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Investigation of Altitude Degradation Effects on KhalifaSat's Imaging Performance

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Abstract

KhalifaSat, launched in 2018 with an expected operational lifespan of five years, has continued to support the Mohammed Bin Rashid Space Centre (MBRSC) as a valuable resource through 2024. This assessment evaluates its performance over six years, focusing on temporal resolution, revisit time, spatial resolution, and image quality. Despite its extended durability, the satellite faces challenges related to altitude degradation, which have affected its imaging capabilities and overall functionality. Temporal resolution, reflecting how frequently the satellite revisits specific locations, has been notably impacted by altitude changes. Gradual altitude degradation has resulted in longer revisit times of 20 days, leading to delays in critical tasks such as mosaic generation and disaster monitoring. Changes in imaging time have presented additional obstacles, including increased shadowing and inconsistent coverage. Narrower swath widths at lower altitudes have diminished overlap zones between image passes, complicating the production of large-scale mosaics. To address this, adjustments have been made to increase the overlap zones to mitigate the impact. Altitude variations have also affected spatial resolution, enabling the satellite to capture finer details due to its reduced distance from Earth. However, this improvement comes with challenges, including inconsistencies in image quality. Despite these technical challenges, KhalifaSat continues to deliver critical data to MBRSC, demonstrating its robustness and adaptability. Nonetheless, ongoing monitoring and innovative adjustments are necessary to sustain performance standards as its operational conditions evolve. This analysis highlights the importance of balancing technical limitations with strategic interventions to optimize satellite capabilities.
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Keywords: KhalifaSat, Temporal Resolution, Spatial Resolution, Altitude Degradation, Satellite Performance, Mohammed Bin Rashid Space Center

1. Introduction

KhalifaSat (KHS) is a low Earth observation satellite developed by the Mohammed Bin Rashid Space Centre (MBRSC) and launched on October 29, 2018, from Japan's Tanegashima Space Centre [1]. The KHS camera is equipped with five spectral bands: one panchromatic (PAN) band with a spatial resolution of 0.73m and four multispectral (MS) bands (Red, Green, Blue, and Near-Infrared) with a spatial resolution of 2.92m, as shown in Fig. 1.

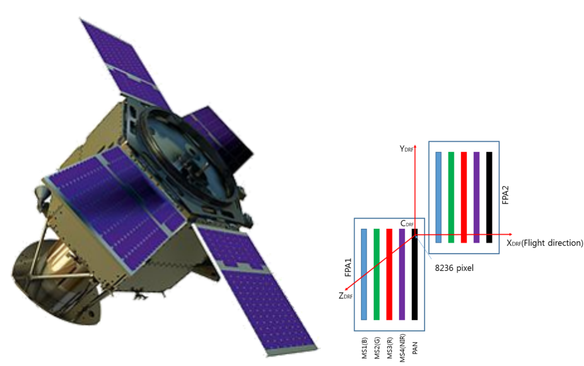


Fig. 1. Khalifasat Spectral Bands.

Originally designed with a five-year operational lifespan, KhalifaSat has surpassed expectations and remains operational into 2025. However, challenges such as altitude degradation have affected key imaging parameters, including temporal resolution, revisit time, and quality metrics. The aim of this research is to evaluate the impact of altitude changes on KhalifaSat's temporal resolution and overall performance, assess key performance metrics such as revisit time, spatial resolution, and imaging consistency, and identify quality issues and challenges. This paper evaluates KhalifaSat's performance over the period from 2019 to 2024.

2. Methodology

This study examines KhalifaSat's performance metrics from 2019 to 2024 using archived image data.The following parameters were analyzed:

2.1. Temporal Resolution and Revisit Time

Temporal resolution refers to the frequency at which a satellite collects data over a specific location, and one of the primary factors influencing it is the satellite's altitude. Lower altitudes typically result in shorter orbital periods, which can enhance temporal resolution by enabling more frequent revisits. However, these lower altitudes often come with narrower swath widths, which may increase the revisit time for specific areas. This longer revisit time can reduce the overall temporal resolution, making data collection less frequent for particular locations [2].

2.2 Altitude Degradation Analysis

Altitude variations in Low Earth Orbit (LEO) satellites are commonly monitored through historical telemetry data, as changes in altitude can significantly impact satellite performance and data collection capabilities. Over time, satellites in LEO may experience a gradual decrease in altitude due to factors such as atmospheric drag, gravitational forces, and limited fuel available for altitude corrections. Atmospheric drag slowly pulls satellites down due to resistance from the upper atmosphere, while limited fuel means satellites cannot perform altitude corrections indefinitely. Gravitational forces from the Moon, Sun, and Earth's uneven gravity can disturb orbital stability and impact altitude. Additionally, wear and tear on systems like thrusters and control mechanisms make it more challenging to maintain altitude over time. These variations can influence the satellite's orbit and temporal resolution, affecting how frequently it revisits and collects data over a specific location. Understanding and tracking altitude changes is crucial for managing satellite operations and ensuring accurate data acquisition for various applications [3].

2.3 Imaging Time Analysis

Imaging time analysis was conducted to assess the impact of altitude variations on data acquisition consistency. The imaging time shifted due to changes in the satellite's altitude and inclination angle. This shift affected the illumination conditions, as the Sun was lower in the sky during later imaging times, leading to longer shadows cast by buildings, trees, and terrain features. Additionally, the degradation in KhalifaSat's altitude resulted in a narrower swath width, reducing the overlap zone between consecutive image passes. This inconsistency impacted large-scale mosaic generation, particularly in the UAE. To mitigate this issue, modifications were made by increasing the overlap zone between passes, ensuring more consistent imaging coverage for mosaic generation and analysis.

2.4 Image Quality Metrics

The evaluation of image quality involves several key parameters that impact the reliability and effectiveness of satellite imagery. These include spatial resolution such as signal-to-noise ratio (SNR) and modulation transfer function (MTF), as well as geolocation accuracy. Changes in altitude have influenced spatial resolution, while variations in SNR and MTF reflect potential degradation effects. Additionally, shifts in geolocation accuracy have introduced challenges for precise mapping applications. Each of these metrics will be discussed in detail to analyze their implications on data quality and overall system performance.

3. Results and Discussion

3.1 Impact of Altitude Degradation on Temporal Resolution

The increase in revisit time from 8 to 20 days significantly delayed data acquisition, impacting critical applications such as disaster response and environmental monitoring. Since the revisit time is related to the satellite altitude, investigation revealed that there was a drastic decrease in the satellite altitude from 608 km to 594 km as shown in Fig. 2. While lower satellite altitudes generally enhance temporal resolution by decreasing the orbital period, this advantage is partially offset by a reduction in swath width. The narrower swath width limits the area covered per pass, thereby reducing overall image coverage despite the increased frequency of satellite revisits. This trade-off between revisit time and coverage area must be carefully considered when evaluating satellite performance for large-scale applications.

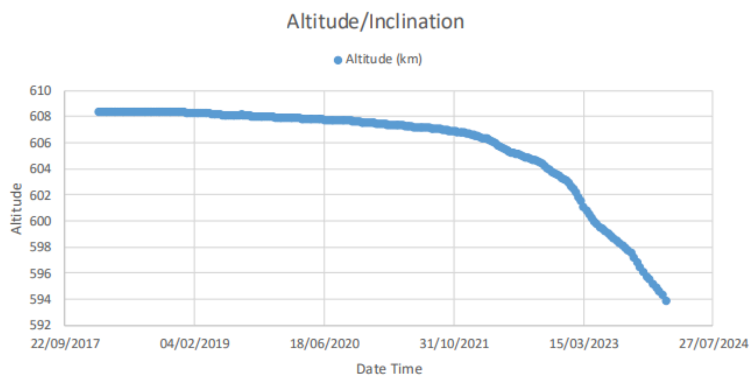


Fig. 2. Variation in Satellite Altitude Over Time.

3.2 Impact of Altitude Degradation on Changes in Imaging Time and Coverage

Upon further investigation, we observed a shift in imaging time from 13:00 PM in 2019 to 15:00 PM in 2024. This change is attributed to altitude degradation and the resulting changes in the satellite's inclination angle, as shown in Figures 3 and 4, respectively. The later imaging time corresponds to a position where the Sun is lower in the sky, causing longer shadows from objects such as buildings, trees, and terrain features as shown in Fig. 5. This shift in imaging time increases shadowing in the images, negatively impacting image quality, particularly for large-scale mosaic generation. Fig.3 illustrates the changes in satellite altitude and Local Time of Descending Node (LTDN) over time. Initially, the altitude remains relatively stable but begins to decline significantly after 2022, while the LTDN follows a steady upward trend. LTDN [4] is a crucial parameter in satellite imaging, as it determines the time when the satellite crosses the equator from north to south. This timing is essential for scheduling imaging passes, ensuring consistent data collection, and maintaining uniform lighting conditions. The observed changes in both altitude and LTDN reflect the satellite's orbital evolution, which directly impacts its imaging capabilities and long-term mission planning. Additionally, altitude degradation resulted in a narrower swath width, reducing the overlap zone between consecutive image passes. This inconsistency in coverage notably affected large-scale mosaic generation, particularly in the UAE. To address this, modifications were made to increase the overlap zone between consecutive passes, improving coverage and mitigating the impact of the degradation.

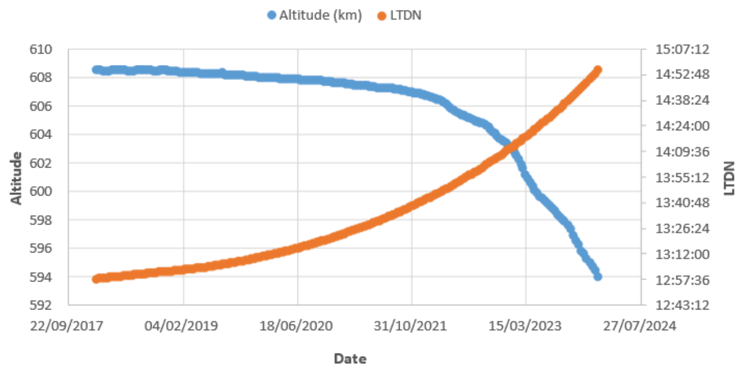


Fig. 3. Variation of Satellite Altitude and LTDN Over Time.

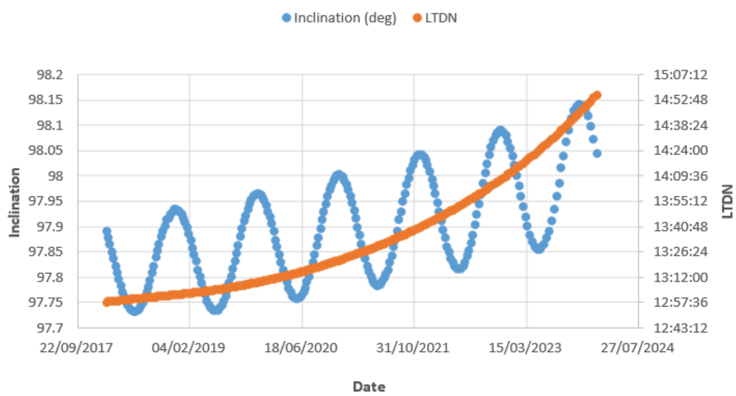
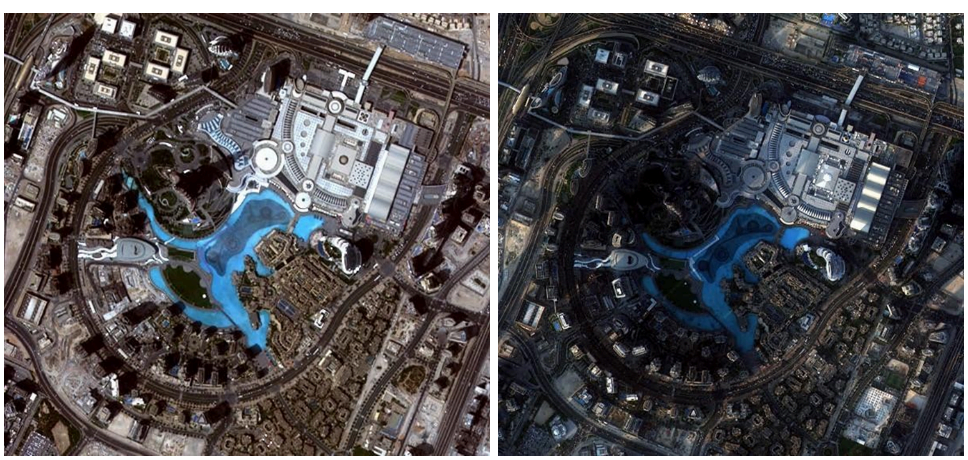


Fig. 4. Variation of Satellite Inclination and LTDN Over Time



(a) **(b)**

Fig. 5 Impact of Later Imaging Time on Shadow Length ((a) 2019 vs. (b) 2024)

3.3 Image Quality Assessment

When satellite altitude changes, it can affect the radiometric and geometric properties of the imagery. This assessment is performed only to validate the data with respect to system requirements given in Table 1.

Table 1 Quality indicators of KhalifaSat

Quality Indicator	Specification
GSD	PAN GSD = 0.73m @ 600 km MS GSD = 2.92m @ 600 km
MTF	PAN ≥ 6.0%, MS ≥ 15%
SNR	≥ 68 for PAN (at nadir @ 600 km with 16 TDI steps with reflectance of 0.25)
Swath	≥ 12.2 km @ 600 km
Geo-location Accuracy	<50m CE90 with GCP @nadir <100m CE90 without GCP @nadir

3.3.1 Ground Sampling Distance (GSD)

As a satellite's orbit degrades over time, its altitude decreases, leading to a slight improvement in GSD and enhancing the level of detail captured in imagery. Our analysis of 2024 KhalifaSat images indicates a slight improvement in GSD due to this effect. However, while a lower altitude can enhance spatial resolution, it may also introduce inconsistencies in resolution across the dataset.In 2019, the GSD for PAN imagery was 0.73 meters at an altitude of 600 km, while the GSD of MS band was 2.92 meters at the same altitude. Both values met the system requirements. By 2024, the PAN GSD had slightly improved to 0.72 meters, and the MS GSD to 2.89 meters. Despite these minor changes, the system requirements continued to be met.

3.3.2 Signal-to-Noise Ratio (SNR)

Most SNR metrics compare the mean target signal with the standard deviation of the noise, so assessing SNR is vital for verifying the quality of satellite images[5]. SNR plays a crucial role in image quality, with higher values allowing for better distinction of features in the imagery. A decrease in altitude can increase the amount of reflected light reaching the sensor, potentially enhancing SNR. However, at lower altitudes, increased atmospheric scattering may introduce noise, reducing image clarity. Each bright and dark region on the artificial target is defined as a Region of Interest (ROI), as shown in Fig. 6. Since the target consists of two bright regions and two dark regions, there are four ROIs in total. For visualization, each ROI is assigned a distinct color:

- **Upper bright region (H1):** Red
- **Lower bright region (H2):** Green
- **Upper dark region (L1):** Yellow
- **Lower dark region (L2):** Blue

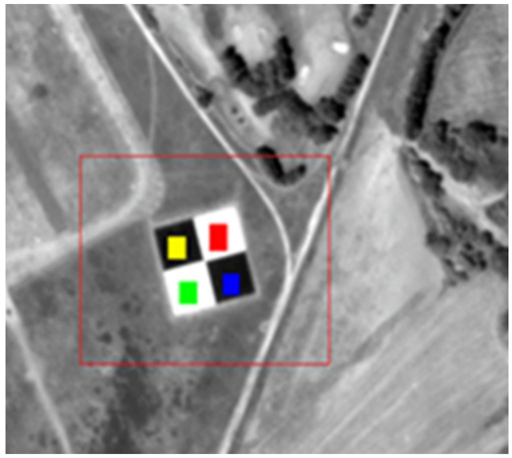


Fig. 6. Defining ROIs and Computing SNR

Statistical tools provided within the ENVI software are utilized to compute the mean(average pixel value of all pixels within the ROI) and standard deviation (amount of variation or dispersion of pixel values within the ROI) for each ROI, as depicted in Fig. 6. Then, the overall SNR is calculated using the below equations.

$$Mean(H, L) = \frac{H1+H2}{2} - \frac{L1+L2}{2} \quad (1)$$

$$Std(H, L) = \frac{\frac{H1+H2}{2} + \frac{L1+L2}{2}}{2} \quad (2)$$

$$SNR(H, L) = \frac{Mean(H,L)}{Std(H,L)} \quad (3)$$

In 2019, the statistical analysis of SNR showed an average SNR of 68.42, meeting the system requirement of SNR ≥ 68. However, by 2024, the average SNR had decreased to 60.14, falling below the required threshold and no longer meeting system requirements.

3.3.3 Modulation Transfer Function (MTF)

The Modulation Transfer Function (MTF) is calculated at the Nyquist frequency in both along-track and across-track directions using Imatest software. The estimation is performed exclusively for the PAN band. The choice between FPA1 and FPA2 depends on the target's visibility. For each available MTF target, two Across and Along regions of interest are selected, as shown in Fig. 7

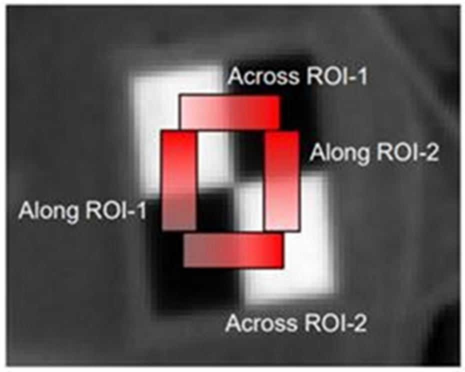


Fig. 7. Process of Computing Across and Along MTF

MTF quantifies the satellite's ability to capture fine details. At lower altitudes, reduced atmospheric distortion can enhance MTF; however, faster orbital motion might introduce motion blur, potentially degrading the performance. Nonetheless, our analysis of 2024 KhalifaSat images confirms that the MTF remains within system requirements.In 2019, the statistical analysis of the MTF showed an average across-track MTF of 19.6 ± 7.7 and an average along-track MTF of 16.29 ± 5.47, both exceeding the system requirement of MTF ≥ 6.0%. By 2024, the MTF values had improved significantly, with an average across-track MTF of 51.3 ± 11.6 and an average along-track MTF of 38.1 ± 0.79, continuing to meet the system requirements.

3.3.4 Geolocation Accuracy

Geo-location accuracy measures how well the satellite's images align with actual geographic locations. Our analysis of 2024 KhalifaSat images reveals that its accuracy falls short of system requirements, compromising tasks that require precise location mapping, such as disaster site analysis, cartography, and the alignment of satellite imagery with ground-based data.In 2019, KhalifaSat's geo-location accuracy had a CE90 of approximately 95.4 meters, meeting the system requirement of CE90 < 100 meters without ground control points (GCP). However, by 2024, geo-location accuracy significantly deteriorated, with CE90 failing to meet the system requirement.

4. Conclusions

KhalifaSat has exceeded its expected five-year lifespan, demonstrating remarkable durability despite various operational challenges. Its new temporal resolution is approximately 20 days and is expected to continue evolving as its altitude gradually decreases. This altitude degradation may be influencing key imaging parameters, including temporal resolution, revisit time, imaging consistency, and geolocation accuracy.

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