# Vicarious Calibration of the IKONOS Earth Observing Sensor Using the Specular Array Radiometric Calibration (SPARC) Method

Stephen Schiller and John Silny

Raytheon Space and Airborne Systems, El Segundo, CA

Martin Taylor

GeoEye, Thornton, CO

11th International Conference on New Developments And Applications in Optical Radiometry (NEWRAD 2011)

Monday, September 19, 2011

The best way to predict the future is to invent it.
Dr. Alan Kay, c. 1971

# Presentation Outline

- Description of the SPARC method as an new innovative vicarious calibration technique.
- Introduce the SPARC radiative transfer equation.
- Establish a SPARC relative calibration as a measure of reproducibility in the sensor response
- Describe the conversion to absolute radiometric calibration coefficients.
- Application of the SPARC method to multiple IKONOS overpasses
- Comparison of IKONOS absolute calibration coefficients derived by the SPARC method with values derived from the standard reflectance-based method.

# The SPecular Array Radiometric Calibration (SPARC) Method

Raytheon
Space and Airborne Systems

## Provides A New Approach to Absolute Vicarious Calibration Using Spherical Reflectors

- Represents a fusion of the reflectance-based vicarious approach with stellar calibration
- Accomplished by creating an array of “solar stars” on the ground with convex spherical mirrors
- Targets are low cost, small and easy to deploy


3

# Spatial Characterization: Oversampling The Sensor Point Spread Function (PSF)



- SPARC uses a grid of spherical reflectors to create points source images at different pixel phasing to oversample the sensor Point Spread Function (PSF)

  Technique developed at South Dakota State University

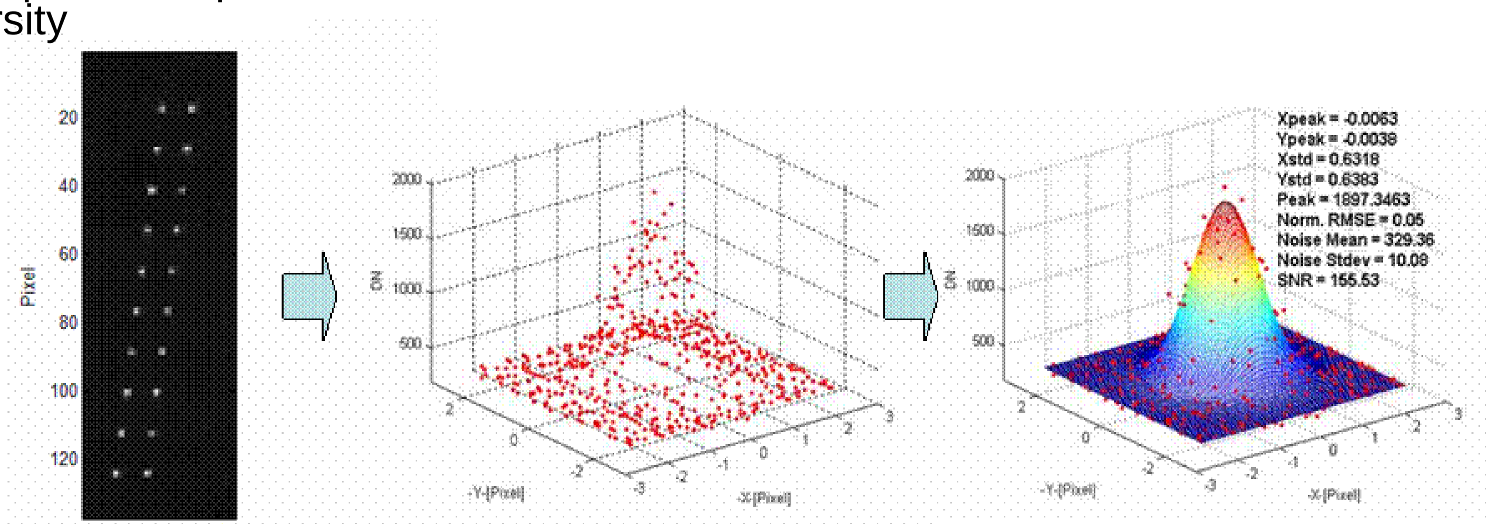



Image of specular mirror array

20 images are centered and combined to give oversampled PSF

Profile is modeled with a Gaussian function

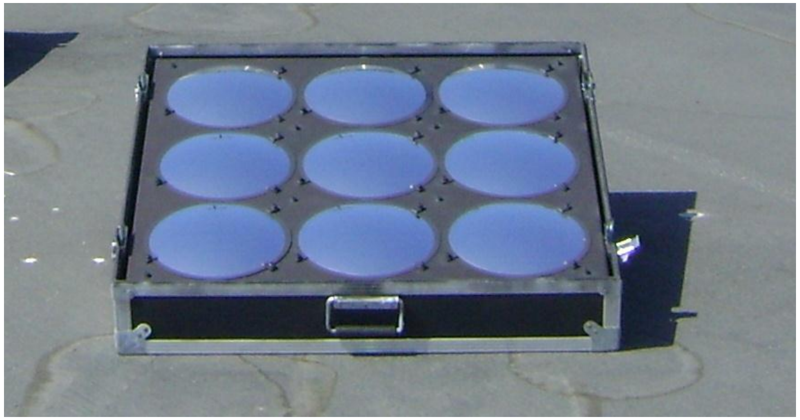
**Measurement provides knowledge of ensquared energy needed to use small targets for radiometric calibration**

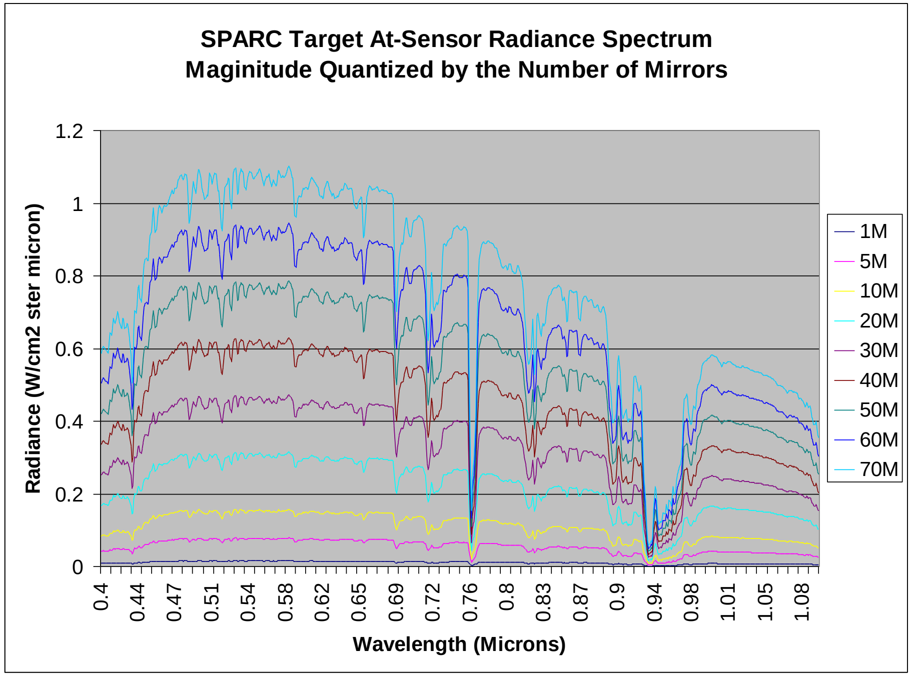
4

# Radiometric Characterization and Calibration

Raytheon
Space and Airborne Systems

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





# SPARC Radiative Transfer Equation For Effective TOA Radiance

## TOA Intensity (Sensor Independent)

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

Watts/( sr micron)/mirror

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

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

Watts/(m$^2$ sr micron)/mirror

$\rho\ (\lambda,\theta_r)$ = mirror specular reflectance

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

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

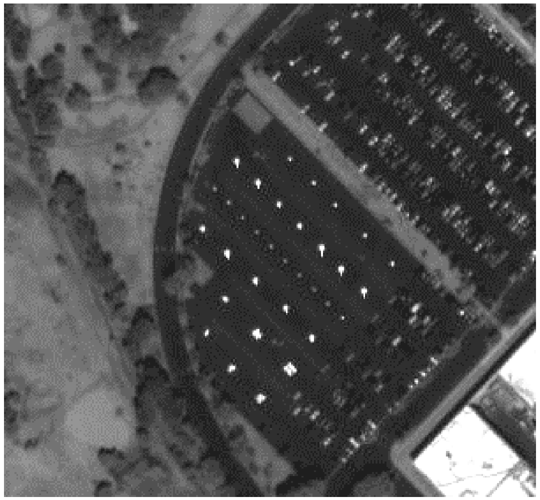
$E_o\ (\lambda)$ = Solar spectral constant
$R$ = Mirror radius of curvature (m)
GSD = Line-of-site ground sample distance (m)

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

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

Raytheon
Space and Airborne Systems

po_365283



po_365284

IKONOS

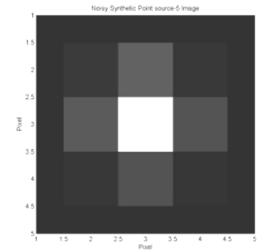
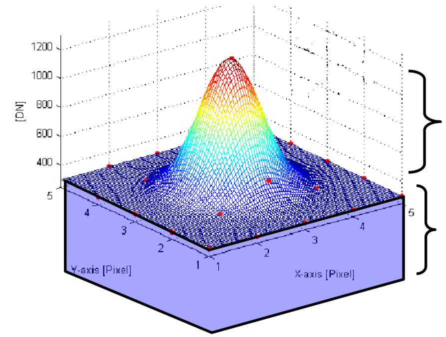


Image of target




Signal from specular target

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

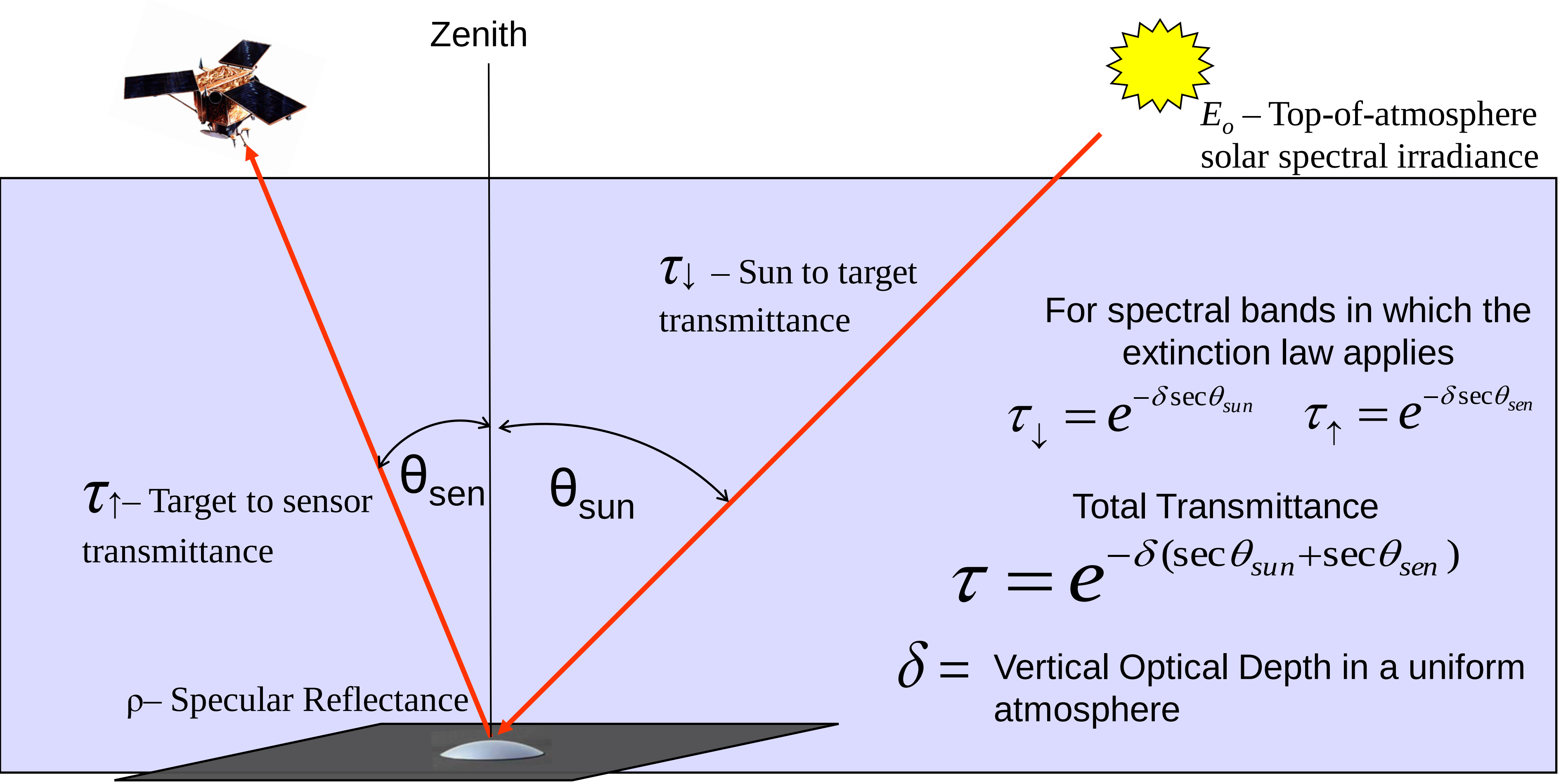
All the energy from subpixel SPARC targets are contained in the image Point Spread Function (PSF).

All other sources (background surface radiance, sky path radiance, adjacency effect, stray light, ect.) are uniform over the size of the PSF and can be subtracted out as a bias.

Allows separation of sensor response to the SPARC target (direct solar signal) from the background based on image data alone

# Transmittance Is the only atmospheric effect in the SPARC at-sensor radiance prediction.






For spectral bands in which the extinction law applies

$$\tau_\downarrow = e^{-\delta \sec\theta_{sun}} \qquad \tau_\uparrow = e^{-\delta \sec\theta_{sen}}$$

Total Transmittance

$$\tau = e^{-\delta(\sec\theta_{sun} + \sec\theta_{sen})}$$

$\delta =$ Vertical Optical Depth in a uniform atmosphere

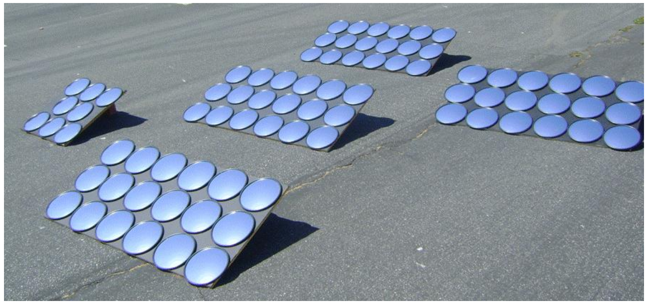
**Vertical optical depth is measured with a sunphotometer and modeled using MODTRAN to calculate in-band transmittance**

# Mirrors Provide Nearly Ideal Reflectance Calibration Targets

Raytheon
Space and Airborne Systems

- High reflectance
- Spectrally Flat
- Nearly constant over the sensor's operational elevation and azimuth
- No foreshortening effects as with small diffuse targets
- No need to measure reflectance in the field at overpass.

- Mirrors are deployed on dark uniform background (asphalt parking lot)
- Mirrors are inexpensive (D.O.T. approved truck mirrors with R = 18.28 +/- 0.10 inches)

•Mirror reflectance knowledge accuracy is ~0.25% VNIR and ~0.5% SWIR (1 sigma). Uncertainty in the reflectance of diffuse targets used in the reflectance based method is much higher (~2%)

•Angle of Incidence variations in reflectance typically negligible (~0.25%)

# SPARC Relative Vicarious Radiometric Calibration

Raytheon
Space and Airborne Systems

- Provides a measurand for the evaluation of the reproducibility of SPARC vicarious calibration method.
- Relative calibration achieved by determining the **"Zero Atmosphere Response Constant" => "*$DN_o$*"** .
  - This is the instrumental digital number (DN) response to a reference SPARC reflector when the atmospheric transmittance = 1.
  - The response is the integrated (∑DN) over the image PSF of a SPARC radiometric target.
- Provides a relative calibration for the response of the imaging sensor similar to the top-of-atmosphere calibration constant of a sunphotometer.

# "Zero Atmosphere Response Constant" – $DN_o$ (SPARC Reproducibility Measurand)

Raytheon
Space and Airborne Systems

- Setting $\tau_{\downarrow}$ =1 and $\tau_{\uparrow}$=1, the SPARC radiative transfer equation becomes

$$L_o^{at-sensor}(\lambda) = \rho(\lambda) E_o(\lambda) \left( \frac{R}{2GSD_o} \right)^2$$

$GSD_o$ =Sensor's Reference GSD
$GSD_o$ (IKONOS Pan) = 0.8m
$GSD_o$ (IKONOS MSI) = 3.2m

- Assuming a linear, offset subtracted response for the imaging sensor then

$$DN_o = gL_{at-sensor}(\lambda)_o$$ so that

$$DN_o(\lambda) = g(\lambda)\rho(\lambda) E_o(\lambda) \left( \frac{R}{2GSD_o} \right)^2$$

$$= \text{"Zero Atmosphere Response Constant"}$$

- Fixed by sensor and mirror parameters, otherwise

$$DN_o(\lambda) \propto E_o(\lambda)$$ Proportional to Solar Spectral Constant

# Measuring $DN_o$ for a sensor collect



- In any atmosphere, when imaging a SPARC reflector, the observed DN/mirror sensor response will be

$$DN(\lambda) = g(\lambda)L^{at-sensor}(\lambda) = \tau_{\downarrow}(\lambda)\tau_{\uparrow}(\lambda)\underbrace{g(\lambda)\rho(\lambda)E_o(\lambda)\left(\frac{R}{2}\right)^2}_{= DN_0 GSD_o^2 \quad (insert)}\frac{1}{GSD^2}$$

Solve for "Zero Atmosphere Response Constant"

$$DN_o(\lambda) == \frac{GSD^2 DN(\lambda)}{GSD_o^2 \tau_{\uparrow}(\lambda)\tau_{\downarrow}(\lambda)}$$

DN/mirror is measured directly from sensor image

$\tau_{\downarrow}\tau_{\uparrow}$ is derived from simultaneous sunphotometer measurements

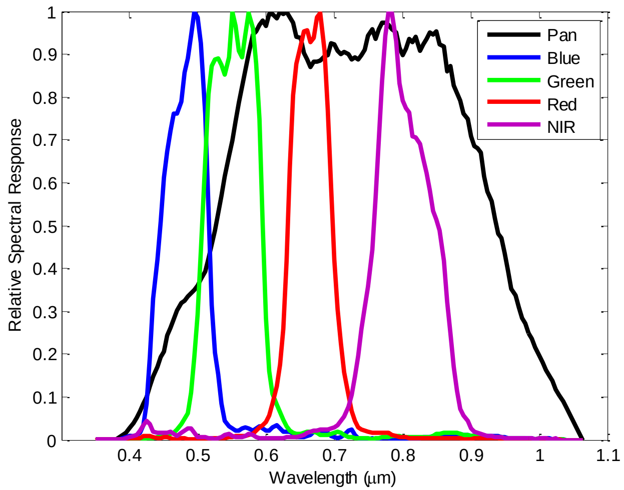
# Measuring $DN_o$ -Part 1

Raytheon
Space and Airborne Systems

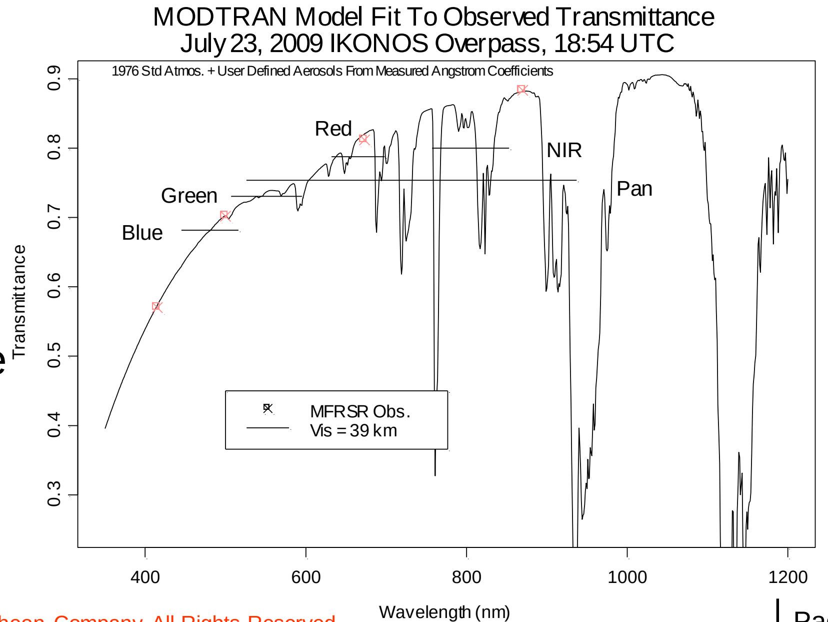
- Operate a sun photometer to measure aerosol optical depth, ozone and water vapor columnar amounts during collects
- Based on sunphototmeter measurements, build a MODTRAN model to produce a $\tau_{\uparrow}(\lambda)$ and $\tau_{\downarrow}(\lambda)$ spectra for the solar and sensor illumination and view geometry of the image.
- Integrate MODTRAN transmittance spectra with sensor RSR to get $\tau_{\uparrow}(\lambda)$ and $\tau_{\downarrow}(\lambda)$ in each sensor band.

Band transmittance =∑(Trans(λ)*RSR(λ))/∑ RSR(λ)

IKONOS RSR Curves



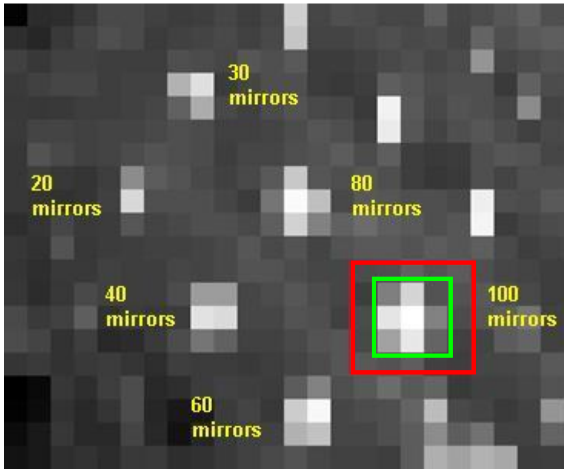

IKONOS band integrated Pan and MSI transmittance values



Raytheon
Space and Airborne Systems

# Measuring $DN_o$ -Part 2

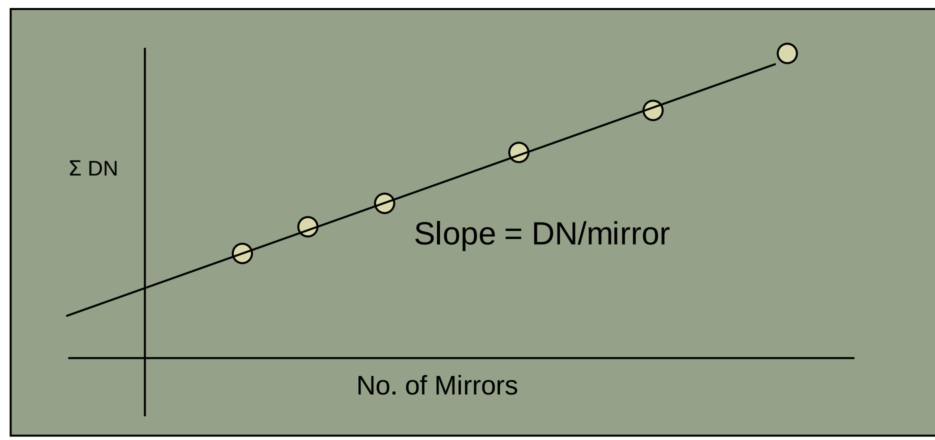
- Analyze image of SPARC target to get DN/mirror response




•Total Target DN summed over 3x3 window (green box)

•$\overline{DN}_{background}$ obtained from perimeter pixel average (red box).

$$\text{Target } \Sigma\text{DN} = \sum_{n=1}^{9}\left[DN(n) - \overline{DN}_{background}\right]$$



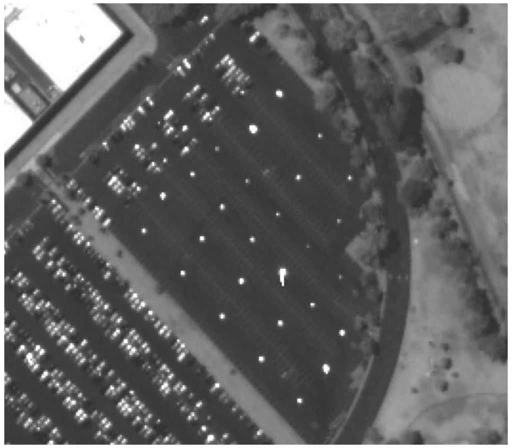

Slope = *DN(λ)/mirror*

for a spectral band

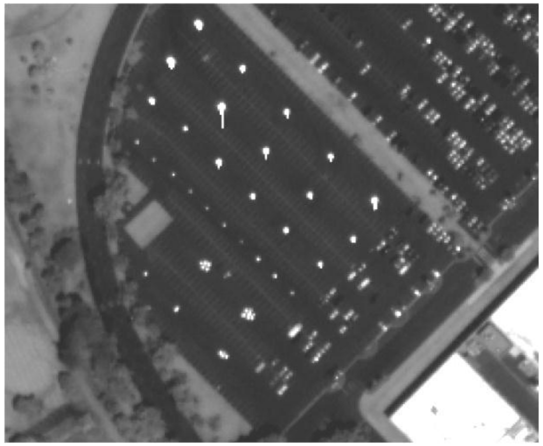
- Solve for $DN_o(\lambda) == \dfrac{GSD^2 DN(\lambda)}{GSD_o^2 \tau_{\uparrow}(\lambda)\tau_{\downarrow}(\lambda)}$

# Vicarious Calibration of IKONOS (2009 collects)

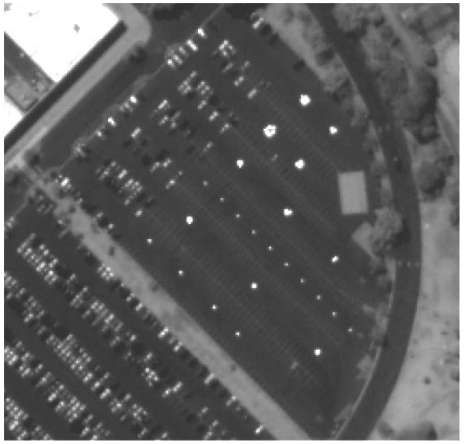
Raytheon
Space and Airborne Systems



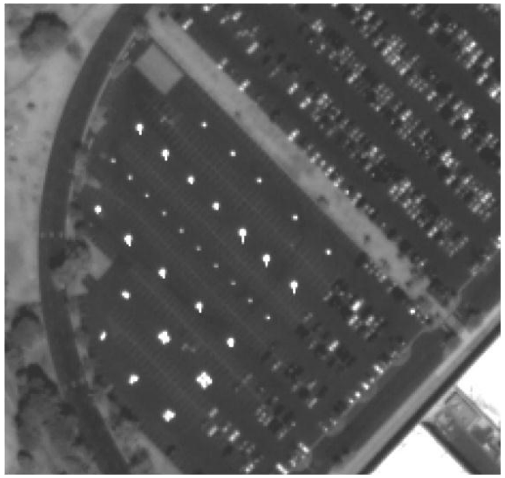
July 23



July 31

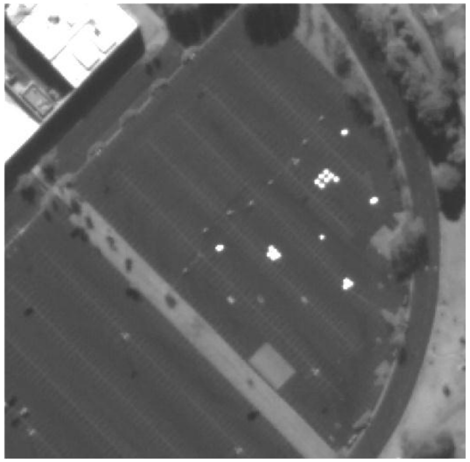


Sept 2



Sept 10

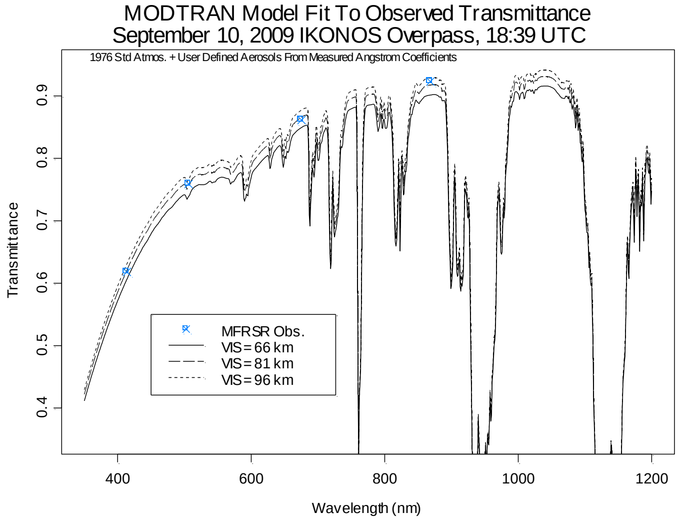
- Five overpass days
- Two collects per overpass
- 10 calibration points



Nov 15

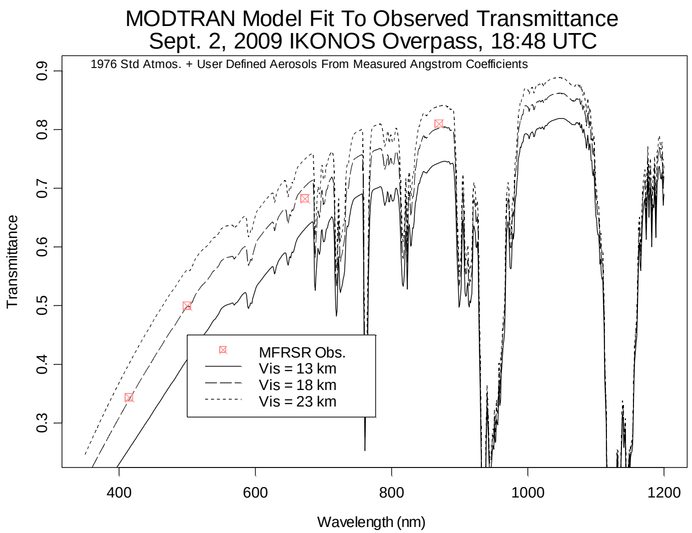
# Band Integrated Atmospheric Transmittance

Raytheon
Space and Airborne Systems




Clearest Day
Sept. 10, 2009
Vis = 81 km

| Sept. 10, 2009 | | |
|---|---|---|
| Image po_365282 | | |
| | $\tau_{\downarrow}(\lambda)$ | $\tau_{\uparrow}(\lambda)$ |
| Pan | 0.7841 | 0.8093 |
| Blue | 0.7357 | 0.7656 |
| Green | 0.7773 | 0.8032 |
| Red | 0.8279 | 0.8476 |
| NIR | 0.8332 | 0.8498 |

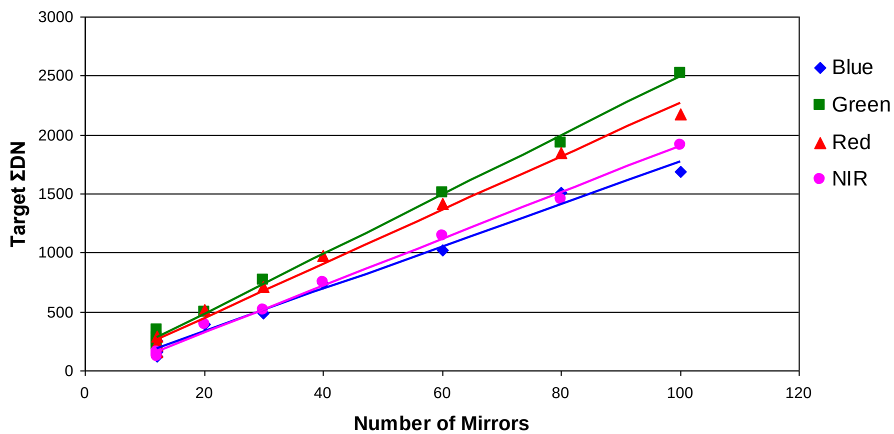



Haziest Day
Sept. 2, 2009
Vis = 18 km

| Sept. 2, 2009 | | |
|---|---|---|
| Image po_364249 | | |
| | $\tau_{\downarrow}(\lambda)$ | $\tau_{\uparrow}(\lambda)$ |
| Pan | 0.6427 | 0.6779 |
| Blue | 0.4748 | 0.5239 |
| Green | 0.5667 | 0.6117 |
| Red | 0.6687 | 0.7048 |
| NIR | 0.7087 | 0.7389 |

# Image Analysis: Measurement of DN/Mirror

DN/Mirror: Image po_365282 Glass Mirror SPARC Target

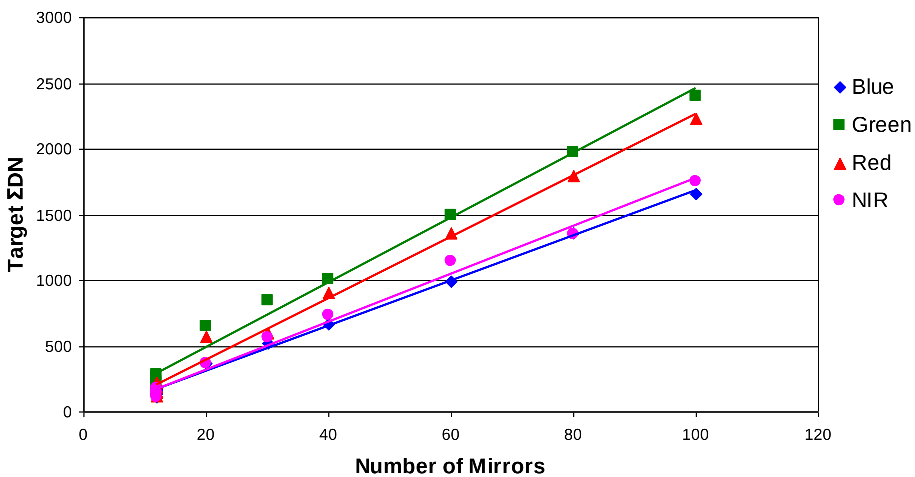



| Spectral Band | Slope: DN/Mirror | $R^2$ |
|---|---|---|
| Blue | 17.9 | 0.9898 |
| Green | 25.2 | 0.9972 |
| Red | 22.8 | 0.9917 |
| NIR | 19.8 | 0.9965 |

Results for Sept. 10, 2009

IKONOS collect.

DN/Mirror: Image po_365283 Glass Mirror SPARC Target



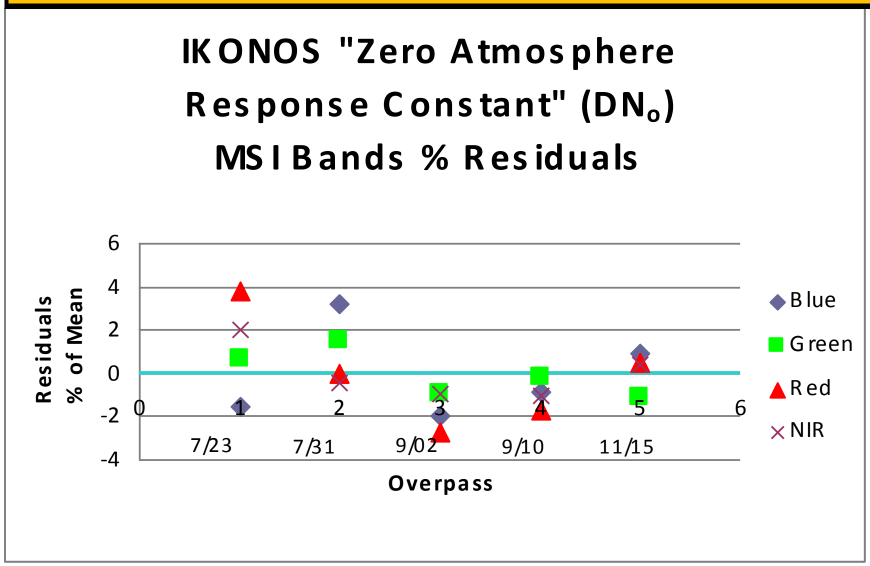

| Spectral Band | Slope: DN/Mirror | $R^2$ |
|---|---|---|
| Blue | 17.2 | 0.9963 |
| Green | 24.8 | 0.9886 |
| Red | 23.4 | 0.9904 |
| NIR | 18.2 | 0.9913 |

# SPARC Relative Calibration of IKONOS

**Raytheon**
**Space and Airborne Systems**

Values adjusted to Sun/Earth Distance = 1AU

| Date | Overpass Average: $DN_o$ - Pan | Overpass Average: $DN_o$ - Blue | Overpass Average: $DN_o$ - Green | Overpass Average: $DN_o$ - Red | Overpass Average: $DN_o$ - NIR | Individual Images: $DN_o$ - Pan | Individual Images: $DN_o$ - Blue | Individual Images: $DN_o$ - Green | Individual Images: $DN_o$ - Red | Individual Images: $DN_o$ - NIR |
|---|---|---|---|---|---|---|---|---|---|---|
| 23-Jul | 558.41 | 36.15 | 47.04 | 40.67 | 32.32 | 554.14 | 38.07 | 45.57 | 39.94 | 31.30 |
| 23-Jul | | | | | | 562.67 | 34.23 | 48.51 | 41.39 | 33.33 |
| 31-Jul | 585.63 | 37.92 | 47.43 | 39.13 | 31.51 | 597.59 | 39.59 | 45.94 | 37.50 | 30.76 |
| 31-Jul | | | | | | 573.68 | 36.26 | 48.91 | 40.76 | 32.25 |
| 2-Sep | 575.45 | 36.00 | 46.28 | 38.08 | 31.36 | 567.98 | 36.37 | 47.22 | 36.99 | 30.83 |
| 2-Sep | | | | | | 582.93 | 35.62 | 45.34 | 39.16 | 31.89 |
| 10-Sep | 592.12 | 36.39 | 46.63 | 38.46 | 31.32 | 608.58 | 36.42 | 46.16 | 37.21 | 32.02 |
| 10-Sep | | | | | | 575.66 | 36.37 | 47.10 | 39.71 | 30.62 |
| 15-Nov | 552.15 | 37.02 | 46.19 | 39.32 | 31.77 | 508.28 | 36.45 | 45.88 | 38.77 | 31.15 |
| 15-Nov | | | | | | 596.02 | 37.60 | 46.51 | 39.87 | 32.40 |
| **Average $DN_o$** | **572.75** | **36.70** | **46.71** | **39.13** | **31.66** | | | | | |
| **Std Deviation** | **17.17** | **0.79** | **0.52** | **0.99** | **0.41** | | | | | |
| **% Std Deviation** | **3.00** | **2.15** | **1.11** | **2.54** | **1.29** | | | | | |




Results validate the <u>reproducablity</u> of the SPARC relative calibration based on 5 collects over a 5 month period to better than 2.5% in the MSI bands. 3% in the Pan band

Raytheon
Space and Airborne Systems

# Absolute Gain Calculation

- Conversion to absolute gain depend only on parameters associated with the mirrors and sensor.

$$g(\lambda) = \frac{DN_o(\lambda)}{L_o^{at-sensor}} = \frac{DN_o(\lambda)}{\rho(\lambda)E_o(\lambda)}\left(\frac{2GSD_o}{R}\right)^2 \quad \text{DN/[Watts/(m}^2\text{ sr micron)]}$$

- To arrive at the in-band absolute scale we must include factors for the bandwidth and ensquared energy correction

$$g(\lambda) = \frac{DN_o(\lambda)}{\rho(\lambda)E_o(\lambda)Bandwidth(\lambda)EnsqEnergyCor(\lambda)}\left(\frac{2GSD_o}{R}\right)^2 \quad \text{DN/[Watts/(m}^2\text{ sr)]}$$

- Uncertainties
  - reflectance ($\rho$) ~0.5%
  - *EnsgEnergyCor.*~ 0.5%
  - Radius of curvature (R) ~0.5%
- Thus, the reproducibility of absolute gain values are determined by reproducibility of the relative response, $DN_{o.}$
- **The in-band gain,$g(\lambda)$, provides the calibration coefficient (*CalCoef*) for IKONOS absolute radiometry**

# IKONOS Absolute Gain Results Using SPARC Vicarious Calibration Method

Raytheon
Space and Airborne Systems

| IKONOS Band (λ) | GeoEye Published *CalCoef.*[a,b] DN/[W/(m² sr)] | SPARC Measured *CalCoef.*[b] DN/[W/(m² 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

Reproducibility provides a measure of the relative error in the derived calibration coefficients using the SPARC method.

The potential systematic errors between the SPARC method and reflectance-based vicarious calibration for equivalent conditions is under investigation.

# Conclusion

- Initial results indicate that the SPARC method is successful as a method of vicarious calibration using small targets.
- SPARC provides a simplified alternative to the reflectance-based vicarious radiometric calibration method.
- The SPARC method is designed to provide simultaneous spatial and radiometric calibration.
- The SPARC method achieves absolute vicarious calibration at a significantly lower cost and effort than the reflectance-based method.
- The SPARC methodology greatly reduces atmospheric effects and target reflectance uncertainty. Results in the potential to achieve better accuracy than reflectance-based method.
- Sensor calibration relative to the solar spectral constant was demonstrated to be reproducible to < 2.5% for the IKONOS MSI bands (3% pan). Note that this validation was accomplished with targets in a major urban setting at sea level.
- The large systemic difference in several bands, between the SPARC measured and GeoEye published, gain values is under investigation.

# Backup Charts

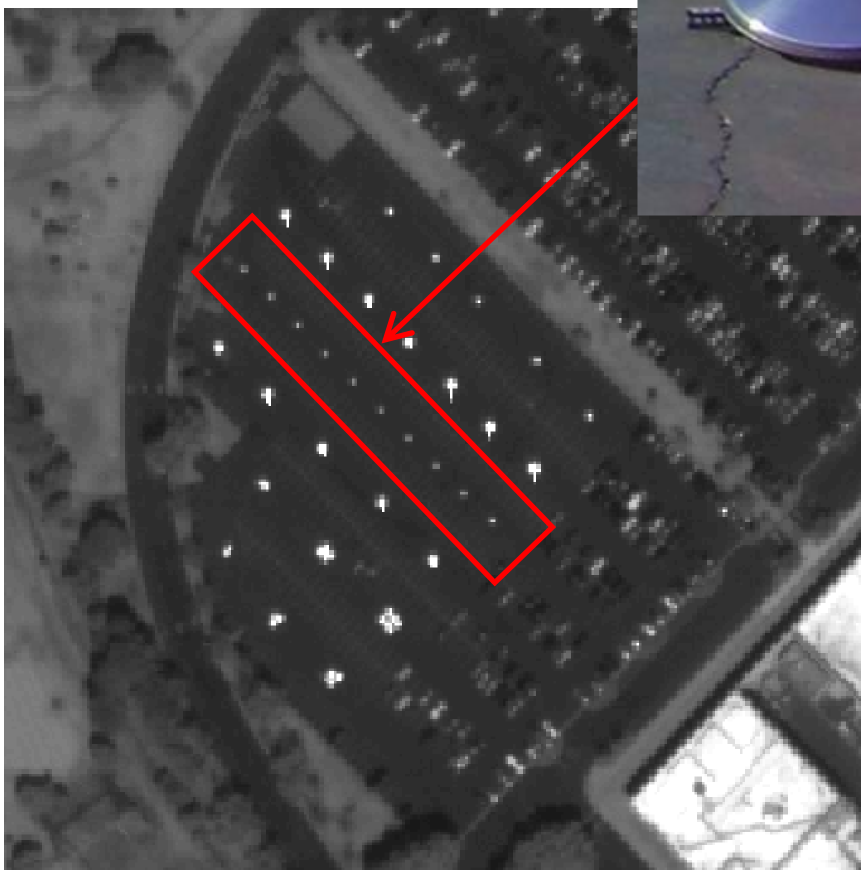
# SPARC Spatial Analysis - Measurement of Sensor PSF and Ensquared Energy



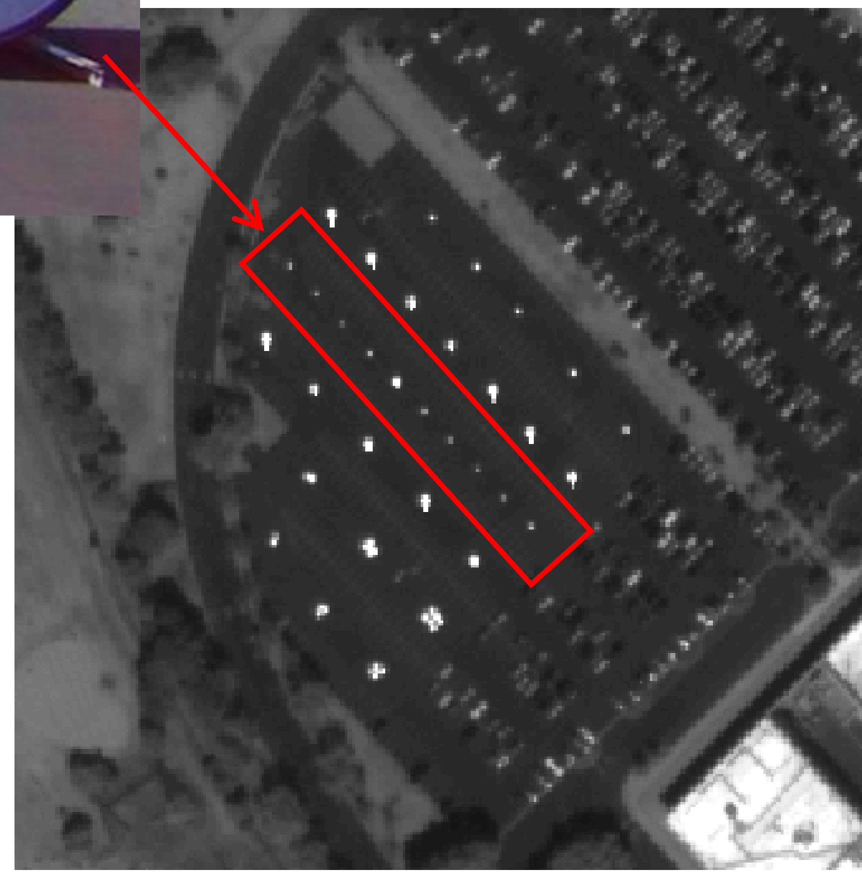
Mirror Array for Pan Band PSF FWHM measurements

20” diameter stainless steel convex mirror, R = 1.25 m

po_365282

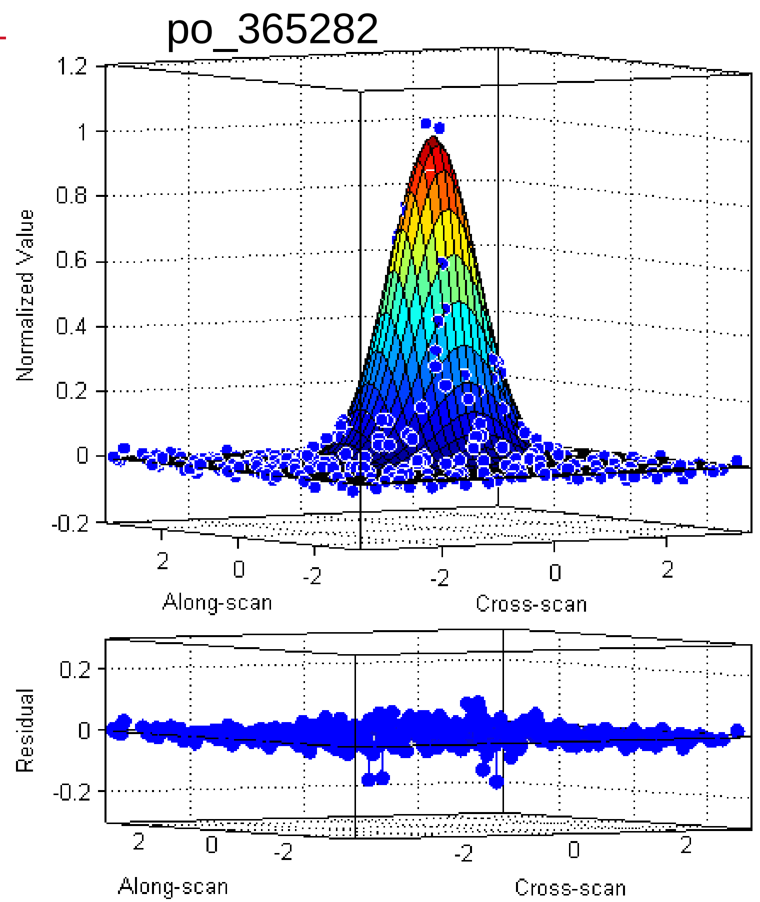


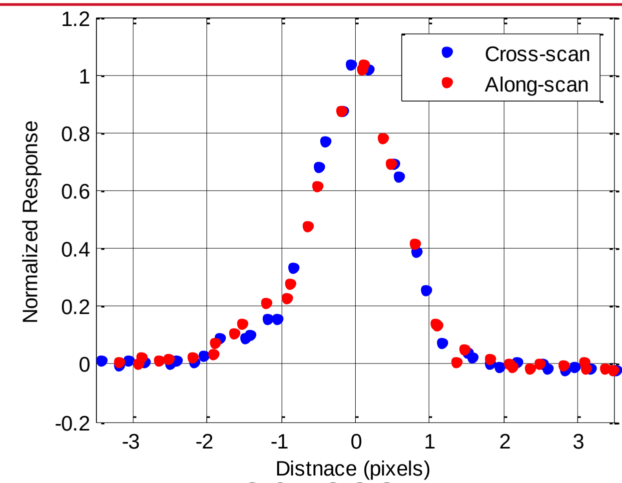
po_365283



# Pan Band PSF FWHM Measurement

Raytheon
Space and Airborne Systems




## 2D Oversampled PSF Profile

Percent RMSE = 3.3%

$R^2$ Coefficient of Determination = 0.96

## Image po_365282

| Cross-scan FWHM | Along-scan FWHM |
|---|---|
| 1.27 ± 0.04 pixels | 1.34 ± 0.03 pixels |

## Image po_365283

| Cross-scan FWHM | Along-scan FWHM |
|---|---|
| 1.27 ± 0.04 pixels | 1.32 ± 0.04 pixels |

Multispectral detector pitch is 4x larger.

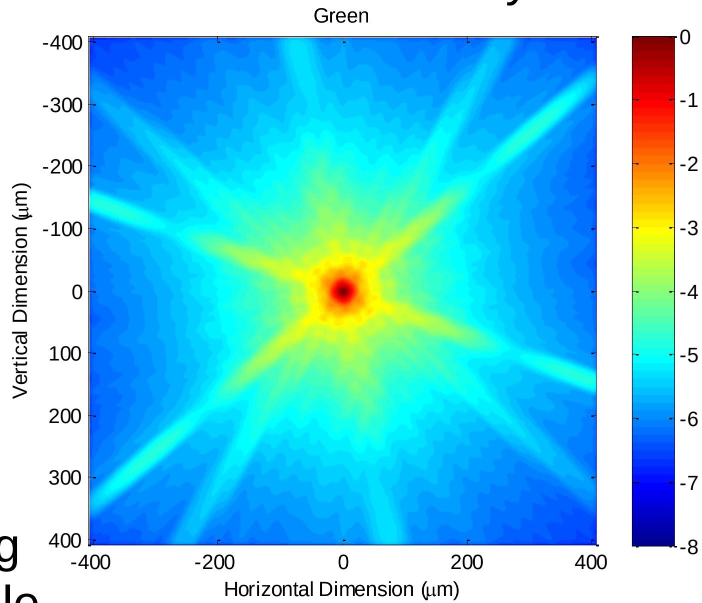
Implies multi-spectral FWHM ≈ 0.3 pixels (Band Dependent)

Confirms optical system can be modeled as roughly diffraction limited with nominal aberrations

# Ensquared Energy Calculations

Raytheon
Space and Airborne Systems

Polychromatic PSF from pupil mask and preflight interferogram based model validated by SPARC PSF analysis.




Log Scale

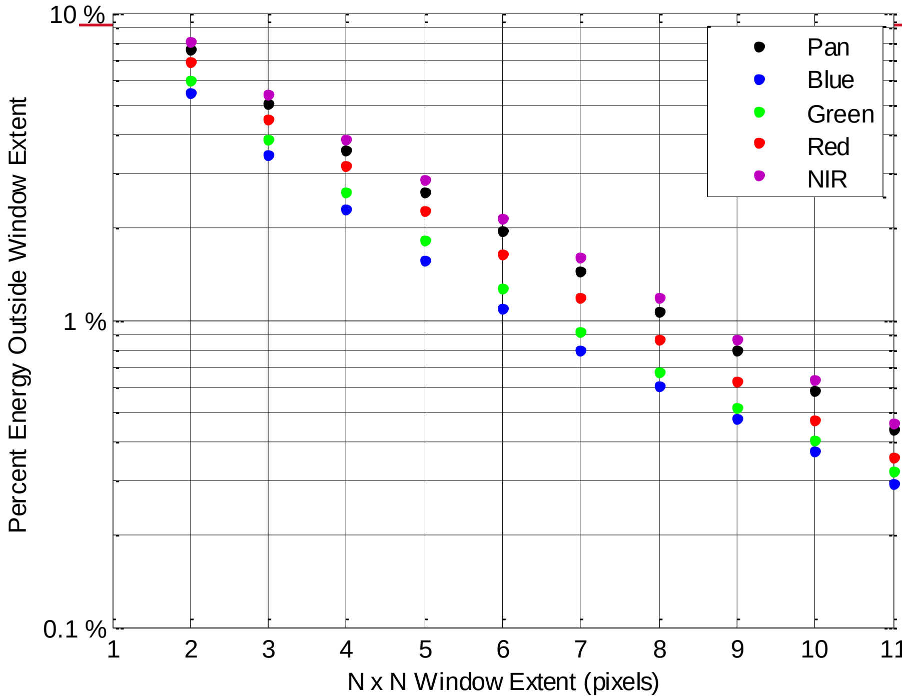



**Image analysis of SPARC target is based on a summing DN values in a 3 x 3 pixel window**

Pixels are 48 μm square MSI band detector elements

Results are accurate to ~0.5 %

**For a 3x3 pixel window the following table presents the Ensquared energy corrections to be used in the absolute gain calculations**

| Multispectral Band | Blue | Green | Red | NIR |
|---|---|---|---|---|
| ***EnsqEnergyCor*** (3x3 pixels) | 0.968 | 0.962 | 0.958 | 0.948 |