Development of an Operating Strategy for On-Demand Earth Observation Missions of the Diwata-2 Microsatellite

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ABSTRACT

Diwata-2 is the Philippines' 2nd microsatellite developed by Tohoku University, Hokkaido University, University of the Philippines, and the Philippine Department of Science and Technology. Its primary purpose is gathering remote sensing data through imaging areas of interest for the Philippines. This paper presents the study of Diwata-2's initial Earth observation pointing performance, investigation of its Attitude Determination and Control System, the tuning of its Star Tracker sensor parameters, the in-flight target pointing calibration, and the sequential scheduling of its components forming an operation strategy for an effective on-demand earth observation mission. This operation strategy has managed to improve the satellite's pointing performance from the initial 2.88°±2.06° RMS pointing error to having an accuracy of 0.204°±0.12° RMS for its High Precision Telescope payload. This strategy has been implemented to the university-built microsatellite for over 400 successful Earth observation missions and has covered about 82.8% of the Philippine's land area with its Spaceborne Multispectral Imager payload.

THE DIWATA-2 MICROSATELLITE

The PHL-Microsat Program

The Philippines is an archipelago of 7,614 islands with a total land area of around 300,000 km^2. It is the 5th largest island country in the world with the 5th longest coastline in the world. It also lies on the Pacific Ring of Fire and is vulnerable to natural hazards such as typhoons, earthquakes, floods, and volcanic eruptions. Therefore, it was an investment taken by the country to produce satellites and have its own capability of monitoring its geography thru satellite imagery. In 2016, the Philippines begun its venture into space under the research program: The Development of Philippine Scientific Earth Observation Microsatellite or PHL-Microsat. This program was funded by the Philippine Department of Science and Technology (DOST) and was a collaboration between the University of the Philippines, the DOST Advanced Science and Technology Institute, Hokkaido University and Tohoku University. The program led the Philippines' progressive improvement in space technology by employing its own satellite design and building capacity. This satellite technology will address the need for near real-time and on-demand access to data that will enhance local planning and decision support for climatology, disaster risk mitigation, and resource management.[1] In 2019, the PHL-Microsat was succeeded by the Stamina4Space program.

The Diwata-2 Project Overview

The microsatellite baseline design and assembly were assigned to Tohoku University while Hokkaido University was tasked with the payload and thermal systems. The Tohoku University – Space Robotics Laboratory have been developing and operating microsatellites over the past decade. This led to flight-proven heritage systems and operational practices. Through this project, Tohoku University provided hands-on training and education to Filipino engineers about space engineering. Diwata-2 was launched on October 29, 2018, the satellite was launched directly into orbit onboard the JAXA's H-IIA rocket from the Tanegashima Space Center. Its predecessor Diwata-1 was earlier launched and deployed into orbit on 2016.

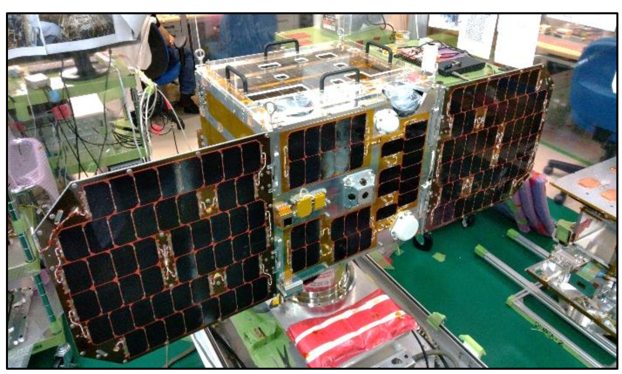

Figure 1: The Diwata-2 Microsatellite

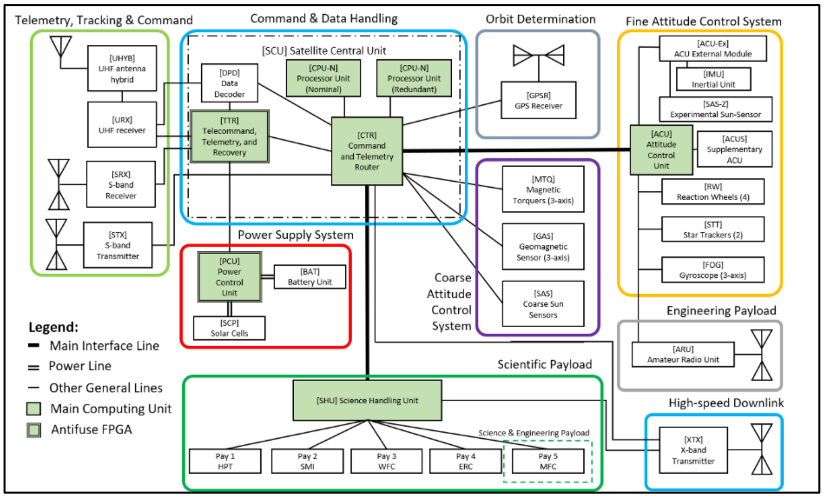

Figure 2: Diwata-2 System Architecture

Table 1. Diwata-2 System Overview

Size	490 mm x 490mm x 490mm
Mass	57.4 kg
Orbit	Low Earth 595km x 616km Sun Synchronous, 97.84º
Power	170 GaAs Solar Cell Units NiMH Batteries, 79.9 Wh
Communi-cation System	UHF-band receiver (URX) S-band receiver (SRX) S-band transmitter (STX) X-band transmitter (XTX)
Ground Station Network	PEDRO Center, Manila, PH CRESST, Sendai, Japan Hakodate GS, Japan Kiruna GS, Sweden

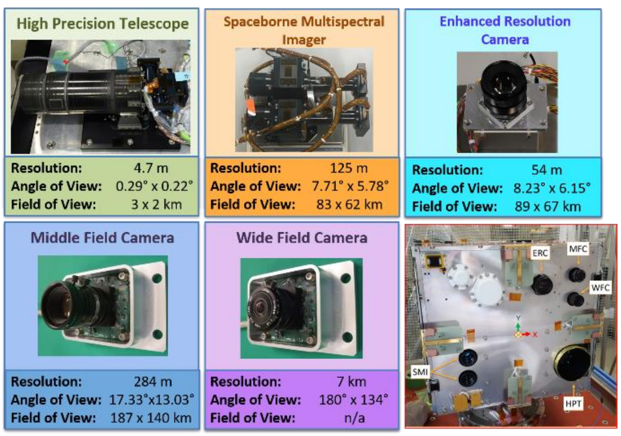

Figure 3. Diwata-2 Optical Payloads

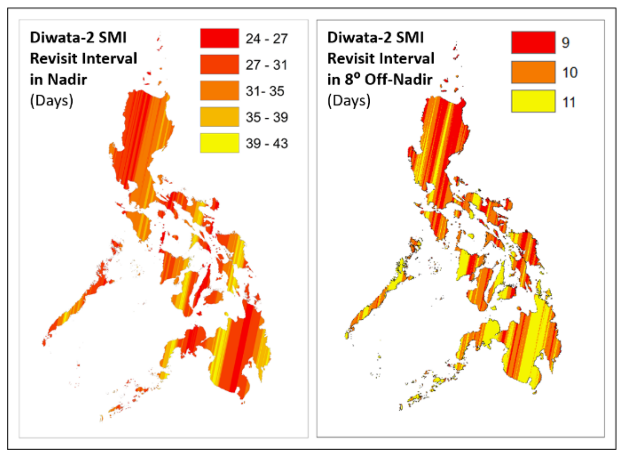

Figure 4: Revisit Intervals of Diwata-2 over the Philippines: (L) nadir pointing, (R) 8° off-nadir pointing.

Diwata-2's mission include: determining the extent of damages from disasters, monitoring natural and cultural heritage sites, monitoring changes in vegetation and oceanology, and observing cloud patterns and weather disturbances. Shown in Table 1 and Figure 2 are details of Diwata-2's specifications, mission, and system.[2] The satellite is equipped with various optical payloads to accomplish its remote sensing missions, as shown in Figure 3, and they are fixed onto one side of the satellite allowing Diwata-2 to serve as an agile platform for observation as it orbits around earth.

On-Demand Earth Observations by Diwata-2

Diwata-2 is then used in an on-demand basis as its mission objectives may require near real-time data such as in cases of disaster risk and assessment. This means that operators select a specific area of interest for observation particularly in the Philippines, rather than for large scale global monitoring.

It also has a low earth and sun synchronous orbit. This is useful for Earth observations as it forms a good global coverage and is even advantageous for the geography of the Philippines as the satellite orbit tracks along the length of the country. For its tradeoff, it has poor revisit intervals for areas near the equator. The traditional nadir scanning methods employed in larger Earth observation satellites are usually optimized for worldwide coverage and may not be effective for Diwata-2. This is evident in Figure 4, where the revisit interval in days are calculated for the swath of the Spaceborne Multispectral Imager (SMI) of Diwata-2. The shortest nadir revisit interval over the Philippine islands are in 24 days. This would even be worse for the 0.29º (3 km) swath of the High Precision Telescope (HPT). If satellite operation would be restricted to nadir pointing, it may result into a low temporal resolution over the Philippines.

Diwata-2 is equipped with an attitude control system that enables off-nadir pointing capability. This type of maneuver is possible for use in routine operations because of the small and compact assembly of Diwata-2. This is in contrast to the larger and more complicated assembly of the traditional Earth observation satellites that may have higher power requirements or other operational considerations. The off-nadir pointing capability, extends the range of observation of the satellite allowing for on-demand observation. Also shown in Figure 3, for an 8º off-nadir angle, the revisit interval has improved significantly with the shortest revisit time of now only 9 days.

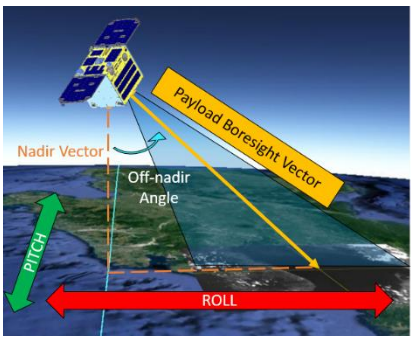

Figure 5. Off-Nadir Target Pointing

However, it is not possible for Diwata-2 to have active control at all times because of power and monitoring limitations. Therefore, the use of Diwata-2's attitude control capabilities is maximized by pre-planning and proper sequential scheduling.

An operating strategy is then designed for the satellite in a dynamic procedure where multiple maneuvers are required while accounting for the orbital conditions as well as the functionality requirements of its attitude components. Using this strategy, the microsatellite's off-nadir pointing capability shall be used to achieve the accuracy demands for a successful observation mission, wherein all mission payloads could capture their targets. This study presents the design of this in-flight operating strategy and includes the study of its attitude determination and control system and its initial performance, the calibration of its star trackers, target pointing calibration, and the sequential scheduling of its components.

ATTITUDE DETERMINATION AND CONTROL

The Attitude Determination and Control Subsystem (ADCS) of Diwata-2 and its primary components are shown in Figure 6. The Attitude Control Unit (ACU) is the on-board computer which manages the ADCS. Its 4 Reaction Wheels (RW) are the system's primary actuators. They are mounted with a 4-skew alignment for complete 3-axis control including a redundancy. The RWs are developed by Tamagawa Seiki Co.

Diwata-2 uses 3 modes for attitude determination.[3] The Coarse Attitude Determination uses the Geomagnetic Aspect Sensors (GAS) and Sun Aspect Sensors (SAS). The GAS is assembled from Honeywell HMC2003 magnetic field density sensors. The SAS system is composed of a series of 8 individual P-type silicon solar cells. These cells are pasted on each side of the satellite. The measured magnetic field vector and the measured solar vector are used in a deterministic approach with theoretical models. The TRIAD algorithm is applied for a determination of the spacecraft's attitude. [4,5]

$$\boldsymbol{q_k} = \frac{\boldsymbol{q_{k-1}} + \frac{\Delta t}{2}\,\boldsymbol{\Omega}_k\,\boldsymbol{q_{k-1}}}{|\boldsymbol{q_{k-1}} + \frac{\Delta t}{2}\,\boldsymbol{\Omega}_k\,\boldsymbol{q_{k-1}}|} \quad (1)$$

$$\boldsymbol{\Omega} = \begin{bmatrix} 0 & \omega_z & -\omega_y & \omega_x \\ -\omega_z & 0 & \omega_x & \omega_z \\ \omega_y & -\omega_x & 0 & \omega_z \\ -\omega_x & -\omega_y & -\omega_z & 0 \end{bmatrix} \quad (2)$$

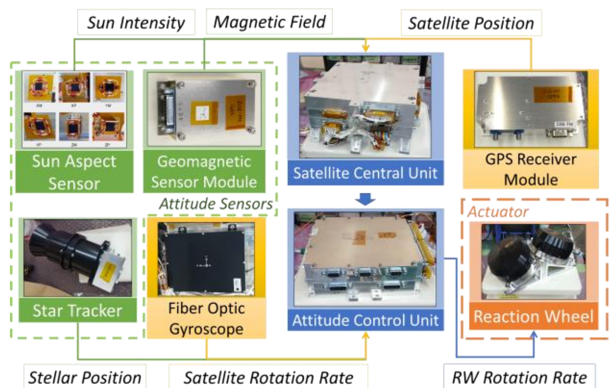

Figure 6: Attitude Determination and Control System

The Fine Attitude Determination uses readings Star Tracker (STT) images. The 2 units of STTs of Diwata-2 are developed in Tohoku University in collaboration with Meisei Electric Co. It has a 0.8 kg mass and a 27.8º FOV.

Lastly, the Fiber Optic Gyroscope (FOG) of Diwata-2 was developed by Tamagawa Seiki Co. It is rated with ±50 mV/(deg/s), and a bias of ±0.1º/hr. It performs the FOG Attitude Integration which propagates attitude readings through time based on the rotation rate measurements. This is calculated inside the ACU as where $\boldsymbol{q}$ is the propagated attitude expressed as quaternions and $\boldsymbol{\Delta t}$ is the time step [6,7]:

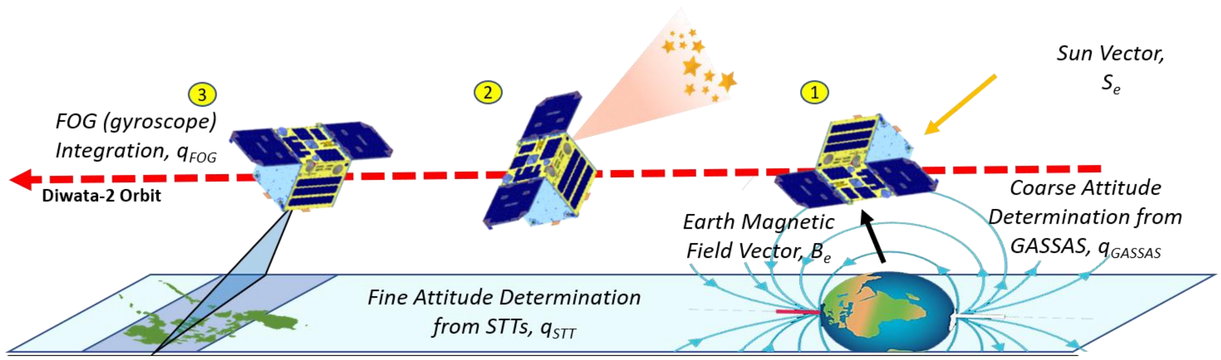

Figure 7: Diwata-2 Earth Observation Mission Procedure

Target Attitude Calculation

The target attitude for Earth observation pointing is computed beforehand on the ground and then uploaded to the satellite as stored commands.[8] It is assumed for the desired capture time, the satellite position, $\boldsymbol{r_I}$, and the position of the ground coordinates to be captured, $\boldsymbol{R_I}$, in the Earth-centered Inertial Reference Frame are known. The target boresight vector required for the payloads is calculated as:

$$\boldsymbol{t_{3,I}} = \frac{R_I - r_I}{|R_I - r_I|} \tag{3}$$

We transform to the local vertical/local horizontal frame (LVLH) where the nadir vector for Diwata-2 is defined as $\boldsymbol{u}_{3,u} = [0,0,1]^T$. The target quaternion, $\boldsymbol{q}_{target,e}$, and the target roll-pitch-yaw Euler angles, $[\boldsymbol{\varphi}, \boldsymbol{\theta}, \boldsymbol{\psi}]_{target}$, can finally be calculated as follows:

$$\Phi_{\boldsymbol{RP}} = \frac{180}{\pi}\arccos\left(\frac{u_{3,u}\cdot t_{3,u}}{|u_{3,u}|\cdot|t_{3,u}|}\right) \tag{4}$$

$$q_{RPY} = q_{RP} \otimes q_Y \Leftrightarrow [\phi,\ \theta,\ \psi]_{\boldsymbol{target}} \tag{5}$$

$$\boldsymbol{q_{target,e}} = q_{I2u} \otimes q_{RPY} \tag{6}$$

RPY Pointing Mode

Diwata-2's ACU is coded with a roll-pitch-yaw (RPY) pointing mode. As the name suggests, the satellite is commanded to a specific roll-pitch-yaw Euler angle attitude with respect to the LVLH frame. This is used for off-nadir target pointing as the roll and pitch Euler angles directly correspond to the satellite's off-nadir orientation. For the special case of $[\varphi=0^o, \theta=0^o, \psi=0^o]_{target}$, the satellite is simply set to nadir. When this pointing mode is active, the satellite will maintain the resulting off-nadir pointing angle. This means that the attitude is continually adjusting and moving with respect to the inertial frame as the satellite passes along its orbit. This operation is visualized in Figure 5.

If used for observations, the images are taken sequentially in a pushbroom scanning manner. Ideally, the image centers will form a line that is parallel to the orbit ground track. This mode is useful for taking panoramic snapshots along its orbit.

EARTH OBSERVATION MISSION SEQUENCE

For an effective utilization of the ADCS components, proper sequential scheduling must be planned. This is formulated in a way that shall maximize each functional condition of the attitude components and minimize their operational limitations. It also should satisfy the accuracy and precision demands for observation.

It is proposed that we have three distinct stages of attitude control and determination as part of our standard operating procedure for daylight Earth observations. This is designed based on the orbit trajectory of the satellite and shall be executed as the satellite approaches its target. This process is visualized in Figure 7.

Stage 1: GASSSAS Phase

To start with the Earth observation mission, Diwata-2 must first recover from its initial lost-in-space attitude. Coarse Attitude Determination with the GASSAS system is sufficient for this activity. As soon as the satellite enters the sunshine phase, the GAS and SAS are activated while the RWs are used to stabilize the satellite into a specific orientation for suitable attitude determination. In this case, the valid detection of sunlight for at least 3 SAS cells, representing 3 sides of satellite body, is desired. The precision of attitude determination is not essential in this stage as long as control is regained.

Table 2: Star Tracker Operating Conditions

Category	Condition	Reqt
Control	Satellite Body Angular Velocity	<0.3°/s
Deep Space Field of View	Sun Incident Angle	> 80°
	Moon Incident Angle	> 50°
	Earth Incident Angle	> 120°
	Number of Stars *3rd to 4th magnitude only	> 12

Stage 2: STT Phase

After regaining attitude control, we can now proceed to the Fine Attitude Determination with the STTs. In this stage, the STTs are pointed to deep space for star pattern detection and should satisfy its operating conditions shown in Table 2.[9]

Stage 3: Target Observation Phase

Then as we approach the target, the satellite shall prepare for observation. It begins to maneuver to its final desired target attitude for Earth observation. Here, the star trackers are generally turned off as it may no longer satisfy the operating conditions as mentioned in Table 2 during this maneuver.[7] Attitude is then supplied by FOG attitude integration. The maneuver is timed where the control system by the RWs reaches sufficient convergence as soon as it arrives to the target. Then, the commanded optical payloads are turned on and images are captured which are saved to the Science Handling Unit (SHU) on-board computer, completing the mission. The satellite is then released from active control and returns to its lost-in-space attitude.

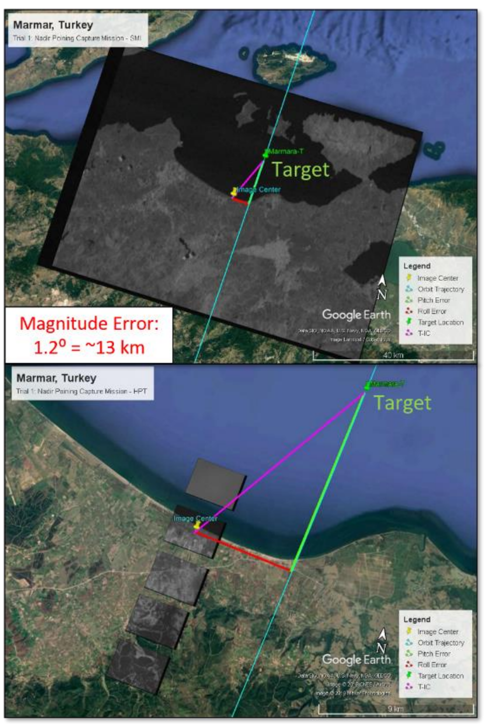

Figure 8: HPT and SMI Capture of Trial Mission

Initial Pointing Performance

Initial Earth observation trials were carried out with clear target locations using the simultaneous capture of the HPT and SMI on the same target using the proposed mission sequence. The pointing-degree error of each trial is then calculated to evaluate the ADCS' performance.[5]

A sample set of these initial trials and its pointing error with respect to the HPT are shown in Table 3. The recorded initial trials resulted into an average of 2.88° error in RMS and a standard deviation of ±2.06°. Both nadir and off-nadir pointing were tested. Figure 8 shows the SMI and HPT images captured during the initial nadir trial (Trial 1). For the SMI the target (shown as the green pin) was captured but was outside the smaller FOV of HPT. This translated into a 0.43º roll error and a 1.12º pitch error for the SMI. On the other hand, the HPT yielded a 0.59º and 1.12º roll and pitch error respectively.

The initial trial results may be acceptable for payloads with a large FOV, such as the SMI and even achieved effective observations up to almost 20° off-nadir angle with the Trial 3 mission. But further work is needed for the HPT. Based on its FOV, a pointing error of less than 0.1º is desired. [3]

Table 3: Initial Earth Observation Pointing Performance Analysis (Errors in Degrees)

Trial ID	Capture Date (UTC)	Target Attitude			Roll Err	Pitch Err	Mag Err
		R	P	Y			
1	19/19/07 11:46:59	0.00	0.00	0	0.59	1.12	1.27
2	19/20/07 13:32:18	6.59	0.71	180	0.95	1.66	1.91
3	19/09/05 10:57:56	-5.5	16.61	-179	0.51	0.62	0.80
4	19/10/09 04:56:41	0.00	0.00	0	1.60	-1.24	2.02
5	20/04/21 11:34:12	0.00	0.00	180	1.40	5.00	5.19

STAR TRACKER SENSOR CALIBRATION

The success of the Fine Attitude Determination is critical for having precise observations. The sequence of attitude determination by the STTs are performed as follows: image acquisition, star detection, centroiding, star identification and attitude calculation. First the CCD image sensor takes images of the stellar sky. Then the image is transmitted to a dedicated FPGA processor that detects the bright pixels for star pattern detection. Centroid calculation is executed and star vectors are calculated . The star tracker has a built-in star catalog which it uses to cross-reference the detected star patterns in the camera field of view and each centroiding star is then associated with a corresponding star identification. Finally the attitude can be calculated by using the TRIAD method with the calculated star vectors. It is also equipped with a fast tracking feature that helps to calculate latest attitude faster than conventional methods by feeding back the previous attitude information.[10]

The in-flight behavior, output, and parameters of the Star Trackers are investigated. The objective of this STT tuning calibration is to have a functional STT attitude measurement in-flight.

STT Image and Sensor Performance Analysis

In-flight STT images during satellite operation are captured and analyzed to study the in-flight sensor condition. The set of images on the left-hand side of Figure 9, shows the image analyses the STT images during its initial experiments. The raw image is first inverted in color to emphasize lights spots captured by the sensor. This is then analyzed on the ground using an STT simulation software. which imitates the on-board algorithm. From this ground analysis, it was confirmed that the initial star images could not produce a valid star pattern detection. The green and blue dots are suspected noise or white spots identified by the software while the red circles are the detected bright stars. In this instance, the bright stars were insufficient to form a star pattern that could be cross referenced with the base star catalog.

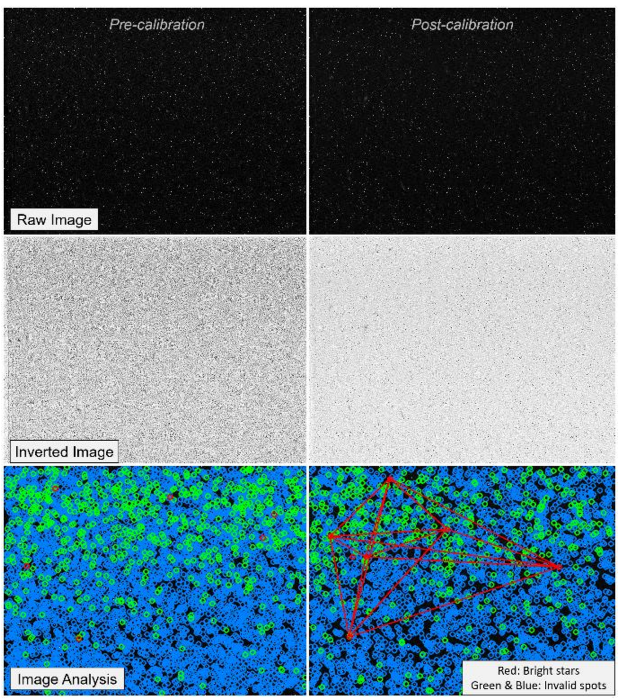

Figure 9: STT Image Analysis:
(L) initial sensor performance, (R) after STT calibration

From the image analysis results, some possible causes of failure were hypothesized and possible countermeasures are suggested:

Image Noise – Since the launch of Diwata-2, the STT images exhibited the presence of white spots. Comparing STT images from one year apart, and using the same sensor parameter settings, it has shown an apparent increase of these white spots as seen in Figure 9. The 2018 image was taken as part of the functional checks for the STT after launch where the sensor produced a valid attitude reading. The 2019 image was part of the initial trials of the Earth observation procedure and now was unable to detect a valid star pattern.

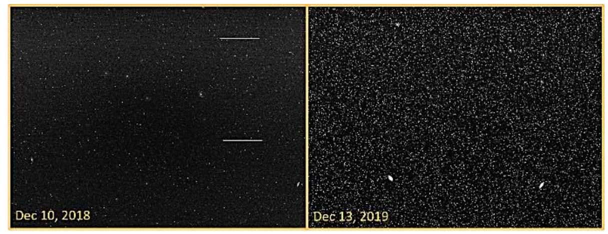

Figure 10: Increase in Noise with STT Images

The white spots may be attributed to the natural degradation of the pixels inside the CCD sensor due the radiation environment. This phenomenon has also been observed in RISING-2 satellite of Tohoku University where the number of white spots increased 6-fold in a span of almost 300 days.[11] The white spots creates noise in the images which masks and disrupts the true stars that may be captured by the star trackers. Although the STTs are coded with a white spot avoidance algorithm, the gradual increase of noise may have overwhelmed this feature. The STT's sensor parameter settings may be adjusted to minimize the effect of noise in the images. However, there are probably no effective solutions for Diwata-2 against the in-flight radiation effects and thus the CCD would continuously degrade over time.

Light Interference – Stray light overexpose the STT images and also masks the star patterns. This poses a challenge for the daytime Earth observation implementation with the strong presence of sunlight. From the recommended minimum incident angles in Table 2, planetary models of the sun, earth, and moon are used to predict the incident angles with respect to the STT boresight vectors. The required incident angles will primarily dictate the attitude command to be set for the STT phase. This attitude will be manually checked on the ground before its execution in-flight.

Insufficient Bright Stars – There is a possibility that there were simply not enough bright enough stars captured by the FOV of the STTs. Table 2 also shows that a recommended minimum number of 12 stars of 3rd to 4th magnitude brightness should be captured inside the STT FOV. For the study and for practical purposes, extending the STT phase duration will be implemented to increase the chances of capturing the required stars by the 2 STTs.

In-flight STT Tuning Calibration

In-flight STT trials were carried out to verify these remedies. This is essential as the STT may only be tuned in-flight and ground simulation of representative mission conditions may not be feasible. Trials were designed to reflect the satellite locations in orbit of the STT phase.

The STT sensors, shown in Table 4, have its parameter settings to adjust the quality of the captured star pattern images. The primary settings to be tuned are the Gain, Exposure Time, and Focal Length values. The right mix of these settings are to be determined for the recognition of a valid star pattern. Figure 11 shows in-flight result samples of different combinations of these settings.

Table 4: STT Sensor Parameter Settings

Parameter	Range	Description
Gain (dB)	0 – 30	Controls apparent sensitivity to light of the sensor. An increase will amplify sensor readings but also includes sensor noise.
Exposure Time (ms)	100 – 500	Controls the amount of light to be detected by the sensor. An increase will make the STT more vulnerable to movement distortion.
Focal Length (f)	1663.0 -1674.0	Adjusts the transformation of the image frame into the local frame by onboard software.

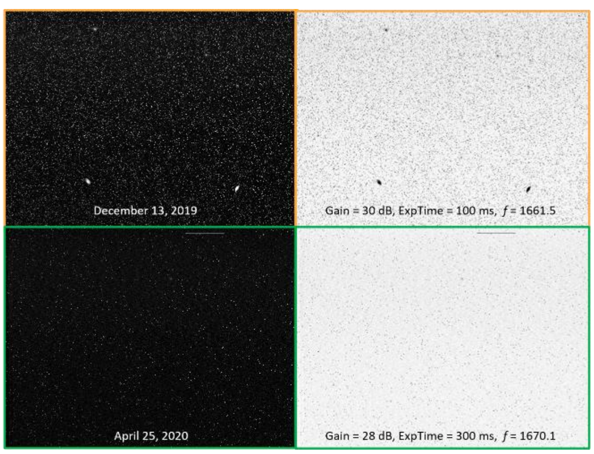

Figure 11: Different STT Parameter Combinations

Then, using the orbital models of the Sun, Earth, Moon and Diwata-2 the incident angles with respect to both the STT1 and STT2 boresight can be predicted throughout the duration of STT phase. This is similar to the target frame calculation for the optical payload. But the calculation will now be relative to the STT1 and STT2 boresight vectors instead of the nadir direction. Based also from the original alignment and assembly design, the STT boresight vectors in the LVLH are defined as follows:

STT1: $$u_{STT1,u} = [0,1,0]^T \quad (7)$$

STT2: $$u_{STT1,u} = \left[0,1,\frac{-\sqrt{3}}{3}\right]^T \quad (8)$$

Figure 12 shows that from a candidate attitude and time duration, its resulting incident angles satisfy the necessary requirements. This attitude shall be maintained throughout the STT phase to minimize the satellite rotation rate.

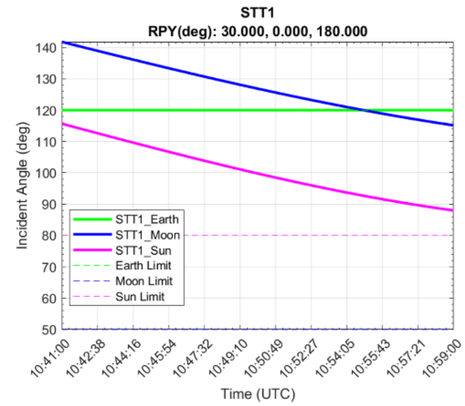

Figure 12: Predicted Incident Angles for STT1

After numerous iterations for the tuning of the proper conditions necessary were performed, a working set for the STT phase is shown in Table 5. The set of images on the right-hand side of Figure 9, confirms a successful star pattern was detected using these conditions. It is also recommended that these working conditions should be checked and updated occasionally due to the dynamic orbit environment.

Table 5: Recommended STT Conditions

Condition	Value
Time Duration	At least 15 minutes
Attitude	*φ=30º, θ=0º, ψ=180º*
Parameter Settings	Gain = 400ms, Exp. Time = 28dB, *f* = 1670.1

Table 6: Observation Results with Calibrated STTs

Trial ID	Capture Date (UTC)	Target Attitude			Roll Err	Pitch Err	Mag Err
		R	P	Y			
6	20/02/27 05:11:30	3.52	0.48	180	0.59	1.12	1.27
7	20/02/28 05:19:53	13.51	0.94	180	0.95	1.66	1.91
8	20/02/29 05:27:21	1.73	- 0.07	- 180	0.51	0.62	0.80
9	20/03/19 05:06:41	-12.0	- 0.42	180	1.60	-1.24	2.02
10	20/03/21 05:37:27	-5.75	- 0.55	180	1.40	5.00	5.19

Earth Observation Implementation

Solutions were incorporated back to the mission procedure and experiments were again performed. Table 6 shows a sample set of these trials. It resulted in an average error of 1.79° in RMS and a standard deviation of ±0.59°. The calibrated trials showed a significant improvement over the 2.88°±2.06° error of the initial experiments. This is especially true for the consistency of the captures. The low precision during the initial trials might be caused by the propagation of the already inaccurate GASSAS readings over an extended integration period.

Overall pointing performance improved, but it did not yet reach the 0.1° average pointing error required for the HPT, as shown in the Mission Trial 9 result in Figure 13. Nevertheless, from these results, the off-nadir pointing capability of Diwata-2 was demonstrated. Also shown in the inset of Figure 13, is the scale of the distance of the target location from the satellite position. In this instance, the satellite was able to take images about 140km away from its orbit ground projection.

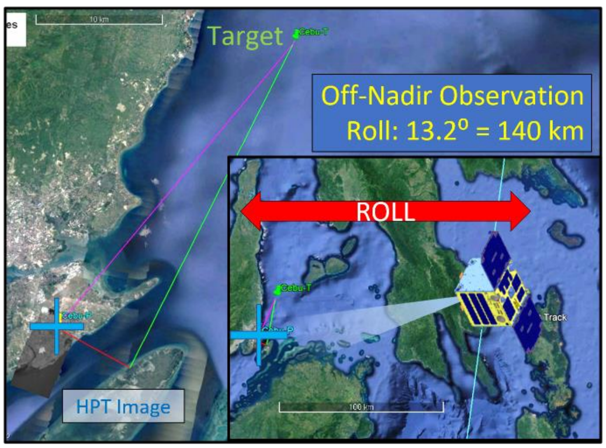

Figure 13: Mission Trial 9 Off-Nadir Observation

TARGET POINTING CALIBRATION

The Star Tracker calibration alone has yet to satisfy the pointing <0.1° average pointing error required, This may be caused by persisting systematic issues such as biases, system latency, alignment errors. The study *In-Flight Target Pointing Calibration of the Diwata-2 Earth Observation Microsatellite* presents further calibration activities conducted on the microsatellite.

Table 7: Diwata-2 Pointing Performance Summary

Version	Roll Error		Pitch Error		Mag Error	
	RMS	Std Dev	RMS	Std Dev	RMS	Std Dev
Initial	0.869°	0.60°	2.745°	2.47°	2.880°	2.06°
Post-STT Calib	0.814°	0.15°	1.596°	0.62	1.791°	0.59°
Post-Target Pointing Calib	0.196°	0.13°	0.058°	0.05°	0.204°	0.12°

An experimental procedure of using Lunar observations were conducted to address the misalignments between the STT and payload boresight vectors. Further fine tuning of the observations was conducted by managing the satellite's execution of its panoramic capture in a deterministic approach. This accounted for the persisting issues with the satellite, such as system latency and orbital model inaccuracies to a certain extent. With this calibration procedure, an overall average of 0.2° in RMS with a standard deviation of 0.12° pointing accuracy for Earth observation was recorded with the latest calibration iteration. In at least 24% of the observation trials, Diwata-2 achieved the 0.1° accuracy requirement needed for an effective observation by its High Precision Telescope. A summary of the satellite's pointing performance improvement from these calibration activities are shown in Table 7.[3]

Figure 14: Diwata-2 HPT Capture Achievement

RECOMMENDED EARTH OBSERVATION PROCEDURE FOR DIWATA-2

From the study, the recommended mission procedure for Earth observations of Diwata-2 can now be formulated. This procedure is shown in Table 8 and follows the general idea given in Figure 7. This detail the timing of commands and the recommended conditions of each stage. A preliminary step of ground mission planning is first conducted. In this *Stage 0*, the target attitude is calculated and the desired capture control settings for the payloads are decided. It is in this stage, that target adjustments would be applied. In *Stage 1*, the Coarse Attitude Determination would be activated few moments after the satellite enters sunshine. Then *Stage 2*, or the STT phase, is where the recommended functional conditions for Fine Attitude Determination in Table 5 are applied. Ideally, this stage would last up to 15 minutes. Finally, *Stage 3* would be the observation phase. The satellite would be reoriented to its target attitude at least 5 minutes before the capture time to allow for sufficient convergence, ideally less than 0.1° control error. Any other adjustments, as suggested by the target pointing calibration procedure, would be executed here. The images are then saved to be downloaded.

Figure 15 shows the attitude flight log data of an actual implementation of this mission procedure. The first graph shows the control error angle where there are three spikes for the three control stages with different set attitudes. Small bumps, usually less than 1º, are also observed with every attitude estimate update from the STTs. The satellite body rotation rate is also shown. The highest rate recorded is from the detumbling of the satellite from its lost-in-space attitude. It then maintains a less 0.2º/sec in Stages 2 and 3. Finally, an STT counter are recorded by the ACU to confirm the functionality of the Fine Attitude Determination.

This procedure shall serve as only as a guide and may be adjusted if needed. In different areas around the world, the timing and conditions might slightly be different. An occasional review of this procedure would also be conducted to maintain its effectiveness.

CONCLUSION

This paper presented the initial observation performance of the Diwata-2 satellite, investigation of its ADCS, the tuning of its Star Tracker sensors, the in-flight target

Table 8: Recommended Earth Observation Procedure for Diwata-2

Stage	Duration (mm:ss)*	Operation
Stage 0	n/a (Plan prior to the nearest opportunity of target capture)	Target Attitude Calculation: Use latest TLE orbit model
		Synchronize and Update On-board Orbital Model
		Upload of Stored Commands
Stage I: GASSAS Phase	S + 0:00 (Begin at least 1 minute after satellite enters sunshine)	Resume ADCS operation: Initialize ACU Turn on Control System and actuators
	S + 1:00	**Coarse attitude estimation is activated**
	S + 1:10	Set satellite for optimum SAS detection: *φ=-35º, θ=-45º, ψ=-180º*
Stage II: STT Phase	S + 3:00	Turn On STT and initialize Parameter Settings: *Gain = 400ms, Exp. Time = 28dB, f = 1670.1*
	S + 5:00	**Fine attitude estimation is activated**
	S + 5:10	Set satellite for optimum STT detection: *φ=30º, θ=0º, ψ=180º*
Stage III: Observation Phase	T - 5:10	Turn Off STT **FOG attitude integration is activated**
	T- 5:00 (At least 5 minutes before mission capture)	Set satellite to target attitude: $[\varphi, \theta, \psi]_{target}$
	T - 4:30	Initialize SHU and Optical Payloads
	T - 3:00	Load capture control Settings for Payloads
	T	**Sequential Image Capture Of Target**
	T + 0:30	Save Images to Flash Memory
	T + 1:00	Turn off SHU and Optical Payloads
	T + 2:00	Release Active Attitude Control: Turn off sensors and actuators

*S = sunshine, T = target capture

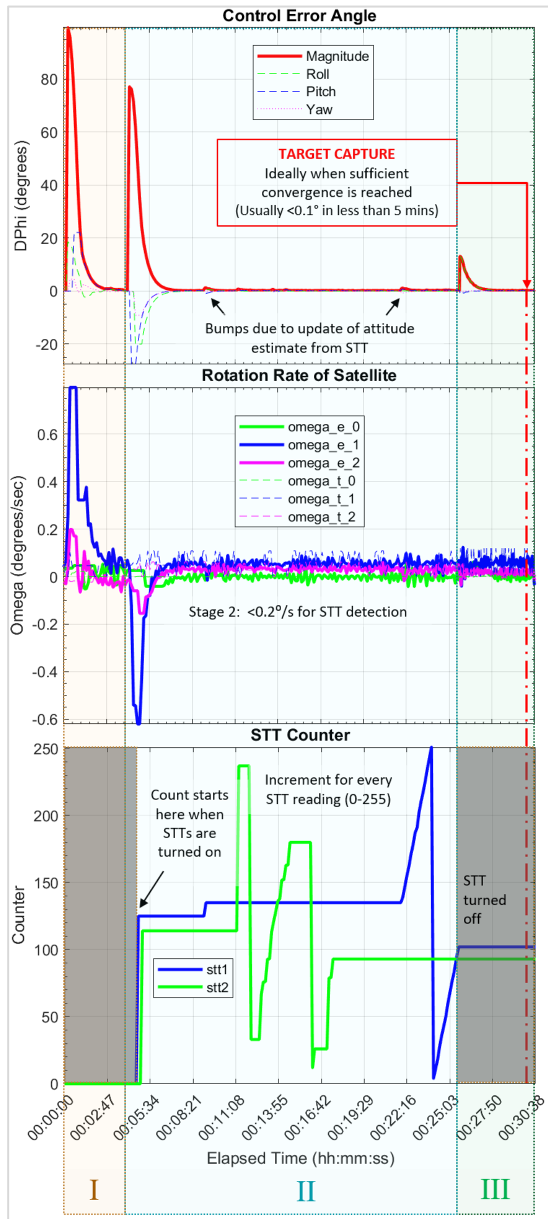

Figure 15: Attitude Logs of Mission Procedure

pointing calibration, and the sequential scheduling of its components forming an operation strategy for successful on-demand earth observation mission. This strategy has managed to improve the satellite's pointing performance up to around 0.2º observation accuracy, in contrast to the initial 2.88º accuracy recorded after its launch 3 years ago. It has even achieved near center capture of its HPT as shown in Figure 14.[3]

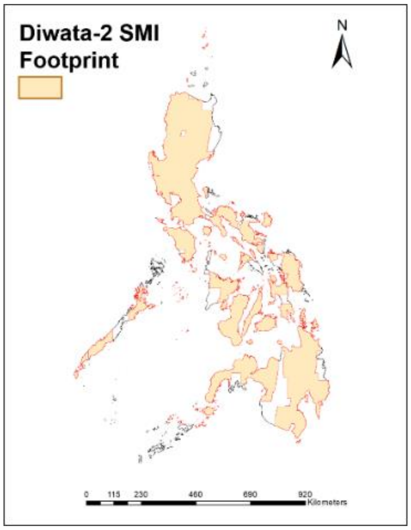

Figure 16: Diwata-2 Coverage of the Philippines as of Q1 2021

This strategy has been implemented to the university-built microsatellite for over 400 successful Earth observation missions and has demonstrated to achieve up to 20° off-nadir angle for on-demand observation. Diwata-2 now has managed to cover about 82.8% of the Philippine's land area with its SMI payload in performing its mission objectives shown in Figure 16.

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