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The FLARE Network: Vicarious Cal/Val for Earth Observation Satellites

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ABSTRACT

Calibration and characterization of radiometric and geospatial performance is necessary for the accurate retrieval of information from Earth Observation platforms. For small satellite constellations, this is especially true to ensure data quality and consistency among multiple craft that lack on-board calibration equipment. The Field Line-of-sight Automate Radiance Exposure (FLARE) Network provides an automated, on-demand calibration solution designed to meet the requirements of both agency and commercial operators by providing NIST traceable data without the need for expensive campaigns or on-board calibration sources. FLARE radiometric performance has been verified with Landsat 8 – OLI. FLARE was successfully utilized with Planet SkySat and PlanetScope assets for rapid verification of resolution performance, and in commissioning efforts of new satellites following launch.

INTRODUCTION

Extensive pre-flight calibration is the standard for Earth Observation satellites and these pre-flight data can be supported, monitored, and updated by on-board equipment like resource-consuming solar diffusers or complex light sources. This may not be feasible for small, inexpensive platforms in the commercial small-sat and cube-sat industries. Re-calibration during mission life is critical to maintaining performance, drift correction, and sensor interoperability among constellations. Radiometric or reflectance calibration to an absolute (traceable) or relative (between craft) standard is a recurring, expensive, and time intensive process. Current practices utilize large pseudo-uniform artificial or natural diffuse targets. Calibration campaigns are demanding on personnel and cost, while natural targets are relatively rare, geographically limited, and must be either instrumented or rely on radiometric assumptions. An alternative approach is comparison to a well-calibrated system with publicly available data such as Landsat or Sentinel, but this relies upon infrequent and geographically restricted Simultaneous Nadir Overpass events over Pseudo Invariant Calibration Sites (PICS) or RadCalNet[1] sites. There is a significant mismatch between the Ground Sample Distances (GSDs) of agency craft (10-30 m) and typical small-sats (≤5 m), calling into question the comparison approach especially for small targets and heterogeneous areas of interest. In the spatial domain, high contrast targets like coastlines, bridges, airports, or purpose-built arrays are utilized to assess Point/Line Response Functions (PRF/LRFs), Modulation Transfer Function (MTF), resolution, and system blur metrics. Opportunistic targets may perform poorly depending on observation angle, orbital orientation, or spatial resolution, while maintaining a distributed network of synthetic targets is a significant budgetary item.

The SPecular Array Radiometric Calibration (SPARC) method, patented by Raytheon and licensed to Labsphere, employs convex mirrors to relay an image of the solar disk to create calibration targets for deriving absolute calibration coefficients in the solar reflective spectrum[2]. By varying mirror curvature and number it is possible to produce a large dynamic range of at-sensor radiance suitable to a variety of instrument classes. Combining SPARC mirrors with automated targeting, radiometric instrumentation, and communications equipment is the basis for the new Field, Line-of-sight Automated Radiance Exposure (FLARE) Network[3]. FLARE represents an on-demand, easily accessible system for NIST traceable, absolute radiometric calibration and validation. With improved understanding of radiometric performance compared to other in-flight vicarious techniques reduced uncertainties in target reflectance, atmospheric effects, and temporal variability are achieved. Mirror technology offers several benefits over traditional methodology. Illumination of most or all of the detector elements, as with on-board solar diffusers or large desert areas, for example, produces an averaged calibration coefficient that masks differences between elements, or can obscure energy loss into adjacent pixels. The use of a point source is important for assessing accuracy with small target radiometry. Further, diffuse targets typically provide calibration at a single radiance level, mirror arrays can be deployed to produce multiple radiometric signal levels allowing for calibration across the sensor's full dynamic range. In the spatial domain, an over-sampled point source can be used to measure a variety of system resolution metrics such as MTF, Point Response Function, band registration, blur, defocusing, cross and along track smear, or image processing artifacts. Mirror point targets are sub-pixel impulse targets, and as such are omni-directional and do not need to be oriented relative to the sensor's orbital path and consistent when viewed from any direction, including off-nadir.

Common and timely calibration improves rapid, seamless harmonization and interoperability of image data. Calibration is inherent to the concept of "Analysis Ready Data" (ARD) – a set of determined quality metrics and measures to create data sets processable by any user with minimum intervention and modification. The FLARE Network represents a ground-based calibration and validation source able to deliver spatial, geometric, radiometric, and geodetic information in a single event across a range of Earth Observation platforms. It can deliver many of the most basic characteristics of a sensor necessary to understand for ARD measurements: MTF/PRF, signal to noise, and uncertainty for spatial and radiometric domains. A FLARE node serves as a calibrated "star" on the ground, providing a well-defined, consistent, and scalable reference. The system is automated, and accessible on demand, enabling Calibration as a Service (CaaS). While FLARE will not replace existing methods and experienced personnel, it represents an effective tool to enhance current programs with tailored, low-cost, high-frequency, high-quality data to operations and calibration teams.

Here, we provide a brief outline of FLARE status and capabilities, with a focus on successful engagement by Planet with the FLARE network. FLARE was used to investigate system spatial performance and resolution metrics among existing SkySat and PlanetScope assets, as well as providing an alternative for inter-sensor comparison during commissioning of new satellites. Metrics generated with FLARE verified system performance across existing sensors and demonstrated increased resolving capability resulting from planned orbital shifts. FLARE was utilized following the launch of new PlanetScope craft, potentially allowing for rapid intra-constellation comparison, optical chain diagnosis, and fine tuning of ConOps, which could reduce the time needed to reach operational status in future.

SYSTEM DESCRIPTION AND OPERATION

A full-function FLARE Node consists of an addressable mirror array, solar spectroradiometer, and power/communications/control equipment. A brief description of the system is included here, but full details have been published[2] and can be accessed through the FLARE website (https://flare-network.com). The basic operation of the system is an automated LOOK. The system opens the appropriate mirrors and positions these to relay the solar signal to the targeted craft; continuously moving to maintain the signal as the craft moves through a defined trajectory. During a LOOK the station also performs necessary radiometric measurements. Finally, the mirrors are covered, stowed, and data is transmitted.

Currently, two full capacity nodes are in operation in Arlington, SD USA (44.410839°, -97.128024°) and Brock, TX USA (32.664241°, -97.961547°). More installations are in planning, with the next at Mauna Loa, HI USA.

Mirror Array Turret

A FLARE mirror turret consists of azimuth and elevation tracking motors and individual mirror bays. The bays are modular and can accommodate multiple mirror types, allowing flexibility in signal and sensor resolutions. Each bay has a cover, used to control dynamic range and protect the mirror surfaces.

The number of bays and the type of mirrors populating a turret creates a trade space for tuning a particular node to different classes of sensor, as well as determining dynamic range. The existing systems are optimized for validation of mid-resolution Earth Observation and commercial sensors across a range of GSDs. FLARE regularly executes against Sentinel 2 A/B MSI (10 – 60 m), Landsat 8 OLI (30 m) and the hyperspectral PRISMA (30 m), as well as the higher resolution WorldView-3 (0.3-3.7 m), SkySat (0.8 m), and PlanetScope (3.7 m) constellations.

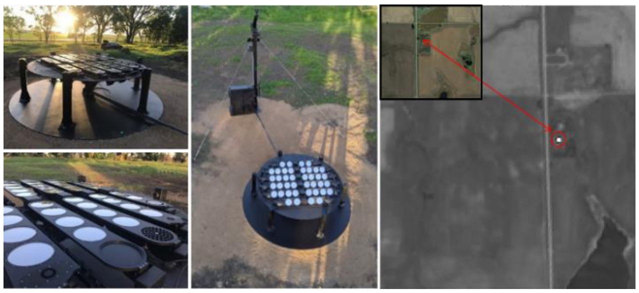

Figure 1. FLARE node in Arlington, SD USA. Left, center: mirror array and instrumentation tower. Right: FLARE as observed by Sentinel 2B.

Radiometric Instrumentation

The FLARE system includes a solar radiometer which performs a series of measurements necessary to derive the effective at-sensor signal. The radiometer consists of a tracking head, foreoptics, VISNIR spectrometer, banded SWIR detector, and a halogen-based calibration source. The spectrometer provides radiometric data between 350 – 1000 nm at 1 nm intervals, while the SWIR detector has 8 bands between 800 and 2500 nm, matched to common remote sensing bands. Both are thermo-electrically cooled and contained in a temperature-controlled housing. During a LOOK, the radiometer locates and tracks the sun and performs scans of solar irradiance. Cloud detection and signal monitoring can be performed manually and through automated routines to ensure data quality. Calibration of the radiometer is performed in two ways. Firstly, a modified Langley approach is utilized, in which the solar signal is extrapolated to the signal that would be measured at Top of Atmosphere and directly related to the solar constant. When Langley-based calibration data are not available or insufficient, the radiometer is calibrated using a NIST traceable, QTH-based absolute radiance calibration source.

Data Services

Two basic types of LOOK can be scheduled, which differ in the data provided to the user and available analysis packages. A LOOK-S points the desired number of mirrors and tracks the satellite and includes necessary metadata. A LOOK-R provides the same data and function as the LOOK-S and includes radiometric data to calculate atmospheric transmission and effective at-sensor spectral radiance. Intermediate spectra are also provided for alternative processing. Users can upload one or a series of images associated with a successful LOOK for evaluation. If the imagery passes internal quality checks, it can be analyzed for both spatial and radiometric parameters. An EVAL-S package provides spatial characterization data for the imagery, while an EVAL-R package includes radiometric calibration coefficients. Individual LOOKs can be scheduled by a user through the FLARE web portal. However, the system is also designed to meet the needs of large commercial constellations and can be easily integrated into extensive, automated data flows with API access and full system automation.

Beyond the standard automated products, a variety of complex maneuvers and targeted campaigns can be conducted such as variable signal levels, rapid targeting of multiple crafts (within seconds), as well as using multiple arrays for rapid characterization of one or more sensors. With multiple successful executions against the same sensor (or distributed constellation), it is possible to produce regular, detailed data quality reports evaluating system radiometric and geospatial performance against mission requirements[4] (Table 1).

Table 1. Example Mission quality metrics that can be assessed, verified, and reported with FLARE.

Quality Parameter	Description
Absolute Radiometric Performance	Imagery reported in-band radiance relative to uncertainty requirements.
Absolute Geolocation	Location error of imagery reported coordinates for FLARE signal center position relative to known values.
Multi-Spectral Registration	Inter-channel spatial band co-registration error based on evaluation of FLARE signal center position in reported bands.
Modulation Transfer Function	Nyquist MTF, other sensor resolution metrics (Point Response Function, Line Response Function, Rayleigh/Sparrow Criterion, Ground Spot Size, etc.).
National Imagery Interoperability Rating Scale	NIIRS value for provided imagery with FLARE target in-scene, derived through General Image Quality Equation v 5. Predicted NIIRS rating for sensor under alternative atmospheric conditions and solar/sensor geometries.

Campaign Services

In addition to automated services, campaign events are conducted in order to rapidly assess multiple sensors (such as during commissioning of new platforms) or for specific experimental characterizations. FLARE campaigns typically involve the deployment of multiple mirror target types, such as MTF sampling arrays, resolution point-pairs, line targets, and dynamic range points for absolute gain calibration (Figure 2).

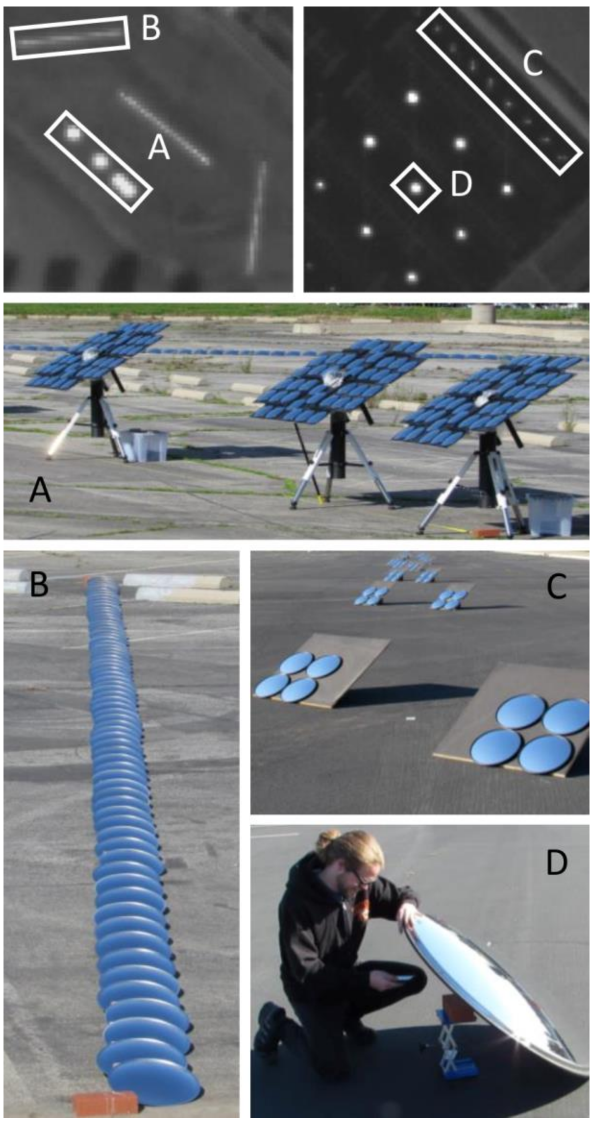

Figure 2. FLARE campaign operations and target types used in rapid commissioning of small sats and verification of performance following orbital maneuvers.

RADIOMETRIC MODEL

Specular target radiometry differs from that describing traditional Lambertian targets used in cal/val activities[1,2]. One of the advantages of the mirror-based approach is that the effects of sky path radiance, multiple scattering, diffuse sky irradiance and adjacency effects are greatly reduced or eliminated. Further, any atmospheric contributions can be assessed and removed from the signal using in-scene information provided the mirror target is on a suitable background.

The at-aperture radiance $L(\lambda)$ (W/m^2/sr/nm) for a sensor viewing FLARE at a given angle θ, for a single mirror, is:

$$L_m(\lambda, \theta_i) = \frac{1}{4} E_0(\lambda) \rho_m(\lambda, \theta_i) \tau_\downarrow(\lambda) \tau_\uparrow(\lambda) \frac{R_c^2}{(GSD_c GSD_a)} \qquad (1)$$

ρ_m: Specular reflectance of the mirrors (unitless)

GSD: Ground Sample Distance, cross/along (m)

E_0: Top of Atmosphere solar irradiance (W/m^2/nm)

$\tau_\downarrow$: Downwelling atmospheric transmittance, sun to mirror (unitless)

$\tau_\uparrow$: Upwelling atmospheric transmittance, mirror to sensor (unitless)

R_c: Mirror radius of curvature (m)

The downwelling atmospheric transmittance is directly measured by the solar radiometer during a LOOK. comparing the measured direct solar irradiance to the ex-atmospheric solar spectral irradiance as reported by the TSIS-1 instrument[5]. The spectral transmission along this path is then geometrically corrected to predict the upwelling path transmission. While this can be performed using multiple methods, a MODTRAN-6 atmospheric inversion model has been incorporated which produces an atmospheric template that recreates the received solar signal and can be used within MODTRAN to both model the upwelling spectral transmission and to provide SWIR measurements at high spectral resolution.

UNCERTAINTY

Analysis Ready Data and Earth Observation metrology require an accurate understanding of not only measured data, but also its uncertainty and traceability. FLARE helps provide traceability and verifiable uncertainty for vicarious calibration to demonstrate the maturity and quality of small sat data products. FLARE follows the recommendations of the European Space Agency's FIDUCEO project, and is committed to providing transparency in uncertainty estimation and data processing. The Monte Carlo Method[6] is utilized to create an uncertainty budget from the known and estimated values for each component of the measurement model. A full description of the FLARE uncertainty budget will be available through the user portal.

The total relative uncertainty (*1σ*) for a representative LOOK on the FLARE Node in South Dakota is ~ 3.5% for spectral intensity over the VIS range (Figure 3), with higher preliminary SWIR band uncertainties (Table 2). The largest single contribution is atmospheric transmission.

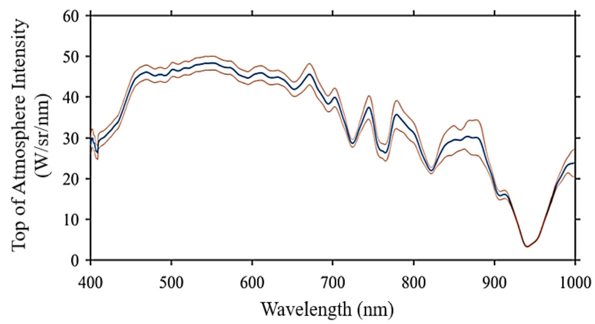

Figure 3. Projected at-sensor spectral intensity, ± 1σ uncertainty for an example LOOK-R with S2A, 16 July 2020.

Table 2. Preliminary relative uncertainties (1σ) for the SWIR bands using a "typical" Langley calibration.

Band	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Center Wvl (µm)	1.24	1.38	1.61	1.66	2.13	2.22	2.25
Band Pass (nm)	20	50	90	30	30	250	60
Unc (%)	3.8	3.9	3.9	3.9	3.9	4.2	4.2

RADIOMETRIC PERFORMANCE ASSESSMENT

To assess radiometric accuracy and establish baseline performance metrics, the FLARE Network routinely targets multiple sensors with publicly available data including Landsat 8 and Sentinel 2A/B. For each successful LOOK, the imagery is retrieved and assessed for quality issues such as cirrus cloud or haze contamination. An EVAL-R is then performed on the imagery, which is processed to ToA radiance (typically either Level 1C or 1B). First, the FLARE signal is found and isolated (Figure 4). A background subtraction based on surrounding pixels and a previously generated pixel "map" is performed to remove atmospheric and surface reflected radiance contributions. This map can be enhanced with a reference image of the node without the mirror signal that is used to scale imagery under evaluation. The remaining signal is integrated based on the Point Response Function of the sensor, and necessary calibration coefficient and numerical offsets (taken from image metadata) are applied. This process is repeated for all bands.

For multispectral sensors, the predicted at-aperture spectral radiance from FLARE is convolved with the reported Relative Spectral Response (RSR) for each band of the sensor under test to produce a FLARE derived in-band radiance. This value is compared to the imagery reported radiance to assess the radiometric accuracy of the sensor under test (Figure 5).

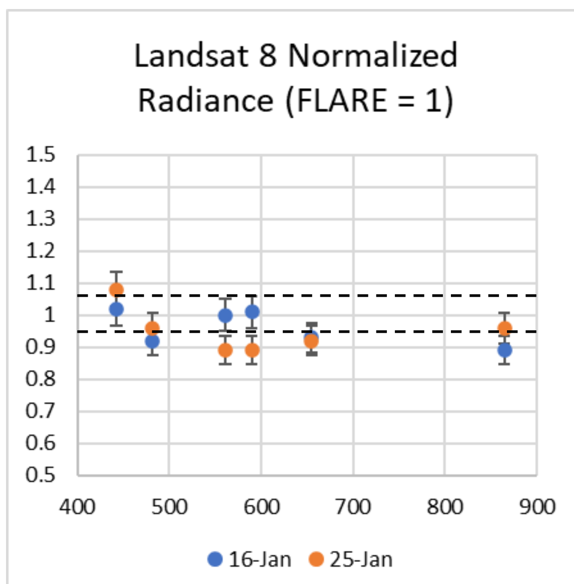

Figure 5. Landsat 8 MSI imagery-reported radiance relative to FLARE radiance during early 2021. Error bars for LS radiance are 1σ mission requirements (5%). Dashed lines represent FLARE in-band radiance uncertainty (~4% 1 σ).

For well-characterized satellites with extensive pre-flight characterization, on-board calibration equipment, and extensive cal/val teams for mission duration, FLARE can serve as an independent performance verification technology. For small sat constellations, FLARE is a simple, NIST-traceable technology that can provide independently verified radiometric calibration and regular data quality performance assessments.

GEOMETRIC PERFORMANCE ASSESSMENT

As the mirror signal is always subpixel by design, FLARE can be used to assess a satellite's geospatial performance. Absolute geolocation and band to band registration are assessed and reported as part of a Data Quality Report, which are available as an analysis service.

A high accuracy (2 cm) GPS survey of the Brock, TX site was conducted by the US National Resource Council, with a survey pin at the center of the FLARE turret. During a LOOK, the angular position of the mirrors is known and the effective signal center may be calculated. If imagery is provided, the sub-pixel center of the FLARE signal can be found by fitting a model of the system PRF to the in-scene pixel values. The interpolated signal center in the imagery can then be compared to the known signal center to measure band registration, Euclidian error, or other geolocation metrics (Figure 6).

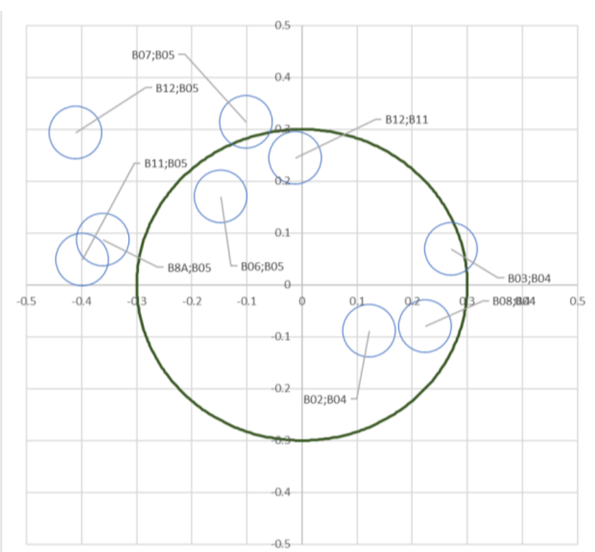

Figure 6. Band to band x/y registration error for Sentinel 2B as measured by FLARE. Circle represents Sentinel mission requirement of < 0.3 pixels at >99.7% confidence.

USE OF FLARE WITH PLANET ASSETS

Collaborative efforts were undertaken between the FLARE Network and Planet during 2020 to demonstrate the utility of mirror targets for small satellite constellations, validate image resolution improvement techniques, and explore the impact of mirror targets on commissioning following launch. These efforts were successful, and the results are summarized below.

SkySat Resolution Improvement Campaign

In early 2020, Planet lowered the orbit of the Skysat constellation from ~500 km to ~450 km. Consequently, the spatial resolution of SkySat data was improved to 50 cm for ortho products and 65 cm (nadir view) for basic products from the original 72 cm ortho and 80 cm basic product resolutions. This was achieved without a reduction in spatial or temporal coverage.

Prior to this orbital shift, a mirror campaign was undertaken to assure that the reduction in altitude would successfully improve spatial resolution. The campaign was conducted in January 2020 in El Segundo, California, USA. Multiple classes of mirror targets were deployed. This included an array of single mirrors, line targets, and spreading point pairs (Figure 2). Lines and point pairs were arranged in cross and along track directions. Mirrors were positioned manually to target multiple Skysat satellites: one that had been lowered to 450 km orbital, and four others in the Skysat constellation operating at the original 500 km altitude. Evaluation of the mirror arrays in SkySat L1A imagery (Figure 7) revealed significant improvements to target resolution in both cross- and along-track directions by decreasing orbital altitude from 500 km to 450 km (Table 3).

Table 3. FLARE derived improvement to SkySat resolution metrics with decrease in orbital altitude

	Orbital Altitude			
	500 km		450 km	
Resolution Metric	**Cross (m)**	**Along (m)**	**Cross (m)**	**Along (m)**
Rayleigh (15.3%)	1.55 ± 0.05	1.61 ± 0.07	1.37	1.39
GSS (0.9%)	1.23 ± 0.04	1.26 ± 0.05	1.09	1.10
Sparrow (0%)	1.17 ± 0.03	1.20 ± 0.08	1.07	1.05

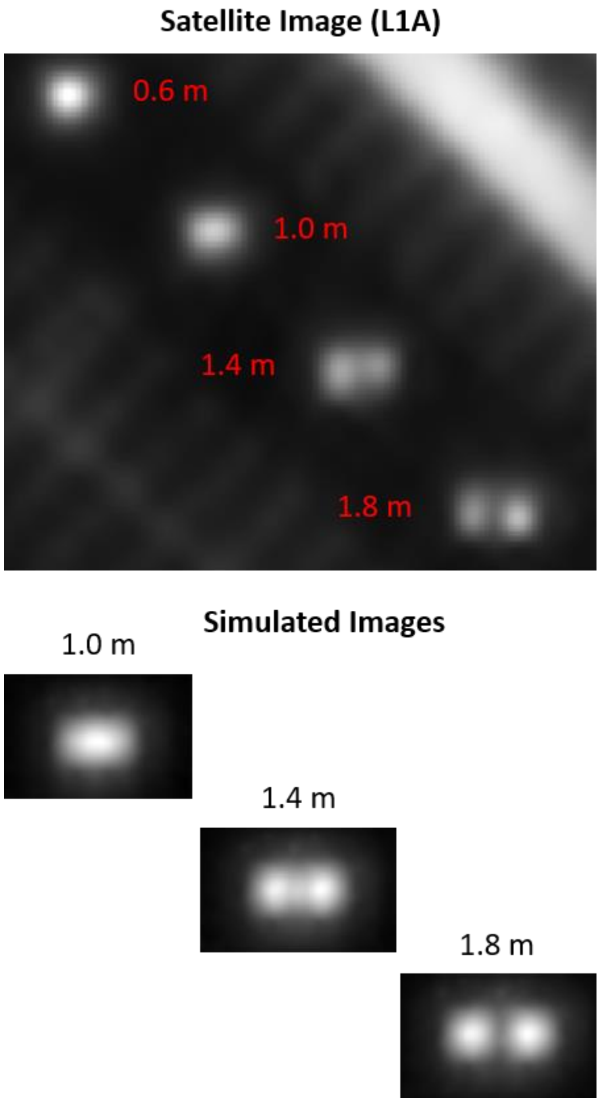

Figure 7. Imagery of mirror point-pairs set at increasing distances, compared to simulated pairs using metrics generated from single points.

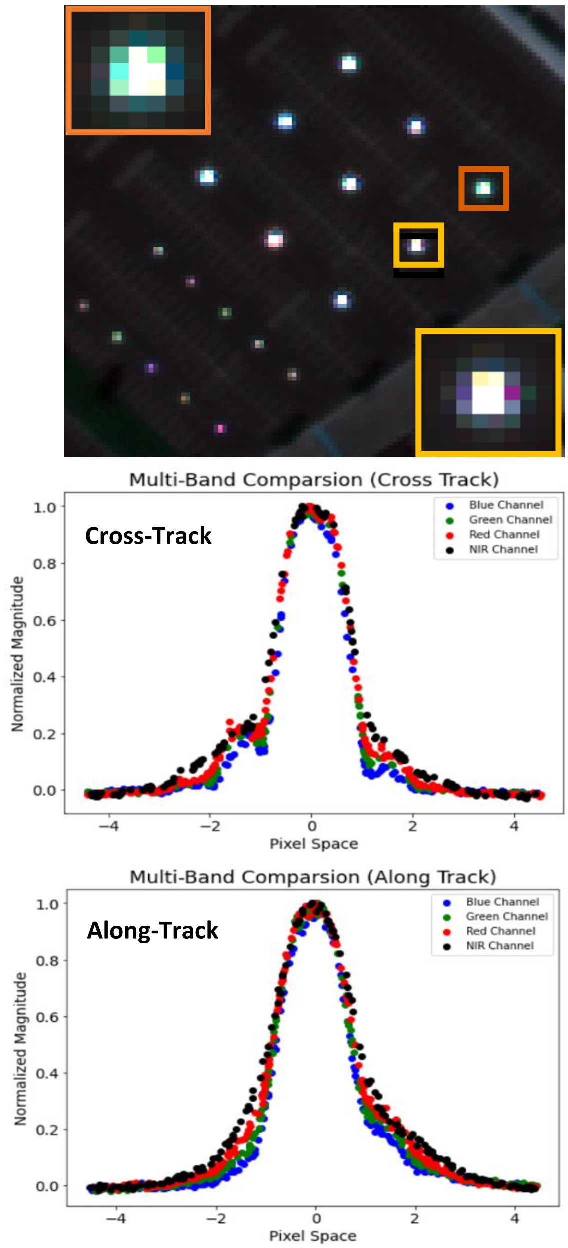

Figure 8. Cross- and along-track response of the Point Response Function reveals good agreement between spectral bands.

In addition, the data set collected with this campaign was evaluated for insights into both SkySat performance and the use of FLARE with image evaluation techniques. Minor differences in point response function (PRF) between spectral bands were identified (Figure 8), and the impact of MTF correction between processing levels was investigated. Both data sets can be utilized in the development of reprocessing kernels to improve image fidelity at all product levels.

SuperDove Commissioning Experiment

FLARE was engaged during commissioning of PlanetScope Flock 4s, following launch in January 2021. Specifically, the objective of this study was to investigate the utility of FLARE to evaluate performance of two new SuperDove satellites (#2419 and 2416) against existing, well-performing units. A series of successful LOOKs were executed against 2416 and 2419, as well as near-simultaneous LOOKS with multiple operational assets using two FLARE nodes: Arlington, South Dakota and a smaller unit at Labsphere headquarters in North Sutton, New Hampshire. Several of these events occurred within seconds or minutes at the same site, demonstrating the successful ability of the FLARE hardware to target multiple craft, as well as the interoperability of mirror assets within the Network. Simultaneously, manually targeted mirror arrays were deployed at the New Hampshire site to increase the number of targets for PRF sampling. While full radiometric and spatial performance analysis of the data has not been completed, the use of FLARE targets provided immediate diagnostic capability and intersensory performance information (Figure 9, 10).

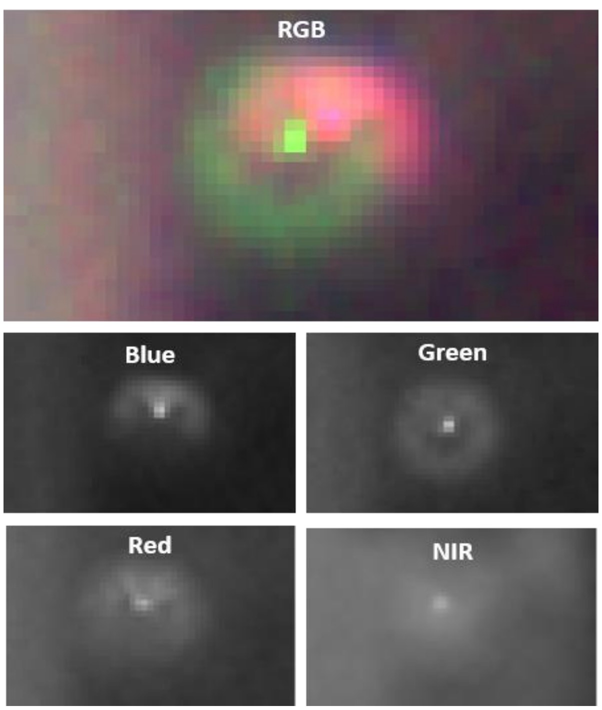

Figure 9. Band-dependent registration and focusing errors identified during commissioning with FLARE. Once identified, these errors were rapidly corrected and subsequent imagery met all quality standards.

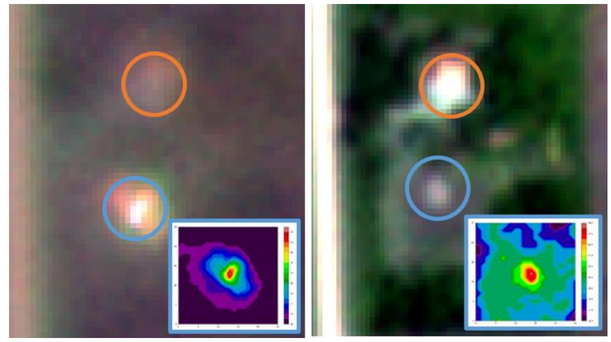

Figure 10. Cross-track blur (left) and defocusing (right) artifacts identified with FLARE. Radiance from the sub-pixel mirror target (blue) was sub-saturating, but can be observed in adjacent pixels. By contrast, a large, bright roof (orange) shows the spread of radiance from an extended target. This data can be utilized to improve telescope focusing and small-target radiometric retrieval techniques.

CONCLUSIONS AND FUTURE WORK

The amount of remote sensing data available today is expanding exponentially, but its inherent quality and radiometric uncertainty is not matching pace. Better data are needed, not just more data. Accelerating the quality of the data demands a new breakthrough system of a high-frequency, reliable, and practical system calibration. The FLARE Network is a proven technical solution for vicarious calibration, validation, and characterization of both large and small satellite platforms. FLARE systems are synthetic targets that offer a huge range of engineered, stable, and calibratable solutions that current natural site methods do not. Commissioning and initial results from the first FLARE nodes and campaign efforts have demonstrated the utility of the technology to small sat constellations, and ongoing validation work against current methodologies will ensure the quality and suitability of FLARE for low uncertainty spatial and radiometric characterizations. Rapid expansion of the FLARE network will result in automation of calibration and inherently better image quality and data. As the world grapples with the "big data" era, fundamentally improving the ARD baseline of that data will enhance the inherent value to customers. Better data will save valuable person hours, enhance data extraction techniques (AI and ML), and allow data-driven systems to make better decisions and develop new capabilities. The FLARE network is the revolutionary new tool in the "calibration tool-kit" to advance the quality of the world's aerial and satellite image products.

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