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Measuring Atmospheric Optical Depth Directly from Satellite Imagery

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The best way to predict the future is to invent it.

Dr. Alan Kay, c. 1971

Presentation Outline

- The SPARC method and radiative transfer equation.
- The SPARC solar radiometry mode.
- Deriving the "zero atmosphere response constant" for the direct solar radiometric calibration of the IKONOS commercial sensor.
- Measuring atmospheric transmittance from image data alone
- Validation of IKONOS/SPARC vertical optical depth measurements relative to ground truth solar radiometry

The SPecular Array Radiometric Calibration (SPARC) Method

Provides A New Approach to Absolute Vicarious Calibration Using Spherical Reflectors

- Combines 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

With a single image collect, a full sensor characterization is available.

- Geometric
- Spectral
- Spatial
- Radiometric

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)

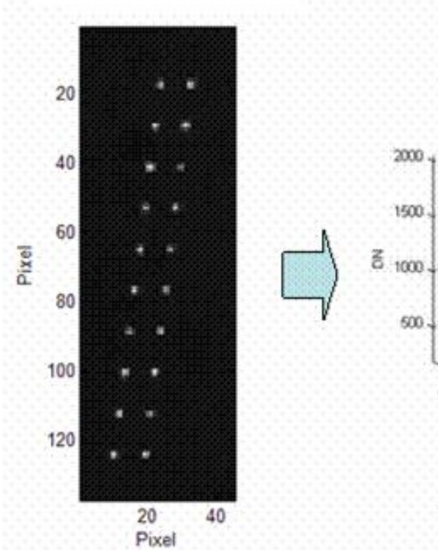
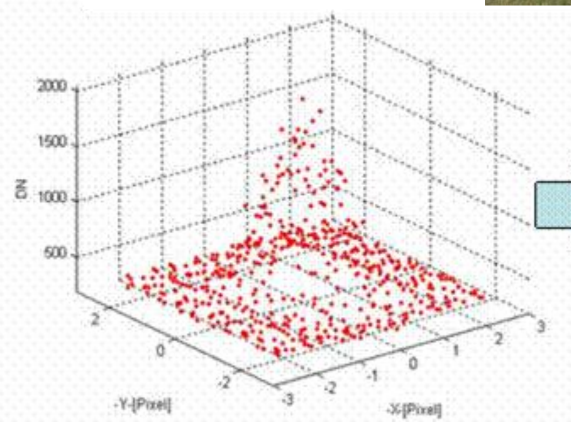
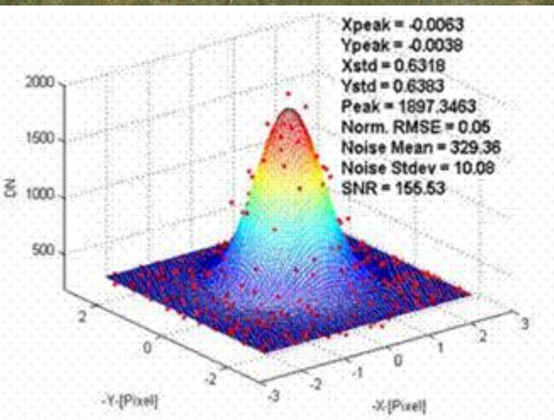


Image of specular mirror array



20 images are centered and combined to give oversampled PSF

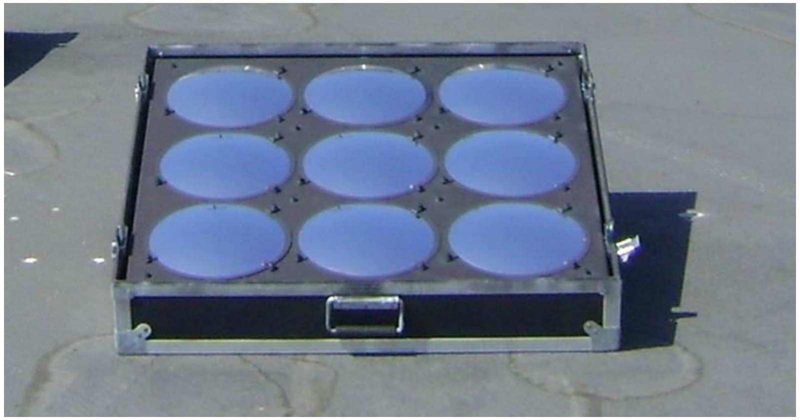


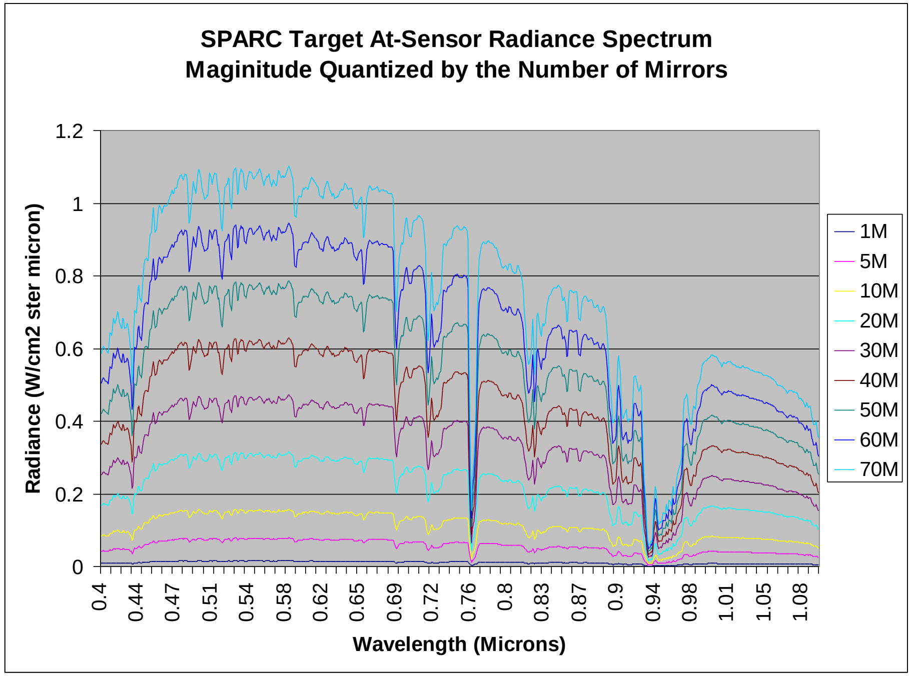
Profile is modeled with a Gaussian function

Knowing the PSF supports radiometry of small targets by telling us how the energy from the target is distributed on the focal plane so it can be measured accurately. 4

Radiometric Characterization and Calibration

- SPARC uses panels of convex spherical mirrors to create a set of radiometric targets with a known at-sensor radiance.
- Individual mirrors produce a virtual image of the sun with an upwelling intensity determined by the mirrors radius of curvature.
- Total intensity of each target is quantized by the number of mirrors.
- SPARC design results in a simplified radiative transfer equation for calculating accurate values of at-sensor radiance.
- Only ground truth data required in the field for the calculation of at-sensor radiance is atmospheric transmittance.
- Provides calculation of sensor calibration coefficients for conversion of pixel digital number (DN) to absolute radiance [Watts/(m^2 ster µm)]





SPARC Radiative Transfer Equation For Effective TOA Radiance

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TOA Intensity

$$I(\lambda,\theta_r)_{TOA} = \tfrac{1}{4}\rho(\lambda,\theta_r)\tau_\downarrow(\lambda)\tau_\uparrow(\lambda)E_o(\lambda)R^2 \qquad \text{Watts/(sr micron)/mirror}$$

At-Sensor Radiance/Mirror

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

Watts/(m^2 sr micron)/mirror

$\rho(\lambda,\theta_r)$ = 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)

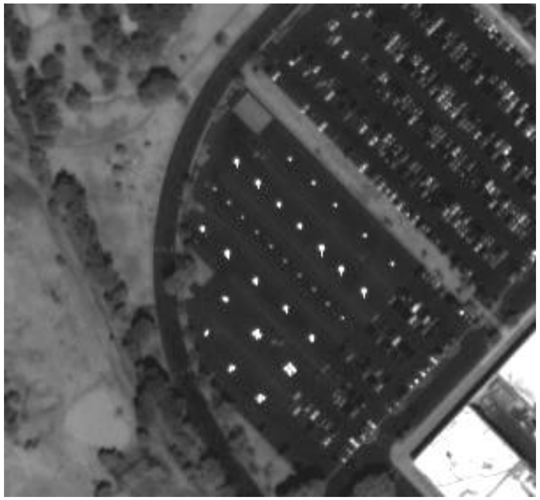
H = Sensor-to-mirror distance (m)

Ω_{IFOV} = Projected solid angle of single detector on the ground

GSD = Ground Sample Distance (m)

SPARC Targets Isolate Direct Solar Signal From Background

po_365283



po_365284

IKONOS

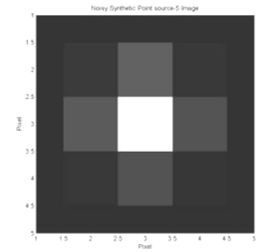
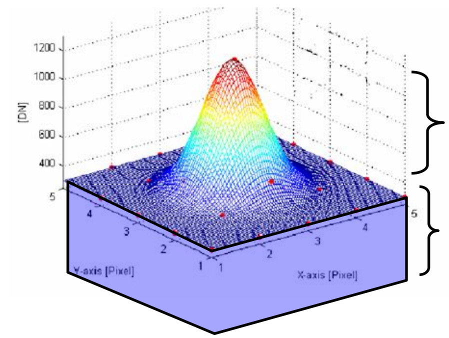


Image of target



Signal from specular target

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

Limited direction of illumination causes SPARC targets to “turn off” when viewed outside the field-of-regard revealing background contribution

This reveals the potential to isolate the direct solar signal reflected by the SPARC target from the background based on image data alone

Transmittance Is The Only Atmospheric Component Affecting The Sensor Response To The Reflected Direct Solar Signal

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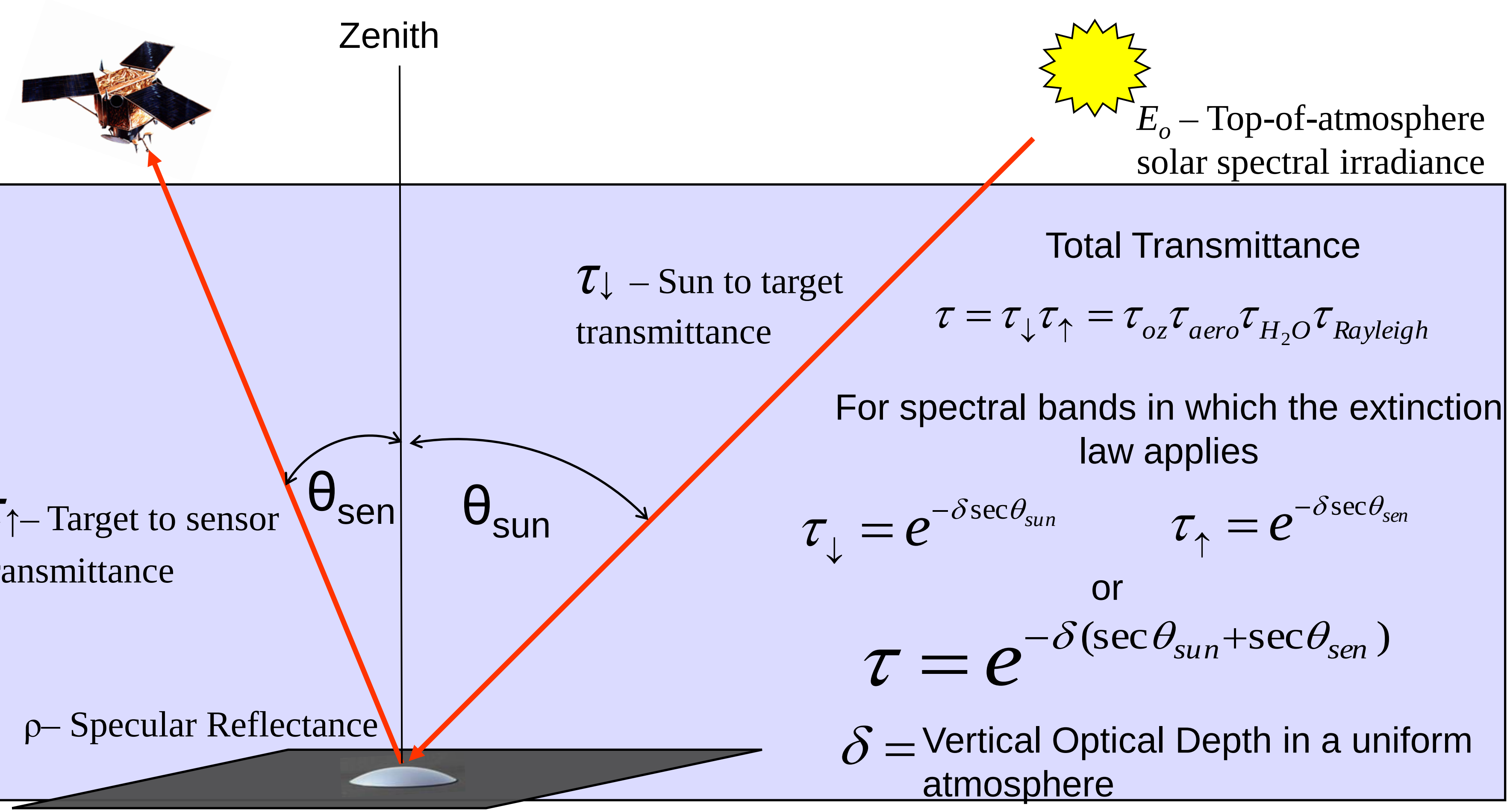


Total Transmittance

$$\tau = \tau_\downarrow \tau_\uparrow = \tau_{oz}\tau_{aero}\tau_{H_2O}\tau_{Rayleigh}$$

For spectral bands in which the extinction law applies

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

or

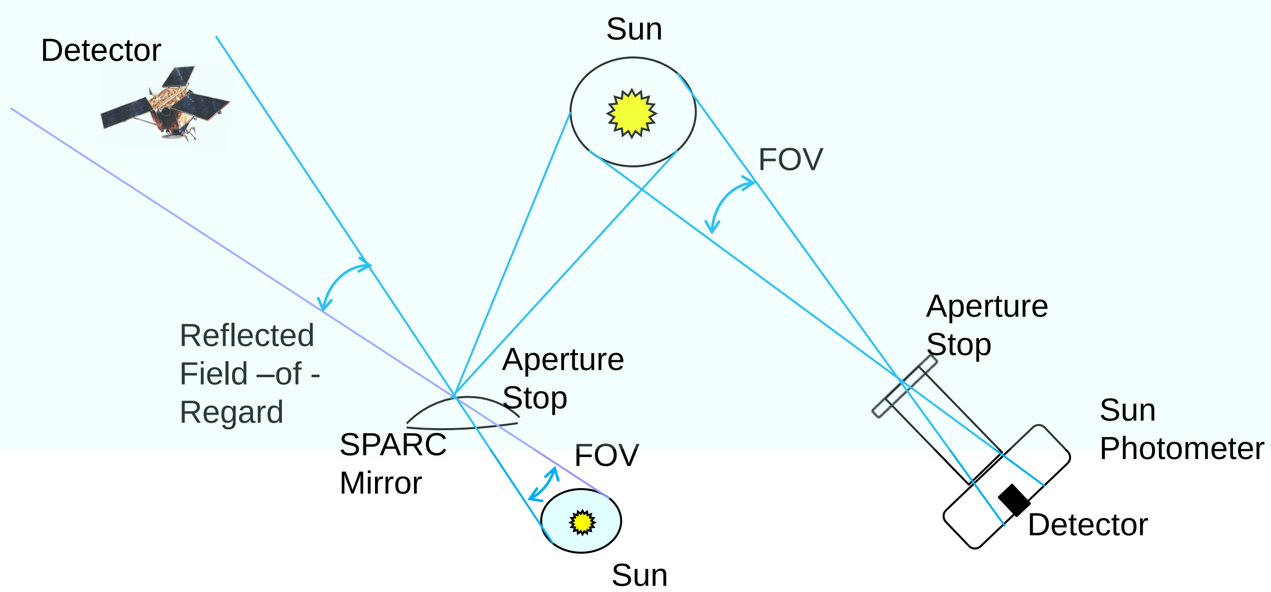
$$\tau = e^{-\delta(\sec\theta_{sun} + \sec\theta_{sen})}$$

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

Outcome is the potential for the satellite to emulate a sun photometer/radiometer using SPARC reflectors

An Orbiting Sensor Operating As A Sun Photometer

Field-of-Regard for mirror acts as a Field-of-View (FOV) aperture stop just as with an aperture stop on a typical sun photometer



The main difference is that the curvature of the mirror scales down the brightness of the sun so that it does not saturate the orbiting sensor

Potential Advantages Of Sensor Based Sun Photometry

Placing a SPARC panel of reflectors somewhere in an image

- Creates the potential to measure the transmittance through the total atmospheric path length affecting the image data (the transmittance from the ground to the sensor cannot be measured directly any other way).
- Allows transmittance to be measured simultaneously with the signal from all the targets in the image. (provides accurate scene-based atmospheric corrections)
- Creates the potential to know the total transmittance even in poor and non-uniform optical depth sky conditions. (Can make measurements of ground reflectance more productive in usually marginal weather conditions)
- Allows transmittance to be measured in the actual Relative Spectral Response (RSR) of a sensor spectral band. (No RSR conversion error)

Once the imaging sensor is calibrated, a simple mirror panel allows the sensor itself to perform the function of an *in situ* solar radiometer

Calibrating The Imaging Sensor For Sun Photometry

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- With a sun photometer, calibration requires determining the top-of-atmosphere response (I_o) representing the solar spectral constant in the instruments radiometric scale .
  - This is usually digital numbers representing the detector output in Volts
- With SPARC sun photometry, the equivalent calibration requires determining the “Zero Atmosphere Response Constant”.
  - This is the orbiting sensor digital number (DN) response to a solar illuminated SPARC reflector when the atmospheric transmittance = 1.
  - The response is the integrated ($\sum$DN) over the image PSF of a SPARC reflector panel containing N identical mirrors.

"No Atmosphere Response Constant" - DN_o

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

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

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

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

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

so that

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

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

- The constant is fixed by sensor and mirror parameters, otherwise $DN_o(\lambda) \propto E_o(\lambda)$

Proportional to TOA Solar Spectral Constant

SPARC Measured Atmospheric Transmittance

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

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

- Solving for Total Transmittance

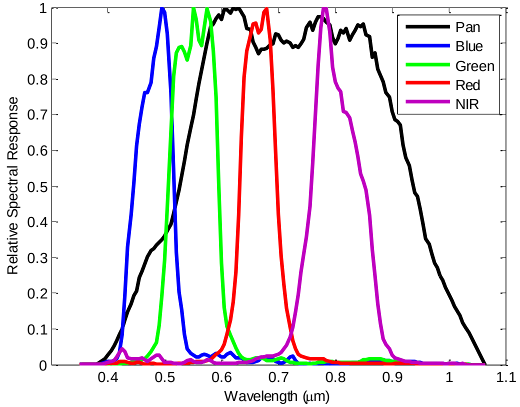
$$\tau(\lambda) = \tau_{\uparrow}(\lambda)\tau_{\downarrow}(\lambda) = \frac{GSD^2 DN(\lambda)}{GSD_o^2 DN_o(\lambda)}$$

- Once the "Zero Atmosphere" digital number (DN_o) response is determined for a imaging sensor, atmospheric transmittance in any spectral band can be measured from image data alone.

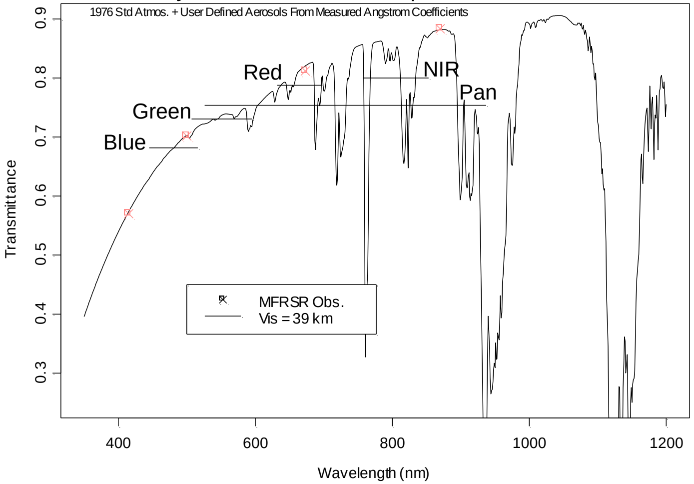
Measuring DN_o -Part 1

- Task sensor under calibration to image SPARC Panels in uniform sky conditions
- Operate a ground based sun photometer to measure aerosol optical depth, ozone and water vapor columnar amounts during collects
- Build a MODTRAN model to reproduce $\tau_{\uparrow}(\lambda)$ and $\tau_{\downarrow}(\lambda)$ spectra for the solar illumination and sensor view geometry of the image.
- Integrate MODTRAN transmittance spectra with sensor RSR to get $\tau_{\downarrow}(\lambda)$ and $\tau_{\uparrow}(\lambda)$ in each sensor band. Band transmittance =∑(Trans(λ)*RSR(λ))/∑ RSR(λ)

IKONOS RSR Curves

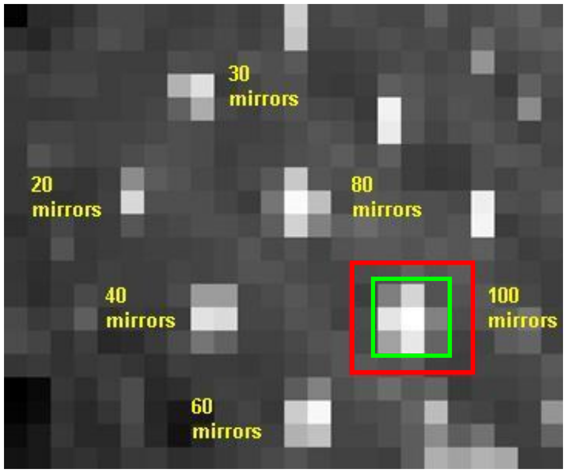


IKONOS band integrated Pan and MSI transmittance values



Measuring DN_o -Part 2

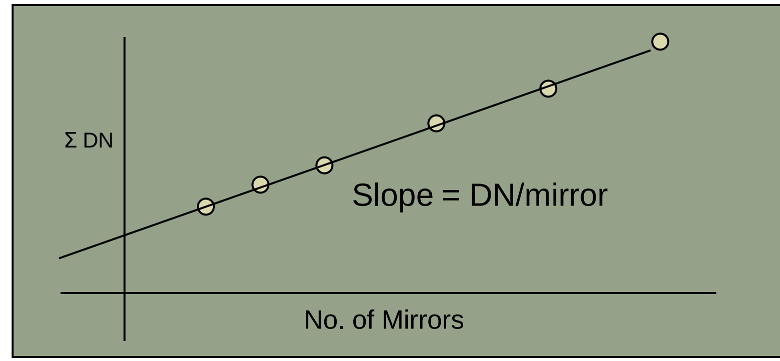
- Analyze image of SPARC target to get DN/mirror response



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

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

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



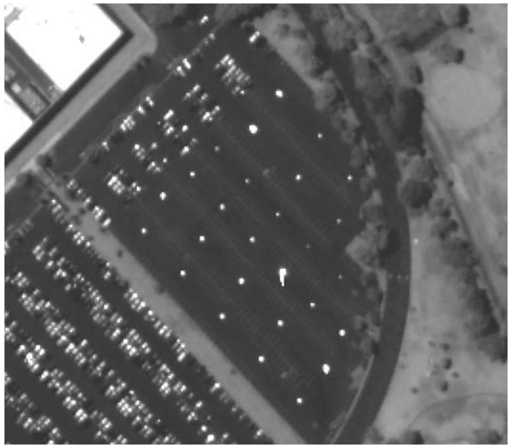
Slope = Sensor response to transmitted solar irradiance at Sensor *GSD* = *DN(λ)/mirror* for a spectral band

- Solve for DN_o

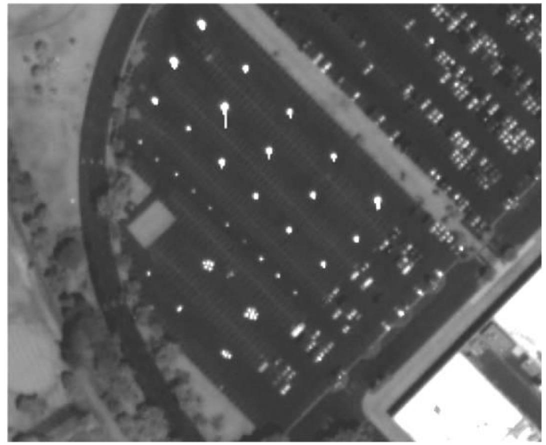
$$DN_o(\lambda) == \frac{GSD^2 DN(\lambda)}{GSD_o^2 \tau_{\uparrow}(\lambda)\tau_{\downarrow}(\lambda)}$$

- GSD is given in the image metafile
- Average DN_o over as many images as possible.

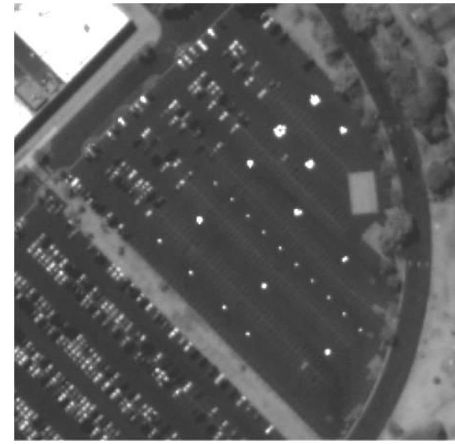
Validation: Sun Photometry Obtained With IKONOS (2009)



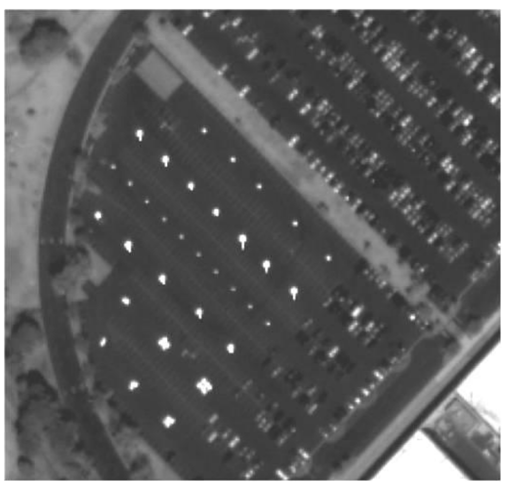
July 23



July 31

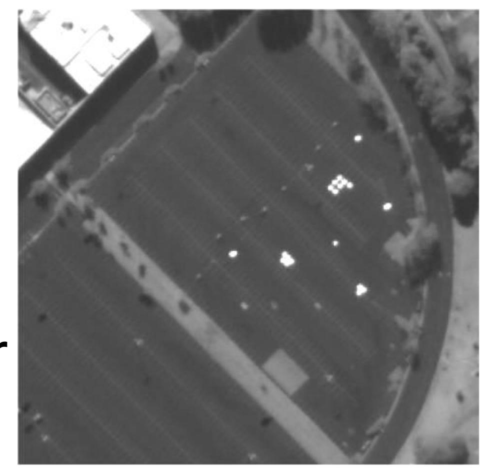


Sept 2



Sept 10

- Five overpass days
- Two collects per overpass
- 10 calibration points for determining an average DN_o.



Nov 15

Band Integrated Atmospheric Transmittance

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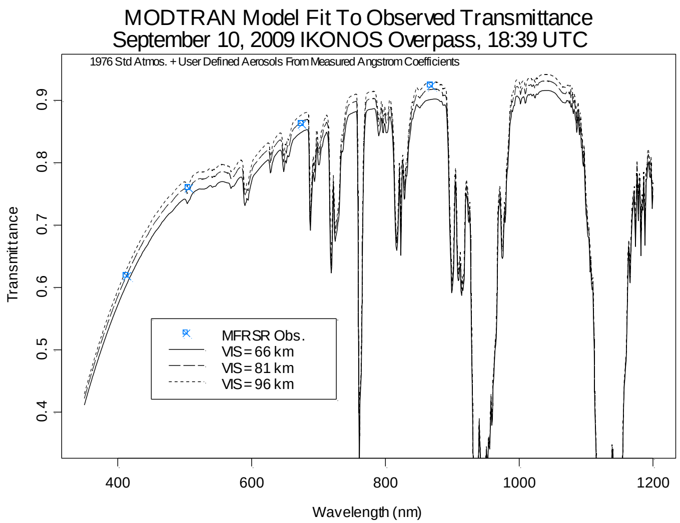
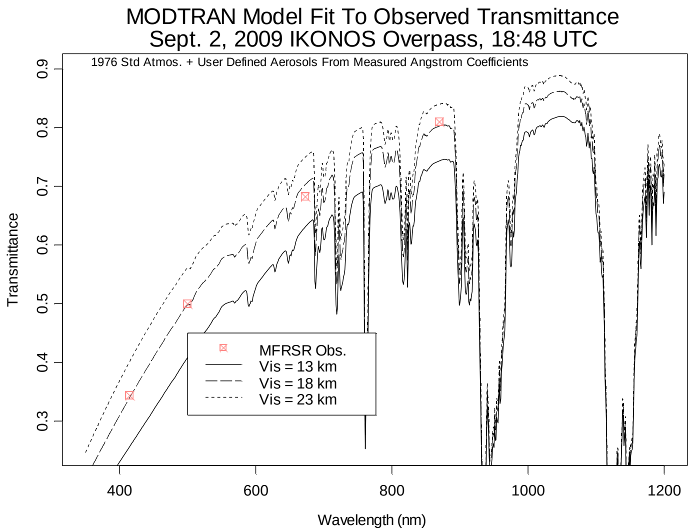


Clearest Day

Sept. 10, 2009

Vis = 81 km



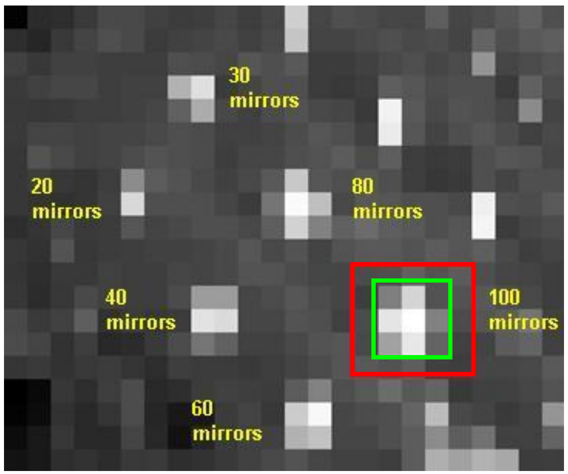
Haziest Day

Sept. 2, 2009

Vis = 18 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
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



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.

"Zero Atmosphere Response Constant" For The IKONOS Spectral Bands

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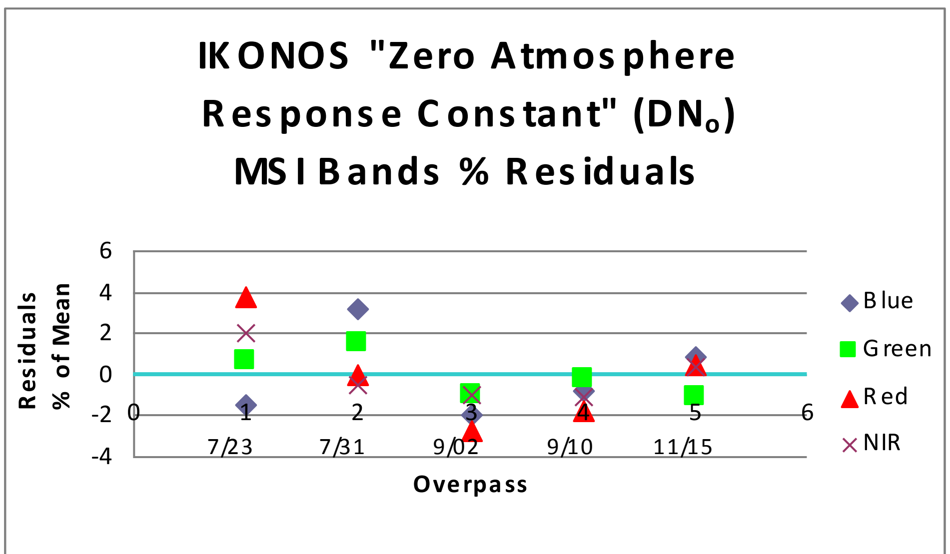
		Overpass Average						Individual Images				
Date		DN_o - Pan	DN_o - Blue	DN_o - Green	DN_o - Red	DN_o - NIR		DN_o - Pan	DN_o - Blue	DN_o - Green	DN_o - Red	DN_o - NIR
23-Jul		558.41	36.15	47.04	40.67	32.32		554.14	38.07	45.57	39.94	31.30
23-Jul								562.67	34.23	48.51	41.39	33.33
31-Jul		585.63	37.92	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		Values adjusted to Sun/Earth Distance = 1AU				
Std Deviation		17.17	0.79	0.52	0.99	0.41						
% Std Deviation		3.00	2.15	1.11	2.54	1.29						

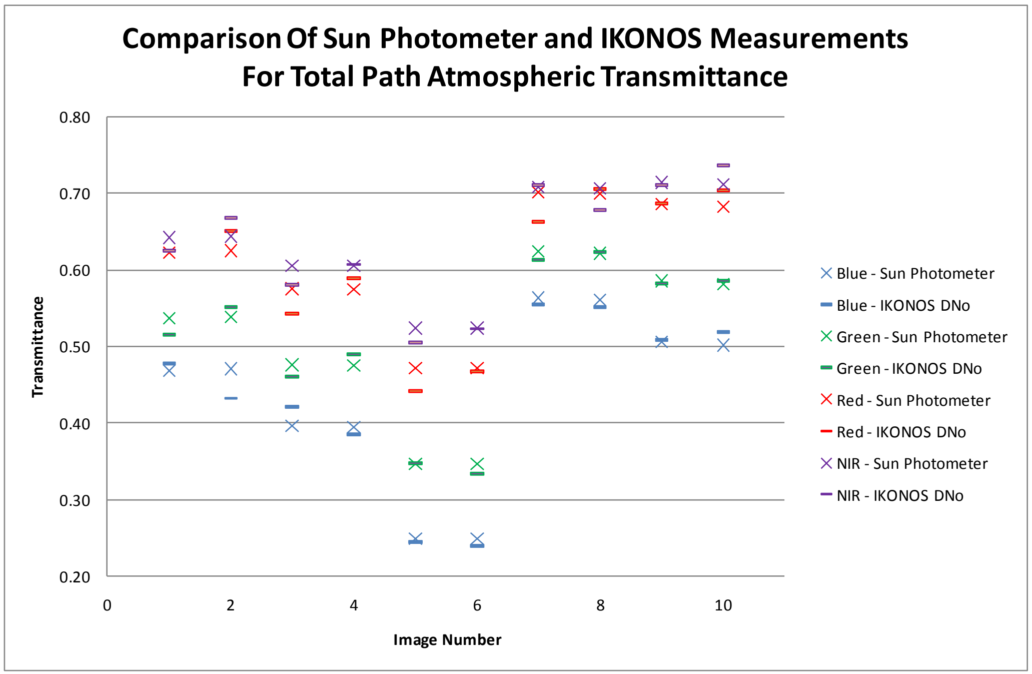


DN_o calculations from band integrated transmittance and Image measured DN/Mirror

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

Atmospheric Transmittance Results

		Sun Photometer Measured Transmittance					IKONOS Measured Transmittance Based on Mean DNo				
	Date	Pan	Blue	Green	Red	NIR	Pan	Blue	Green	Red	NIR
1	23-Jul	0.570	0.468	0.536	0.623	0.642	0.535	0.478	0.515	0.626	0.625
2	23-Jul	0.573	0.471	0.539	0.625	0.644	0.546	0.432	0.551	0.651	0.668
3	31-Jul	0.529	0.396	0.476	0.575	0.606	0.536	0.421	0.461	0.543	0.580
4	31-Jul	0.528	0.395	0.475	0.574	0.605	0.513	0.384	0.490	0.589	0.607
5	2-Sep	0.436	0.249	0.347	0.471	0.524	0.422	0.244	0.347	0.442	0.506
6	2-Sep	0.436	0.249	0.347	0.472	0.524	0.433	0.240	0.333	0.468	0.523
7	10-Sep	0.635	0.563	0.624	0.702	0.708	0.660	0.555	0.613	0.663	0.711
8	10-Sep	0.632	0.560	0.622	0.700	0.706	0.622	0.552	0.623	0.705	0.679
9	15-Nov	0.641	0.506	0.586	0.686	0.714	0.566	0.508	0.582	0.687	0.710
10	15-Nov	0.638	0.501	0.582	0.683	0.711	0.661	0.519	0.585	0.703	0.736



Based on the SPARC radiative transfer model, method and targets, results show IKONOS is able to measure atmospheric transmittance over a wide range of atmospheric conditions within a few percent of the ground based sun photometer.

Optical Depth Retrieval For Each Overpass

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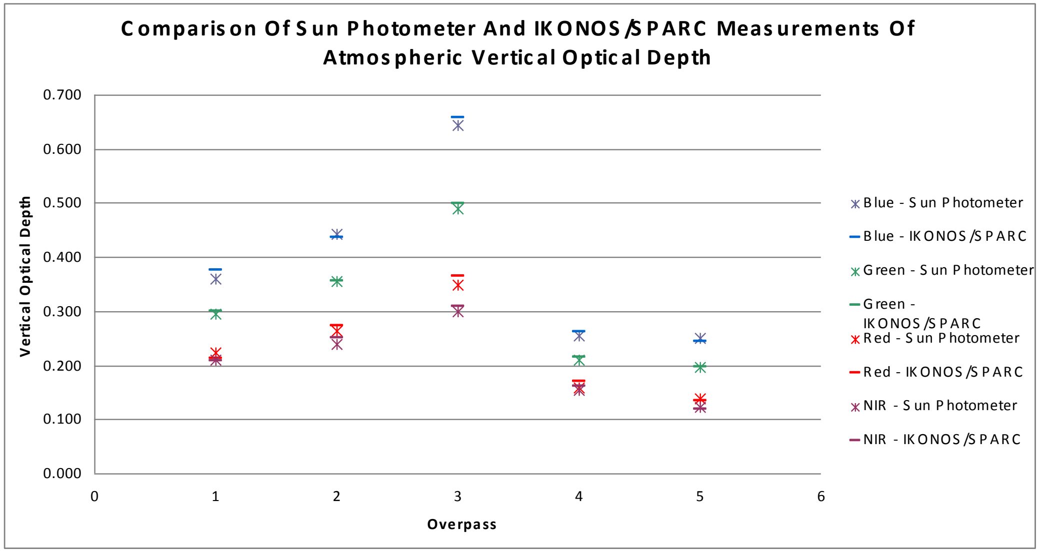
- Assuming a uniform plane parallel atmosphere, The transmittance can be converted to an optical depth.

$$\delta = \frac{-\ln \tau}{(\sec\theta_{sun} + \sec\theta_{sen})}$$

- The average residual between the ground based sun photometer measurement and the IKONOS/SPARC measurement is ≤0.01 for each band

Residuals	Pan	Blue	Green	Red	NIR
23-Jul	0.020	0.015	0.004	0.011	0.002
31-Jul	0.003	0.008	0.000	0.008	0.010
2-Sep	0.002	0.013	0.008	0.017	0.008
10-Sep	0.012	0.007	0.004	0.011	0.008
15-Nov	0.011	0.007	0.000	0.006	0.005
Mean	0.009	0.010	0.003	0.010	0.007

Noise reduction by averaging measurements from 2 images per overpass



Performance of ground based sun photometer is accurately transferred to IKONOS

Conclusion

- SPARC targets provide a practical approach for measuring atmospheric transmittance directly from image data alone recorded by an over flying sensor.
- Once the sensor is calibrated for a panel of mirrors (based on ground truth sun photometry), transmittance can be measured at any location by simply placing a panel with equivalent mirrors in the scene.
- Transmittance measurements are for the full sun-to-ground-to-sensor atmospheric path length and are recorded in the actual pass band of the sensor.
- Sensor calibration, in the instrumental radiometric scale, was achieved at ≤ 2.5% 1σ repeatability for the IKONOS MSI bands (5 overpasses, 5 months).
- Results demonstrated average residuals ≤0.01 in measurements of vertical optical depth from image data alone compared to the coincident sun photometer measurements used for calibration.

Acknowledgement: We want to thank Martin Taylor and GeoEye for their collaboration in providing the IKONOS data used in this research.