Comprehensive Vicarious Calibration and Characterization of a Small Satellite Constellation Using the Specular Array Calibration (SPARC) Method

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ABSTRACT

With a rapidly growing small satellite industry deploying constellations of low cost imaging sensors for academic, commercial, civil, and intelligence applications, the quality and exploitability of data products will play a critical role in maintaining that growth. As a result, absolute intersensor calibration is critical in providing reproducible and accurate measurements over time for delivering image data that is affordable, maximizes information content, and optimizes value added potential. A significant part of keeping the cost down has typically been the elimination of on-board calibration and relying on vicarious calibration methods. Robust techniques are required to ensure that observations from different instruments establish a reliable form of traceability and can be normalized to a common absolute radiometric scale for achieving seamless physics based exploitation. Outlined in this paper is a versatile and effective method for achieving calibration equalization and performance characterization of a constellation of imaging sensors in the solar reflective spectrum. The Specular Array Calibration (SPARC) method, is an adaptable ground based system that uses convex mirrors to create small reference targets revealing radiometric, spatial, spectral, geometric and temporal characteristics of individual sensors for transforming them into a unified earth-monitoring system. Overall, the wide range of SPARC capabilities provides the potential to minimize pre-flight requirements (reduce cost and schedule) by being able to shift more calibration and validation analysis on orbit, completed quickly after launch and continued routinely through the life of each imaging system and duration of the constellation.

INTRODUCTION

Maximizing spatial and temporal coverage of the Earth is generally the objective of an EO/IR constellation and as a result one can imagine dozens or hundreds of satellites at any time achieving persistence over many points of interest around the world. Persistence does not limit members of this constellation to a common orbital altitude and inclination. Members of the fleet can have a variety of orbits as well as imaging systems having a dissimilar field-of-view (FOV) and instantaneous field-of-view (IFOV). To build a relationship that establishes the constellation, one can imagine the bond being a capacity for effective exploitation within the fleet image data. Thus crafting a "Radiometric Constellation" to achieve dynamic and functional exploitation introduces the need for applying a common calibration methodology across the fleet, producing image products that are platform independent. The result is to make each sensor system in the fleet interchangeable toward contributing to a spectral radiometric observatory by transforming their responsivity through intersensor calibration to a common radiometric scale, which one can define as the "fleet average".

With a rapidly growing small satellite industry deploying constellations of low cost imaging sensors, the quality and exploitability of data products will play a critical role in maintaining that growth. As a result, absolute calibration and intercalibration of the satellite instruments are critical for user applications to be successful and provide reliable accurate and consistent measurements over time. Industry growth has been driven by a host of paying customers eager to get their hands on regularly refreshed satellite imagery from multiple satellites that are affordable and optimizes value added potential. A significant part of keeping the cost down has typically been the elimination of on-board calibration systems compelling small sat developers to rely on vicarious calibration methods to achieve optimal information content users are expecting. Robust techniques are required to ensure that observations from different instruments establish a traceability path and can be normalized to a common scale for achieving seamless physics based applications. As a major player in the satellite industry, Raytheon is in the unique position of offering its own proprietary state-of-the-art solution for post launch sensor calibration, optimization, and assessment to data suppliers and users across the industry. Presented is Raytheon's highly versatile and effective technique for achieving calibration and performance equalization of a constellation of imaging sensors within their operational environment that can include space-based and airborne systems imaging from visible to MWIR wavelengths. The Specular Array Radiometric Calibration (SPARC) method, is an adaptable ground based system that uses convex mirrors to create small reference targets revealing radiometric, spatial, geometric, spectral and temporal characteristics of individual sensors for transforming them into a unified earth-monitoring sensor system.[1] SPARC has the potential to provide in-flight absolute calibration and sensor performance validation to an unprecedented level of repeatability, accuracy, and application in a wide variety of operational environments, while simultaneously simplifying sensor design and reducing flight system cost by removing the need for on-board calibration. The ability for SPARC to become the foundation for a ground station image assessment system (IAS) is also outlined.

Value of calibration and intersensor calibration

Calibration is the process of quantitatively defining the system responses to known controlled inputs. A digital number (DN) response has no link to physical units until a transformation function is established by looking at a reference source traceable to absolute radiometry. Assuming the transformation function is linear, the goal is to derive a gain and bias, with uncertainties, that equalizes the response of all detectors on an absolute scale. The function can be established before launch with laboratory measurements but must be recalibrated on orbit due to the harshness of launch and through the operational life of the sensor system because of changes in the operating performance from contamination and aging.

Creating more than a pretty picture, radiometric calibration provides the means to extract information from image data not otherwise attainable. Conversion from digital number (DN) to absolute units (i.e. intensity, radiance) allows physics-based exploitation for creating value added products and enhanced data mining. Exploitation capabilities with calibrated spectral data include: matching pixel data with specific spectral signatures contained in spectral libraries (target detection), finding changes at a geographic location between multiple scenes (change detection), assigning a label to each pixel surveying scene content (classification), and applying atmospheric corrections using radiative transfer models (deriving surface reflectance).

Establishing a radiometric constellation for optimum exploitation requires intersensor calibration. Intersensor calibration minimizes the radiometric difference between sensor systems when exploiting targets of interest and monitors the relative stability of the data they acquire. It identifies and potentially removes the biases that will likely exist between individual sensor systems even if they are designed to be "identical".

It is important to be aware that intersensor calibration is not cross-calibration. Intersensor calibration between multiple sensors does not require simultaneity of measurements (time, view geometry and spectral band). It is simply employing the concept that multiple sensors calibrated in the same laboratory, viewing the same repeatable reference, should agree with each other.[2] The application of the SPARC method can provide such an in-flight reference. It allows a consistent collection and processing methodology across the constellation with sufficient reproducibility to establish a "fleet average" radiometric scale rapidly while in flight.

VICARIOUS CALIBRATION

The precision of vicarious approaches for radiometric calibration are now at a level that allows them to be used for intercalibration. If fact, in meeting many radiometric requirements, vicarious calibration methods have been shown to meet or exceed the performance of on-board calibration systems.[3]

By definition, on-board calibration instrumentation on its own cannot establish intercalibration since the reference radiometric source can only be viewed by the sensor it is designed to support. Thus a collective vicarious calibration target, accessible to all sensors, is essential and necessary to transfer a common radiometric scale across the constellation. Even if one of the constellation members is utilized as a primary reference instrument (on-board calibration or not), through which the radiometric traceability of the constellation is established, its calibration must still be transferred to the others through one or many mutual ground targets. As a result, the properties of the targets used and their stability will ultimately impact the radiometric characterization of the constellation. Primarily from the fact that observational simultaneity of any of the ground targets by all constellation members will generally not be possible.

The moon is attractive as a common vicarious radiometric target because it is a highly stable irradiance source all members of the constellation can independently view.[4] However, the moon still has some challenges. First, observing the moon takes the sensor platform out of its normal nadir viewing requiring a pitch maneuver and uniformly scanning the entire lunar disk at a constant rate to properly utilize the lunar irradiance model. Next, the moon is also generally observed when the satellite is in the shadow of the earth with different thermal and scattered light conditions compared to the nominal environment when viewing the daytime earth. Furthermore, the ultimate goal is to establish the best methodology to derive surface reflectance of targets on the earth. For this reason, radiometric calibration targets viewed under similar operational conditions as targets of interest on the ground are most desirable in order to minimize potential biases. In addition, taking advantage of accessible ground sites for acquiring in situ measurements, augmenting calibration reference knowledge, provides the opportunity to validate reflectance directly or incorporate controlled calibration surfaces supporting not only radiometric calibration but spatial, geometric and spectral assessment as well. As a result, our attention in achieving intersensor calibration turns to vicarious calibration methods based on ground targets.

Vicarious Calibration Methods Using Ground Targets

The reflectance-based method is widely accepted as the standard vicarious technique in the remote sensing industry for predicting at-sensor radiance from ground reference targets providing absolute calibration in the solar reflective spectrum. Sufficient repeatability of these targets allows data from individual sensors to be compared making possible intersensor calibration using this method[5,6,7].

Reflectance-based methods typically utilize instrumented sites from which *in situ* surface spectral reflectance and atmospheric measurements are collected and input into a radiative transfer code to predict a top of the atmosphere (TOA) radiance used for calibration. The resulting TOA radiance not only includes the signal from the reference ground target but also an atmospheric contribution from single and multiple scattering. Accounting for this diffuse sky path radiance requires the use of a radiative transfer code to predict its contribution and can be the largest source of uncertainty in the predicted TOA radiance.

Transforming a sensor response to radiance units using reflectance targets on the earth's surface have been identified to have the best reproducibility when the test site has the follow characteristics[8]:

1. High reflectance (at least 30%) to reduce the impact of atmospheric errors.
2. Low aerosol loading to minimize the adjacency effect and sky path radiance contribution to the at-sensor radiance from the site.
3. Reflectance spatial uniformity across the calibration site allow rapid characterization with a field spectrometer.
4. Spectrally flat reflectance over the range of multispectral bands or hyperspectral channels recorded by the sensor under calibration.
5. The surface is near-lambertian to minimize bi-directional reflectance factor effects.

In principle, the reflectance-based method can be applied at any site located on spatially uniform terrain as long as the spectral surface reflectance and atmospheric optical properties are recorded coincident with the sensor overpass and with similar view geometries. The reference area must also be larger than the sensor's radiometrically accurate instantaneous field-of-view (RAIFOV)[9]. This is approximately 4 times larger than the FWHM of the sensor PSF[10]. In the end, however, the magnitude of the uncertainties, and thus the quality of the calibration, depends on how well the target site fits the ideal conditions listed above.

A successful reflectance-based approach not relying on *in situ* measurements is the use of highly stable natural sites known as pseudo invariant calibration sites (PICS). These are typically spatially homogeneous dry lakebeds, salt flats and desert sand sites located in arid regions that are consistently viewable under clear sky conditions. Long term monitoring with calibrated sensors have shown that these sites can be very stable with annual variations in their TOA reflectance of only 1% to 3%. However, significant analysis and updates are needed to build and maintain a comprehensive and accurate calibration model with absolute traceability for each site[11].

Traceability based on the TOA solar irradiance spectrum

Radiometric analysis of image data, in general, is concerned with modeling the radiative transfer process for accurately describing the propagation of optical radiation between targets of interest in a scene, the intervening optical medium and the detector of the optical energy. The result is a functional relationship between the at-sensor flux and the instrument output. Knowledge of this functional relationship is established by utilizing a stable and repeatable absolute reference source. For vicarious applications, the most accessible absolute reference source available is the Sun. The challenge, of course, is the Sun's brightness which is many magnitudes greater than most targets of interest requiring a reduction of its radiant flux to fit within the operational dynamic range of a sensor system under calibration. In earth remote sensing, this challenge is typically met by using diffusers reflecting direct sunlight. While the reflectance-based techniques described above, utilizing the solar illumination of diffuse surfaces have been employed for years, their limitation is that the diffuse surface, being Lambertian-like, adds unwanted light from a complex combination of environmental scattering processes diluting the traceable direct solar irradiance signal. The reflected radiometric signal intended to provide the TOA calibration metric, has been modified with additional downwelling illumination from an entire hemisphere onto the diffuse reference target (atmospheric scattering and adjacency effect) and upwelling illumination into the sensor's IFOV (path radiance). This external radiance, of both atmospheric and terrestrial origin from the surround, adds significant uncertainty within the traceability path to the solar spectral constant that is site dependent and must be accounted for within the reflectance-based method.

THE SPECULAR ARRAY CALIBRATION (SPARC) METHOD

The Specular Array Calibration System provides an alternate ground based vicarious calibration approach that utilizes spherical convex mirrors to isolate the direct solar flux from the background radiance providing a more rigorous tractability path that significantly reduces the uncertainties from the reference target's surround when performing intersensor calibration.

In addition, SPARC reference targets successfully dilute the solar flux. They act as ideal neutral density filters with the attributes of being spectrally flat across the full solar reflective spectrum using specular reflectance and adjusting to any desired intensity range by simply selecting the appropriate radius of curvature and duplicity of mirrors. With almost limitless trade space for intensity control, the application of spherical mirrors provide the potential to make the solar spectral constant readily accessible for intersensor calibration. In effect, the SPARC method allows each sensor to tap into a traceability path similar to the proposed Climate Absolute Radiance and Refractivity Observatory (CLARREO) by producing a direct "pinhole" view of the solar disk through the full optical path of the sensor under calibration[12]. An advantage of the SPARC approach is that an array of these solar images projected onto the focal plane can be recorded simultaneously with a variety of intensities each having identical spectral content. A PICS site, in comparison, can only provide a single reference radiance.

The ability to view the sun directly does not in itself establish *System International d'units* (SI) traceability. However, a SPARC intersensor calibration based on an improved transfer to the solar spectral constant for unifying the calibration among the constellation members, can establish a "fleet average" radiometric scale the remote sensing community can have confidence in. Any residual absolute bias that may be present can potentially be estimated by a broader intercalibration done by comparing the SPARC calibration to the results of other independent calibration methods (i.e. Lunar cals). In any case, the bias will be stable through consistent application of the SPARC method and its absolute validation will come at a later date when on-orbit SI-traceable intercalibration instruments and techniques become available[13].

Characteristics of SPARC reference targets

Convex mirrors deployed in the field act as very stable and reproducible reference sources for absolute vicarious calibration in the solar reflective spectrum. The SPARC method allows any earth observing sensor to be calibrated to the solar spectral constant just like a solar radiometer as displayed in Figure 1. The reflective disk of the mirror acts as a FOV aperture stop allowing the sun to be isolated and viewed directly as an absolute reference.

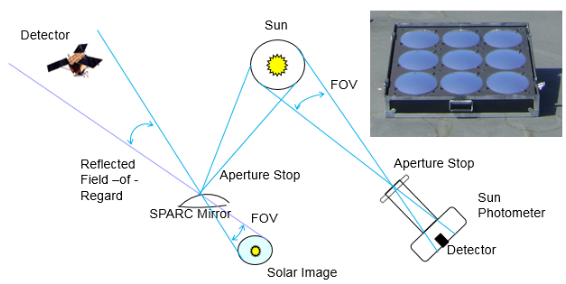

Figure 1. SPARC targets allow the orbiting sensor to record the direct solar signal similar to a sun photometer.

The upwelling intensity from each mirror can be directed anywhere in the sky. The intensity is uniform over a circular solid angle centered on the direction of the angle of reflectance unit vector produced by the incident solar illumination. The width of this upward solid angle illumination is determined by the mirror diameter and radius of curvature and is referred to as the mirror's field-of-regard (FOR).

By placing the targets on as uniform and low reflectance surface as possible, the digital number (DN) response to only the direct solar signal can be extracted from the image data alone. Figure 2 illustrates how the SPARC method isolates the direct solar signal from all other background radiances which can be subtracted out. The background subtraction eliminates the need in the

SPARC method to account for adjacency effect, scattered light and sky path radiance reducing uncertainties compared to the reflectance-based method.

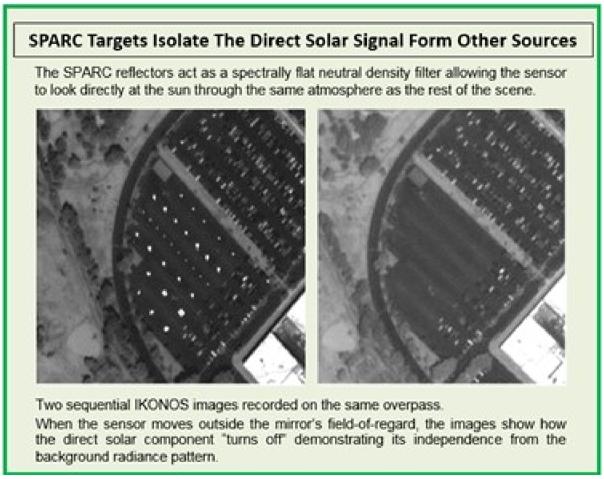

Figure 2. Mirror targets isolate the detector response to the direct solar signal from the background in the sensor image.

Mirror reflectance can be measured in the laboratory close to an order of magnitude more accurately than the diffuse Lambertian-like surfaces typically imaged in the reflectance-based vicarious calibration efforts. In addition, the accuracy knowledge of the reflectance can be maintained when deployed in the field because of the rigid and specular properties of a fixed mirror. Finally, the reflectance variability with changing illumination and view geometry is small and well characterized. The targets do not experience the complicating effects of illumination foreshortening and BRDF as diffuse semi-Lambertian targets do. Example reflectance spectra of mirrors used in SPARC targets are shown in Figure 3.

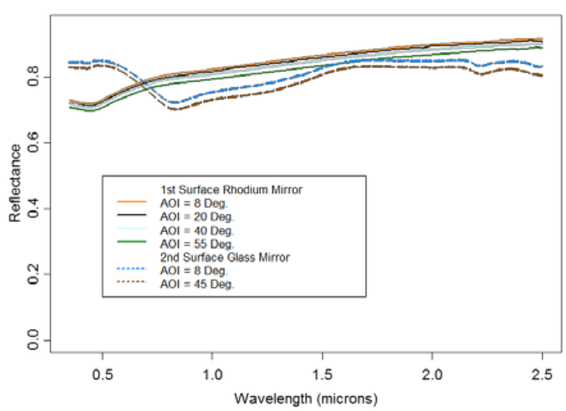

Figure 3. Example mirror reflectance spectra showing variation with wavelength and angle of incidence.

Methodology for predicting at-sensor effective radiance of SPARC targets

It can be shown that the directional upwelling spectral intensity leaving a single convex spherical mirror illuminated by the sun is given by

$$I_M(\lambda,\theta_o,\phi_o,\theta,\phi) = \rho(\lambda,\theta_o,\phi_o\theta,\phi)E_o(\lambda)\left(\frac{R}{2}\right)^2 \tau_{sun}(\lambda,\theta_o,\phi_o)$$

[Watts/(sr µm)]. [1]

where,

θ_o,ϕ_o =altitude and azimuth of the sun at the reflector,

θ,ϕ = altitude and azimuth for the directional components of the upwelling intensity unit vector from the mirror toward the sensor,

$\rho(\lambda,\theta_o,\phi_o\theta,\phi)$ = directional reflectance of convex mirror surface,

$\tau_{sun}(\lambda)$ = atmospheric transmittance from Sun to SPARC reflector,

$E_o(\lambda)$ = Top-of-atmosphere solar spectral constant,

R = mirror radius of curvature,

Propagating the flux from the ground to the sensor requires multiplying the upwelling spectral intensity by the transmittance along that path, τ_{sens}. Conversion to an effective at-sensor spectral radiance is accomplished by applying the inverse square law for the distance, *H*, from the mirror to the sensor and dividing by the solid angle of a single pixel, Ω_{IFOV}. .

$$L_{sen}(\lambda,\theta_o,\phi_o,\theta,\phi) = \rho(\lambda,\theta_o,\phi_o\theta,\phi)$$

$$\tau_{sun}(\lambda,\theta_o,\phi_o)\tau_{sens}(\lambda,\theta,\phi)\frac{E_o(\lambda)}{\Omega_{IFOV}}\left(\frac{R}{2H}\right)^2$$

[Watts/(m^2 sr µm)] [2]

Equation [2] applies to a single mirror. For a panel of N identical mirrors, the net effective at-sensor spectral radiance is simply scaled by the number of mirrors. Also, the radiance can be expressed in a terms of the along-scan(x) and cross-scan(y) sensor ground sample (GSD) distance normal to the line-of-sight by setting $\Omega_{IFOV}H^2 = GSD_x GSD_y$. As a result, equation [2] can be rewritten to give the effective at-sensor spectral radiance of a SPARC radiometric calibration panel as

$$L_{eff}(\lambda,\theta_o,\phi_o,\theta,\phi) = N\rho(\lambda,\theta_o,\phi_o,\theta,\phi)*$$

$$\tau_{sun}(\lambda,\theta_o,\phi_o)\tau_{sen}(\lambda,\theta,\phi)E_o(\lambda)\left[\frac{R^2}{4GSD_x GSD_y}\right]$$

[Watts/(m^2 sr µm)] . [3]

It is important to recognize that the effective spectral radiance, L_{eff} , corresponds to the total response of the sensor to the SPARC target signal. That is, the integrated DN response of the target image recorded by the sensor.

In order to accurately extract the integrated signal, knowledge of the sensor PSF is required. An image quality analysis of the sensor provides this information and is described in the next section.

SPARC IMAGE QUALITY ANALYSIS

In a SPARC calibration, two groups of mirror targets are generally deployed to provide both image quality and detector response information needed for a SPARC vicarious calibration analysis.

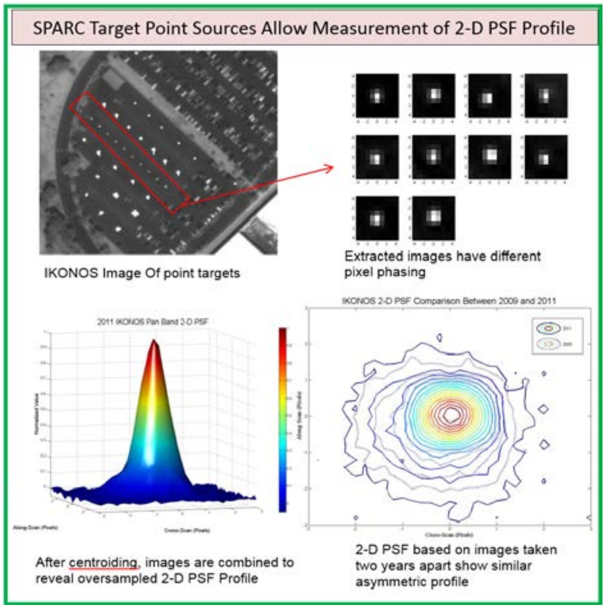

Figure 4. Creating a 2D PSF from images of SPARC point targets.

One group is an array of point targets made with duplicate single mirrors spaced so that individual targets are offset differently relative to pixel centers when imaged. Combining the point target profiles of each produces an over-sampled two-dimensional system level PSF providing a detailed image quality assessment that maps the energy distribution of the target projected by the optical system onto the focal plane. Analysis of the cross-track and in-track profiles verifies the effective ground instantaneous field-of-view (GIFOV). Figure 4 illustrates this process.

The purpose of this step for SPARC radiometric calibration is to verify the ensquared energy distribution of small targets for the sensor under calibration[14]. The radiometry derived from the SPARC method relies on the fact that all the energy from a point target will be confined within the system PSF. This allows the direct solar signal from the target to be measured in image processing as simply an integrated radiance over a small square area of pixels centered on the target. The objective is to use as small an area as possible for the DN integration in order to minimize the potential effects of background non-uniformity when subtracting out the background. The knowledge of the ensquared energy distribution provides the correction for the energy from the calibration target that will fall outside the pixels defining the integration window in the image.

Introducing bright point targets within a scene, capable of building an oversampled PSF profile, provides references revealing changes in the system PSF that occur at different levels in the image processing chain as well as temporal stability. Figure 5 demonstrates the ability of the SPARC target data to reveal the changes in the width of the system PSF between the processing steps of detector equalization, resampling for image registration and MTF compensation for the IKONOS sensor[14].

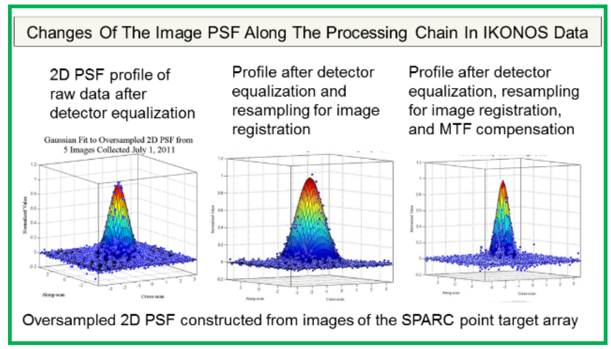

Figure 5. Illustration of the PSF analysis to be carried out at different tap points in the image processing chain.

Small Target Radiometry

Test sites on the surface of the Earth, used for reflectance-based vicarious radiometric calibration, consist of an extended uniform surface filling a large area of the sensor's focal plane. The ability to sample the site with a large number of detectors establishes a mean response to the predicted at–sensor reference radiance with high precision and in the process averages out the blurring effects induced by the imaging system. The procedure derives radiometric gain coefficients with uncertainties that can be maintained through the image processing chain to higher level products but only for large uniform scenes. However, many targets of interest are small, typically subpixel to a few pixels in diameter, and the degrading effects of the sensor from contrast loss due to the systems modulation transfer function (MTF) makes the application of the large area gain coefficients to the pixels associated with small targets unreliable[10]. Because the SPARC method analyzes both the radiometric and spatial performance of a sensor with small intensity targets, it is the most effective vicarious calibration method for addressing issues related to small target radiometry. The potential with the SPARC method is the ability to characterize a sensor's radiometric performance even with sub-pixel targets of interest

SPARC ABSOLUTE CALIBRATION

Once the integration window size and ensquared energy enclosed in the window is evaluated from the PSF analysis, the calculation of the absolute gain coefficient for a sensor can proceed. Integrating the total *DN* in a pixel window enclosing each target (after background subtraction) provides a measurement of the integrated response, ΣDN, within each spectral band imaged by a sensor. Assuming relative flat field equalization of the image DN values has been accomplished to remove banding and striping, the absolute gain calibration coefficient is calculated based on the following equation,

$$G(\lambda) = \frac{\Sigma DN(\lambda)}{L_{eff}(\lambda)} \left(\frac{1}{\cdot \, Bandwidth(\lambda) \cdot EnsqEnergyCor(\lambda)} \right)$$

$[DN/(W/m^2 sr)]$ [4]

where, $\frac{\Sigma DN(\lambda)}{L_{eff}(\lambda)}$ is the slope of the regression line for a spectral band in the resulting integrated DN response vs. predicted effective radiance for a set of SPARC radiometric targets,

$L_{eff}(\lambda)$ = Predicted equivalent at-sensor effective radiance for the spectral band [$W/(m^2$ sr μm)] per mirror (N =1) from equation [3],

ΣDN = integrated background subtracted *DN* response per mirror derived from the SPARC radiometric targets imaged in a spectral band [DN],

Bandwidth = bandwidth of spectral band [μm], and

$EnsqEnergyCor_k$ = estimated fraction of the ensquared energy contained within the pixel integration window used to measure ΣDN.

Validation of the SPARC calibration method

Figure 6 shows the measurement of the integrated DN response to a set of SPARC targets with different numbers of mirrors for image data collected with the IKONOS sensor[15]

As an example, the green box represents the integration window enclosing a target containing 100 mirrors and the red box outlines the parameter pixels used for estimating the average background DN per pixel. The sum of the pixel DNs in the green box minus the background average DN estimates the integrated response to the target. The plot shows the resulting tight linear fit with a slope giving DN/mirror. The residuals relative to the straight line fit are primarily due to the noise from background non-uniformity. Equation [3] is used to calculate the effective at-sensor radiance per mirror (L_{eff}/mirror) and the resulting ratio gives the absolute calibration gain coefficient. Table 1 presents the results of a study of IKONOS deriving gain coefficients based on 5 overpasses collected in a 7 month period[15].

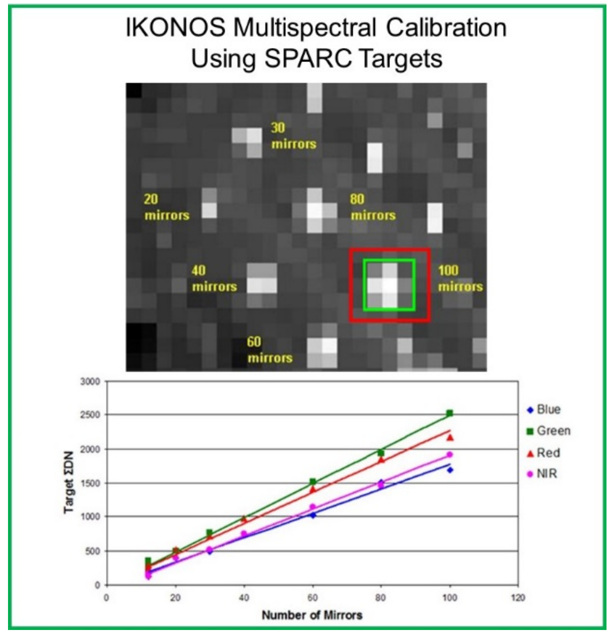

Figure 6. Application of the SPARC method for evaluating the multispectral integrated response.

The reproducibility presented here represents the standard deviation in a single observation. With better than 2.5% in the Multispectral bands and 3% in the Pan band, the results demonstrate the stability of the SPARC method for supporting intersensor calibration and the potential to validate on-orbit performance rapidly after launch.

Table 1. Reproducibility of the measured gain coefficients for IKONOS multispectral bands based on 5 overpasses from SPARC analysis.

IKONOS Band (λ)	GeoEye Published *CalCoef.*[a,b] $DN/[W/(m^2 sr)]$	SPARC Measured *CalCoef.*[b] $DN/[W/(m^2 sr)]$	SPARC *CalCoef* Measured Reproducibility (5 Overpasses)	Cal. Coef. Difference (Pub.–Meas.)/Pub.
Pan (TDI=13)	16.1	15.9	3.0%	1.2%
Blue	72.8	62.3	2.2%	14.4%
Green	72.7	67.3	1.1%	7.4%
Red	94.9	95.8	2.5%	-0.9%
NIR	84.3	78.7	1.3%	6.6%

[a] Post 2/22/01 *CalCoef.* derived from reflectance-based vicarious calibration. Reference: Martin Taylor (2005), *IKONOS Radiometric Calibration and Performance after 5 Years on Orbit*, Proceedings of CALCON 2005 Conference, Logan, Utah, 22-25 August 2005

[b] Used the bandwidth and in-band solar irradiance (E_o) presented in the reference "IKONOS Planetary Reflectance and Mean Solar Exoatmospheric Irradiance" at www.geoeye.com

INTERSENSOR CALIBRATION USING SPARC

SPARC radiometric target spatial harmonization

One of the challenges in using natural diffuse targets, such as PICS sites for intersensor calibration, is scaling the calibration target area reflectance and uncertainties to account for differing FOVs, IFOVs and the viewing geometry of the sensors under comparison. Figure 7 shows a Landsat image of the Lybia-4 calibration site recorded by Landsat 7 and the recommended calibration area (red box) presented within the CEOS IVOS CalVal portal[16].

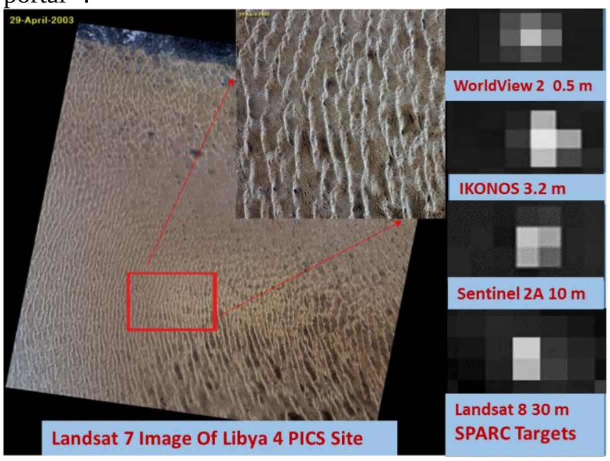

Figure 7. Landsat 7 image of the Libya 4 PICS site located in the western Libyan Desert. The image illustrates the varying spatial appearance with sensor resolution of the calibration area. In comparison, is the repeatable spatial structure of SPARC targets with varying GSD.

Though the site is very stable, the radiometric signal and the associated uncertainty depends on the resolution and how well the target area is spatially matched by each sensor system that images the site. In contrast the spatial structure of the radiometric signal from each SPARC calibration target is fundamentally the same independent of the spatial resolution and view geometry thus reducing uncertainties due to differences in sensor collocated footprints.

Defining the Fleet Average Gain Coefficient

Radiometric traceability for absolute calibration of the constellation can be defined by a virtual reference sensor based on the average gain performance of the constellation during the initialization of the constellation members. This "Fleet Average" gain, G_F for N_c constellation members can be based on gains for each individual sensor X from equation [4].

$$G_F(\lambda) = \frac{1}{N_c}\sum_{X=1}^{N_c} G(\lambda, X) \qquad [5]$$

The performance of the fleet average sensor would be established at a specific date, fixing the constellation gain to a reference DN response scale that each member of the constellation can be transformed to. The fleet average gain would be monitored and maintained throughout the lifetime of the constellation which will likely be much longer than any constellation member.

Defining a reference sensor establishes a baseline to characterize the performance of individual sensors in the constellation and the constellation performance as a whole over time. This relation establishes all members of the constellation to the same radiometric scale with a single potential absolute bias term that that can be identified, if present, relative to sensor systems or calibration methodologies external and independent of the SPARC intersensor calibration.

USING SPARC TARGETS TO SUPPORT AN IMAGE ASSESSMENT SYSTEM

The inclusion of an image assessment system (IAS) within a constellation's ground station architecture provides the means to maintain the fidelity of data products and monitor compliance with data quality requirements. Regular collection of SPARC calibration targets can enhance the effectiveness of the IAS not only for spatial and radiometric validation, as already shown, but for geometric and spectral performance monitoring as well.

Analysis of Optical Distortions and Geometric calibration

The application of an image assessment system generally include the temporal analysis of the sensor's optical distortions that impact the mapping of the scene of interest onto the sensor system's focal plane. The IAS provides a platform for systematic geometric performance monitoring, characterization, and calibration under operational conditions when good ground control points (GCPs) are available.

Systematically imaging SPARC point ground targets of known longitude, latitude and height can enhance the ability to relate location in image space to geodetic object space within a scene and maintain that knowledge over time. With these small portable targets they can be placed anywhere in the study scene and are especially useful in complex terrain. Generally, locating GCPs within band, detector and sampling space is difficult to accomplish with accurate subpixel resolution. Single convex mirrors, however, create virtual images of the sun millimeters in size (~3cm for Landsat targets), of high contrast within a scene that can be centroided with subpixel accuracy[17]. The procedure is to create an oversample 2D Gaussian PSF based on an array of targets of varying pixel phasing in the scene as described previously. The composite PSF is then fit to individual targets through regression analysis to find the centroid location.

Figure 8 shows an array of SPARC point targets imaged by IKONOS in the green band at 3.2 m GSD. The 12 targets are first combined to generate the composite PSF for the sensor. The composite PSF is than fit through regression analysis to each individual target. With this procedure, the located (x,y) target centers are generally extracted within an uncertainty better than 1/20th of a pixel width.

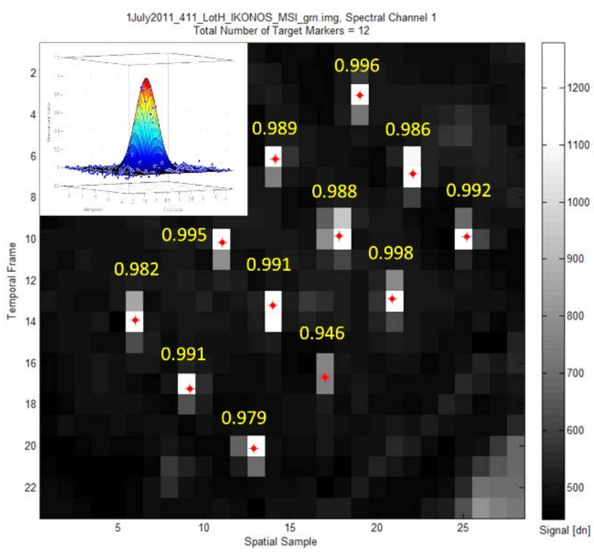

Figure 8: Finding the target centers (red + symbols) by fitting the composite oversampled 2D PSF (inset). Numbers indicate R-squared goodness-of-fit values based on the regression residuals relative to individual target pixel values.

In addition, this in-flight procedure is extremely useful for analyzing spatial–spectral distortions in dispersive imaging spectrometers since the targets provide a high contrast spectrum that is reflectively flat over the full solar reflective spectral range. The spatial position and PSF FWHM can be tracked through each spectral band to accurately analysis smile and keystone effects.

In multispectral sensor systems, registration errors can be readily revealed by imaging an array of spectrally identical SPARC point targets. Due to time delay between bands when imaging a spot on the ground, the changing view geometry and jitter, along with the pixel resampling used in registration processing, result in residual spatial offsets in the final geometric pixel alignment between bands. When a false color image is produced, the presence of residual registration errors is revealed by the resulting rainbow of colors for the array of point targets as illustrated in Figure 9.

Since the reflectance of each target is spectrally flat, the point targets should all appear white after registration but instead appear in a range colors. Note that the radiometric panels in the image do appear white as they should. Since they consist of mirrors spread over an area larger than a pixel they are partially resolved and thus less susceptible to subpixel registration errors. In contrast, when an array of point targets are imaged with a hyperspectral dispersive imager, no rainbow effect is seen since all spectral channels are imaged simultaneously.

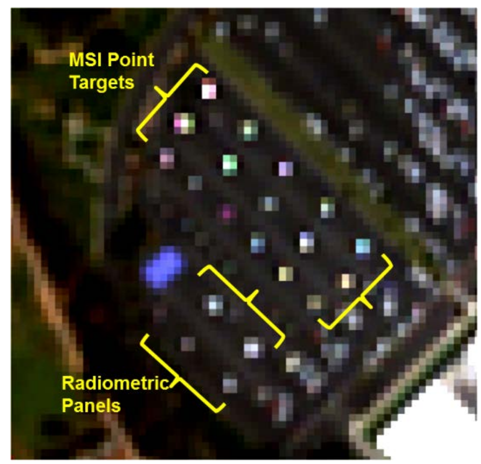

Figure 9: Registered and resampled RGB image of SPARC targets recorded by IKONOS. The rainbow of colors in the point target images reveal residual registration errors between bands.

Spectral response validation

The spectral performance of an imaging system can also be monitored with SPARC targets using mirrors designed with spectral absorption or interference coatings. The parameters for multiple mirrors within a target (reflectance, radius of curvature, and number of mirrors) can be adjusted to synthesize a full-spectrum reference of any brightness for use in ground based detection experiments[18], The targets are compact and flexible in design allowing a “target in a briefcase” to be created. These can be set up at a SPARC or other field site for target and anomaly detection testing and deriving performance metrics for the constellation such as the receiver operating characteristic (ROC) curve. An illustration of methodology for creating a synthetic spectrum is presented in Figure 10.

In addition, a resolved array of colored targets each reflecting a specific narrow bandpass can be deployed as well. This allows a vicarious calibration to that target bandpass providing a verification of the relative spectral response or out-of-band response of a sensor evaluated under operational conditions.

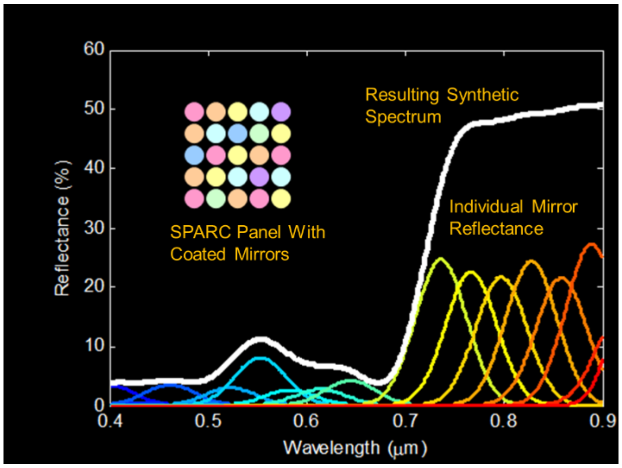

Figure 10: Options for grouping narrow bandpass mirrors within a single pixel to create an arbitrary synthetic spectrum

CHARACTERISTICS OF A SPARC CALIBRATION SITE

SPARC targets are robust, compact and easy to deploy. They can be set up on permanent fixtures or designed to be highly portable. Figure 11 provides examples of how they have been configured in the field. The specific layout and area needed depends on the GSD of the sensor. One simply needs to make sure the targets are separated enough so that the sensor PSF produced by these small targets do not overlap and within that PSF the background is as uniform as possible. Cleary the smaller the GSD the easier it is to find a site location. Parking lots or accessible tarmacs are most useful. The desire to keep the mirrors pristine for the radiometric targets is clearly a concern but is not difficult to deal with. The mirrors are generally deployed only an hour or two before the overpass so they are not exposed to the weather for a significant amount of time. The SPARC calibration is less sensitive to atmospheric instability than using diffuse targets because the at-sensor radiance prediction only requires knowledge of transmittance. A calibrated solar radiometer, automated or hand held, provides the only in situ measurements required for the calibration. Since the mirror reflectance (including view geometry variations) is already established in laboratory measurements there is no need to walk the site and characterize the target surface reflectance with a field spectroradiometer. As a result all the information needed to predict an at-sensor effective radiance for calibration is known almost instantaneously with the image collect. This relaxes the need for highly stable atmospheric conditions making site selection easier and increasing the frequency of successful calibrations.

Even for moderate resolution sensors SPARC calibration reference targets remain compact and portable. Though a more accurate tracking mount is required to effectively align the mirrors with the sun and sensor, the ability to set up an array at any location within a few hours of the sensor overpass is maintained. The tripod mounted mirrors shown in Figure 11 are capable of supporting the calibration of sensors with GSDs out to 50 meters and have been successfully applied to Landsat 8[19]. The computer controlled alt-azimuth mount also demonstrates the potential to fully automate a SPARC calibration site.

Figure 11. Examples of deployed SPARC spatial and radiometric calibration targets.

Multiple calibration sites

The ability to replicate SPARC calibrations at multiple locations improves the opportunity to precisely assess the performance of a sensor system in a short period of time. This capability is most valuable when trying to minimize the on-orbit checkout period after launch and quickly bring the sensor into a full operational mode. To illustrate, the following instructive simulation is presented. A single satellite is placed in orbit at the altitude and inclination of the International Space Station (ISS) to represent a small satellite launched from that facility. The sensor on the satellite is considered to have a means of imaging up to 10 degrees off of nadir.

There are two sets of SPARC calibration target sites compared. The upper row is at 50 degrees N latitude and the lower is at 45 degrees N latitude. Both collections of target sites consist of six sites separated by 2 degrees of longitude. In Figure 12 above, the two rows of target locations are shown. Targets A1 through A6 are the 50 deg N latitude set, while Targets B1 through B6 are the 45 deg N latitude set.

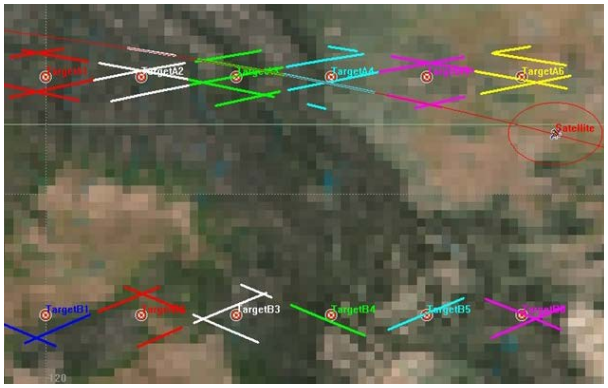

Figure 12. Target set locations at 45 and 50 deg N latitude and satellite orbit used for access modeling. The portions of orbits within a 10 deg LOS of target sites are shown (thick lines of various colors) over the arbitrary seven day period of May 23-29.

Each access of the individual targets are computed and shown with matching lines of the same color. An access is defined to be a period of time where the line of sight (LOS) between the satellite and the target exists, and the target is within the 10 degree off nadir as viewed from the satellite. Simulations of both of the target rows were completed over the simulation span of 1 week. The results show that the windows at 50 deg N latitude have the advantage of being numerous, providing between two and six accesses per day. At 45 deg N latitude the windows are fewer, providing between zero and four accesses per day. Though the access opportunities appear to be frequent, it should be noted that the above simulations do not consider lighting conditions necessary for solar reflective calibrations. Inserting the condition that the solar altitude is above 45 deg at overpass, this phasing affect when applied to these simulations will reduce the usable accesses to two over the seven day period for the 50 degree N latitude row in May. The results highlight that the potential portability and spatial duplicity for SPARC calibrations provides a distinct advantage for optimizing calibration and validation frequency.

CONCLUSION

Intersensor calibration of a constellation using vicarious ground reference targets relies on the implementation of stable well characterized targets and consistent image collection and processing methodologies applied to all members of the fleet. Utilizing reflected light of the sun, a traceability path is established to absolute units through our knowledge of the solar spectral constant. With this combination, a "fleet average" radiometric scale can be defined with uncertainties to produce image products that are sensor independent and highly valuable to the remote sensing user community. Absolute radiometric calibration makes possible target analysis and detection utilizing spectral libraries, change detection, pixel classification, atmospheric correction using radiative transfer codes to derive surface reflectance, and general physics-based exploitation.

Reflectance-based methods, that use instrumented or pseudo-invariant sites to produce targets of known TOA radiance, provide an effective approach for intersensor calibration. The methods have been well tested and validated and continue to be developed though many challenges remain for improving their application.

In this presentation, the SPARC method is offered as an evolutionary step forward, in meeting the intricate goals of intersensor calibration and establishing a common reference scale for a constellation of sensors, compared to reflectance-based approaches using diffuse reference targets. The unique approach offers improvements in function, precision and absolute traceability for supporting a constellation of high and moderate spatial resolution sensors. SPARC reference targets are more compact, portable and reproducible at multiple sites offering greater utility in supporting a constellation's operational structure and needs. The SPARC method also goes beyond radiometric calibration, consolidating into a common target set the ability to analyze spatial, geometric and spectral performance. Finally, these results can be incorporated into the constellation's image assessment system to create and maintain optimal product quality leading to innovation and growth within the EO remote sensing community.

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