Image targets

During initial inflight calibration, two aspects were addressed: image geometry and image radiometry. For geometric calibration, it is required that the images are over flat areas. In addition, the images need to be as cloud- and waterbody-free as possible, with the sensor pointing nadir. The images need to be geometrically rich to facilitate dense tie-point detection. Figure 11 and Figure 12 show examples of images that meet these requirements.

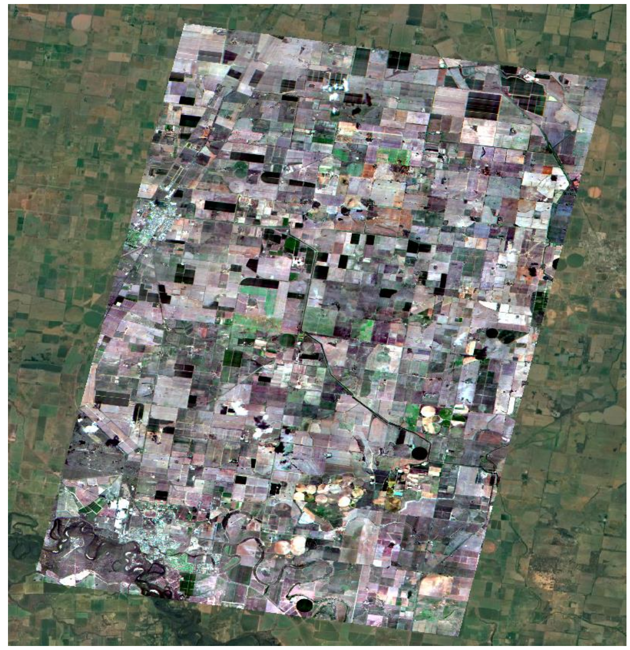

Figure 11: Australia, south-east of Finley (Lon = 145.65784, Lat = 35.69889, Acquired: 2022-02-07).

Figure 12: USA Kansas (Lon = -101.37, Lat = 39.25, Acquired: 2022-01-20).

For radiometric calibration, images under various conditions and for a diverse range of targets are required. These images also need to be as cloud- and waterbody-free as possible. The imagery was used to determine bias and gain values to translate digital numbers as reported by the sensor detectors, into radiance values. The target sites include Pseudo Invariant Calibration Sites (PICS) in addition to the imagery acquired for geometric calibration.

An example of such a PICS site is shown in Figure 13. This image was acquired over a desert area in Libya, where the conditions of the dunes do not change much over time (from a radiometric point of view), and there is a relatively homogenous distribution across the detector array.

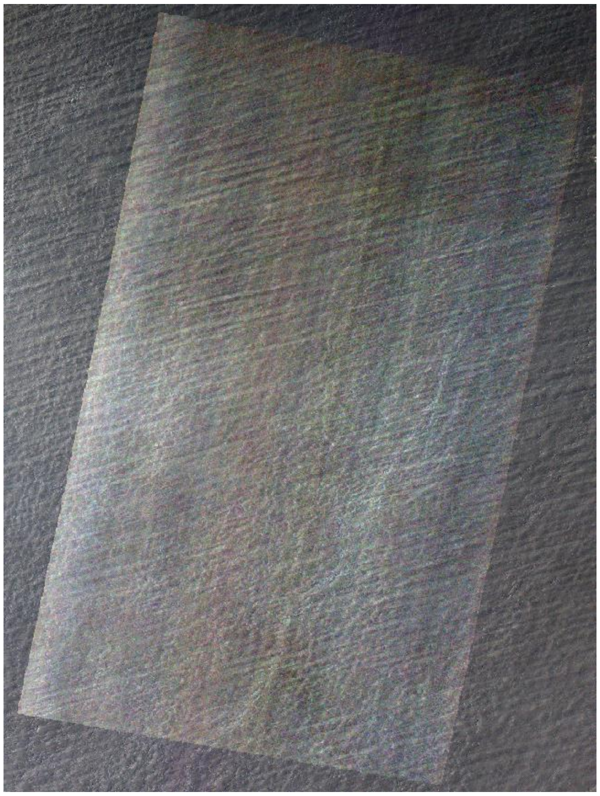

Figure 13: Libya 4 (PICS, lon= 24.46, lat=27.17, acq-date= 2022-02-10).

Note the subtle differences between the bands across the detectors, as well as the effect of striping for these uncalibrated acquisitions.

2.3 Imaging efforts and initial results

During commissioning ISISPACE has taken over hundreds of images to support Pinkmatter's calibration efforts as well as determination of the platform performance. The capability of the camera to use a multitude of TDI levels allowed ISISPACE to test this for different scenes on ground. Figure 14 shows an example set of similar scenes taken with different TDI-levels, with the goal of finding an optimal setting for the camera with which the majority of scenes can be captured, such to serve as input to the first round of calibration.

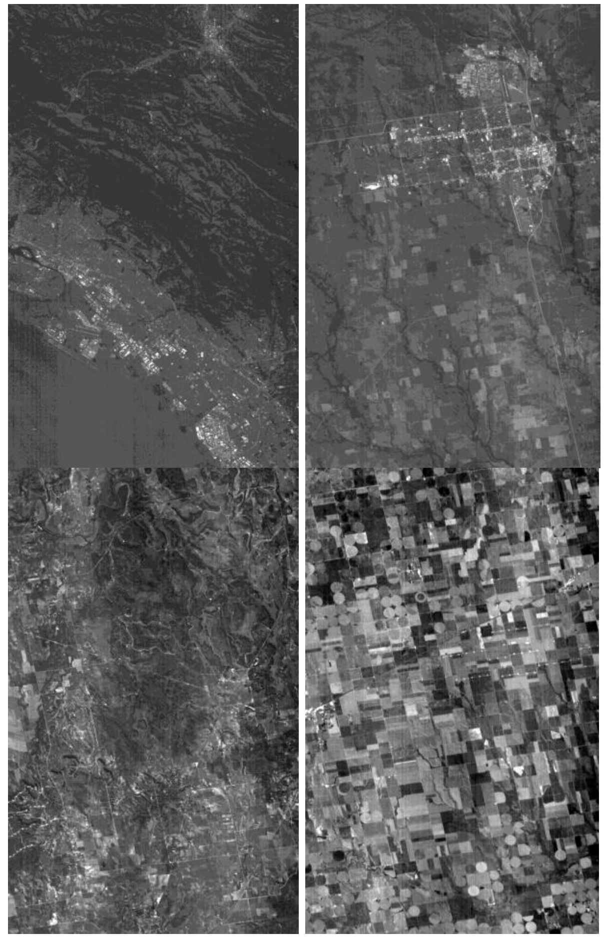

Figure 14: Different TDI levels applied, and the resulting signal level as shown in low-resolution thumbnails (manually increased brightness for comparison). From left to right: TDI 1, 2, 4, and 8.

At the same time, signal received is also very much dependent on the scene observed, the time of the day, and weather conditions. These directly impact the signal received by the camera and thus (may) require an operator to change the TDI setting of the camera. An example of the variety of terrain is shown through Figure 15, where different terrain is visualized.

Each successful capture was downloaded – after inspecting a low-resolution thumbnail – and pushed to Pinkmatter's FarEarth application for calibration purposes.

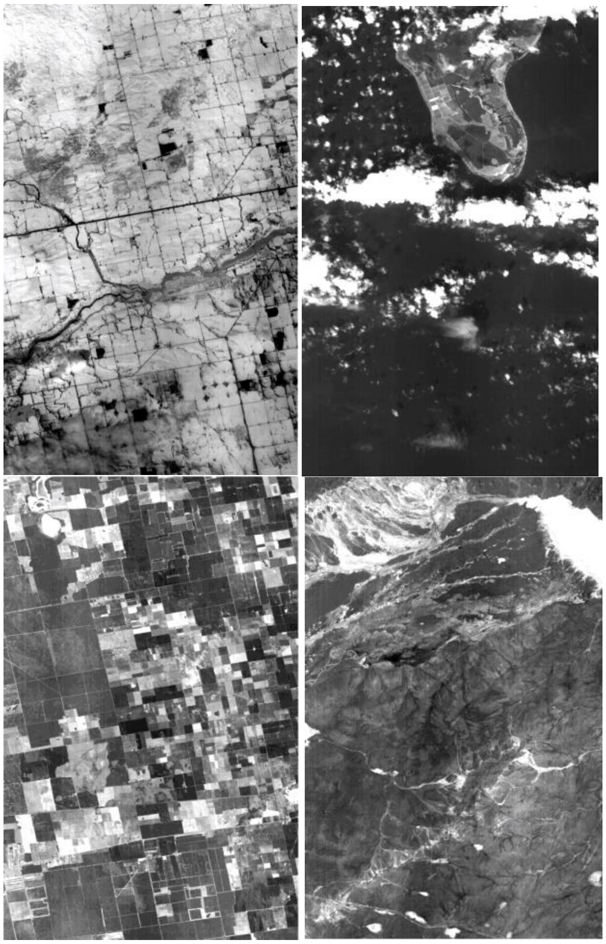

Figure 15: Different types of terrain and conditions captured, impacting the signal received by the camera. Clockwise from top-left: Salt Lake City region covered in snow, Bonaire island with clouds, Farm fields in Argentina, Mountain features in Argentina.

Finally, not every acquisition resulted in a useful image. Even though wheather forecasts were extensively checked, it remains unpredictable and several times clouds were imaged. In addition, operator (timing) errors during a flight plan, a wrongly set attitude, or an uncontrolled spacecraft sometimes led to real pieces of 'art'. Figure 16 shows several images being a result of the spacecraft not performing as it should.

Nevertheless, these all contributed to improvements and optimizing operations in the long run.

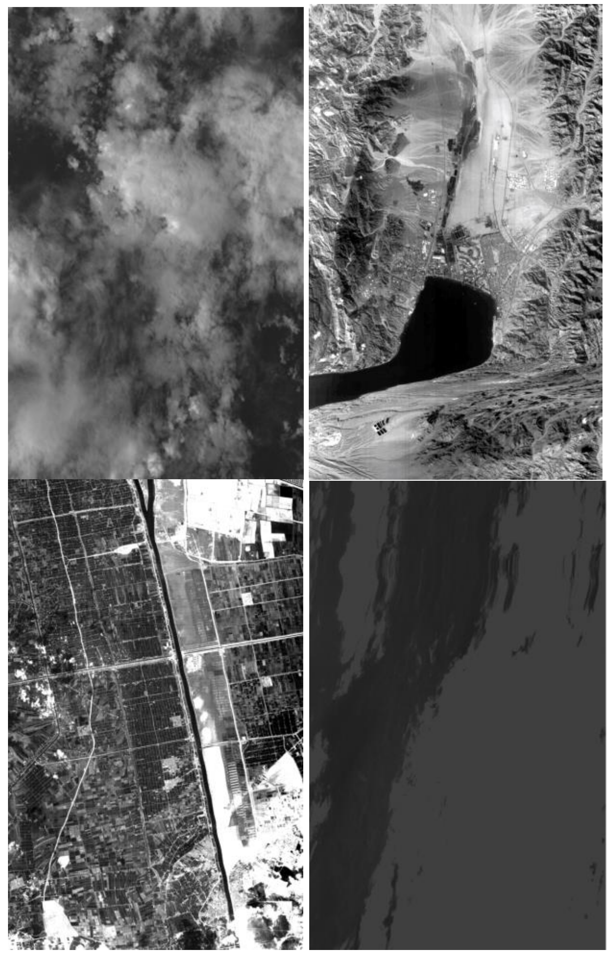

Figure 16: Unsuccessful acquisitions made by NAPA-2. Clockwise from top-left: clouds obscuring intended target, an ADCS manoeuvre executed too early, instability causing a wobbly image result, and an uncontrolled spacecraft while imaging.

3. Onground image processing

After the raw data has been downlinked from NAPA-2, 7 raw data files, each containing one of the spectral bands, are ingested into FarEarth for processing. FarEarth is a software processing suite developed by Pinkmatter Solutions. The processing flow is shown in the diagram visualized in Figure 17.

Session Assembly - The session assembler is responsible for decoding all session data. Pixel data (scanline and thumbnail), all sensor metadata, sensor temperature, as well as the satellite's attitude and ephemeris data are extracted.

Level 0 (L0) Generator - All extracted session data is written to an HDF5 (Hierarchical Data Format version 5) file.

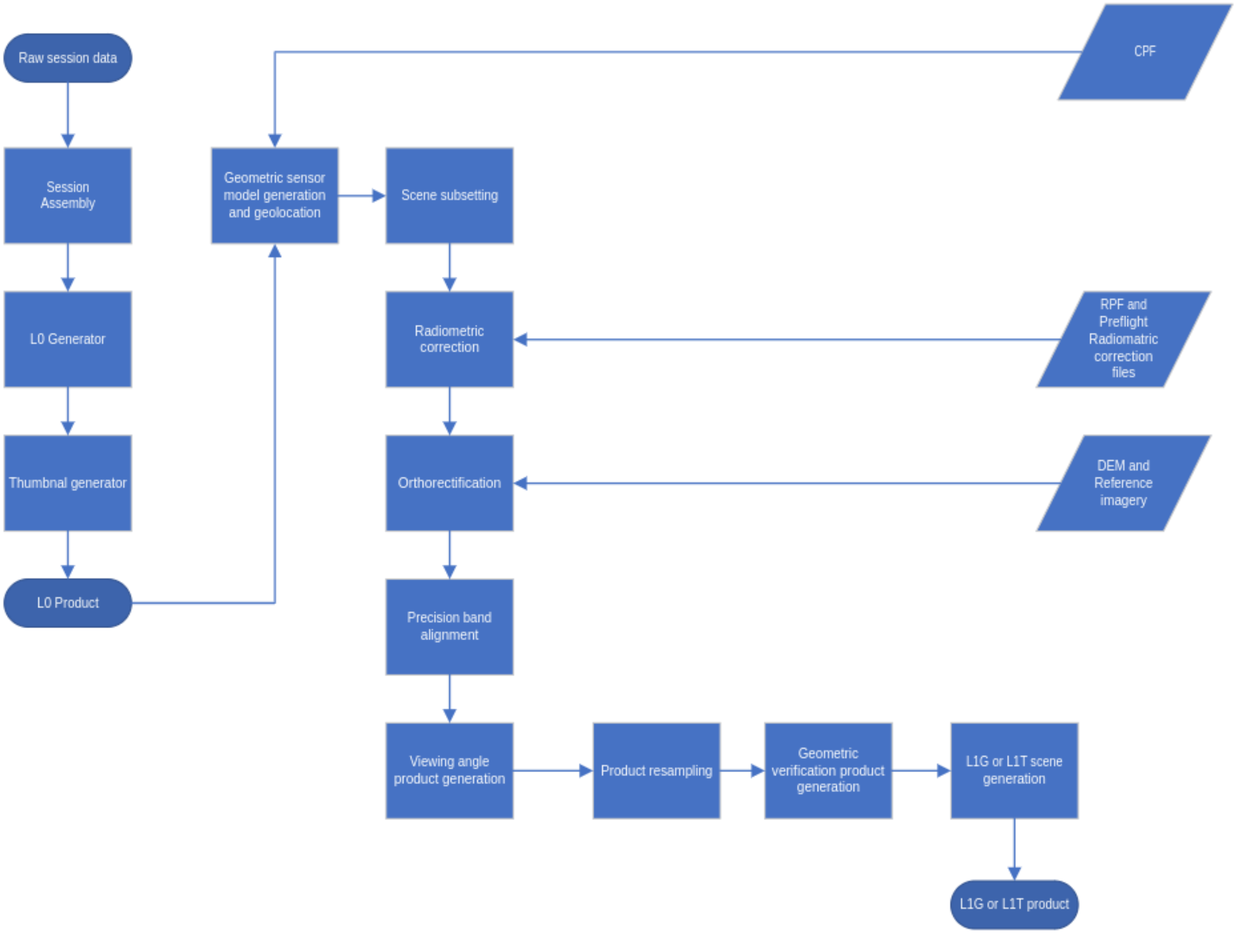

Figure 17: Processing flow applicable to the FarEarth processing chain.

Thumbnail generation - Thumbnails are generated for all bands present in the Level 0 product. These thumbnails, also referred to as browse files, are saved alongside the L0 HD5 file.

Geometric sensor model and geolocation - The satellite's attitude and ephemeris data are extracted from the Level 0 product. These are used to generate a geometric sensor model. The geometric model can be used to describe each pixel geometrically. The sensor model requires a Calibration Parameter File (CPF) which contains all the necessary geometric parameters to geolocate pixels. After geolocation, a temporary HDF5 file is stored which contains latitude and longitude coordinates for each pixel of each band.

Scene subsetting - Scenes are formed by grouping geometrically overlapping pixel data. It may be possible that more than one scene is extracted depending on the configuration.

Radiometric correction - For each scene, the pixel data is radiometrically corrected. This stage requires two ancillary files: a Radiometric Parameter File (RPF) and a preflight radiometric calibration parameter file. The preflight calibration file is used to create a translation for each DN (digital number) to radiance. The RPF is used to fine tune any inaccuracies which could not be modelled during preflight calibration. The RPF contains a set of bias and gain values which must be applied to radiance values after the preflight calibration parameters have been applied. Finally, the earth-sun distance and solar incidence angles are calculated for each spectral band and the Extra-Terrestrial Solar Irradiation (ESUN) is stored along with the radiance products. The final radiance product for each band is written to disk in a temporary HDF5 file.

Orthorectification - During orthorectification, radiometrically corrected scenes are terrain corrected and precision geolocations are determined. A Digital Elevation Model (DEM) and reference imagery is required to determine Ground Control Points (GCPs). The GCPs are used to model any geometric disparities between calculated pixel locations and true location. This correction is done in two stages. First, a geolocation bias is calculated for the input scene. This is accomplished by collecting tie-points between the input NAPA-2 scene and the reference imagery. This tie-point average disparity is calculated and applied to the scene. Secondly, an extensive GCP collection is performed. The NAPA-2 scene is matched to the reference imagery and tie-points are collected. An elevation lookup is then performed and added to each tie-point to generate GCPs. These GCPs are in turn used to geometrically correct the NAPA-2 scene. This stage may fail in which case a fallback yielding a systemically corrected scene is processed.

The precision terrain corrected scene is referred to as an L1T product, whereas the systematically corrected scene is referred to as an L1G product. L1G scenes do not correct for any terrain or geolocation disparities.

Precision band alignment - During this stage, the L1G or L1T bands are aligned to each other. This ensures that pixel data from different spectral bands align and nest within each other.

Viewing angle product generation - Using the NAPA-2 geometric sensor model, two viewing angle datasets are calculated, namely the satellite azimuth and incidence angles. These two products are written to the final Level 1 output products.

Product resampling - All geometric translations are combined into a single translation map. This translation is then applied to the pixel data, to resample and project the NAPA-2 imagery. By combining the temporary translation maps, the pixel data is only resampled once. Each band is written to a temporary HDF5 file.

Geometric verification product generation - This stage is only executed for Level 1T products. The NAPA-2 pixel data is matched to the reference imagery which was used during orthorectification to calculate a geometric disparity map. This map is also added to the final L1T product. This map describes the geometric accuracy of the scene. The accuracy report is added to the L1T metadata (GeoJSON file), as well as a browse file containing visual indicators of the scene's geometric accuracy.

The following two images (Figure 18 and Figure 19) are an example of the output of this stage.

The color of the Geometric Accuracy indicators represent:

- Green: disparity between 0 and 0.5 pixels
- Teal: disparity between 0.5 and 1.0 pixels
- Blue: disparity between 1.0 and 2.0 pixels
- Yellow: disparity between 2.0 and 5.0 pixels
- Red: disparity larger than 5.0 pixels

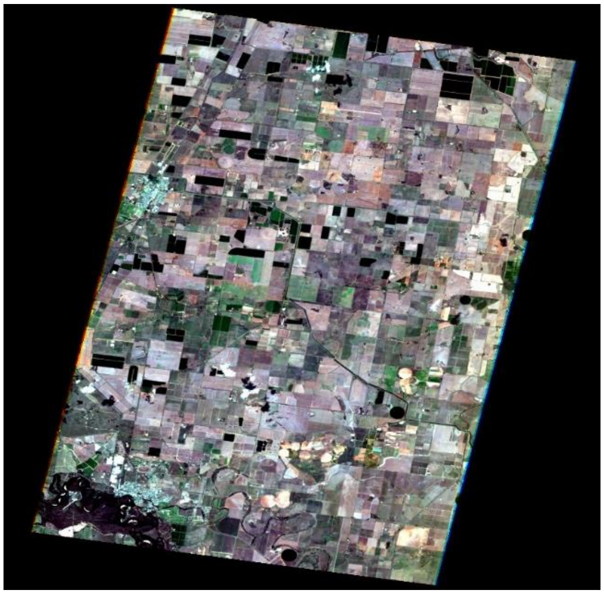

Figure 18: Level 1T Browse Image.

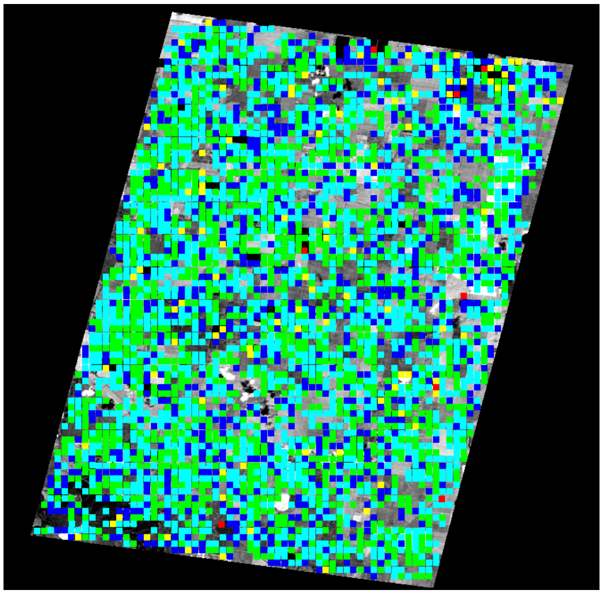

Figure 19: Level 1T Browse Image with Geometric Accuracy overlay.

Level 1G or Level 1T scene generation - The final processing stage is to generate browse files, a metadata file, and geolocated GeoTIFF files. The final product contains:

- One GeoTIFF file for each spectral band
- Two viewing angle GeoTIFF files (azimuth and incidence)

- Browse image files (in PNG or JPEG format)
- A geometric accuracy browse file (Level 1T only, Figure 20)
- A metadata file in GeoJSON format

TDI results and optimal settings - During NAPA-2 commissioning images with different TDI settings were acquired. It was determined that four TDI stages produce good radiometric responses (Figure 14). Further investigation may be required to determine if this is still the case.

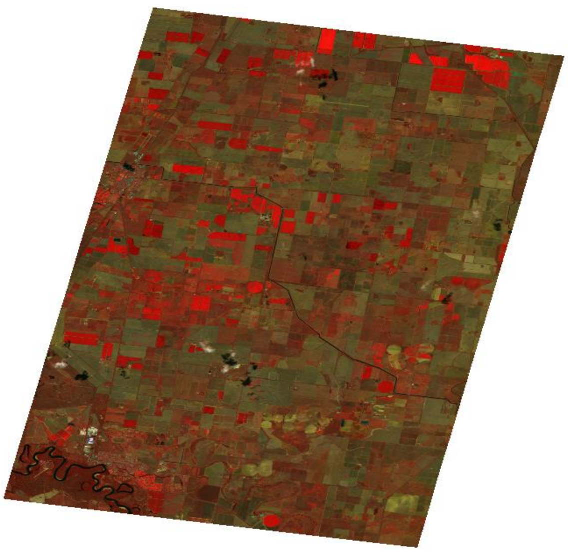

Figure 20: Example Level 1T (NIR, Red, Blue).

Band-alignment results - An example L1T with a closeup of the upper-right corner is shown in Figure 20 and Figure 21. The band combination is NIR, Red and Blue. These images visually show the accuracy of the band-alignment, with no artifacts visible.

Band-to-band analysis - The geometric accuracy between different bands can also be measured using the method described above. Figure 22 shows the geometric analysis browse image for a comparison between bands 1 and 2.

Table 3 shows the number of pixels that match the different categories of the geometric analysis. Note that band 1 (blue) correlates well to band 2 (green), aided by the fact that the spectrums are well correlated (the pixel values move together).

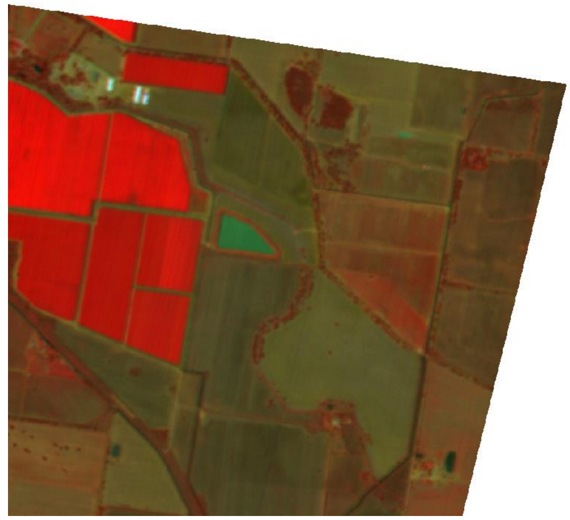

Figure 21: Closeup of Example L1T (NIR, Red, Blue).

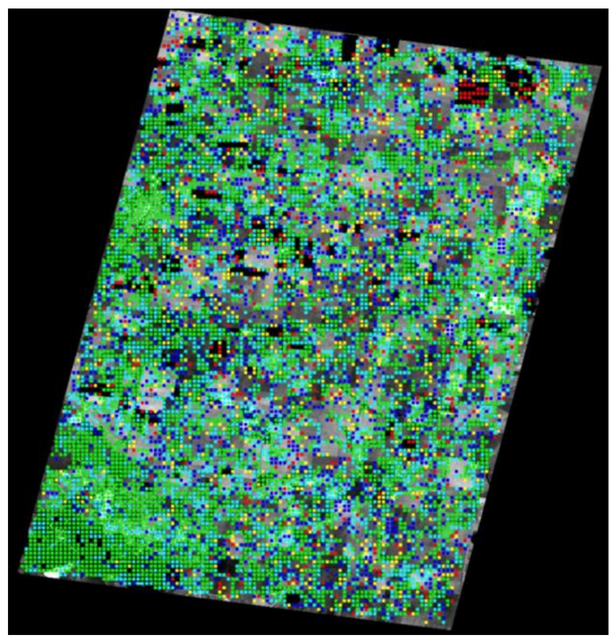

Figure 22: Geometric validation between band 1 and band 2.

In contrast, an example of two bands that do not correlate well is shown in Figure 23. The radiometric differences between Band 4 (Red Edge 1) and Band 5 (Red Edge 2) highlight different ground features, causing the geometric verification to underperform. The geometric verification algorithm struggles to find matching pairs of tie-points, due to the large differences in the radiometric properties of these two bands. Therefore, the band-to-band geometric verification is subject to radiometric artifacts and spectral band wavelength differences, which introduce correlation errors which could affect the calculated disparities negatively.

Table 3: Matched pixels for the different categories for band 1 and 2.

Level	Disparity X (avg pixels)	Disparity Y (avg pixels)	Matched Points
Green [0 <-> 0.5)	0.184	0.161	4354
Teal [0.5 <-> 1.0)	0.520	0.376	2781
Blue [1.0 <-> 2.0)	1.014	0.685	1792
Yellow [2.0 <-> 5.0)	2.354	1.278	851
Red [5.0 <-> inf)	9.040	6.820	462
All [0 <-> inf)	1.00024	0.70453	10240

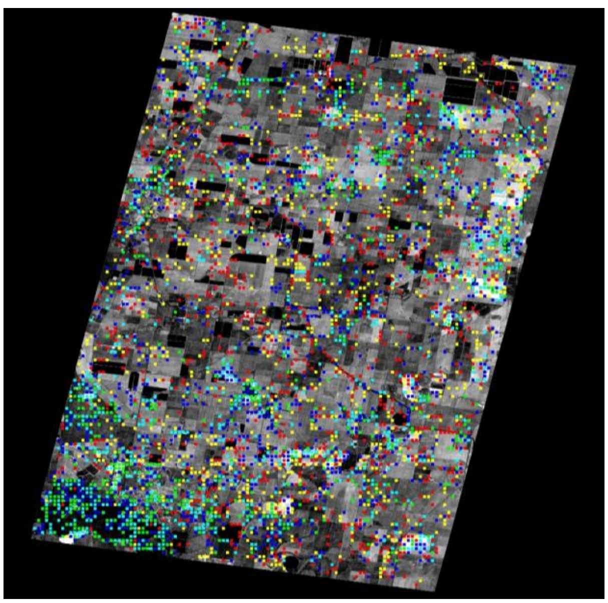

Figure 23: Geometric validation between Band 4 and Band 5.

Table 4: Matched pixels for the different categories for band 4 and band 5.

Level	Disparity X (avg pixels)	Disparity Y (avg pixels)	Matched Points
Green [0 <-> 0.5)	0.205	0.182	532
Teal [0.5 <-> 1.0)	0.531	0.420	799
Blue [1.0 <-> 2.0)	1.066	0.752	1050
Yellow [2.0 <-> 5.0)	2.315	1.451	923
Red [5.0 <-> inf)	8.181	6.320	982
All [0 <-> inf)	2.75858	2.04562	4286

Effective GSD - The MultiScape 100 sensor utilizes 4096 across-track detectors. Analyzing the Australia orthorectified scene acquired on 2022-02-07, the measured scene width was 20.771 km. Calculating the mean GSD directly from the detector count and scene width yields just above 5m (the calculated GSD will vary depending on NAPA-2's orbit):

$$GSD_x = \frac{Width}{DetectorCount} = \frac{20771m}{4096} \approx 5.071m$$

Another way for calculating the GSD is to project adjacent detectors using a rigorous model. Projecting three pixels to the ground produces the following:

$$GSD_x = |NadirDet_{T0} - RightOfNadirDet_{T0}| \approx 5.068m$$

$$GSD_y = |NadirDet_{T0} - NadirDet_{T1}| \approx 5.254m$$

with:

$$NadirDet_{UTM,T0} = (x = 382060.3422, y = 6066764.8201)$$

$$RightOfNadirDet_{utm\,t0} = (x = 382065.3566, y = 6066764.0840)$$

$$NadirDet_{utm\,t1} = (x = 382059.2874, y = 6066759.6722)$$

With, *NadirDet*: Detector at nadir (detector #2048), *RightOfNadirDet*: Detector at nadir, one over to the right (detector #2049), *t0*: Scanline under consideration (position along track), and *t1*: Next scanline under consideration.

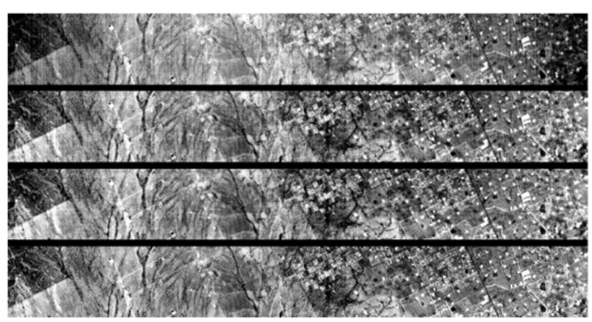

Figure 24: Example of the step-wise processing result with (from top to bottom): RAW image, result using pre-flight calibration parameters, result using

in-orbit calibration parameters, and comparison with Sentinel-2 reference data.

Thus, the effective across-track GSD is calculated as 5.068m, and the along-track GSD is 5.254m. The targeted GSD is 5m. This shows that the geometric sensor model is close to the measured results. The slight difference can be attributed to the variation in height above sea level, and the effect of terrain elevation.

With the processing chain in place and images supplied by the satellite, the resulting steps were also visualized with help of images and discussed between ISISPACE and Pinkmatter. An example of such a visualization is shown in Figure 24.

4. Processed image data

More than hundreds of captures were successfully acquired and downloaded. Obviously, as part of all these captures, several images featured an endless variation of clouds or turned out blurry due to operational errors. Nevertheless, the majority of these captures proved to be what was strived for and have been fully processed to showcase the satellite's performance and camera's capabilities. Some of the highlights are showcased hereafter through various images. Yet, more to capture and process in the future!

Figure 25 shows an image taken over Delft, The Netherlands at a roll-angle of 26°. The image is an overlay of three bands, red, green and near infrared. This combination displays vegetation (red) and can be used for crop-identification and monitoring.

With a 5-meter GSD, roads, houseblocks, and large ships are clearly and directly visible when imaging cities and harbors. For smaller ships, the wakes thereof betray their presence, as clearly visible in Figure 26 showing the San Francisco city and harbor area.

Furthermore, human landscaping and usage thereof can be monitored as shown through the image taken of agricultural area over Australia (Figure 27).

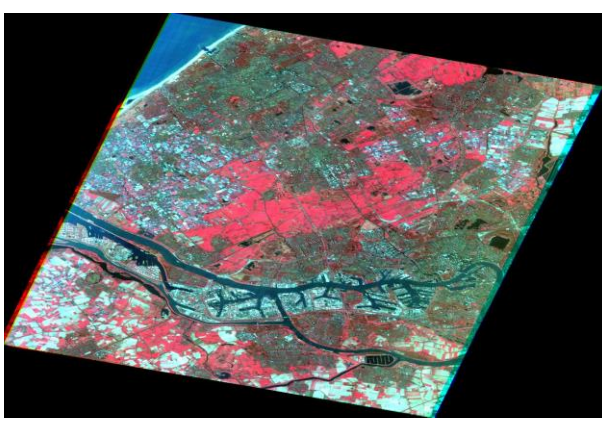

Figure 25: High-resolution NRG image of Delft, The Netherlands taken at a 26° roll angle, showing vegetation in red (acquired 5-3-2022).

Figure 26: High-resolution RGB image of San Francisco (top) and a zoomed in snippet (bottom) showing the shadow of the Golden Gate bridge and the wakes of several ships (acquired 20-5-2022).

Further, coastal desert regions, mountains with farmland, and areas with clear distinguishable features were successfully captured, as shown through images Figure 28 (the city Jeddah in Saudi Arabia), Figure 29 (Permian base in the United States), Figure 30 (agriculture and mountain ridge in South Africa, and Figure 31 (the city Timbuktu in Mali).

Figure 27: High-resolution RGB image of farmland of Australia (acquired 16-12-2021)

Figure 28: High-resolution RGB image of Jeddah, Saudi Arabia (acquired 12-5-2022).

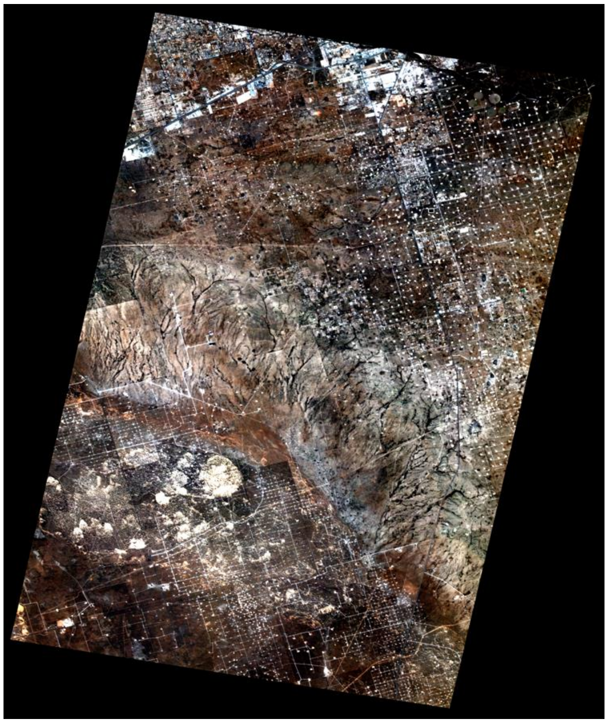

Figure 29: High-resolution RGB image of the Permian Base, United States (acquired 21-1-2022).

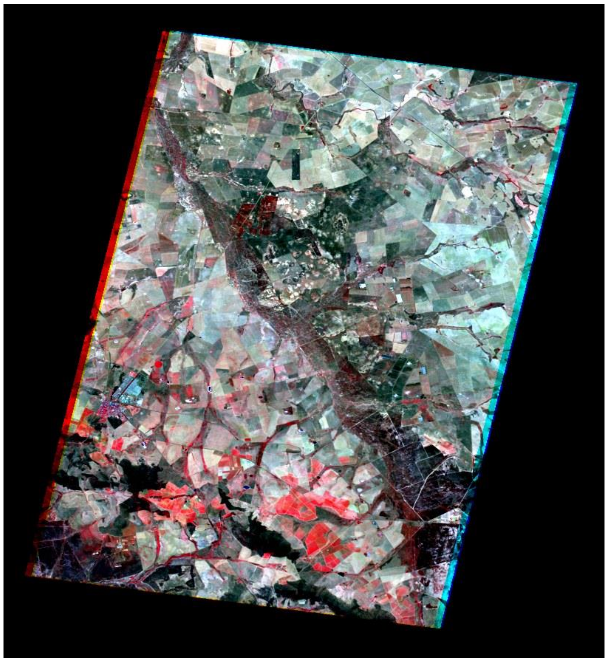

Figure 30: NRG images of agriculture in South Africa (acquired 26-01-2022).

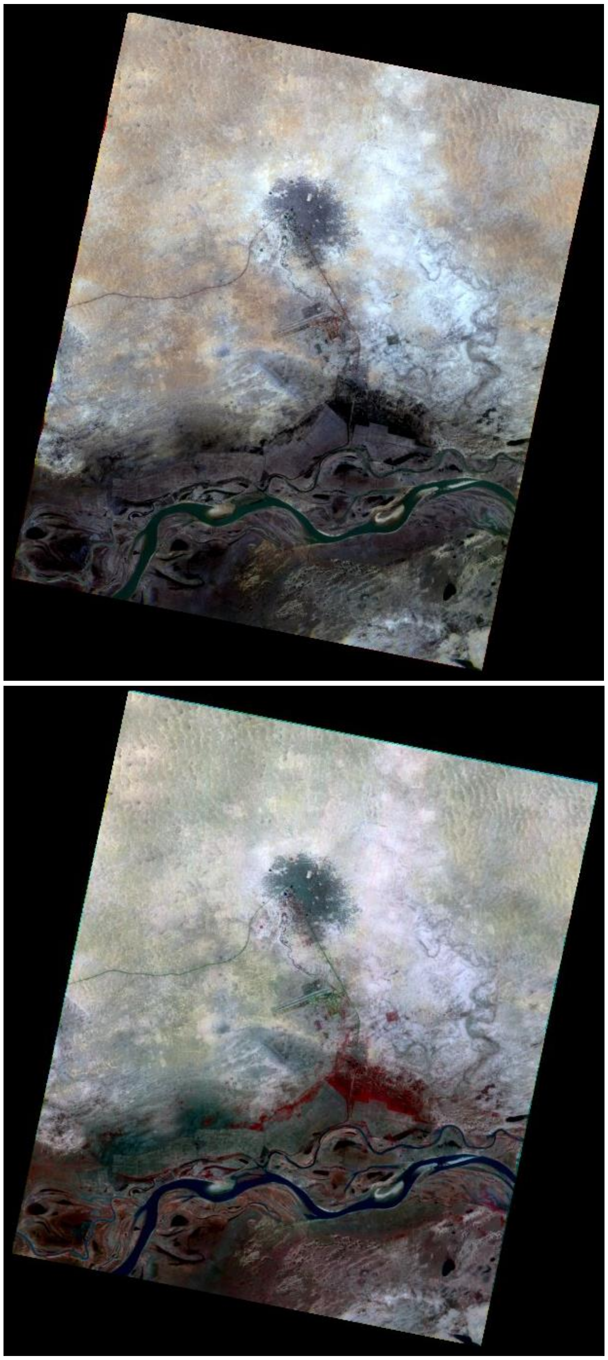

Figure 31: High-resolution RGB (top) and NRG (bottom) processed images of Timbuktu, Mali (acquired 2-4-2022).

5. ADCS in-orbit performance

Alongside the radiometric and geometric calibration efforts, ISISPACE also focused during the commissioning on identifying and optimizing the ADCS' performance. This, not only to comply with the requirements imposed by the NAPA-2's customer, but also to have in-orbit proof of platform and ADCS capabilities for future missions. For this reason, pointing accuracy and knowledge error analyses was performed on a set of images. An image example is shown in Figure 32 from which the pointing accuracy and knowledge error were determined. From these (and others) an absolute pointing accuracy on platform level of <0.1° is achieved, while the absolute attitude knowledge error is estimated to be 0.05°.

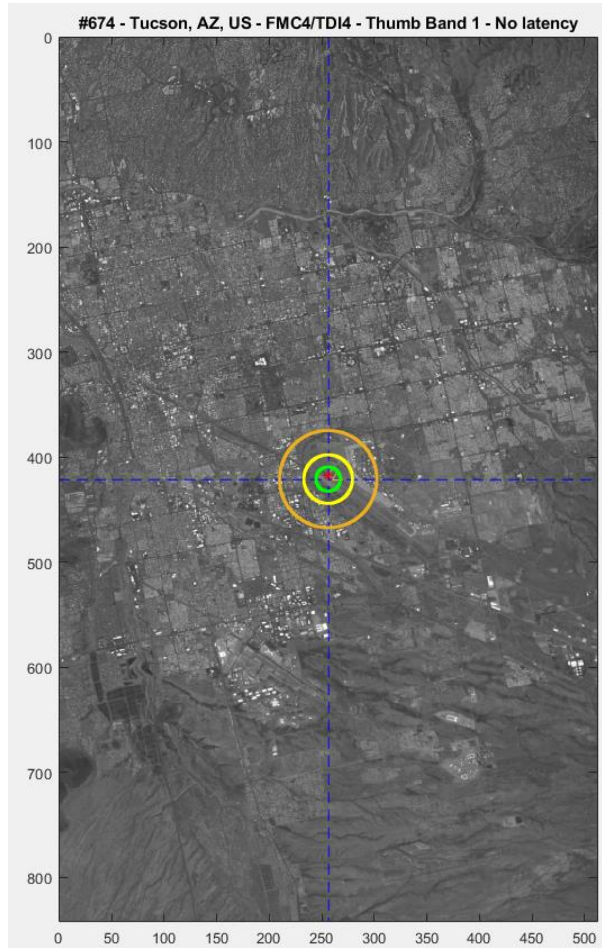

Figure 32: Pointing accuracy and knowledge error computation. Green circle 0.05°, yellow circle 0.1°, and orange circle 0.2°.

The images taken for calibration purpose were taken while the spacecraft was flying over the target with a roll-angle set when necessary. However, ISISPACE tested another technique – next to utilizing TDI – to improve the signal captured by the camera: forward-motion compensation (FMC). Herewith, the satellite reduces the relative ground speed by pitching the satellite forward and backwards while flying over the target such that it remains in sight for a longer period.

To stress-test the ADCS' performance two of such FMC manoeuvres were executed in rapid successfully succession as shown in

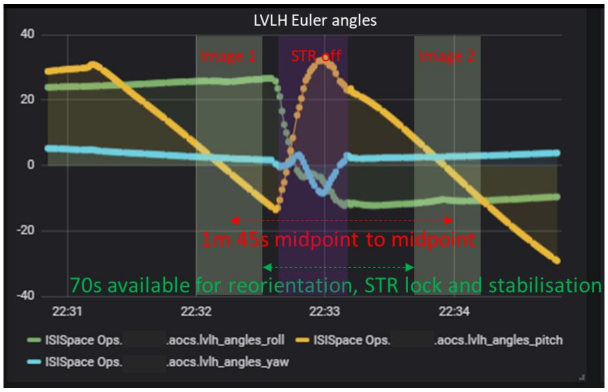

Figure 33: Two FMC manoeuvres executed by NAPA-2 in rapid succession. The graph shows a steady roll (green) and yaw (blue), while the pitch (yellow) various overtime to reduce the ground speed velocity.

A multitude of FMC manoeuvres have been successfully executed at different factors (reduction in ground speed), ranging from FMC1 to even FMC50 (50 times ground speed reduction. Figure 34 show an image result (RAW) for a TDI2 and FMC7, showcasing the capabilities and performance of the ISISPACE ADCS.

6. Future outlook

With a successful NAPA-2 mission, ISISPACE has increased its knowledge and (hands-on) experience and can utilize this for future Earth observation missions. With in-orbit image data to show, along with proven platform performance, ISISPACE can further educate customers on expectations and the feasibility of their requirements. Future missions will continue the path set out by ISISPACE and benefit automated operations, execution of advanced maneuvers (FMC- and super-resolution imaging), optimizing design to support high-end cameras (multi- and hyperspectral imagers).

The calibration of NAPA's images is an ongoing process and will continue over the course of its mission. This, to support the wide range of radiometric properties of the various scenes on ground and the usage of different TDI settings. Any new insights or images captured will be gladly shared in the future.

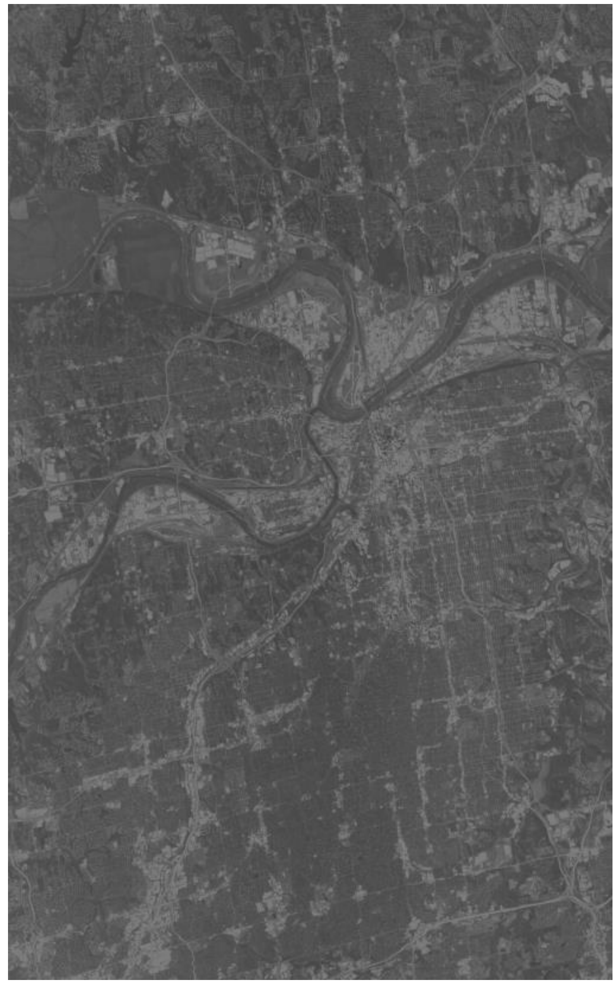

Figure 34: Raw image data of Kansas City taken with TDI2 and FMC7 by NAPA-2.

References

[1] Brouwer, H.S.B., Oei, H.Y., Aalbers, G.T., Garcia, L., Verdugo, M., Cavalli, D., Strobino, L., "Earth through the Eyes of NAPA-1: Commissioning Results and the Next Steps in CubeSat Earth Observation," Proceedings of the 35th Annual Small Satellite Conference, Logan, UT, August 2021.

[2] Brouwer, H.S.B., Oei, H.Y., Botma, P., Santos, H., de Groot, Z., Rotteveel, J., Langbroek, M., "High-Resolution Operational Earth Observation from a 6U Small Satellite," Proceedings of the 72nd International Astronautical Congress (IAC), Dubai, United Arab Emirates, October 2021.

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