Assessing the Effects of Orbital Shift on Diwata-2 Microsatellite Operation through Simulations

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***Abstract*—Diwata-2 has been in orbit for three years since its launch on October 29, 2018. Thus, the effects of its orbital configuration are much more noticeable than in its earlier stages. This paper investigates the effects of orbital drift on the current issues that are affecting the operations of the satellite such as satellite communications and image quality. Using five simulations involving the determination of the limits of acceptable passes, culmination events over the Philippines, the shift in time of the passes, and the changes to the satellite's temporal resolution, it was found out that the satellite passes have shifted by over an hour from its design at launch. The rate of its nodal precession has increased, resulting to later passes. The temporal resolution of the satellite also changed from 31 days to 11 at the expense of less area coverage. Using the historical two-line element (TLE) data, future passes were also simulated. It was found out that currently, there is a problem involving blind spot areas at nadir pointing, which covers 58% of the Philippines' entire area. Two predictions were also done to determine when the satellite passes over the 3 PM local time. The first is by using linear regression on the culmination events of the satellite, and the second is by using the satellite's historical TLE. Both predictions were in agreement that the event would happen in August 2023. As such, after this limit, a large portion of the passes would not be ideal for image acquisition.**

***Keywords*—orbital drift, simulation, pass events, microsatellite, sun-synchronous low earth orbit, Diwata-2**

I. Introduction

Diwata-2 is the Philippines' current and lone Earth observation microsatellite after its predecessor, Diwata-1 re-entered the Earth's atmosphere in April 2020. Both satellites have been used for their high spatial and spectral resolution payloads that are suitable for vegetation monitoring and post-disaster assessment [1]. Diwata-2 has five optical payloads and an Amateur Radio Unit (ARU) to fulfill its missions. The High Precision Telescope (HPT) has four bands (blue, green, red, and near-infrared) and is used to capture high spatial resolution images at the expense of spectral resolution and a small swath (3.1 km x 2.3 km). The Enhanced Resolution Camera (ERC) is a panchromatic high spatial resolution camera with a large swath (89.8 km x 67.5 km), making it an ideal candidate for pansharpening purposes. The panchromatic Wide Field Camera (WFC) is a fisheye camera used for weather monitoring due to its very large swath, and the colored (blue, green, and red) Medium Field Camera (MFC), with also a large swath (189.3 km x 141.9 km), is used for geolocation purposes. However, the images from the Spaceborne Multispectral Imager (SMI) fitted with a liquid crystal tunable filter (LCTF) is the most commonly used data due to its multispectral capabilities and its use in environmental monitoring. At an altitude of 621 km, it has a ground swath of 83.7 km x 62.7 km at nadir and is capable of using 27 bands in the visible range (412 nm – 750 nm) and 13 bands in the near-infrared region (740 nm – 1020 nm) with a 10 nm bandwidth. Fig. 1 shows the comparison of coverage areas among the payloads.

The Diwata-2 is currently handled by the Sustained Support for Local Space Technology and Applications Mastery, Innovation, and Advancement program (STAMINA4Space). The STAMINA4Space program is a

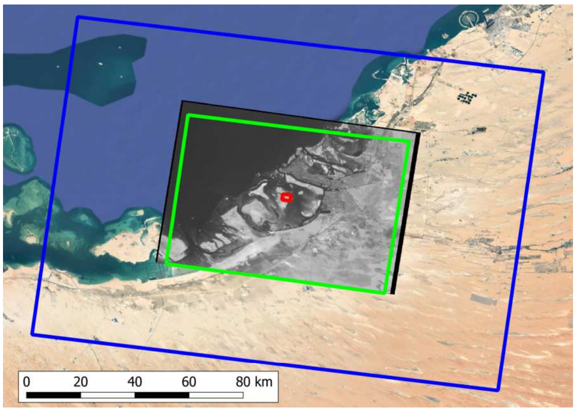

Fig. 1. Swaths of Diwata-2 payloads: ERC (grayscale image), MFC (blue), SMI (green), and HPT (red).

The STAMINA4Space program is funded by the Philippine government's Department of Science and Technology.

space research and development program and currently maintains the Philippines' satellites.

Currently, Diwata-2 is orbiting at an altitude of 590 km to 600 km. It has a sun-synchronous orbit with an inclination angle of 97.9° and a period of 96.5 minutes. Table 1 shows the initial two-line element (TLE) data of Diwata-2 after its launch. It has been in orbit for three years since its launch on October 29, 2018. With this, the satellite has reached half of its expected lifespan and may have been affected by orbital shift.

Therefore, this paper investigates if the Diwata-2 satellite has drifted from its original orbital configuration over the past three years. This paper visualizes the magnitude of the orbital drift of the satellite by investigating the change in time of Diwata-2's passes over the receiving station at the Philippine Earth Data Resource and Observation (PEDRO) Center, Quezon City, Philippines (14.64725° N, 121.07201° E). In addition, the paper also investigates the effect of the orbital shift to the satellite's temporal resolution and projects yearly scenarios that would give insights on proper adjustment in operation to compensate for such changes. Thus, over the course of this research, multiple simulations have been conducted to produce the satellite's orbital drift values and to visualize their effects on operation time, image quality, and changes to the satellite's temporal resolution. Finally, the simulation results can be used to predict the satellite's two-line element (TLE) for 2023, the year when the satellite's expected lifetime ends.

II. The Effects of Orbital Drift to Diwata-2

Sun-synchronous satellites are very useful for remote sensing purposes due to their ability to capture the same area under similar illumination conditions [2]. To obtain a sun-synchronous configuration, the orbital plane of the satellite must precess by approximately one degree per day to account for the Earth's revolution. The angle of precession needed to sustain a sun-synchronous orbit depends on the altitude and the inclination of the satellite. Through its lifetime, Diwata-2's inclination was obtained through its historical two-line element data while its elevation is simulated over the entirety of the satellite's lifetime since its launch and averaged over a 31-day period. These values were calculated using Skyfield [3] and are shown in Fig. 2 and 3. Fig. 4 shows the changes in the right ascension of the ascending node (RAAN) per day.

As shown in Fig. 2 and 3, Diwata-2's inclination values are increasing, and the altitude values are decreasing. Although this happens very slowly, the satellite's changing altitude and inclination require new nodal regression values for the satellite to stay in its orbit. However, without having a propulsion system, the satellite has no capability to correct the effects of the shift. Thus, the satellite is very prone to the effects of orbital drift, and this affects both the image quality of its products and the operational time for satellite communications. Fig. 4 shows that the nodal precession of Diwata-2 increases over time with minimal changes from 0.992° to 1.008° per day. The authors of [2] state that the required nodal precession of a sun-synchronous satellite must be 0.9856° per day. This means that Diwata-2 is precessing more than the required angle, and this is a cause of later passes over time.

Reference [4] listed the effects of orbital drift on image quality and reflectance values. An orbital drift would introduce changes in the solar zenith angle (SZA) at the time of observation, which could introduce issues such as a longer irradiance path leading to a worse signal-to-noise ratio (SNR), introduction of haze, and changes due to the bi-directional reflectance distribution function, which has an effect to the collected radiance values of the satellite. Reference [5] has studied the effects of orbital drift on the EO-1 satellite as its attitude was declining at the time. However, the authors concluded that the effects of the orbital drift on the image data especially when creating spectral indices such as the Normalized Difference Vegetation Index (NDVI) were minimal. The authors also cautioned that the changes in the

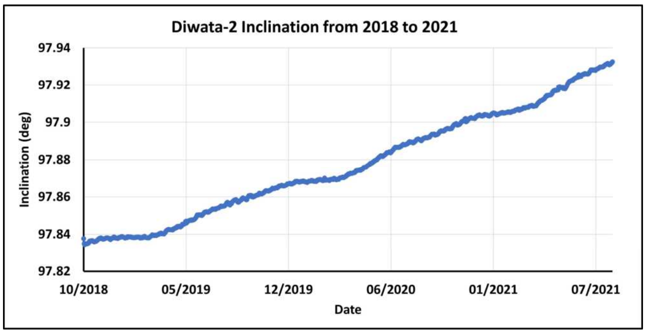

Fig. 2. Diwata-2 inclination values.

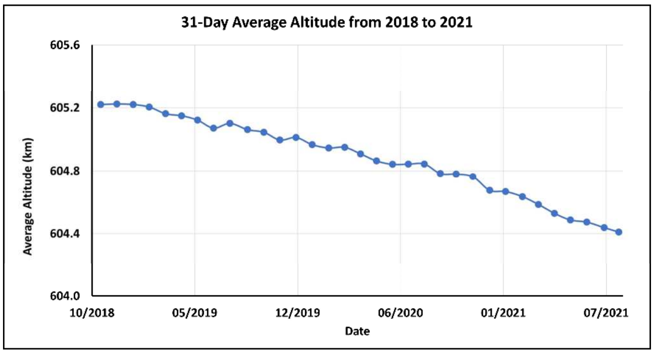

Fig. 3. Diwata-2 average altitude values.

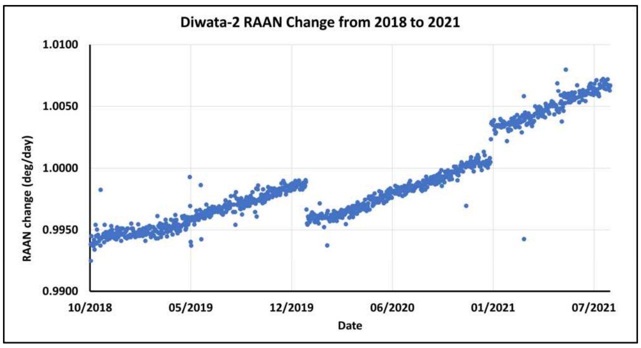

Fig. 4. Diwata-2 nodal precession.

TABLE I. First Recorded Diwata-2 TLE Data

First TLE Record (October 29, 2018)								
1 43678U	18084H	18302.30219663		-.00000057	00000-0	00000+0 0	9995	
2 43678	97.8377	52.8562	0011621	358.5994	95.6495	14.91537062	09	

SZA will cause changes in the reflectance values due to a more pronounced presence of shadows.

Orbital drift also affects the operational flexibility of communications to the Diwata-2. In the past, manned operational routines could be shifted from daytime to nighttime with minimal complication. As nighttime passes gradually occur at later times, manned communication operations at night become less feasible to carry out routinely. Currently, communication operations that require personnel are designated to daytime passes, while mainly automated processes are allocated for nighttime passes.

Reference [6] also noted for the Diwata-1 satellite that it uses a sun aspect sensor (SAS) to determine orientation. While the study was done for the Diwata-1 satellite, Diwata-2 uses a similar payload that defines orientation using solar illumination. Thus, a difference in the solar zenith angle would also interfere with the satellite's pointing capabilities, which depends on the intensity of the sun's illumination to determine its orientation

III. Orbital Drift Simulations

As the data collected from the TLE of a certain epoch is only accurate within a few days, the simulations using satellite positioning uses historical daily data as was recorded by the operations team of Diwata-2 for better accuracy. These historical TLE data are propagated using the SGP4 propagator [3]. While it propagates its orbital elements with a simplified model of perturbations, it is enough to visualize the magnitude of orbital drift using pass times and culmination events [7].

A. Solar Zenith Angle Determination

Reference [8] studied the effects of the solar zenith angle changes on the reflectance values. A change of 3° at 20° SZA would introduce a ~2% RMSE change to the reflectance values. The author also states that the reflectance RMSE values increase moderately until 50°, where it increases exponentially after that. The Philippines generally have lower SZA values in a year due to its location near the equator. However, higher SZA values would still occur, and this idea would set the limits of Diwata-2's drift for its data to be still usable.

The first simulation involves calculating the solar zenith angle values for the Philippines using Systems Tool Kit [9]. The solar zenith angles were calculated and simulated for the PEDRO center at the current operational extreme times (10 AM and 2 PM local time). To account for the effects of the earth's revolution, the simulation was done over the whole year of 2020. The results can be seen in Fig. 5 and 6. SZA values during 10 AM range from 27° to 48° and 2 PM values range from 28° to 50°. SZA values are higher during the winter solstice when the sun reaches its minimum declination. These are acceptable values, as the SZA values do not exceed 50° throughout most of the year. Additionally, these values allow satellite passes to exceed the 10 AM to 2 PM window by a small amount. Since the 2 PM values are still acceptable, the limit for usable passes is set to 3 PM when the effect of the solar zenith angle becomes substantial.

B. Culmination Events over the PEDRO Center

The second simulation involves measuring when the satellite culminates over the PEDRO center. Culmination times of Diwata-2 passes over the PEDRO center in local time were simulated starting from launch until the TLE epoch on July 1, 2021, with the results shown in Fig. 7. Diwata-2 passes over the Philippines twice a day, one in the daytime when the satellite passes its descending node, and the other at nighttime when the satellite passes its ascending node. Both passes are used by the operations team to upload and download satellite commands. However, this simulation will only investigate the drift during day passes to determine when the satellite passes over the limits set earlier. This massive number of events were averaged over a 31-day period to account for the satellite's temporal resolution (Fig. 8).

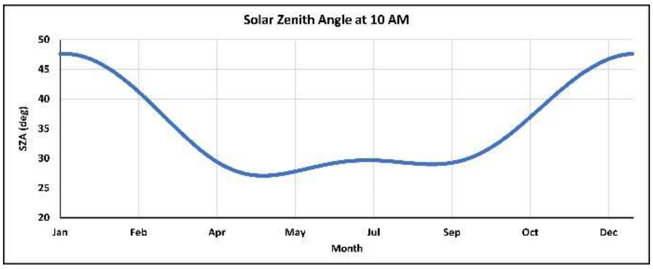

Fig. 5. Solar zenith angles at 10 AM.

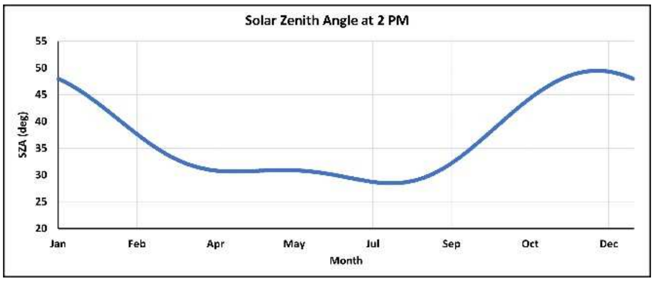

Fig. 6. Solar zenith angles at 2 PM.

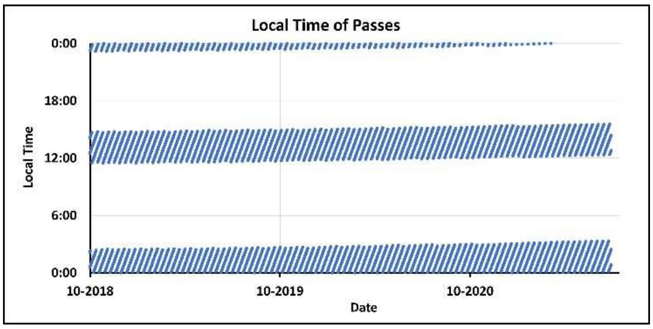

Fig. 7. Diwata-2 passes in local time over the PEDRO center since its launch.

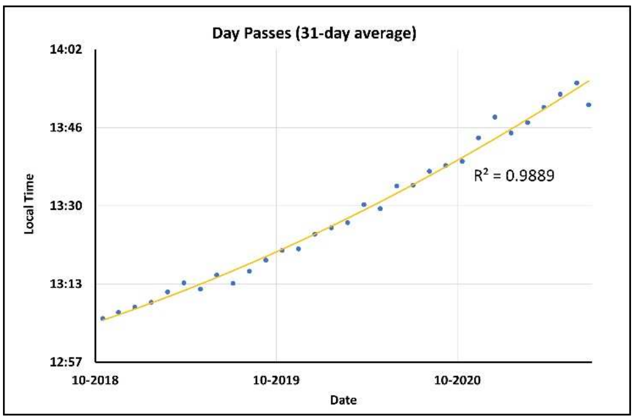

Fig. 8. The average time of Diwata-2 day passes every 31 days.

The data is then fitted using a quadratic function and has an R squared value of 0.9889 which is the most acceptable result for all simulated trendlines. This means that the culmination times over the PEDRO center would happen at a much later time over the next few months.

It can also be seen that the 31-day average would pass over the 2 PM mark sometime soon. To further give a more exact idea of when the event happens, the trendline is used. Using the trendline, the date when the satellite passes the 2 PM mark is on September 9, 2021. The date when the satellite passes over the 3 PM mark is also determined to be on August 17, 2023, which is almost 2 months short of Diwata-2's fifth anniversary in orbit. These data are acceptable, as the unsuitability of the satellite products at that time would coincide with the degradation of the satellite's electrical components.

C. Comparison of Diwata-2 Passes over its Lifetime

To further show the drift, simulations were done to determine the satellite's position for over a month on a one-minute interval. This set of points were then clipped to a 3000 km coverage from the PEDRO center, which is its approximate range, and night passes were removed. Then, the passes were grouped according to the hour of the event. Fig. 9 to 12 show the results of the simulation for November 2018, July 2019, July 2020, and July 2021, respectively. In these maps, the orbital drift is much more noticeable, with earlier missions showing 11 AM passes which do not happen anymore with the current setup. The average time of passes over the Philippines has shifted by an hour from late noon passes to earlier 2 PM passes.

When comparing the four figures above, one can notice the gradual changes in the distances between passes as seen in Fig. 13 and 14. As the orbit changes through time, the effects in the temporal resolution make the gap between passes become wider to as much as 220 km. This is the gap between succeeding day passes. However, upon closer inspection, the passes just shifted closer to one another to as close as 2 km as seen in Fig. 15. During its early stages of the satellite, its orbit is designed to have a gap of 84 km between passes, as this is the width of the SMI products. However, the shift of gaps from a uniform 84 km between passes to a pattern of wide and narrow gaps indicates a change in temporal resolution. This

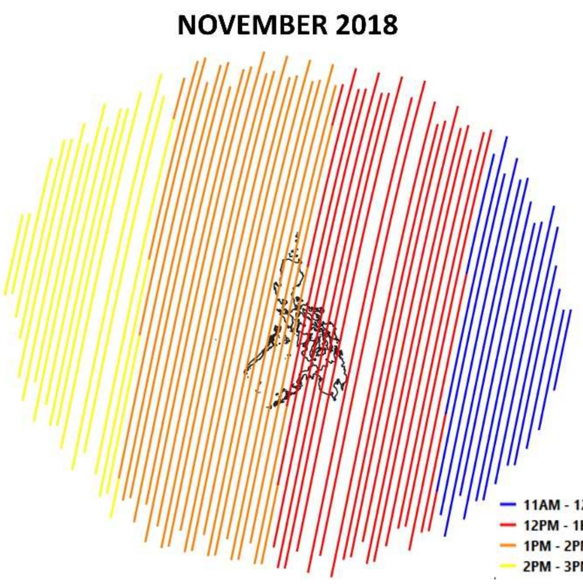

Fig. 9. Simulated passes of Diwata-2 for November 2018.

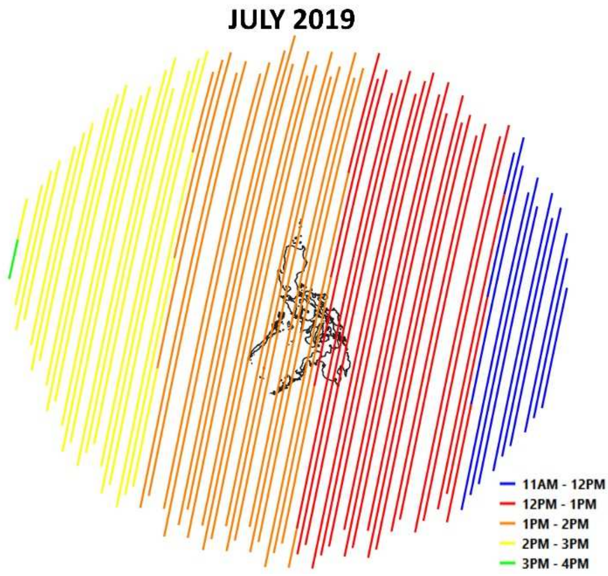

Fig. 10. Simulated passes of Diwata-2 for July 2019.

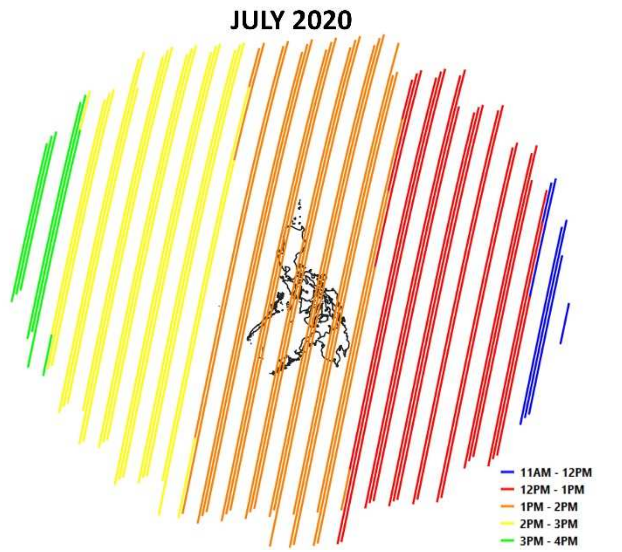

Fig. 11. Simulated passes of Diwata-2 for July 2020.

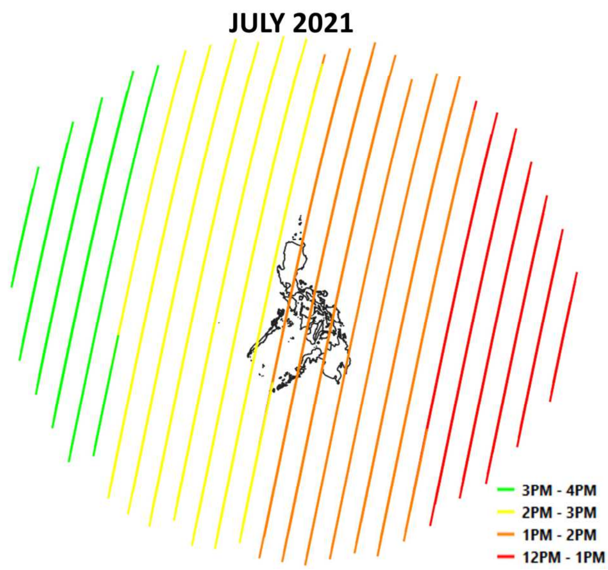

Fig. 12. Simulated passes of Diwata-2 for July 2021.

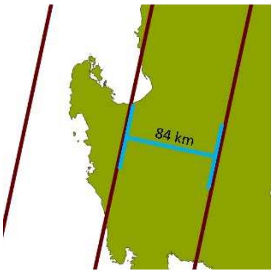

Fig. 13. Pass gap distance in 2018.

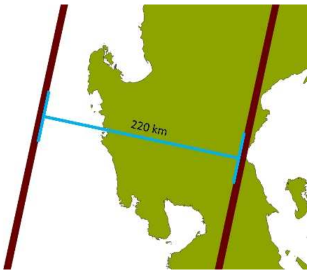

Fig. 14. Pass gap distance in 2021.

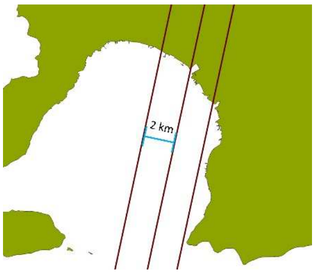

Fig. 15. Zoomed pass gap distance in 2021 between nearby passes.

means that after a certain number of days, which in this case is determined to be at least 11 days, the satellite passes over the same area. This shift is very significant as it affects the observation coverage of the satellite.

D. *Effects on the Temporal Resolution*

To further show the temporal resolution of the satellite and the areas it covers, coverage maps are made using the satellite passes simulated over three months. The original configuration of the Diwata-2's temporal resolution is at least 11 days for the satellite to capture the same area again at an 8° pointing angle and at least 31 days at nadir (Fig. 16). The cumulative SMI footprints over a period of 100 days using two pointing modes, at nadir (Fig. 17) and an 8° angle range from the nadir (Fig. 18), were mapped over the Philippines. The algorithm counts, then, the number of passes that happened for every 1 km x 1 km pixel, and the output is divided from the total simulation period to obtain the revisit time.

As seen in Fig. 16, during Diwata-2's early days in orbit, almost all areas in the Philippines can be accessed by the satellite's nadir pointing at its intended temporal resolution. However, in Fig. 17, passes are overlapping over an 11-day temporal resolution. While it may have some advantages, especially with regards to it visiting the same area over a shorter period of time, some areas will not be covered by the satellite, therefore introducing blind spot areas. The blind spot area as shown in Fig. 17 would cover 172812 km2 or 57.6% of the entire Philippines. This means that for its operations, missions involving image collection must be set to a target as opposed to simply letting the satellite capture the areas below it. However, as seen in Fig. 18, this problem of fewer area

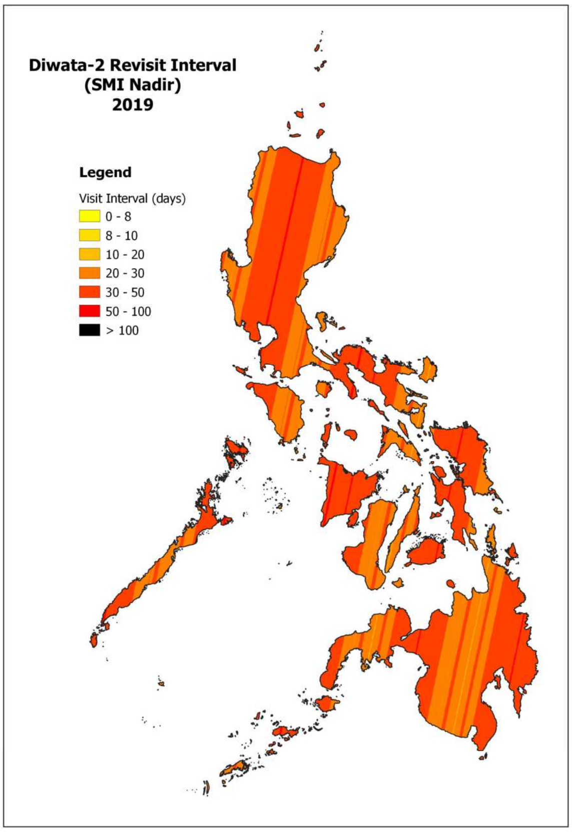

Fig. 16. SMI footprint at nadir in 2019 showing revisit interval.

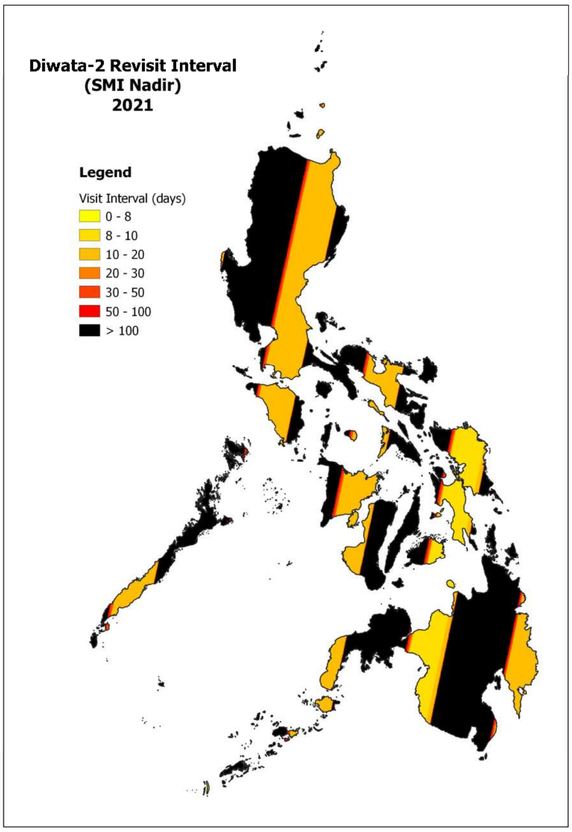

Fig. 17. SMI footprint at nadir in 2021 showing revisit interval.

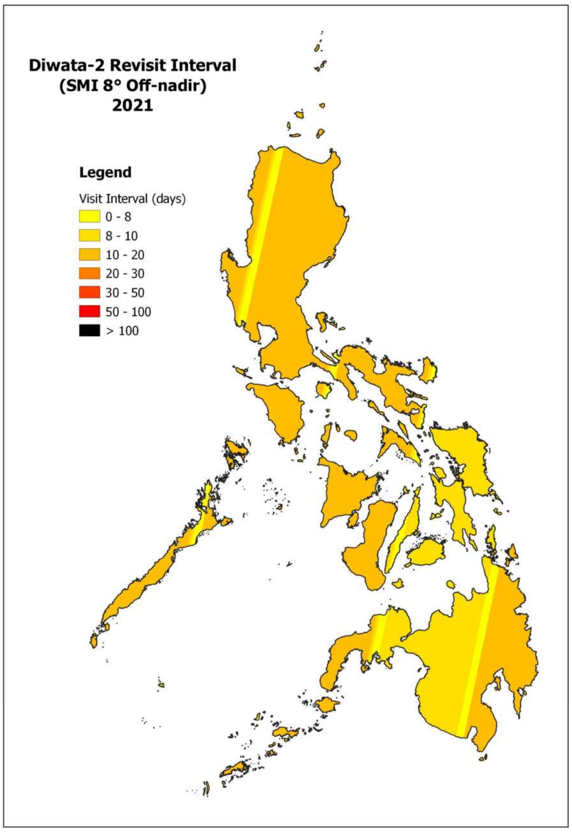

Fig. 18. SMI footprint at off-nadir in 2021 showing revisit interval.

coverage can be solved by using off-nadir targeting modes. The targeting mode of 8 degrees may still be used to fully cover the country.

E. Diwata-2's Period

Diwata-2's period was also obtained through its TLE data. As shown in Fig. 19, Diwata-2, while arriving later over time, has its period slowly getting shorter, with a change of about 1.2 seconds since its launch. This is due to its slowly decreasing altitude, as shown earlier in Fig. 3.

F. Simulation of Future Passes

To have an idea of the orbital configuration of future passes, the TLE of future passes is also simulated using linear regression of the satellite's recorded orbital elements. It must be noted that satellite position prediction remains a challenge due to the external forces that will affect the satellite. Reference [10] estimated satellite position and velocity vectors using a predicted TLE created through the least-squares estimation of the satellite's orbital elements and drag coefficients, with a noticeable improvement of 15% on the positional accuracy in Planet Labs 1B satellites. A similar procedure was done using Diwata-2 historical data and yielded the following TLE data shown in Table 2 with its epoch on July 1, 2023, at midnight. Thus, for the simulation, in which its goal is to present a very rough estimate of the time when the satellite reaches the limit of image capturing, the use of linear regression to the orbital elements and drag components is deemed sufficient. A similar simulation as in section C was done and its results are shown in Fig. 20. The effect of the orbital drift is very noticeable at this time as 4 PM passes are now a big part of the overall passes. In the figure, the current blind spot issue can be seen to be fixed in 2023, due to further orbital drift. However, as established earlier, a big portion of the passes would be unfavorable due to the substantial effect of the SZA past 3 PM.

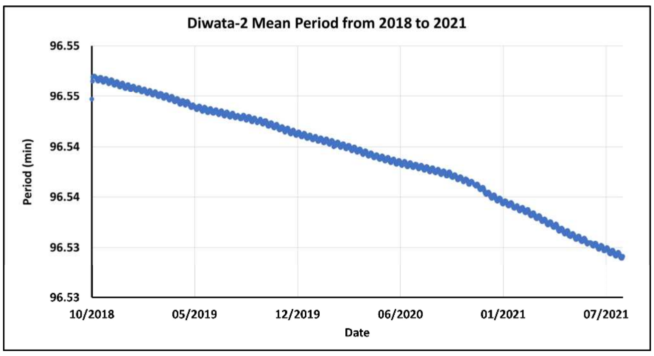

Fig. 19. Diwata-2's period.

It can also be noted that the simulation done using TLE prediction and the regression of culmination passes have the same output as both predictions show that the satellite passes over the 3 PM mark by this time.

IV. Addressing the Effects of the Orbital Shift in Operation

As Diwata-2 does not have a propulsion system, the procedures regarding operations must adjust to the effects of the orbital drift. As shown in the simulations, the current setup of the passes introduces blind spots with regard to nadir pointing. Thus, there must be increased reliance on target pointing for the satellite to cover the entire Philippines.

TABLE II. Computed Orbital Elements for July 1, 2023, Midnight

Epoch	23182.0
Inclination	97.9932°
Right ascension of ascending node	296.0528°
Eccentricity	0.0010225
Argument of perigee	112.0295°
Mean anomaly	199.5409°
Mean motion	14.91940128 rev/day

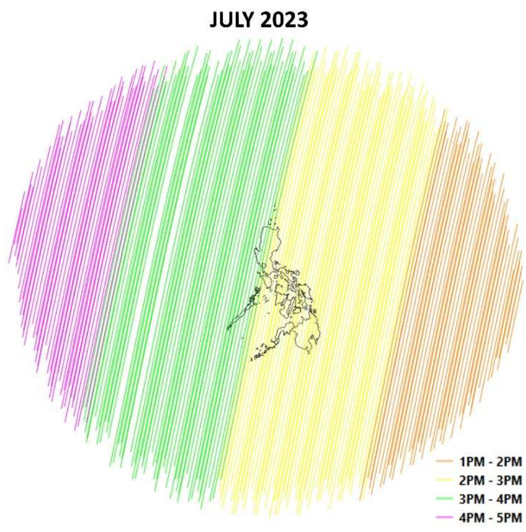

Fig. 20. Simulated passes of Diwata-2 for July 2023.

Reference [1] has shown that the accuracy of the Diwata-2's target pointing is at least 1.75 degrees or 26 km, so for the SMI footprint, this accuracy is acceptable.

With non-nadir pointing comes the pros and cons of the technique such as the much more pronounced effect of shadows, in addition to the effect of the SZA for later passes. With this, it is recommended to utilize and combine the Diwata-2's payloads in missions to compensate in addition to the target pointing operations to cover the blind spot areas in the meantime. Although the current orbit introduces problems with regards to its blind spots, the satellite continues to drift, and the blind spots would disappear over time. In addition to this, shifting the focus to payloads with larger swaths would also be useful on missions past the recommended limits. In the case of Diwata-2, there have been 206 missions involving the HPT but only 181 missions involving the SMI and ERC payloads from January to July 2021.

As its spectral data would change due to later passes, the satellite's spectral products may not be as accurate even after atmospheric corrections. Thus, it may also be necessary to shift the Diwata-2's mission to utilize its high spatial capabilities more. Applications using the satellite's spatial resolution such as visual change detection, object inventories, and damage assessment would be less affected by orbital shift.

The satellite may also be used to capture targets outside the Philippines where the illumination conditions are still acceptable even after orbital shift. Capturing targets outside the country is currently done even without the effects of orbital shift whenever the weather conditions in the Philippines are not conducive to producing a good set of products. Of the 206 missions involving the HPT from January to July 2021, only 17 missions were carried out in the Philippines. If the effects of the orbital shift become drastic in the future, missions outside the Philippines may still be usable.

With regards to the adjustments to the operation of the satellite, it is useful to contact the satellite using multiple ground receiving stations (GRS). Aside from the GRS at the PEDRO center, the Diwata-2 satellite may be accessed at the Hakodate and Kiruna stations in Japan and Sweden, respectively. With its differences in the time zone, manned operations and communications with the satellite can happen in a more flexible schedule.

Satellites to be developed in the future must also be able to address the effects of orbital shift. A jet propulsion system may be used to maintain the satellite's orbit and adjust to the motion of the Earth. For microsatellites that may not have the space for such mechanisms, careful decisions on the satellite's orbital elements may be necessary to plan for earlier passes, to account for the eventual orbital shift.

V. CONCLUSIONS

Diwata-2, in its third year in operation, is observed to have drifted from its original pass times over the Philippines due to its nodal precession being more than what is required for a sun-synchronous satellite. This change in pass time has affected the flexibility between manned daytime and nighttime communication operations, as the night passes, in particular, continue to occur at increasingly later times. Simulations show that orbital drift may also affect the frequency and coverage of captures over the Philippines due to changes in temporal resolution. Further study of this effect may be done by comparing the simulations to data gathered from capture operations over the Philippines.

Care must be taken when designing future missions as the effect of the solar zenith angle becomes significant in the later stages of Diwata-2's life. Thus, with the effect of shadows from the solar zenith angle and the compensation through target pointing, it is not recommended to continue collecting images after 3 PM, when the higher values of the SZA would greatly affect the image data. Although [5] has shown that the effects on the reflectance values are insignificant, missions involving height determination may not be feasible anymore due to the effects of the shadows.

In conclusion, while small satellite technology has surged in recent years, the effects of orbital drift have to be considered when designing small satellites especially as its effects become more significant in the latter years of its lifetime. As some small satellites such as the Diwata-2 would not be controlled in orbit, further measures must be implemented to account for the effects of the orbital drift. Target pointing, as well as using a payload with a larger swath, would be the solution to the problem of blind spots, as the 8º off-nadir pointing is sufficient enough to cover the entire Philippines without accounting for a large effect from the view angle. Although currently, Diwata-2 experiences the issues of blind spots due to its overlapping passes, it was also shown that this will not be an issue for future passes, as the satellite would continue to drift until the end of its lifetime.

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