

On-Orbit Focal Plane Calibration Strategies for the FORMOSAT-8 Remote Sensing Instrument

Chun-Han Chou^a, Chi-Yun Chen^a, Shih-Fang Liao^a, Tse Li^a, Wei-Hsun Cheng^a, Tzu Hsin Lin^{a*},
Po-Hsuan Huang^a

^a Taiwan Space Agency, 8F., No. 9, Prosperity 1st Rd., East Dist., Hsinchu City, Taiwan 300

ABSTRACT

This paper proposes two on-orbit focal plane optimization strategies for the FORMOSAT-8 (FS-8) remote sensing instrument (RSI). The FS-8 constellation is designed to deploy multiple 1-meter and sub-meter resolution satellites into a sun-synchronous orbit. The first satellite successfully launched on November 29, 2025. Although the satellite's structural design is highly robust, the intense vibrations experienced during rocket launch inevitably degrade optical imaging quality. From the FS-8 environmental test results indicate that launch vibrations induce an estimated focal plane displacement of 70 to 120 μm in the RSI, resulting in an approximate 5%~10% degradation in optical performance. Therefore, the method of on-orbit calibration is essential to restore optimal imaging capabilities. Traditionally, on-orbit optical calibration relies on imaging ground calibration sites. However, this approach is highly susceptible to environmental variables such as atmospheric turbulence, weather conditions and pollution, making it extremely challenging to determine the optimal focal plane. Therefore, the paper proposes and analyzes two innovative, point spread function (PSF) based focusing compensation strategies tailored to the FS-8 system. The first strategy is the active ground light projection method. This method explores projecting a specific light source from the ground to the satellite to establish focus compensation logic via PSF analysis. The second strategy is the stellar observation method. This method employs satellite attitude maneuvers to image stars, leveraging the atmosphere-free stellar PSF for high-precision focal plane calibration. This paper details the implementation mechanisms and analytical frameworks of both strategies. The preliminary planning and evaluation presented herein provide a crucial theoretical foundation and engineering guidelines for standardized on-orbit focusing procedures in the future FS-8 constellation.

Keywords: FORMOSAT-8, On-orbit calibration, Point spread function

1. INTRODUCTION

FORMOSAT-8 (FS-8) is a high-resolution optical remote sensing satellite constellation domestically developed by Taiwan Space Agency. The constellation comprises six 1-meter and two sub-meter resolution satellites operating in a 561-km sun-synchronous orbit. Equipped with a long-focal-length optical payload, multispectral filters, and time delay integration (TDI) technology, the FS-8 is capable of precisely resolving 1-meter ground details from its orbital altitude. The first satellite of the constellation, FS-8A, has successfully demonstrated these capabilities in orbit, as illustrated in Figure 1. Once fully deployed, the constellation will achieve global coverage with three daily revisits over Taiwan, establishing a stable and near-real-time surface image database. This system is designed to support diverse applications, including disaster management, agricultural monitoring, and scientific research, marking a significant milestone in Taiwan's autonomous space capabilities.

During the rocket launch phase, the satellite is inevitably subjected to severe dynamic environments, including acoustic noise, random vibration, and separation shock. Comprehensive ground environmental testing of the FS-8 has revealed that these launch-induced mechanical loads cause the optimal focal plane to shift by approximately 72.7 μm . According to the FS-8 system analysis, this focal plane displacement results in an estimated 10% degradation in overall optical quality. To mitigate this performance loss, a thermal refocusing system is incorporated into the FS-8 design. This mechanism allows for on-orbit adjustments of the focal plane based on image evaluation, ensuring that the optimal focal plane of the optical structure assembly (OSA) precisely aligns with the focal plane assembly (FPA).

*lin871597@tasa.org.tw; <https://www.tasa.org.tw/zh-TW>



Figure 1. Taipei Port and the Danjiang Bridge, captured by the first FORMOSAT-8 satellite.

Traditionally, on-orbit focal plane calibration relies on daytime imaging of designated ground calibration sites. However, this approach is highly vulnerable to environmental variables such as atmospheric turbulence, unpredictable weather conditions, and air pollution, which severely limit the accuracy and frequency of calibration[1]. To overcome these constraints and effectively determine the optimal compensation parameters for the Thermal Refocusing system, this paper proposes two innovative on-orbit calibration strategies: the Active Ground Light Projection Method and the Stellar Observation Method. By conducting a comparative analysis of their respective advantages, limitations, and operational constraints, this study evaluates the practical implementation of both strategies. Establishing these robust calibration frameworks is critical not only for restoring the optimal imaging performance of the first FS-8 satellite but also for formulating standardized on-orbit refocusing procedures to support the sequential deployment and operational readiness of the entire future constellation.

2. FS-8 REFOCUSING MECHANISM

The FS-8 thermal refocusing system serves as a critical precision component within the optical payload subsystem, as illustrated in Figure 2. To ensure baseline optical stability, the entire Remote Sensing Instrument (RSI) is actively thermally managed and maintained at $20 \pm 2^\circ\text{C}$. Against this stable background, the thermal refocusing system utilizes localized thermal regulation to precisely displace optical elements and compensate for launch-induced structural shifts or thermal-elastic deformations. Specifically, the active refocusing mechanism operates over a temperature control range from -15°C to 50°C . Ground environmental testing has verified that within this operational temperature envelope, the system delivers a robust refocusing range of $\pm 320\ \mu\text{m}$ at the focal plane. In orbit, the system relies on image-based feedback to determine the necessary thermal compensation and accurately fine-tune the optical assembly to its optimal focal plane position.

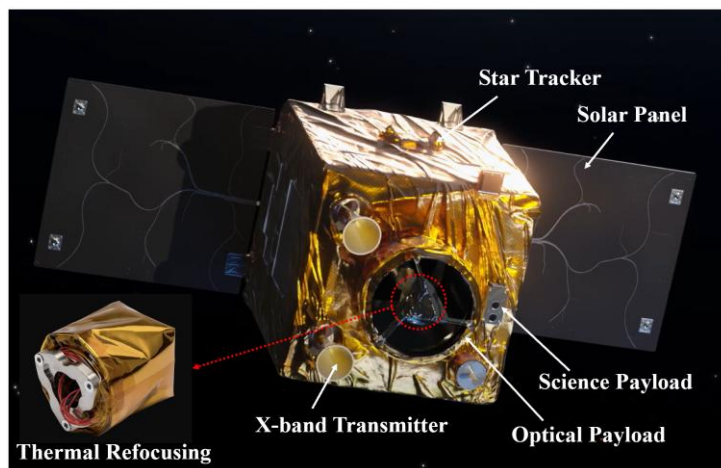


Figure 2. Schematic illustration of the FS-8 satellite configuration.

3. ON-ORBIT FOCAL PLANE OPTIMIZATION STRATEGIES

3.1 Active Ground Light Projection Method

The Active Ground Light Projection Method establishes a direct optical link from the ground to the FS-8 satellite to measure the point spread function (PSF)[2] of its imaging system. The experimental setup involves projecting specialized ground-based light sources towards the satellite during its nighttime orbital passes. To accommodate the satellite's trajectory and avoid building obstructions, the light sources were oriented westward to target the satellite's pass over the western side of Taiwan, achieving a highly favorable observation elevation angle of approximately 30 degrees.

The optimized configuration utilized three specially designed wide-angle lamps to acquire multi-scale PSF responses, as depicted in Figure 4. To prevent the light sources from aligning in a single linear axis and confusing the resolution analysis, they were arranged in a specific non-linear geometric pattern. The two primary sources, S1 and S3, each featured an emitting area of $0.7 \times 0.7 \text{ m}^2$ with an intensity of approximately 2,100~2,200 W/sr, and were spaced 24.4 meters apart. A secondary source, S2, featuring a smaller emitting area of $0.28 \times 0.28 \text{ m}^2$ and a lower intensity ($\sim 300 \text{ W/sr}$), was strategically positioned 14.2 meters to the northwest of S1.



Figure 4. Nighttime operational deployment of the Active Ground Light Projection Method, illustrating the three strategically positioned wide-angle light sources (S1, S2, and S3) projecting calibrated beams toward the target satellite.

During a two-month (June to July) testing period, the research team conducted 15 orbital shooting attempts, achieving 11 successful image captures. The four failures were entirely attributed to adverse weather conditions, specifically rain and thick cloud cover, highlighting the environmental dependency of this method. As successfully demonstrated in Figure 5, the on-orbit panchromatic (PAN) sensor clearly captured the ground-based light sources. The magnified and enhanced windows reveal the distinct PSF profiles of the three lamps. The outer sources (S1 and S3, $\sim 2,100 \text{ W/sr}$) exhibit strong, distinct pixel responses, whereas the smaller source (S2, $\sim 300 \text{ W/sr}$) presents a correspondingly weaker signal. On-orbit imaging results indicated that the spatial distance between the two main light sources spanning 24.4 meters registered as 12 pixels on the sensor, corresponding to a ground sampling distance of roughly 2.03 meters per pixel. The observed PSF distribution for each point source spanned an area of approximately 4×4 pixels.

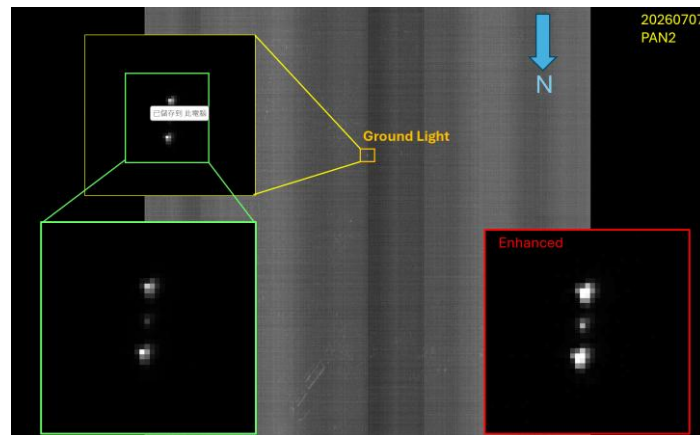


Figure 5. On-orbit panchromatic (PAN) image captured by the FS-8 satellite on July 7, 2026. The magnified and enhanced insets highlight the distinct Point Spread Function (PSF) profiles corresponding to the varying emitting areas.

Currently, the research team is actively processing the acquired PSF imagery. The ultimate objective is to statistically aggregate the results from the 11 successful observational passes to precisely evaluate the full width half maximum (FWHM) of the PSF profiles. These comprehensive empirical datasets will serve as the critical quantitative basis for adjusting the focal plane of the OSA, ultimately guiding the thermal refocusing mechanism to restore the satellite's optimal imaging capabilities.

3.2 Stellar Observation Method

As daytime ground imaging is heavily influenced by atmospheric scattering and lacks ideal point light sources, obtaining a precise PSF for the RSI is highly challenging. To address this issue, the Stellar Observation Method utilizes stars as ideal, atmosphere-free point sources. Drawing methodological inspiration from the Pleiades-HR mission[3], this approach employs precise satellite attitude maneuvers to scan deep-space star fields.

Star Selection Algorithm and Equivalent Radiance

To identify suitable target stars, the research team established a rigorous screening algorithm based on the Gaia[4] star catalog. Initially, approximately 450,000 stars with complete spectral data and a visual magnitude of 10 or brighter were extracted. To accurately predict the sensor's response, the algorithm calculates the "Equivalent Radiance" for each candidate star by weighting its raw spectral data against the specific quantum efficiency (QE) and filter transmittance profiles of the FS-8 optical payload. As illustrated in Figure 3, applying the operational imaging constraints—specifically a line rate of 2,000 lines/sec and a target Digital Number (DN) range of 1,000 to 3,000—yields a refined selection of 56,794 viable candidate stars for the FS-8 system.

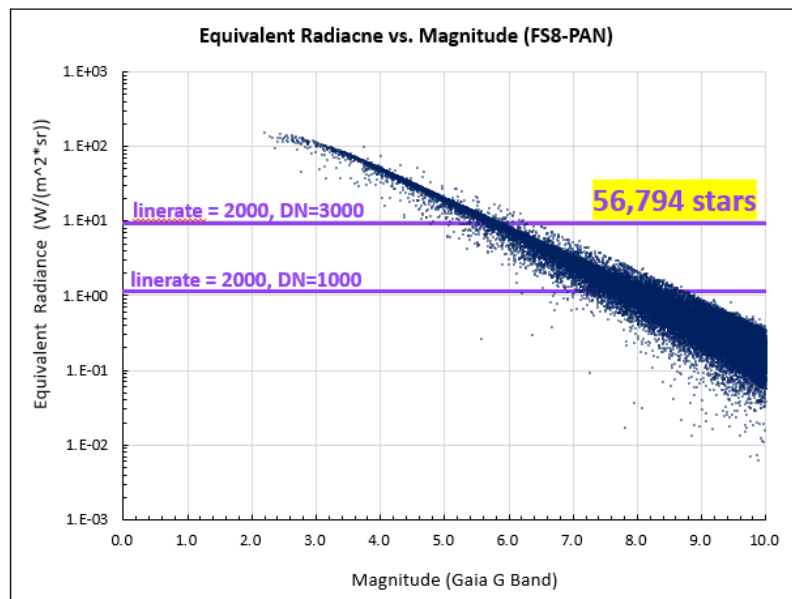


Figure 3. Scatter plot of Equivalent Radiance versus Gaia G-band Magnitude, highlighting the 56,794 candidate stars that satisfy the FS-8 panchromatic (PAN) sensor's optimal DN target range (1,000–3,000) at a 2,000 lines/sec line rate.

Geometric Constraints and Operational Parameters

While 56,794 stars meet the brightness criteria, ensuring operational safety and high-quality imaging requires the targeted celestial fields to strictly satisfy several geometric constraints. First, the observation must occur on the anti-sun side of the orbit. Second, the fields of view of both onboard star trackers must remain completely unoccluded by the Earth to maintain precise attitude determination. Third, the satellite maneuver must not compromise the orientation of the solar panels, ensuring continuous power generation. Lastly, the target fields are ideally selected near the celestial equator to provide a longer operational time window.

After applying these stringent constraints, the observable region is reduced to roughly one-eighth of the celestial sphere, leaving approximately 7,000 or fewer stars for actual operation. During the observation, the satellite will perform a continuous single-axis roll scan along the flight direction, synchronized with an attitude slew rate of approximately 0.2

deg/sec. Preliminary attitude control simulations have confirmed that both star trackers remain unoccluded throughout the maneuver. As illustrated in Figure 4, the simulated target star field highlights the selected observation swath. Future work will focus on verifying the precise spatial alignment between the RSI boresight and these predicted star fields to ensure successful on-orbit execution.

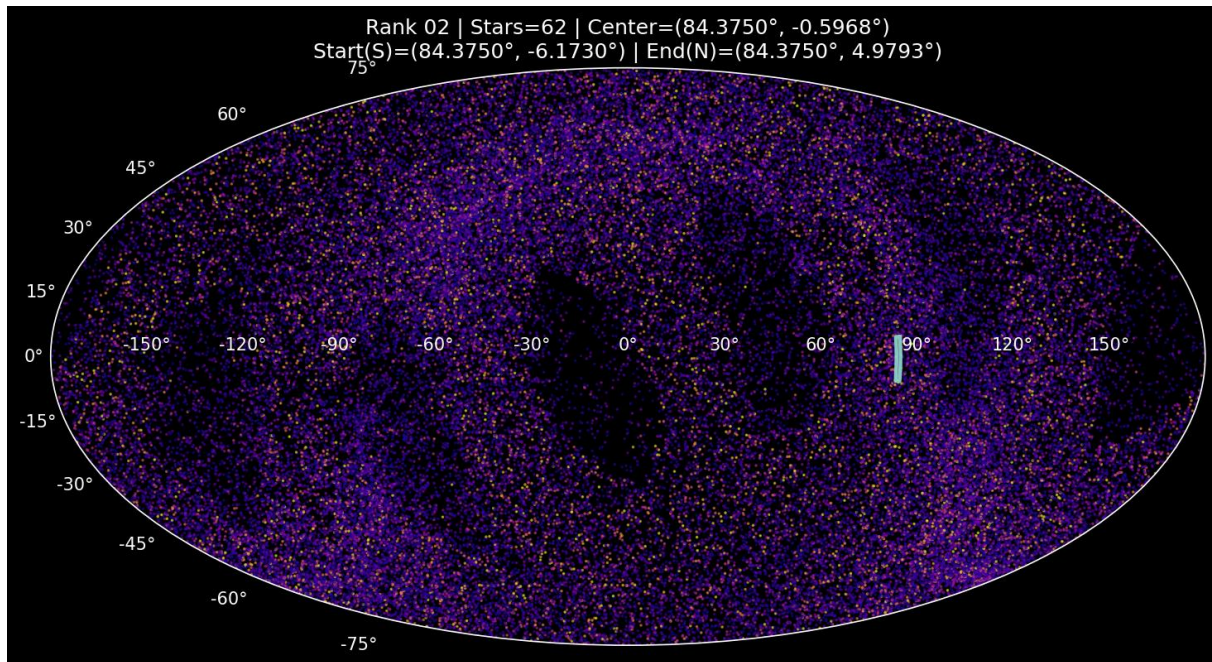


Figure 4. Simulated target star field map for the Stellar Observation Method, highlighting the optimal observation swath near the celestial equator (Rank 02).

4. DISCUSSION

To establish a robust and reliable standardized on-orbit focusing procedure for the FS-8 constellation, it is crucial to evaluate the operational trade-offs between the Active Ground Light Projection Method and the Stellar Observation Method.

Active Ground Light Projection Method:

The primary advantage of this approach lies in the absolute controllability of the target. Engineers can precisely configure the radiometric intensity, divergence angle, and geometric layout of the artificial light sources to acquire multi-scale PSF responses tailored to the sensor's characteristics. Furthermore, it allows for focal plane evaluation without requiring complex spacecraft maneuvers. However, its significant drawback is a high susceptibility to tropospheric variables. Atmospheric scattering inevitably degrades the purity of the point source, and unpredictable weather conditions (such as heavy cloud cover or rain) can completely obstruct the optical link, thereby limiting the frequency and reliability of calibration opportunities.

Stellar Observation Method:

Conversely, observing deep-space stars entirely circumvents atmospheric disturbances, providing pristine, ideal point sources for high-precision PSF characterization. This method is geographically independent and can be executed consistently. The main trade-off, however, is its high operational complexity. It demands highly precise satellite attitude maneuvers (e.g., synchronized single-axis roll scanning) and is strictly bounded by geometric constraints. Ensuring simultaneous star tracker visibility and optimal solar panel orientation reduces the executable observation window to only a fraction of the celestial sphere, demanding sophisticated mission planning.

Complementary Synergy:

Rather than serving as mutually exclusive alternatives, these two strategies are highly complementary. The Ground Light Projection Method is extremely valuable during the initial in-orbit checkout phase, providing a localized baseline calibration without risking complex spacecraft maneuvers. Once the satellite's attitude determination and control subsystem is fully verified, the Stellar Observation Method can be deployed to achieve the ultimate high-precision,

atmosphere-free calibration. By integrating both methods, the FS-8 mission establishes a hybrid, weather-resilient, and operationally flexible refocusing framework. This synergy ensures that regardless of ground weather or immediate operational constraints, the constellation can systematically recover and maintain its optimal high-resolution imaging performance throughout its lifespan.

5. CONCLUSIONS AND FUTURE OUTLOOK

This paper presents two PSF-based on-orbit focal plane optimization strategies to mitigate launch-induced optical degradation in the FS-8 RSI. The Active Ground Light Projection Method was empirically validated through nighttime orbital testing. By deploying wide-angle light sources in a non-linear arrangement, multi-scale PSF data were successfully captured for initial focal plane assessment. Complementarily, the Stellar Observation Method was established via precise attitude control simulations, offering high-precision, atmosphere-free calibration through single-axis roll maneuvers.

Currently, ongoing work focuses on finalizing the statistical full width half maximum (FWHM) analysis from the ground light experiments to precisely adjust the first FS-8 satellite's focal plane. Ultimately, these two complementary and weather-resilient strategies establish a robust, standardized on-orbit refocusing procedure, ensuring the sustained high-resolution imaging performance for the future deployment of the entire FS-8 constellation.

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