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A WORLD OF INNOVATION

Using Vicarious Calibration To Evaluate Small Target Radiometry

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Introduction

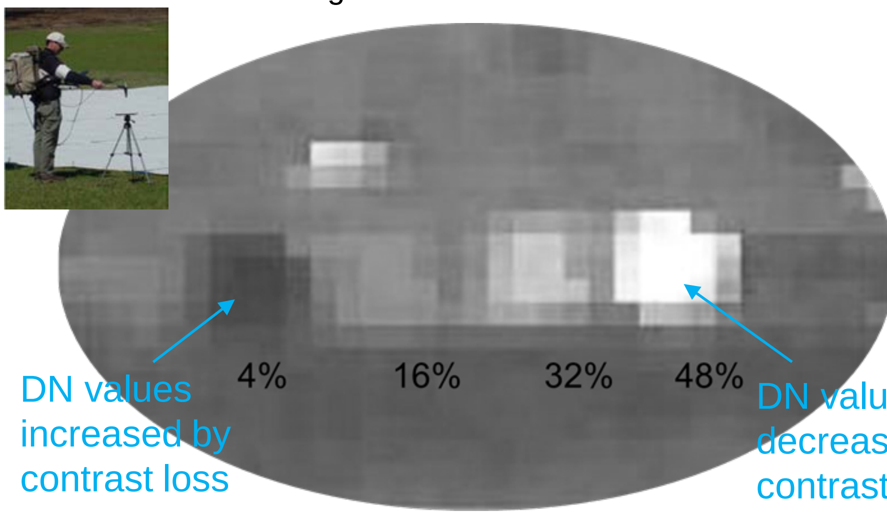
- NIST recommended best practice to validate end-to-end system level calibration requirements is to view a uniform source of known radiance (preflight or on-board) that fill the sensor field-of-view (FOV).
- Calibration process smooths out spatial effects so that the radiometric gain is derived independent of the system spatial fidelity.
- However, for any spatially detector limited remote sensing system imaging of a non-uniform radiance scene, there is a target pixel width in which system modulation transfer function (MTF) starts to reduce target contrast.
- For small targets the result is radiometric degradation, producing a larger radiance uncertainty than reported by the requirements validation process.

Because of MTF effects, system radiometric accuracy requirements do not apply to pixels associated with small targets

Illustration of the Degradation In Small Target Radiometry Resulting from the Sensor System MTF

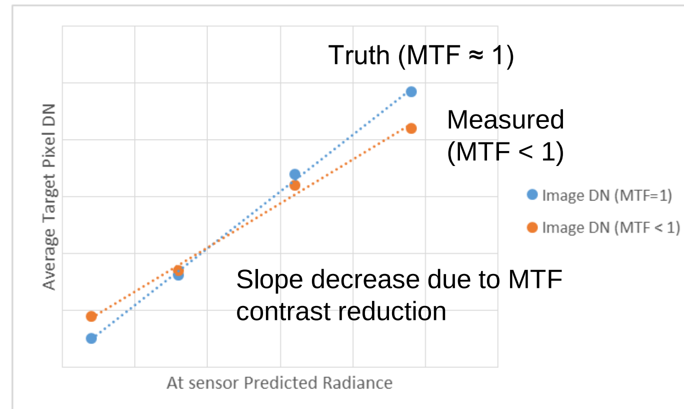
Contrast reduction by the sensor system MTF introduces an error in the derived sensor gain if one applies the **reflectance-based vicarious method** using small targets.

In scene "Lambertian" targets used for reflectance/radiance calibration



Central 2x2 pixel DN values are used to estimate the response to the at-senor radiance from each target.

Effect of MTF on Small Target Reflectance-Based Vicarious Calibration Gain Measurement



The result is a gain value (slope = DN/radiance) less than the true gain.

MTF <1 makes bright targets fainter and dark targets brighter relative to the average background radiance

Small target radiometry requires knowledge of both radiometric response and spatial image quality

Defining A Small Target: Radiometrically Accurate Instantaneous Field-Of-View (RAIFOV)

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Properties of a Small Radiometric Target

- A target is considered small when the system image quality impacts the application of the calibration gain coefficients (derived from large uniform scenes) to the target of interest.
- The target becomes dependent on the radiometric properties of the target background.

Parameter That Defines a Small Radiometric Target Pixel Size

- What pixel size constitutes a small target will be specified by the “radiometrically accurate instantaneous field-of-view (RAIFOV)” as defined by G. Joseph (2005).

RAIFOV = the image resolution (cycles/pixel) for which the MTF is > 0.95

George Joseph, “Fundamentals of Remote Sensing”, University Press, 2005

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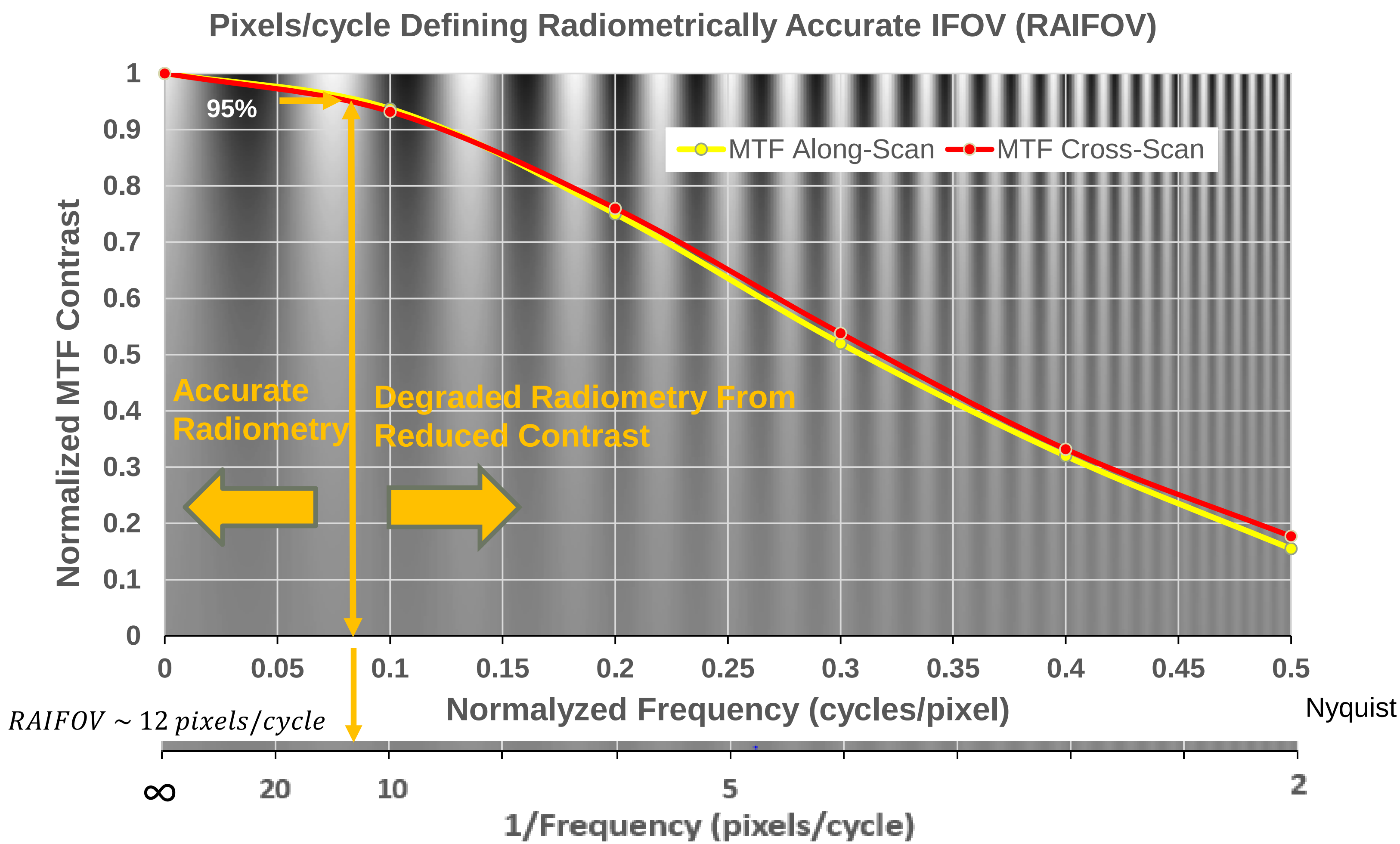
Interpreting RAIFOV From The Measured Sensor MTF



The spatial frequency that occurs at MTF=0.95 determines the number of pixels that must fit in a single square-wave cycle (bright and dark target pair) recorded by an imaging system to get accurate radiometry.

Quantitative Estimate of RAIFOV Pixel width Using A Gaussian PSF Approximation

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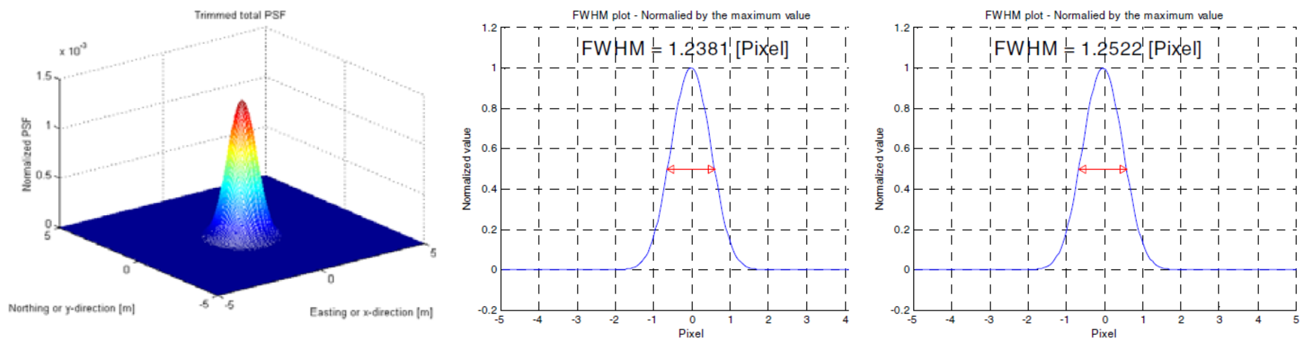
- The spatial resolution of a sensor can be defined as the FWHM of the system PSF, the two dimensional inverse Fourier transform of the MTF.



(a) The system PSF (b) Along track LSF (c) Cross track LSF

- Under the assumption of a Gaussian PSF, a simple relation between the Gaussian FWHM (w_{FWHM}) and the RAIFOV (w_{RAIFOV}) can be analytically derived with the approximate result that

$$w_{RAIFOV}(pixels/cycle) \approx 8.33 w_{FWHM}(pixels/cycle)$$

Derivation presented in a backup chart

Radiometrically Accurate Minimum Target Pixel Width (W_{RAIFOV})

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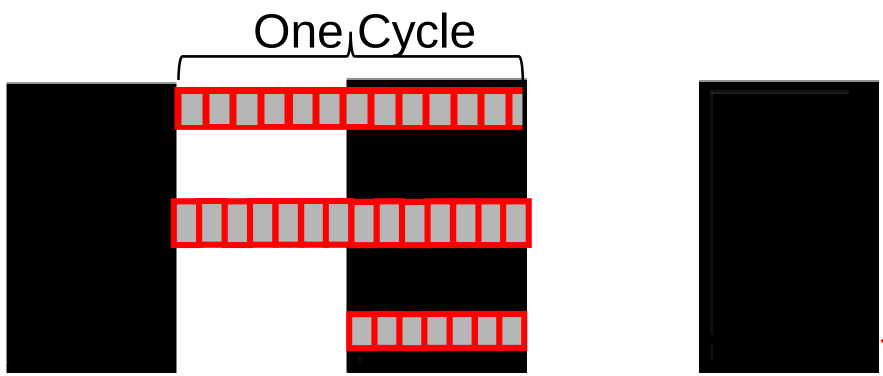
Geometric Tri-bar Ground Target



From measured FWHM of system PSF

$w_{RAIFOV} \approx 8.33 w_{FWHM} (pixels/cycle)$

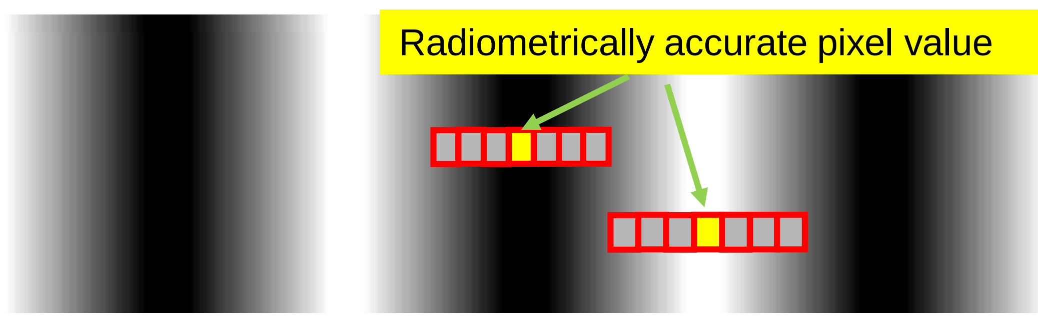
Apply integer ceiling function (pixels/cycle)

$\lceil w_{RAIFOV} \rceil = min\{n \in 2 \cdot Z_{odd} \mid n > w_{RAIFOV}\}$

Target integer pixel width fills half a cycle

$W_{RAIFOV} = \lceil w_{RAIFOV} \rceil$ /2 (pixels)

Image of Ground Target



For a ground target of geometric width W_{RAIFOV} pixels, only the image pixel containing the target centroid will have a radiance value that is radiometrically accurate for that target (bright or dark).

W_{RAIFOV} Determines the Number of Adjacent Pixels That Influence an Individual Pixel Response

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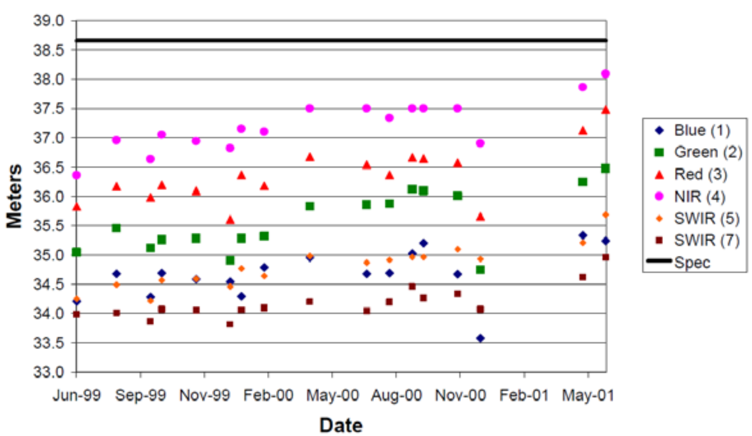
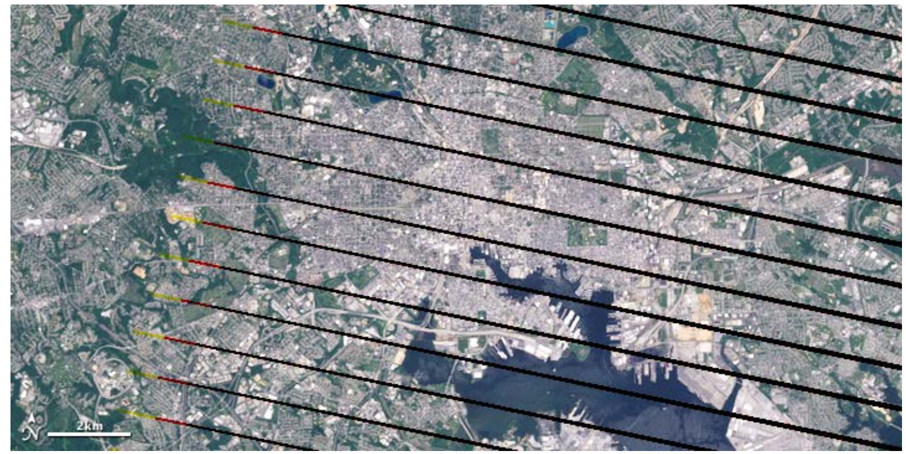
VNIR/SWIR PSF FWHM Resolution vs. Date





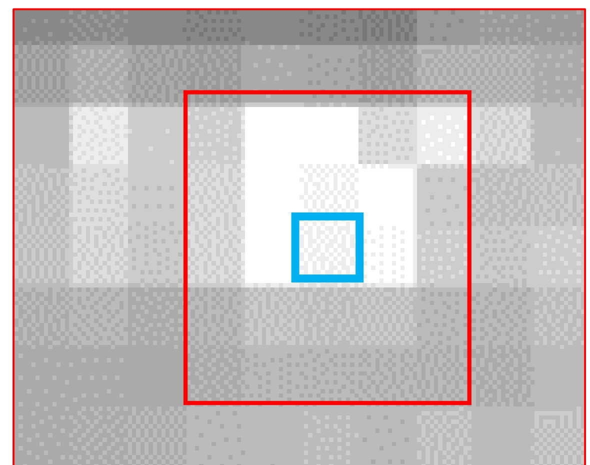
Landsat 7 Multispectral Bands

Measured: $w_{FWHM} \approx 1.2$ pixels*

➔ $W_{RAIFOV} = 5$ pixels

Due to the sensor MTF, each pixel value response is influenced by all surrounding radiance sources in a 5x5 pixel area. (2-dimensional effect)

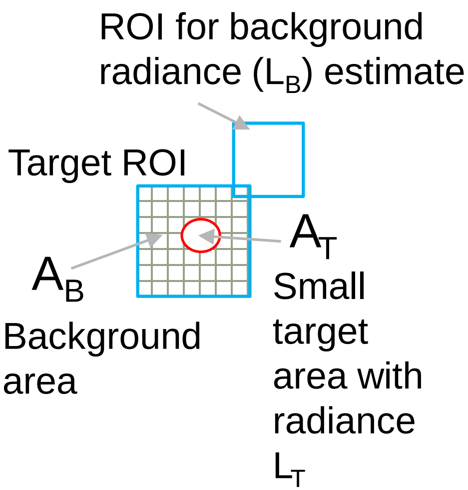
Holds for raw data prior to any resampling.



***Landsat 7 on-orbit modulation transfer function estimation,** James Storey, *Proc. SPIE* 4540, Sensors, Systems, and Next-Generation Satellites V50 (2001)

Radiometry of Small Targets: Radiance or Intensity?

For a small target (size < W_{RAIFOV} (pixels)), absolute radiance is no longer directly measurable, only apparent radiance.
(without having knowledge of the small target area A_T)



However, a small target may be dealt with as an intensity source (W/sr) that is mixed with the background radiance.

Integrated intensity (I_{ROI})= $1/G_I * \sum DN_{ROI} = L_B A_B + (L_T - L_B)A_t$

Were G_I is the is absolute intensity gain coefficient, DN/(W/sr)
Solving for target radiance

$$L_T = (1/A_t)[I_{ROI} - L_B(A_B - A_T)]$$

Target area accuracy is limited to unit pixels for radiance calculations

For small targets, the **<u>intensity spectral signiture</u>** is the more fundamental and potentially accurate quantity to be measured of the target of interest..

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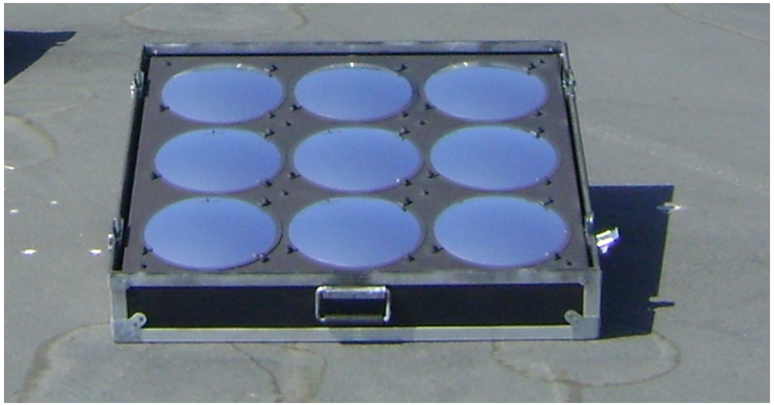
The Specular Array Radiometric Calibration (SPARC) Method

Radiometric Panel



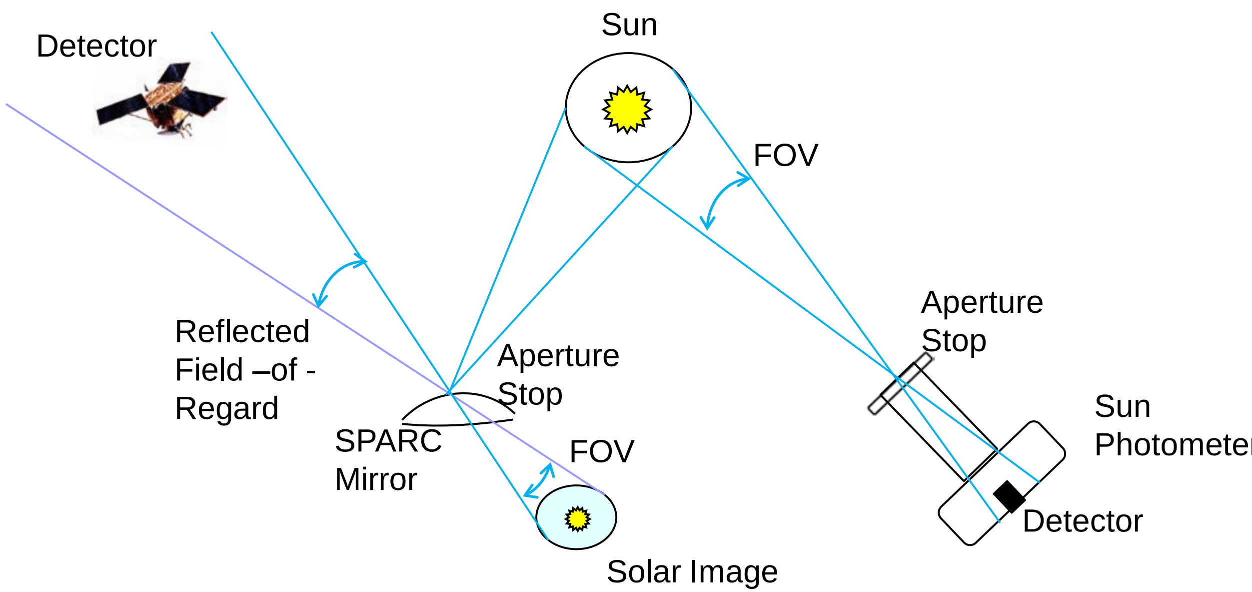
Point Source Array

- The technique provides accurate intensity sources traceable to the solar spectral constant and full 2-D point spread function analysis, both needed for small target performance assessment and calibration of imaging systems.

Conceptualizing The SPARC Method

The SPARC method allows any earth observing sensor to be calibrated to the solar spectral constant just like a solar radiometer.

The mirror acts as a Field-of-View (FOV) aperture stop just as with an aperture stop on a typical solar radiometer allowing the sun to be viewed directly as an absolute reference.



The spherical mirror scales down the brightness of the sun to an intensity that does not saturate the sensor focal plane.

SPARC Radiative Transfer Equations
Predicting At-sensor Intensity and Radiance

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TOA Intensity (Sensor Independent)

$$I(\lambda,\theta_r)_{TOA} = \tfrac{1}{4}\rho(\lambda,\theta_r)\tau_{\downarrow}(\lambda)\tau_{\uparrow}(\lambda)E_o(\lambda)R^2$$

Watts/(sr micron)/mirror

Effective At-Sensor Radiance/Mirror (sensor and collection geometry specific)

$$L_{at-sensor}(\lambda,\theta_r) = \rho(\lambda,\theta_r)\tau_{\downarrow}(\lambda)\tau_{\uparrow}(\lambda)E_o(\lambda)\frac{R^2}{4GSD(x)GSD(y)}$$

Watts/(m^2 sr micron)/mirror

$\rho(\lambda,\theta_r)$ = Mirror specular reflectance at the reflectance angle θ_r

$\tau_{\downarrow}(\lambda)$ = Sun to ground transmittance

$\tau_{\uparrow}(\lambda)$ = Ground to sensor transmittance

$E_o(\lambda)$ = Solar spectral constant
R = Mirror radius of curvature (m)
GSD = Line-of-site ground sample distance (m), cross-scan and along-scan

For a small target, the effective at-sensor radiance depends on sensor line-of-sight Ground Sample Distance (GSD).

Small SPARC Targets Isolate The Direct Solar Signal From All Background Sources

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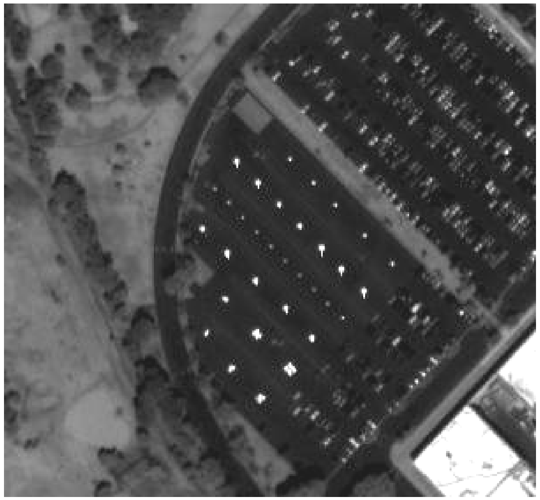
po_365283



po_365284

IKONOS

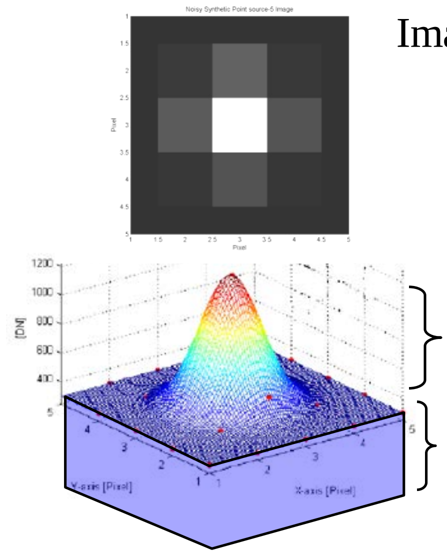


Image of target

Signal from specular target

Signal from background surface, sky path radiance, adjacency effect, stray light, etc.

The integrated energy from a SPARC target is contained in the image profile within a pixel boundary defined by the RAIFOV.

All other sources (background surface radiance, sky path radiance, adjacency effect, stray light, etc.) are uniform over the small target area and can be subtracted out as a bias.

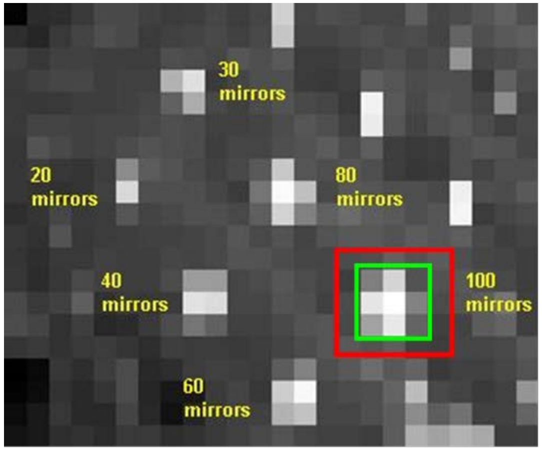
Sensor Integrated Response To SPARC Targets Applies To Subpixel and Small Extended Area Targets

2.4 m Extended Area Target

0.4 m subpixel target

Results in quantized intensities relative to the number of mirrors in the SPARC target.

Targets can be designed to cover full dynamic range of PAN and MSI bands

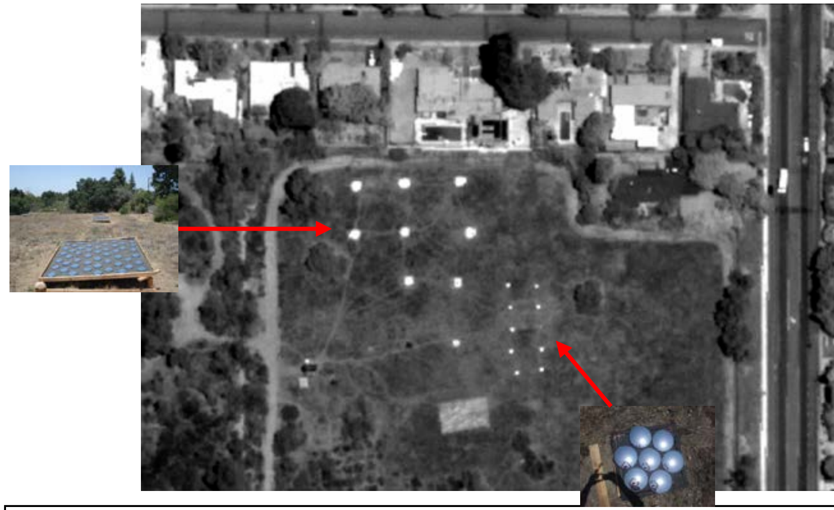


Ensquared energy integrated DN response for each target is measured above the background

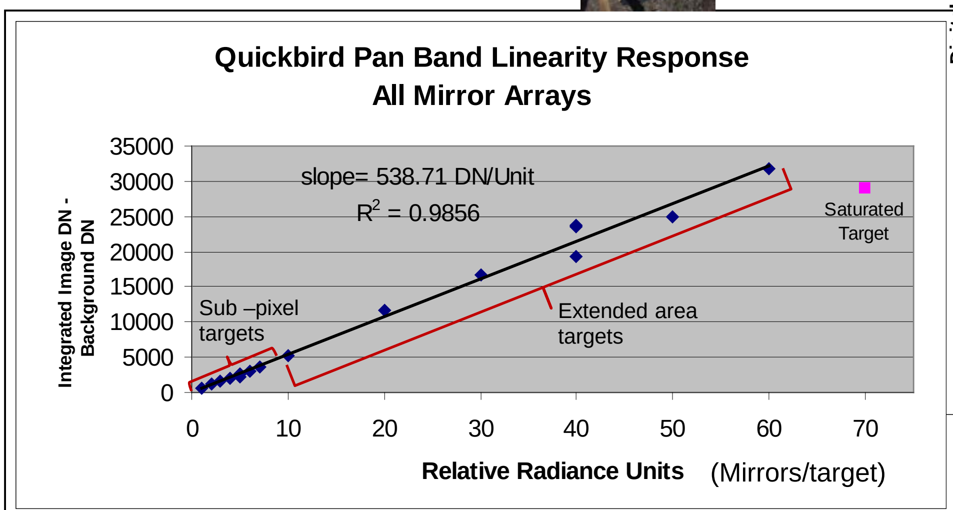
$$\text{Measured Ensquared Energy} = \Sigma \text{DN} = \sum_{n=1}^{9}\left[DN(n) - \overline{DN_{background}}\right]$$

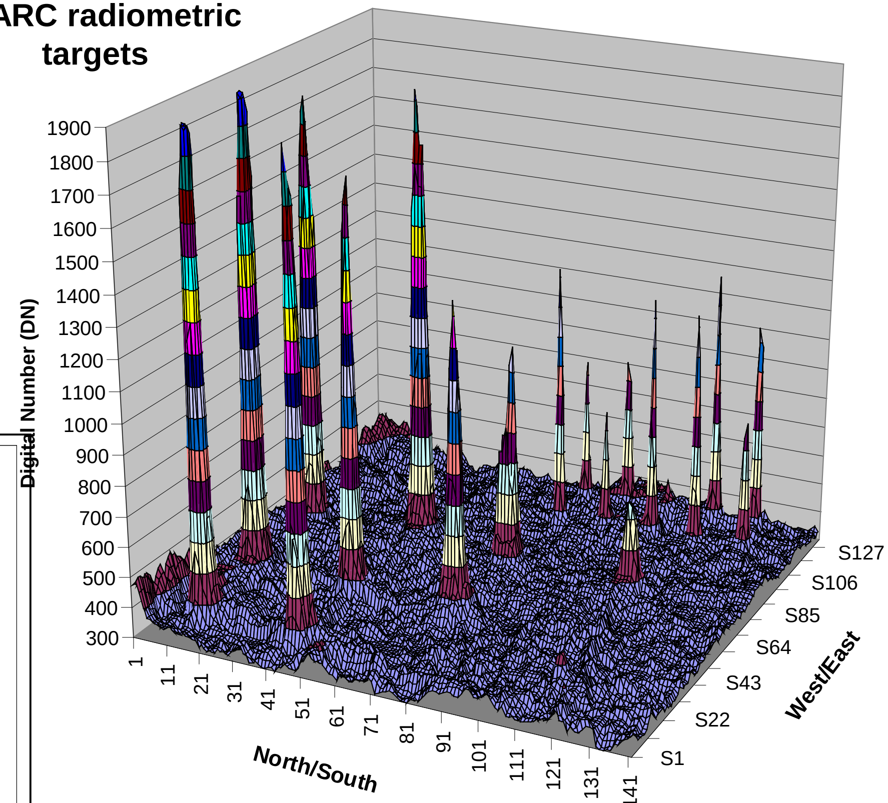
- Total target DN is summed over 3x3 window (green box).
- Average background DN is obtained from perimeter pixel average (red box).

Linearity And Dynamic Range Analysis Using SPARC Method: Independent of target size and shape



QuickBird Pan Image of SPARC radiometric targets





Digital Profile of SPARC Targets

Note that the integrated response to the target is linear with the number of mirrors in the target independent of its size and shape

Spatial Characterization: Oversampling The Full System Point Spread Function

- SPARC uses a grid of spherical reflectors to create point source images at different pixel phasing.
- As a result, the oversampled PSF can be generated from a single image of a mirror array (an instantaneous PSF) or from multiple images of the array for better sampling statistics (a time averaged PSF).

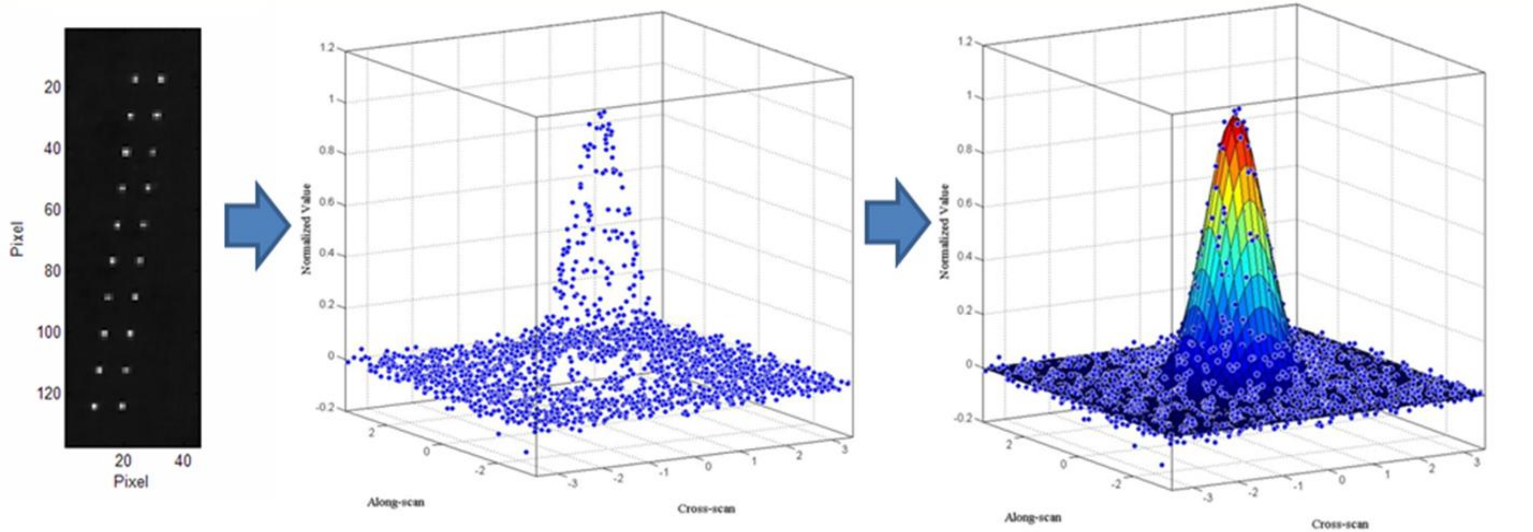
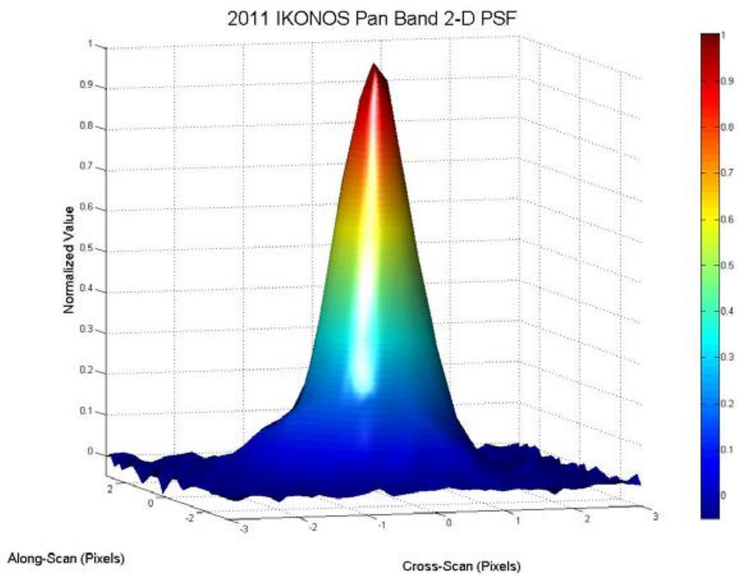


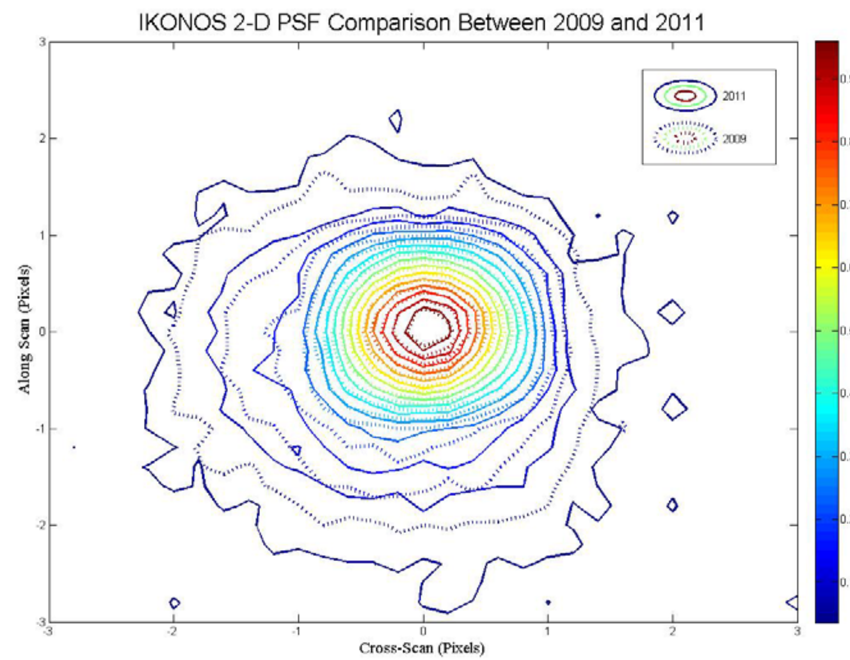
Image of specular mirror array

Individual target images are centered and combined to give oversampled system spatial response function

Profile is characterized with a parametric two dimensional Gaussian model

Detailed Profile of the IKONOS 2-D PSF





•Composite 2-D PSF for IKONOS Pan band from all images collected in 2009 and 2011 – Reveals asymmetry in sensor PSF.

•Detailed knowledge of the full system PSF can be used to establish better resampling and restoration kernels for improved product generation and exploitation.

SPARC Can be Applied to Large Footprint Sensors In a Compact Design

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SPARC Radiometric Target Designed For Multispectral Calibration of Sensor Systems up to 100 m GSD

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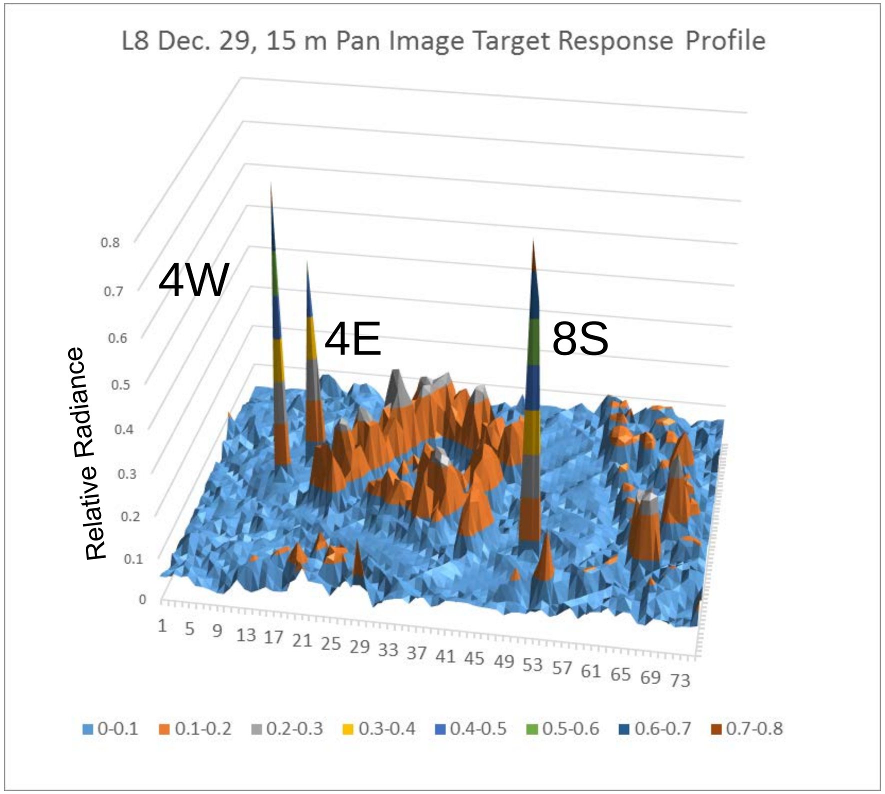
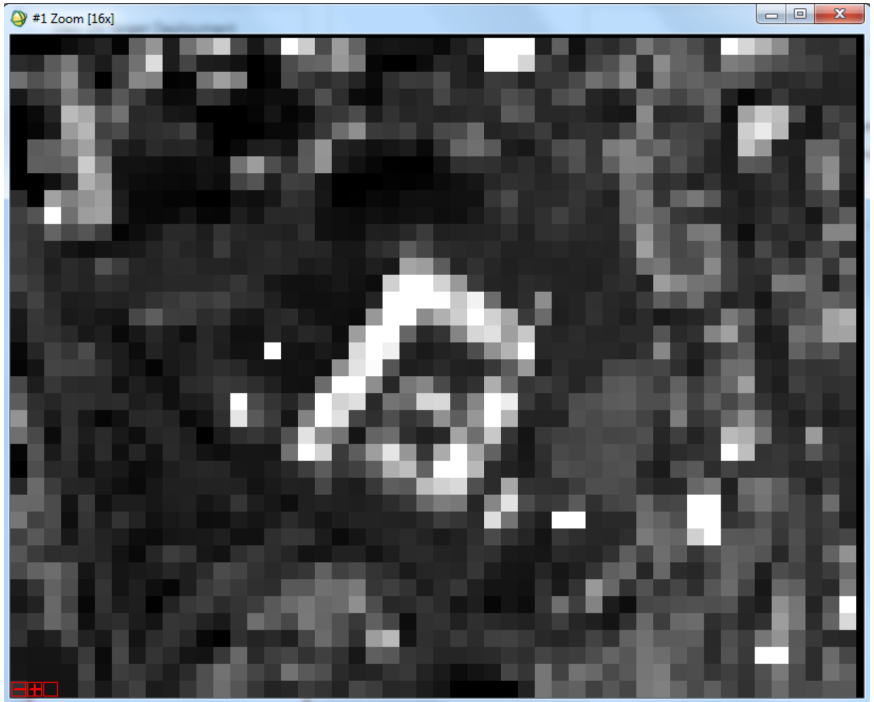
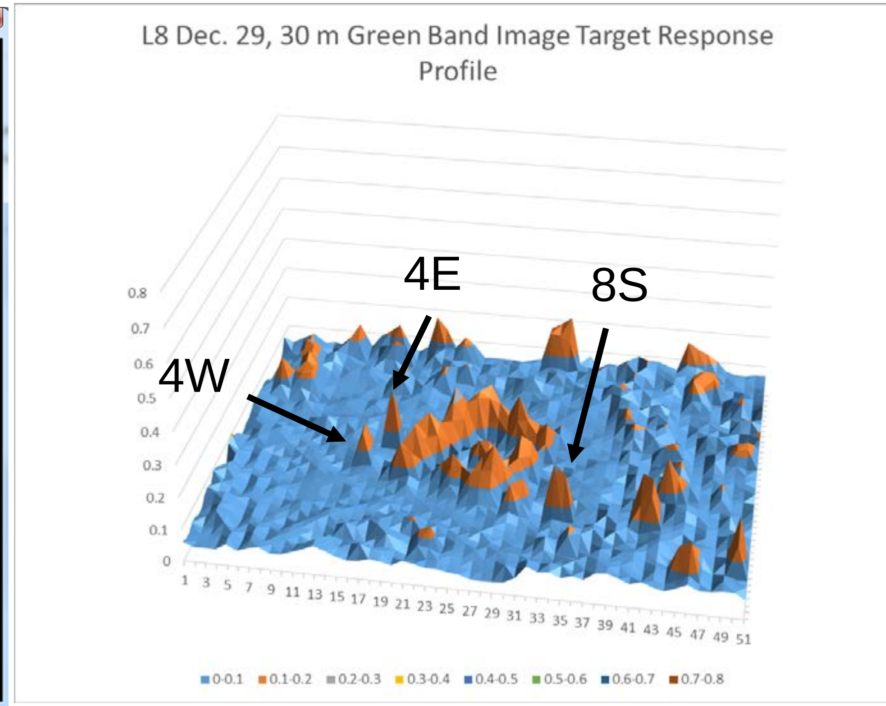
L8 Pan Image SPARC target Response



3D plot shows the relative brightness of the large footprint mirror targets compared to the rest of the scene. The central pixel response to target 8S is equivalent to a top-of-atmosphere Lambertian diffuse reflector of about 80% reflectance.

L8 Green Multispectral Band





- For small targets the apparent radiance is clearly GSD dependent.
- Calibration to intensity rather than radiance will remover the GSD dependency

Creating A Line Spread Function Vicarious Ground Target

- A line target can be created using a continuous line of mirrors that can be easily deployed and set at any a orientation.

po353725

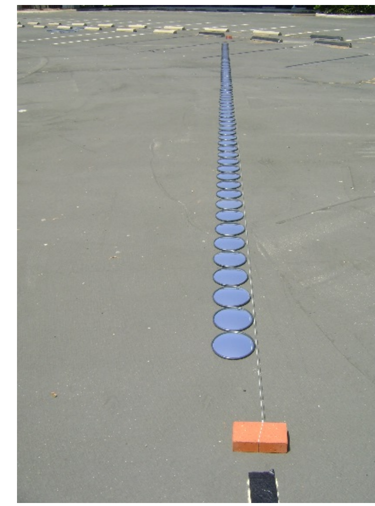
Forward Scan

po353726

Reverse scan

po353727

Target turned off revealing background radiance non-uniformity



70 point facets create the linear target

- Result is a true linear Delta function for 1-dimensional PSF analysis with less noise and better spectral uniformity then derived from edge targets.

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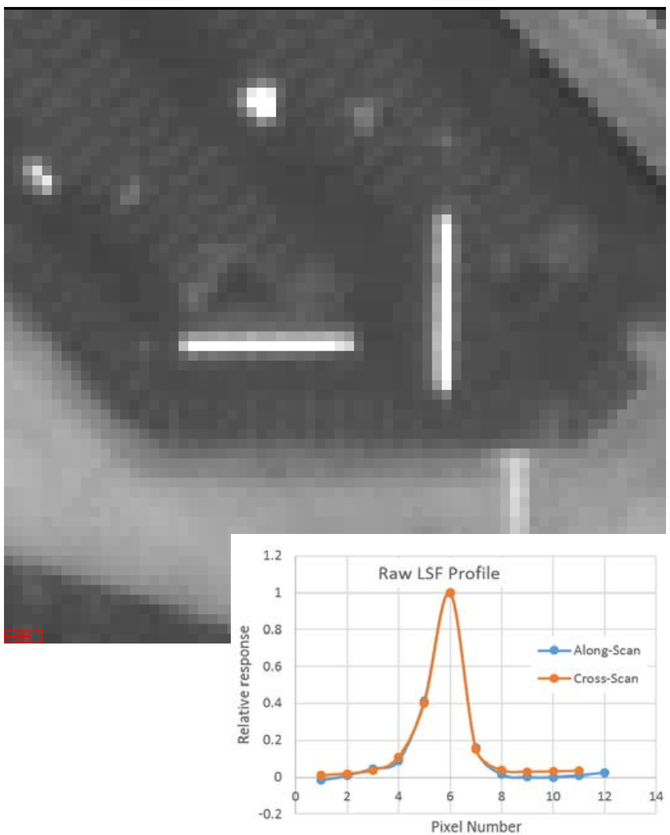
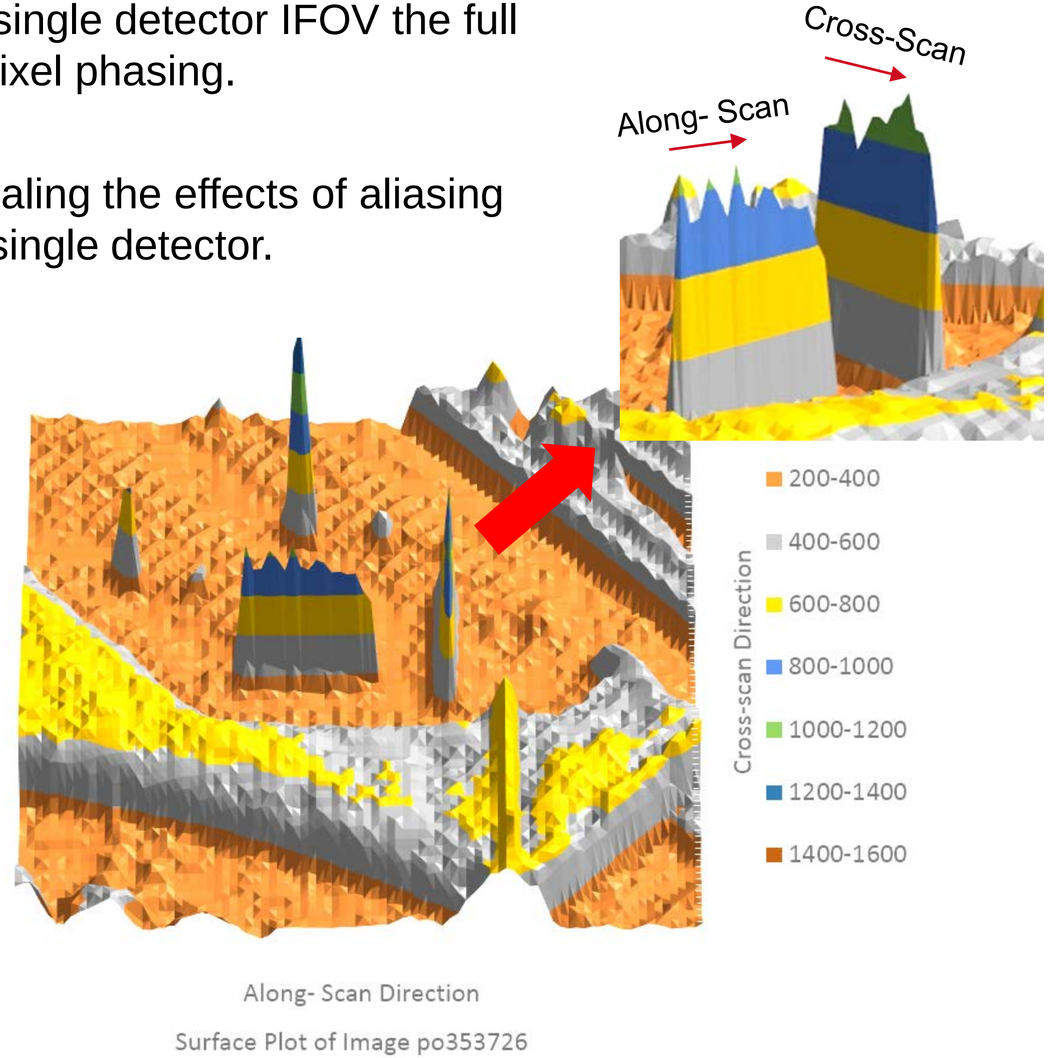
Linear Target Reveal Small Target Issues

- The along-scan line center lies within a single detector IFOV the full length of the target with slowly shifting pixel phasing.
- The varying line brightness may be revealing the effects of aliasing and/or non-uniform sensitivity across a single detector.

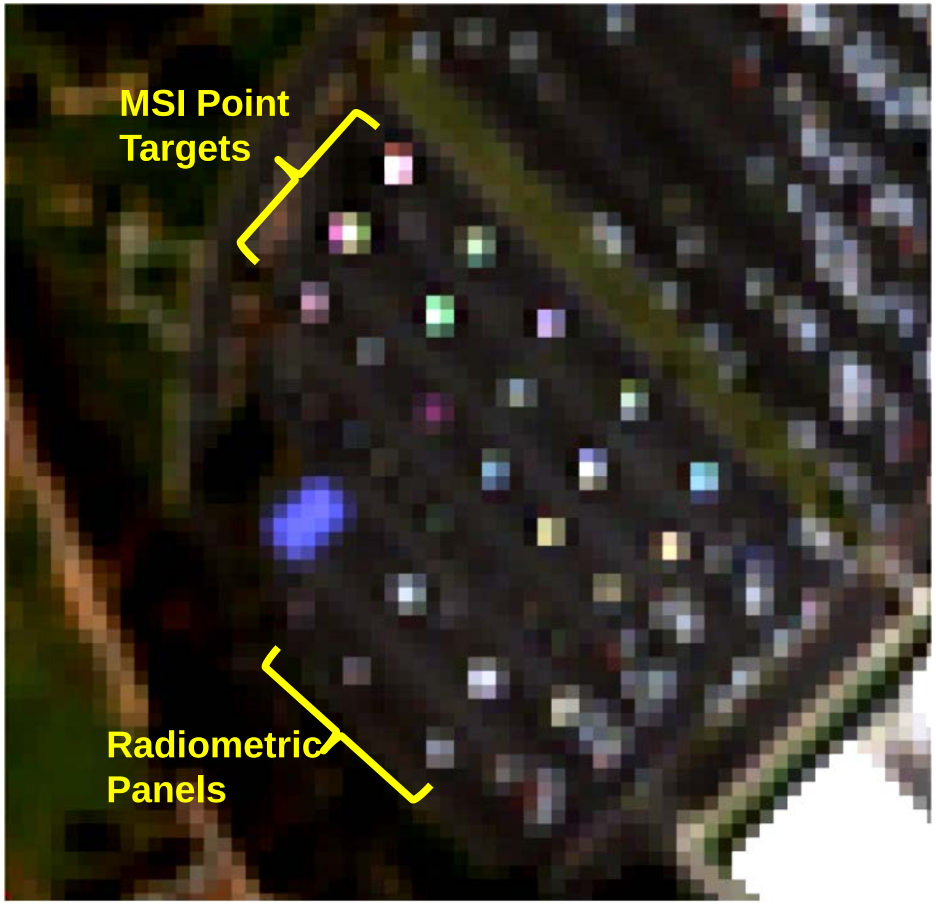




The asymmetry in the IKONOS PSF is easily revealed in the raw data

MSI Point Source Rainbow Effect Reveal Spectral Effect Likely From Band-to-Band Misregistration

Level 0 Processing



IKONOS "true color" RGB Image po_353731 of SPARC targets recorded July 31, 2009

Image implies there is a sub-pixel target size at which the spectral signature may become indeterminable For MSI sensors **no mater how bright the target is!**

Sentinel 2A 10 m GSD Image Presentation of SPARC Targets

- Targets are subpixel, > 1.5 m in size.
- The intensity step size is incremental from 1 to 4 without saturation.
- Targets are visibly affecting pixels in a 6 x 6 pixel area (processing includes resampling for orthorectification).

- Resampling methods need to be improved so as to use PSF/MTF information to direct the energy back into the pixel that contains the target.

Summary

- All of us who use remote sensing image data know that there are issues with the radiometry of small targets that need attention.
- Currently, there are no operational procedures in place within the remote sensing community for analyzing the radiometric uncertainties of small targets.
- The significance of this issue becomes most obvious when imaging bright subpixel targets on a uniform background (SPARC targets).
- The importance of these types of targets is that they highlight the reality within the image processing chain of all small targets in a typical scene that are generally too cluttered to evaluate how the spatial performance is affecting the radiometry of the image data.
- When one has a capability to reveal and quantify the effects of a sensor's system response to small targets, new improved processing methods can be developed and uncertainties analyzed and validated even at the individual pixel level.
- The SPARC vicarious calibration method provides the reference targets capable of making the improvements needed for small target performance analysis and calibration of solar reflective earth remote sensing systems.

Backup Charts

Mainstream Vicarious Calibration Methods are Intended to Verify Prelaunch or On-board Derived Absolute Gains

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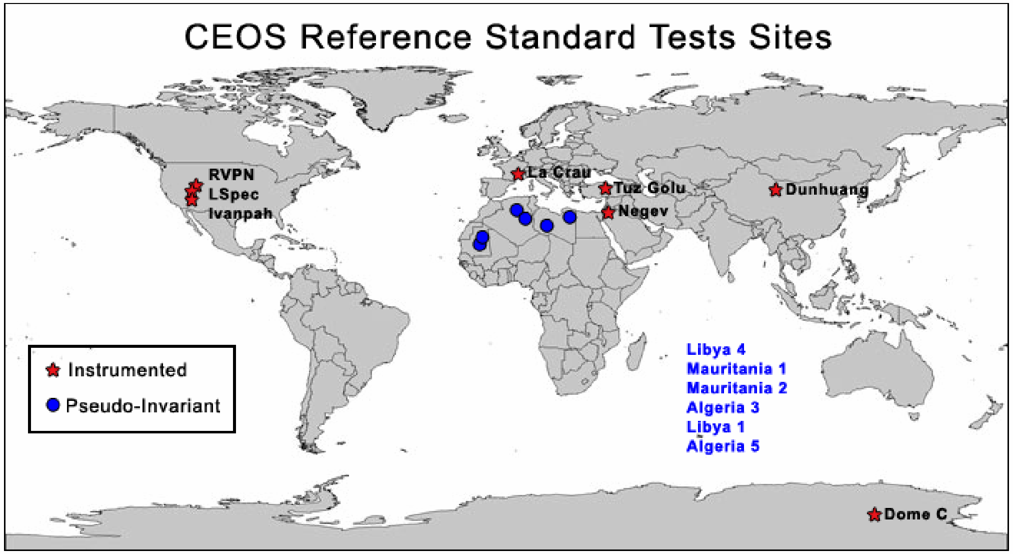
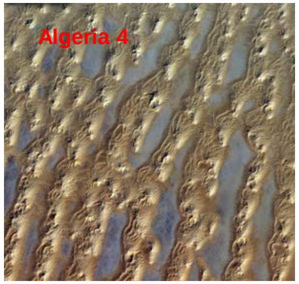
- Terrestrial vicarious test sites provide a convenient means of obtaining information to verify sensor radiometric performance and derive knowledge of biases between sensor.
- These are typically large area desert instrumented or pseudo-invariant sites that fill a large fraction of the sensor FOV for validating the prelaunch or on-board derived gain coefficients.





- The vicarious calibration targets are assumed large enough that the system spatial resolution does not effect the vicarious derived gain coefficients.

Standard vicarious calibration methods for deriving system radiometric gain coefficients do not apply to small targets.

Radiometric Characterization and Calibration

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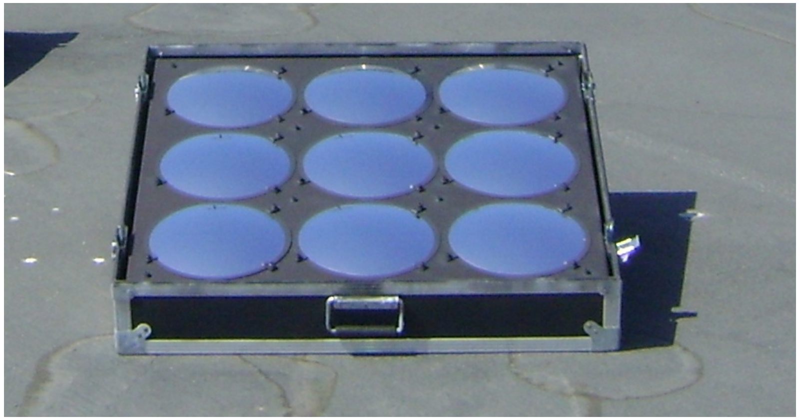
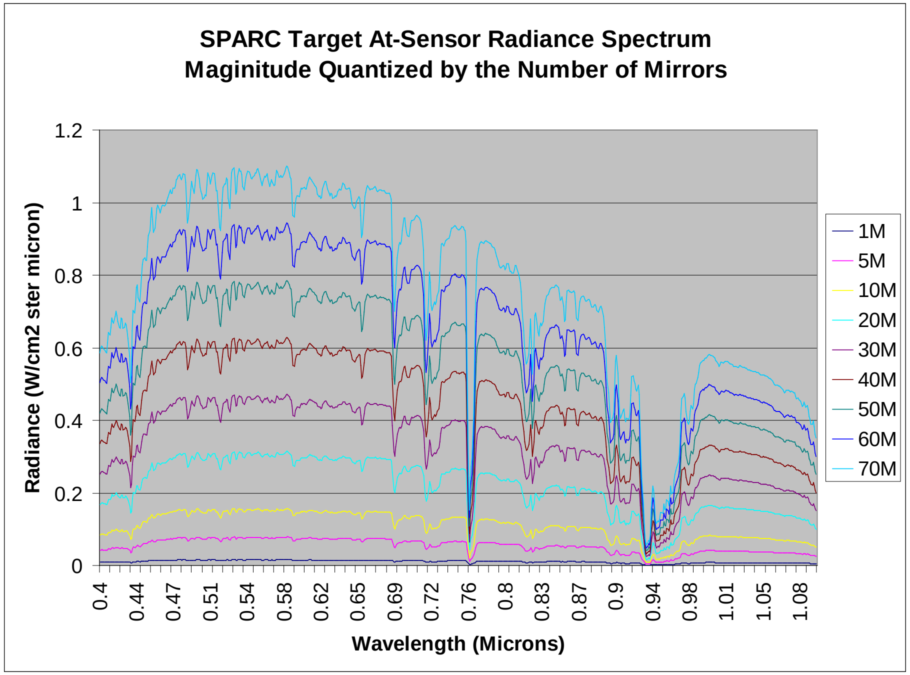
- SPARC uses panels of convex spherical mirrors to create known at-sensor intensity.
- Individual mirrors produce an upwelling intensity controlled by the mirror's radius of curvature.
- Total intensity of each target is quantized by the number of mirrors.
- Method results in a simplified radiative transfer equation for calculating accurate values of at-sensor radiance.
- Only ground truth data required is measurements of atmospheric transmittance.





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Derivation of the Spatial RAIFOV Approximation

The radiometrically accurate IFOV (RAIFOV) of a sensor quantifies the required spatial extent of an extended area target for use in accurate radiometric calibration. Under the assumption of a Gaussian SpaRF, a simple relation between the Gaussian FWHM and the RAIFOV can be analytically derived with the approximate result that

$$w_{\mathrm{RAIFOV}} \approx 8.33\, w_{\mathrm{FWHM}}$$

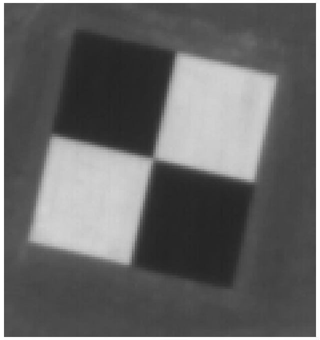
in which
$w_{\mathrm{RAIFOV}} \equiv$ radiometrically accurate IFOV [pixels], and
$w_{\mathrm{FWHM}} \equiv$ SpaRF FWHM resolution [pixels].

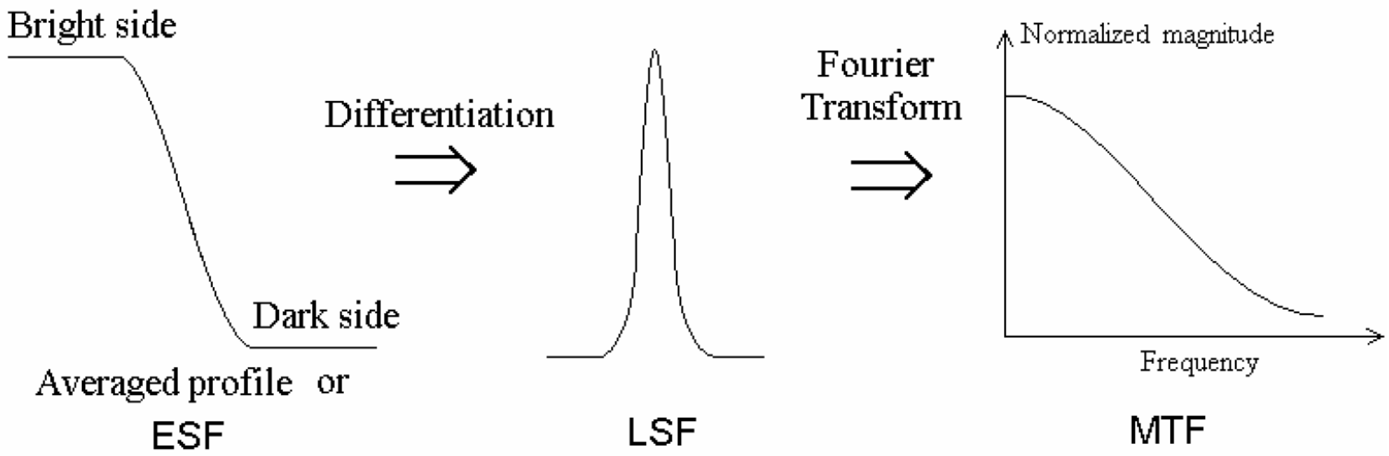
The straightforward derivation of the above relation proceeds as follows. For simplicity and without loss of generality, consider a zero-mean one-dimensional Gaussian function (representing either the cross-scan or along-scan one-dimensional SpaRF profile) of the form $y(x) = a\exp\left[-\alpha x^2 / w_{\mathrm{FWHM}}^2\right]$ in which a is the amplitude, w_{FWHM} is the FWHM in the spatial domain, and $\alpha = \ln(\sqrt{256})$ is the scaling constant such that the width is a FWHM. Calculating the modulation transfer function (MTF) is equivalent to computing the DC normalized Fourier transform of the SpaRF. Define the Fourier transform of the SpaRF as $Y(f) = F\{y(x)\}$ where $F\{\cdot\}$ is the Fourier transform operator. Then, $\mathrm{MTF}(f) \equiv |Y(f)/Y(0)|$. Now, the Fourier transform of a Gaussian function is another Gaussian function. The modulus operator and DC normalization of the MTF do not affect the Gaussian width in the spatial frequency domain. Given a SpaRF with FWHM w_{FWHM} in the spatial domain, the FWHM of the MTF function in the spatial frequency domain can be directly computed as $\hat{w}_{\mathrm{FWHM}} = \beta^2(2\pi w_{\mathrm{FWHM}})^{-1}$, in which $\beta = \sqrt{\ln(256)}$ is the conversion from Gaussian 1-sigma width to FWHM: $w_{\mathrm{FWHM}} = \beta\sigma$. Then, the MTF can be analytically expressed as $\mathrm{MTF}(f) = \exp\left[-\alpha f^2 / \hat{w}_{\mathrm{FWHM}}^2\right]$, or after substitution $\mathrm{MTF}(f) = \exp\left[-\alpha(2\pi)^2 f^2 w_{\mathrm{FWHM}}^2 / \beta^4\right]$. Finally, the $\mathrm{RAIFOV} \equiv 1/f^*$ in which f^* is the frequency such that $\mathrm{MTF}(f^*) = 0.95$. Computing the results directly and simplifying yields the following exact relationship for the RAIFOV: $w_{\mathrm{RAIFOV}} = \left(\frac{\pi}{\beta}\sqrt{\frac{-2}{\ln(0.95)}}\right) w_{\mathrm{FWHM}}$ or after evaluating the terms in parentheses $w_{\mathrm{RAIFOV}} \approx 8.33\, w_{\mathrm{FWHM}}$. q.e.d.

Schiller, S. J. and J. Silny, "ARTEMIS - Advanced Responsive Tactically Effective Militarily Imaging Spectrometer On-Orbit Radiometric And Image Quality Analysis Using Small Ground Targets" 2010 MSS Passive Sensors.

SPARC Targets as an Alternative To Edge Targets For Deriving a Line Spread Function (LSF)

- Edge targets are most commonly used for MTF analysis of sensor system spatial performance.
- The edge response is differentiated to obtain a LSF





- Because differentiation always reduces the SNR, creating a line target of very high contrast to skip this step has the potential improve MTF analysis.