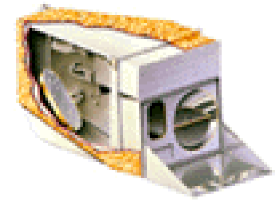

Modeling MODIS performance/radiometric ray tracing

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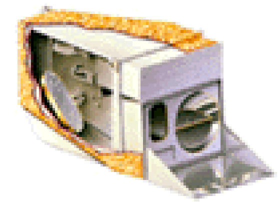
3. SSAI, Greenbelt, MD

Guideline

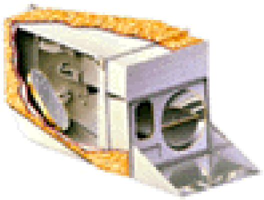


•The generic key elements of pre-launch characterization, on-orbit responsivity tracking and vicarious calibration of satellite ocean color radiometers;

•The implementations of these elements as applied to SeaWiFS and MODIS, especially in the context of ongoing difficulties in deriving water-leaving radiances, from Terra and Aqua MODIS data, that are accurate enough to derive Climate Data Records (CDR) of acceptable quality;

•**Lessons to be learned and applied as NASA and other agencies prepare for future pre-launch and on-orbit characterizations of ocean color satellite missions, including VIIRS on NPP and NPOESS.**

Lesson learned



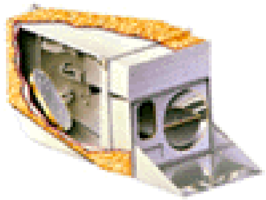
•Improve radiometric models.

•Radiometric models <=> Simulations (traceable to first principles)

•Start developing the simulations in support of instrument testing and preferably in proposal and pre-phase A.

•Refine the simulations during instrument testing.

Simulations



Simulations are used to model phenomena which is, because of complexity, analytically intractable.

Simulations are computer processing intensive.

First computer simulation (in the modern sense) was

Monte Carlo radiation (nuclear) transport

Other (closer to home) examples:

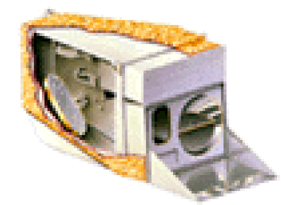
•Image formation of complex (MODIS) optical systems. (Light) Ray (simulation) tracing predicts image quality.

•Structural NASTRAN (simulation) model.

•Thermal SINDA(?) (simulation) model.

•MODIS Ghosting, stray light and point spread function (simulations – not closed form but lots of rays)

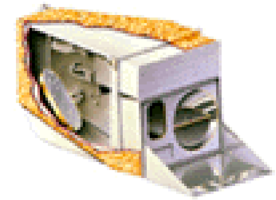
Is it worth the price?



Effort and expense in creating simulations is not small because of fewer approximations and amount of detail required. (Was computer intensity, but not as big a problem at 3Ghz. Compare to 25Mhz in 1990. Not to mention storage capacity.)

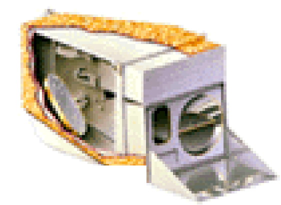
Benefit is great, especially in a long, multi-year and multi-instrument effort because a *virtual instrument* is created.

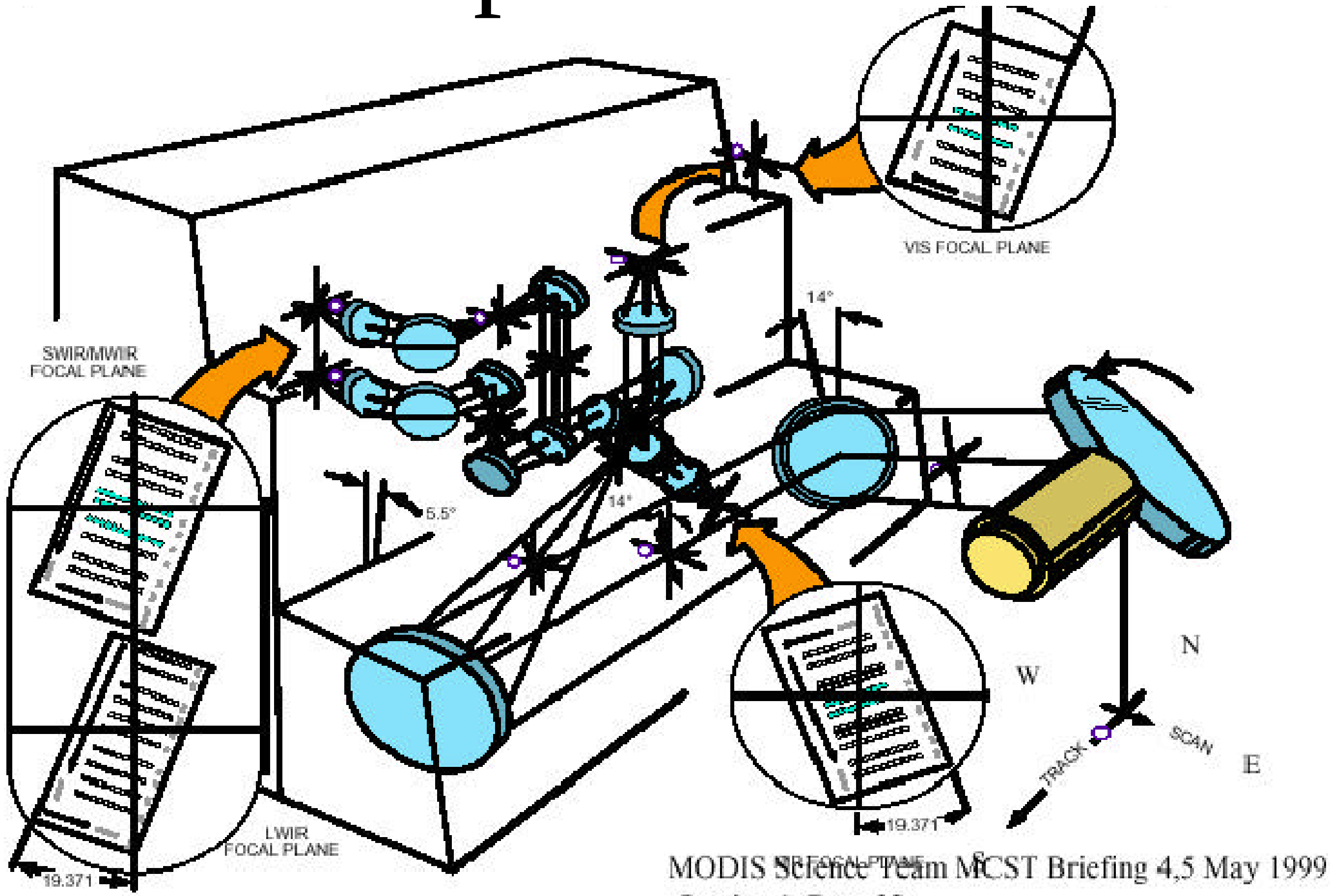
Current MODIS Radiometric Modeling/Simulations



- Solar Diffuser with attenuation screen ray trace radiometric model
  - Model, modeled and actual results.
- New and old polarization models.
- Briefly discuss the primary mirror and surrounding structure stray light.

MODIS Optics Schematic





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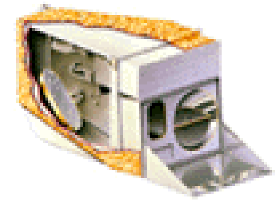
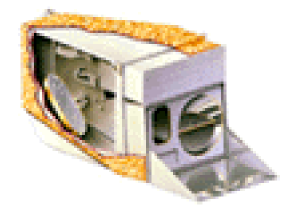
Section 1, Page 32

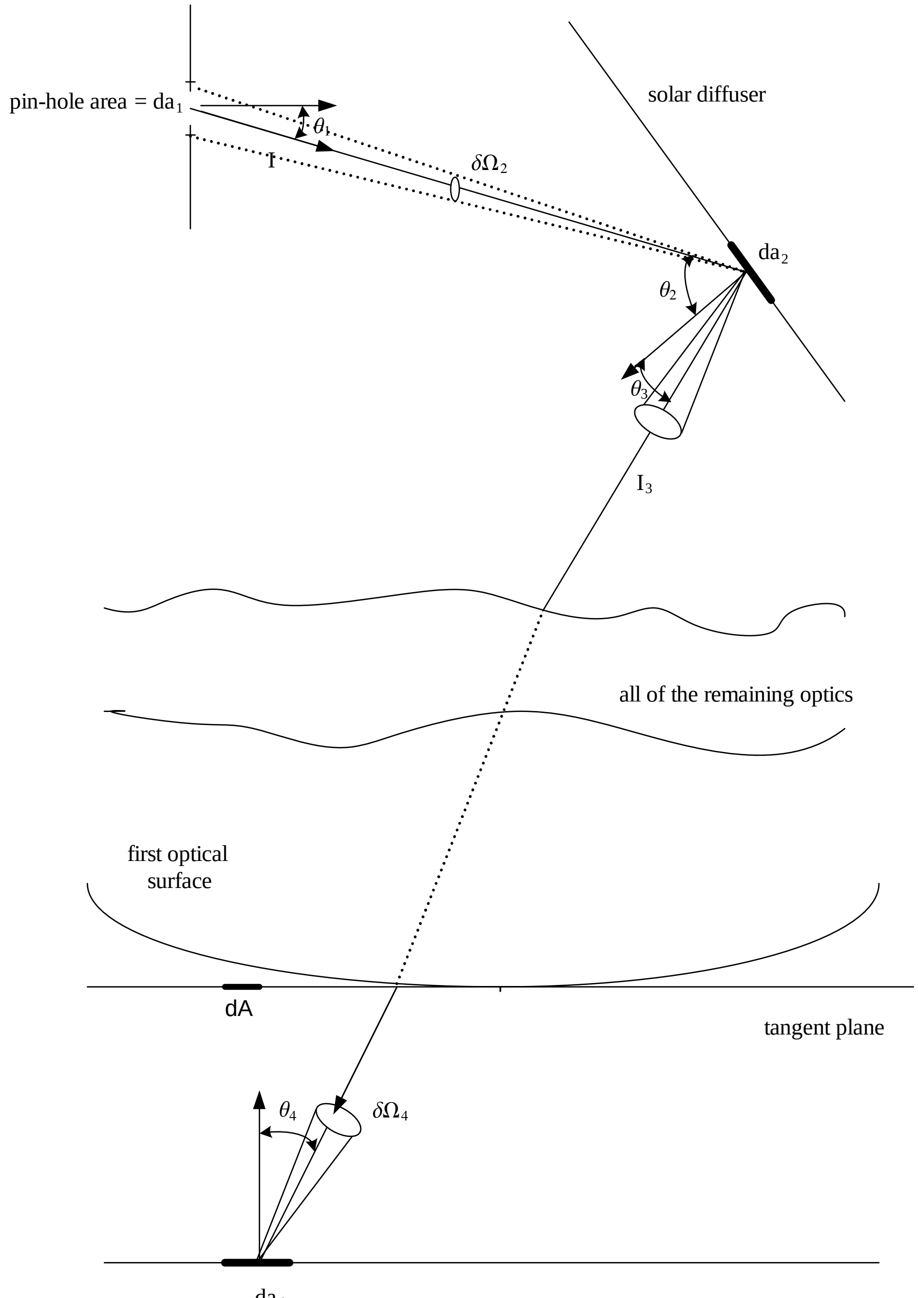
- "Paddle-wheel" cross-track scanning imaging system
- Scanning Mirror points to diffuser scatter plate each scan

Solar Diffuser and attenuation screen ray trace radiometric model



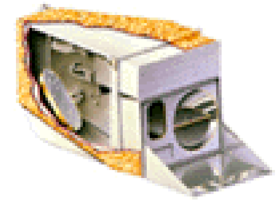
- During solar calibration determine visible focal plane illumination variations
  - Attenuation screen with all the pinholes
  - Solar diffuser (currently Lambertian)
  - All of the optics (scan, fold, primary, secondary, beam splitters, aft-optics) – currently no polarization
- Motion of the sun
- Rotation of scan mirror
- At (almost) all the detectors





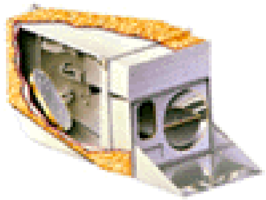
Light from pin hole to focal plane

Computational approach



- Rays are traced through all of the optics (polarization is not considered)
- The solar diffuser is illuminated by a multitude of pin hole images of the sun.
- The Goddard FORTRAN computer code, RAYPKS, was used to perform the bulk of the raytracing (but will transition to ZEMAX?)
- The computational time was significantly shortened by starting the very dense ray fans at the visible focal plane detector elements.
- Each, very dense bundle of rays, for each detector, entirely fills, with a square grid, the aperture of the optical surface immediately above the visible focal plane.
- Approximately 7.2 million rays (for one scan mirror position and one solar angle) eventually reach the solar diffuser.
- If a ray falls within one (or more) of the, approximately 600 pin hole images of the sun (as seen by any one detector), the appropriate intensity (as describe below) is added to a detectors total.

Compute Incident energy

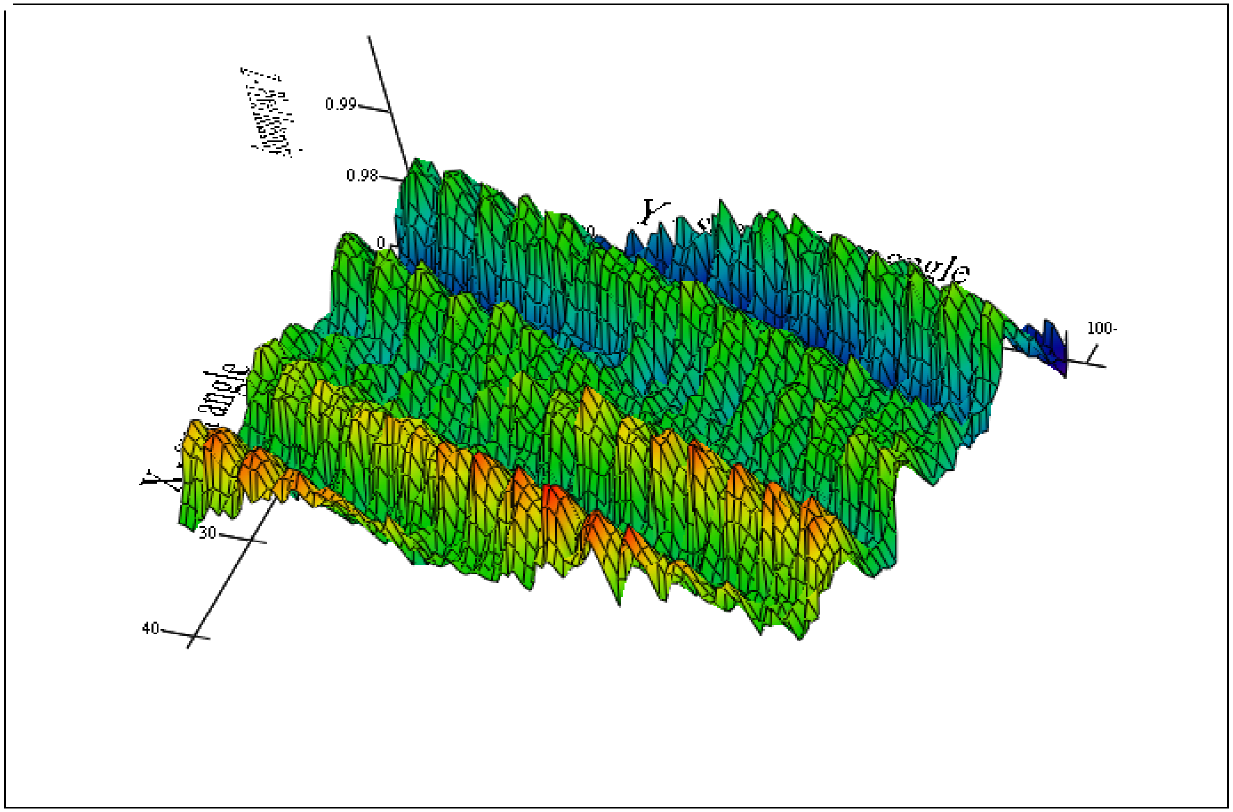


- At 70 VIS detector locations (7 bands,10 detector per band)
- For 101 scan mirror positions
- And 41 sun positions

Interpolate to *actual* mirror and sun positions taking into account the

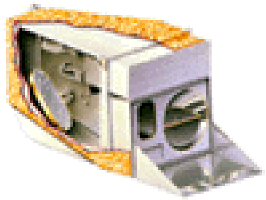
- frame rate of $333.3 \cdot 10^{-6}$ seconds
- mirror rotation rate of 2.956 seconds/revolutions
- Sun motion (December)

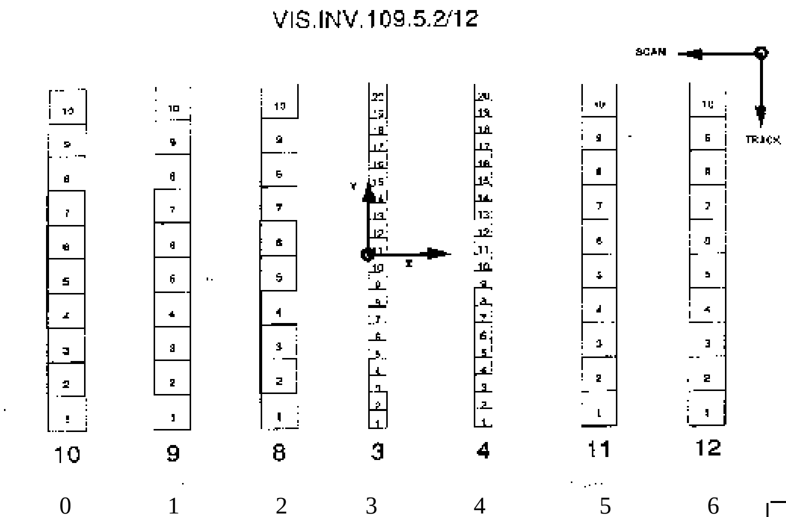
For each of 70 detector locations we have …



Middle Detector band 3, all computed mirror and and all computed sun angles. Total of 41*101=4141 data points.

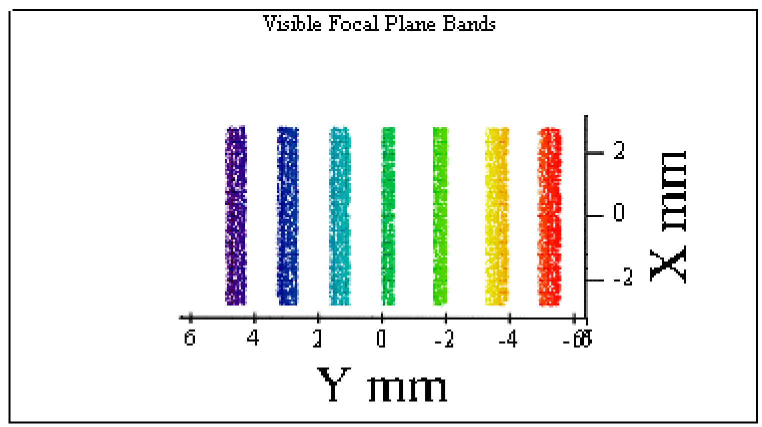
MODIS Visible Focal Plane





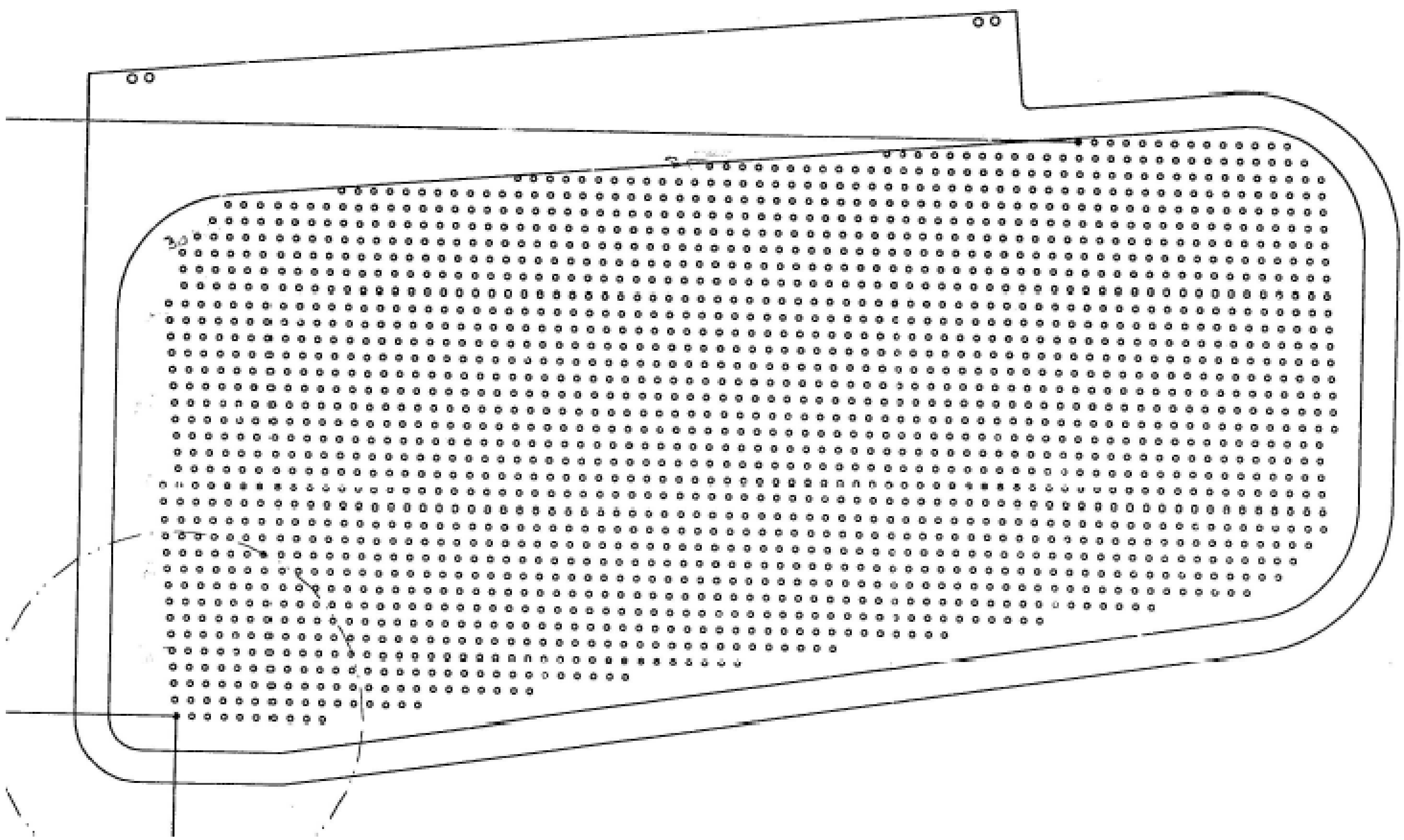
Rays start at the center of the detector elements.

Bands 3 and 4 have 10 detectors.

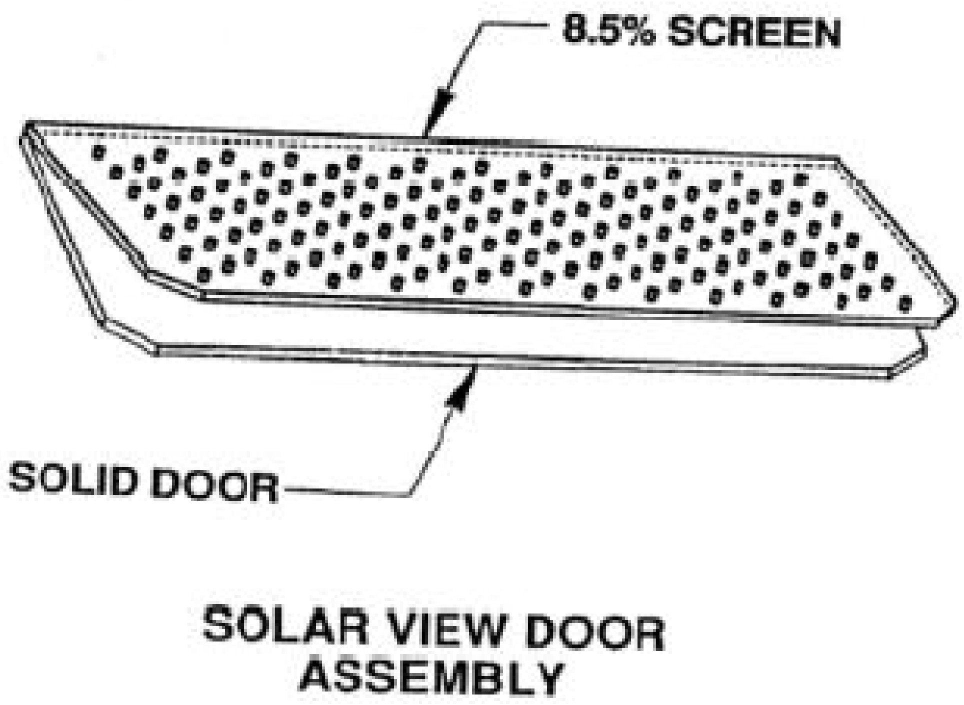


(X,Y,-Y)

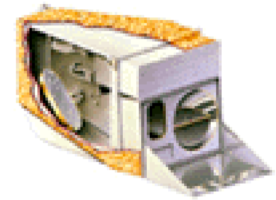
MODIS attenuation screen



SD Screen Design



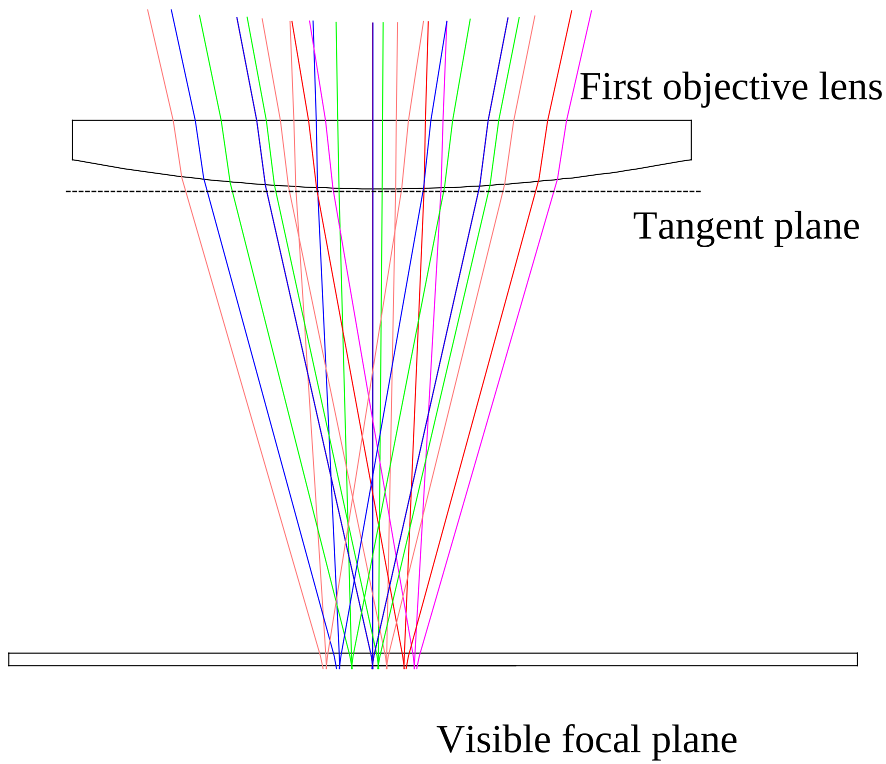
Ray bundle starts at each detector

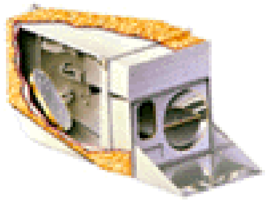


Center point of detector and grid points on tangent plane determine ray bundles for each detector.

7 bands

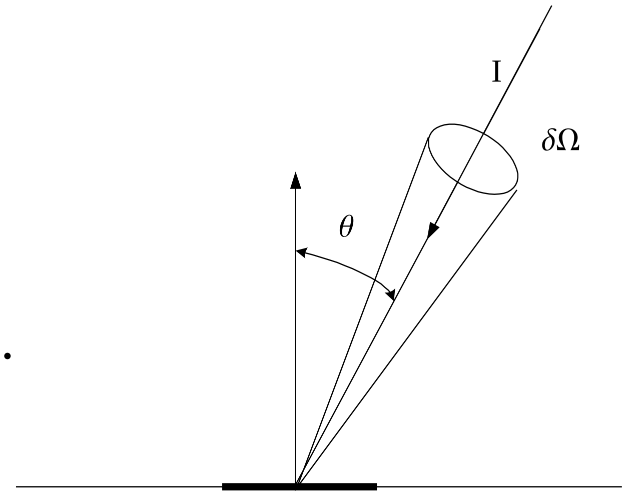
10 detectors/band





Radiometry

Each ray represents
a pencil of light.



$$dE = I(\theta,\phi,\lambda)\cdot\cos\theta\cdot d\Omega\cdot da\cdot d\lambda\cdot dt.$$

$$E = \int_{\Omega}\int_{\lambda}\int_{t}\int_{a} I_{\lambda}(\theta,\varphi)\cdot\cos\theta\cdot d\Omega\cdot da\cdot d\lambda\cdot dt.$$

Ray from focal plane to solar diffuser to pinhole(s)

$$dE_4 = I_4 \cdot \cos\theta_4 \cdot d\Omega_4 \cdot da_4$$

$$I_4 = (transmission\ loss) \cdot I_3$$

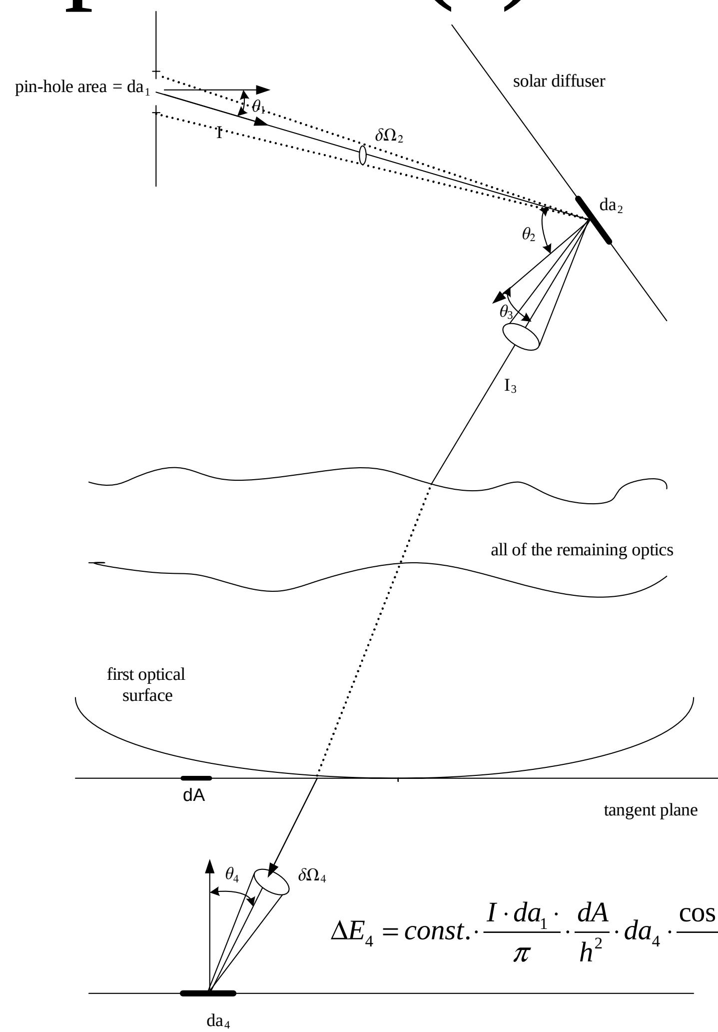
Energy incident on solar diffuser at da_2 from a pinhole

$$dE_2 = I \cdot \cos\theta_2 \cdot d\Omega_2 \cdot da_2$$

$$d\Omega_2 = \frac{da_1 \cdot \cos\theta_1}{r^2}$$

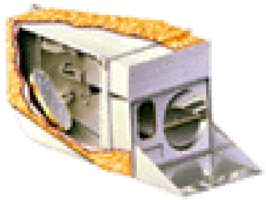
For Lambertian reflector

$$I_3 = \frac{I \cdot \cos\theta_2 \cdot da_1 \cdot \cos\theta_1}{\pi \cdot r^2}$$



$$\Delta E_4 = const. \cdot \frac{I \cdot da_1 \cdot}{\pi} \cdot \frac{dA}{h^2} \cdot da_4 \cdot \frac{\cos\theta_2 \cdot \cos\theta_1 \cdot \cos^4\theta_4}{r^2}$$

Energy incident on detector



Energy deposited on a detector by a single ray

$$\Delta E_4 = (transmission\ loss) \cdot \frac{I \cdot \cos\theta_2 \cdot \Delta a_1 \cdot \cos\theta_1}{\pi \cdot r^2} \cdot \cos\theta_4 \cdot \Delta\Omega_4 \cdot \Delta a_4$$

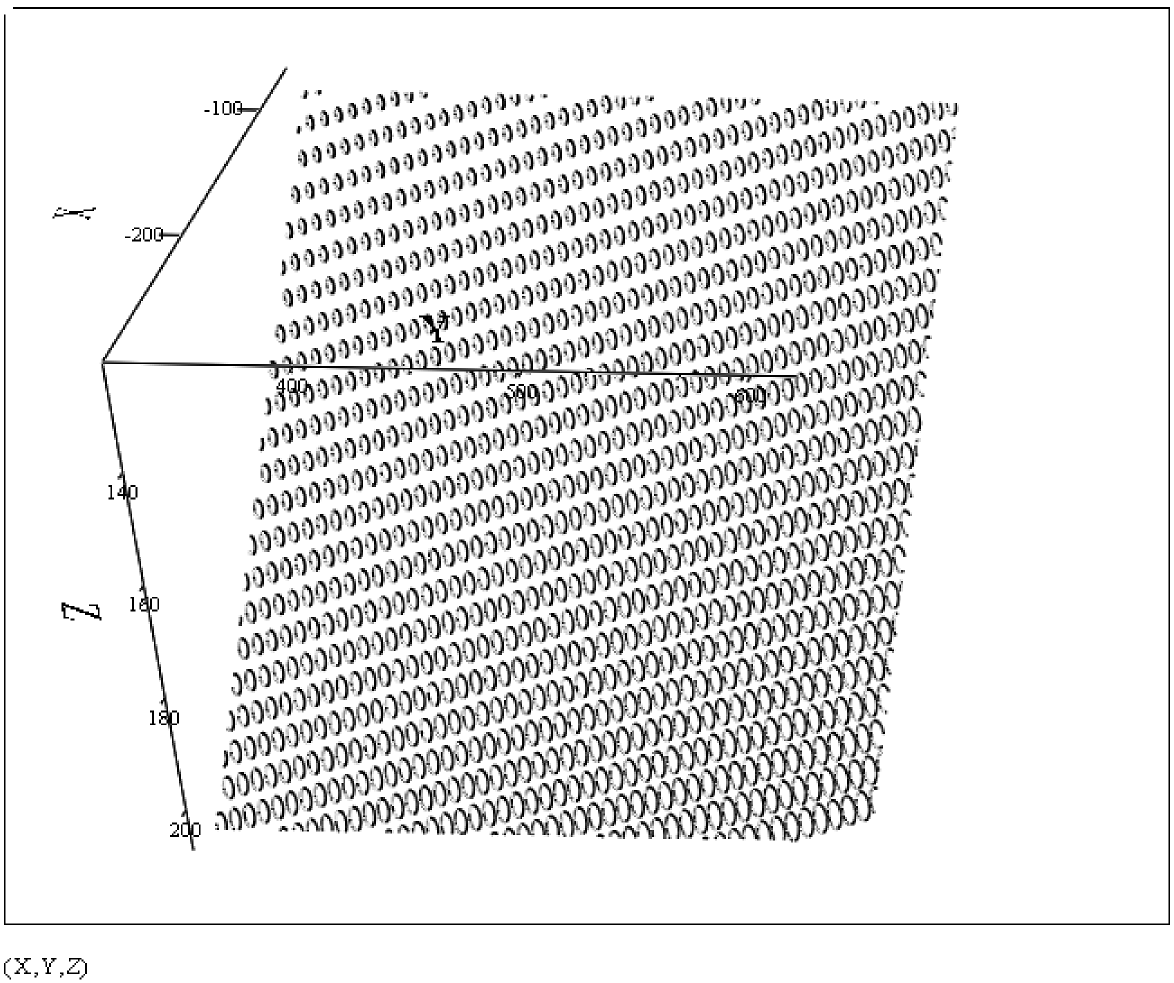
$$\Delta E_4 = const. \cdot \frac{I \cdot \cos\theta_2 \cdot \Delta a_1 \cdot \cos\theta_1}{\pi \cdot r^2} \cdot \cos^4\theta_4 \cdot \frac{\Delta A}{h^2} \cdot \Delta a_4$$

Total Energy deposited on a detector

$$E = \sum_{all\ rays} \Delta E_4$$

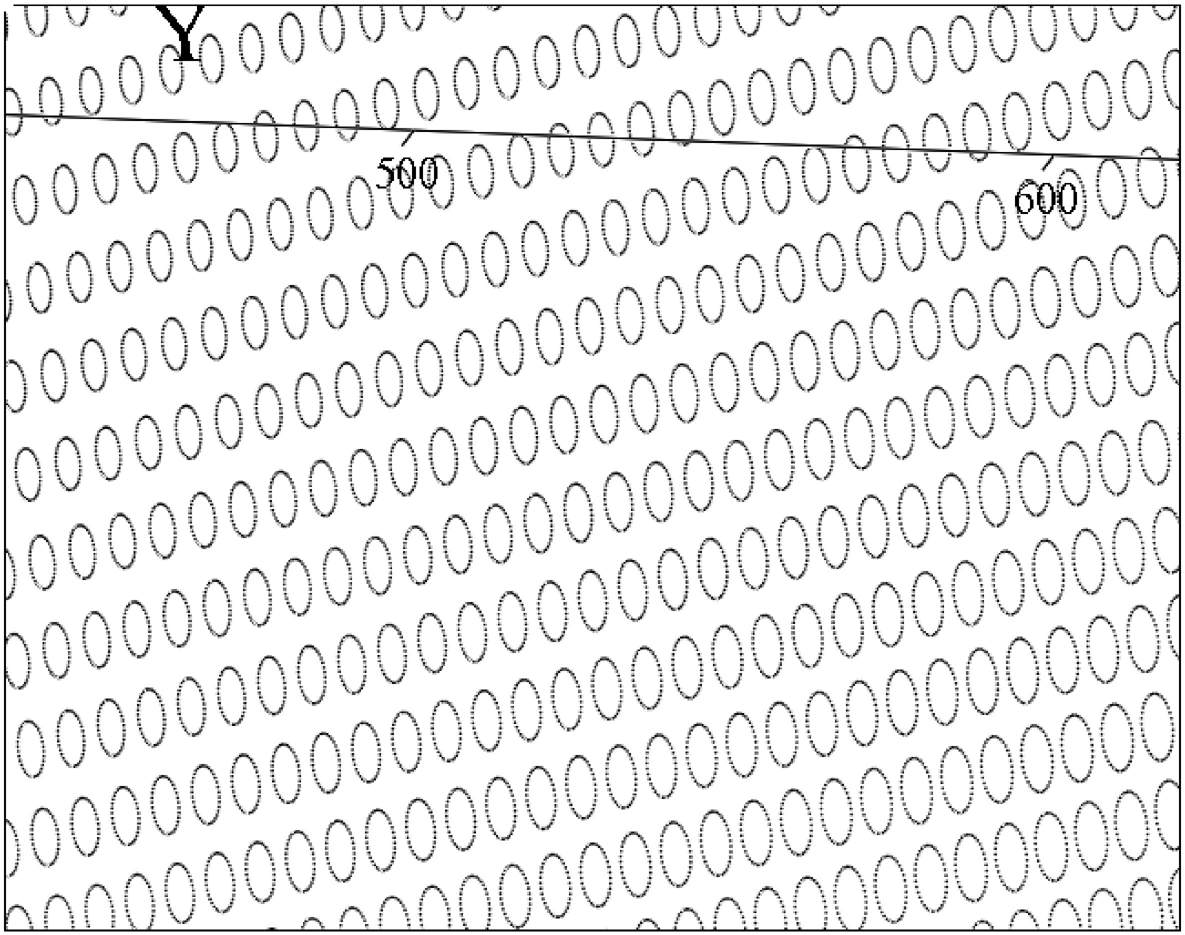
Note: Seasonal earth to sun distance variations effect only the size of the pinhole images of the sun on the solar diffuser.

Attenuation screen pinholes produce pinhole images of sun on solar diffuser



- Screen used for low reflectance bands
- Rays from each SD screen pin hole onto SD
- Fired in 0.5° cone
- Ellipse size on diffuser varies due to tilt between surfaces

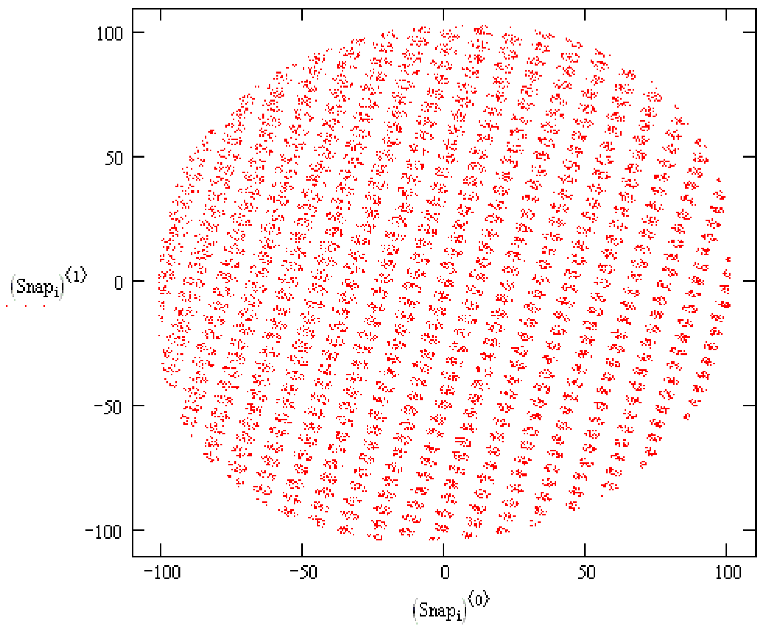
Closer view of pinhole images

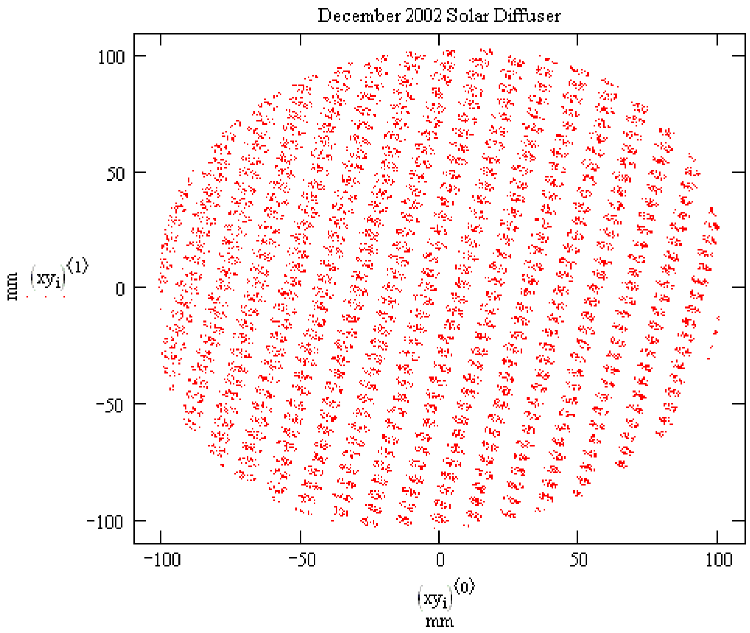


(X,Y,Z)

Motion of pinhole images

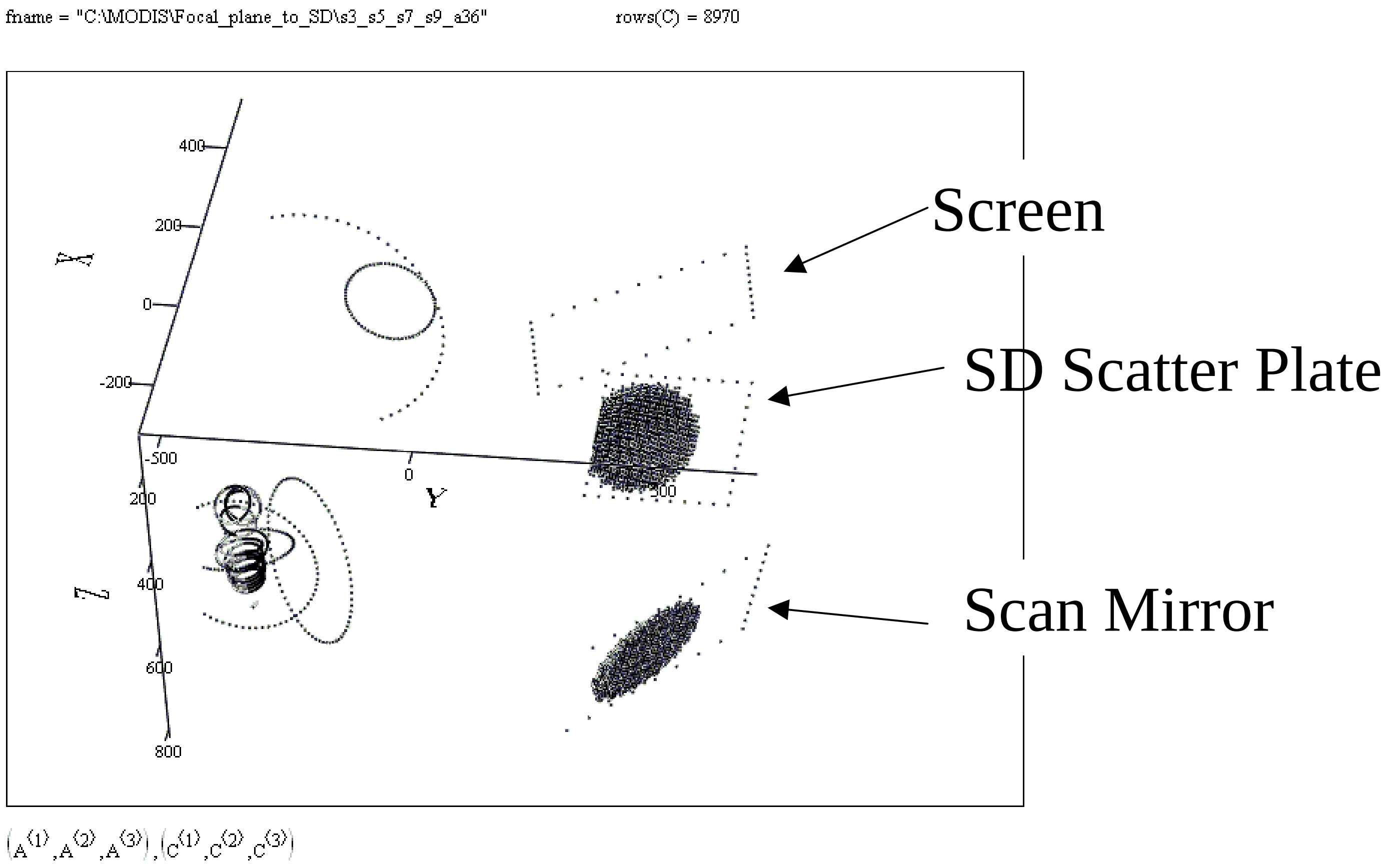
i := FRAME



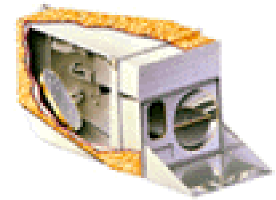


Motion due to sun angle changing.

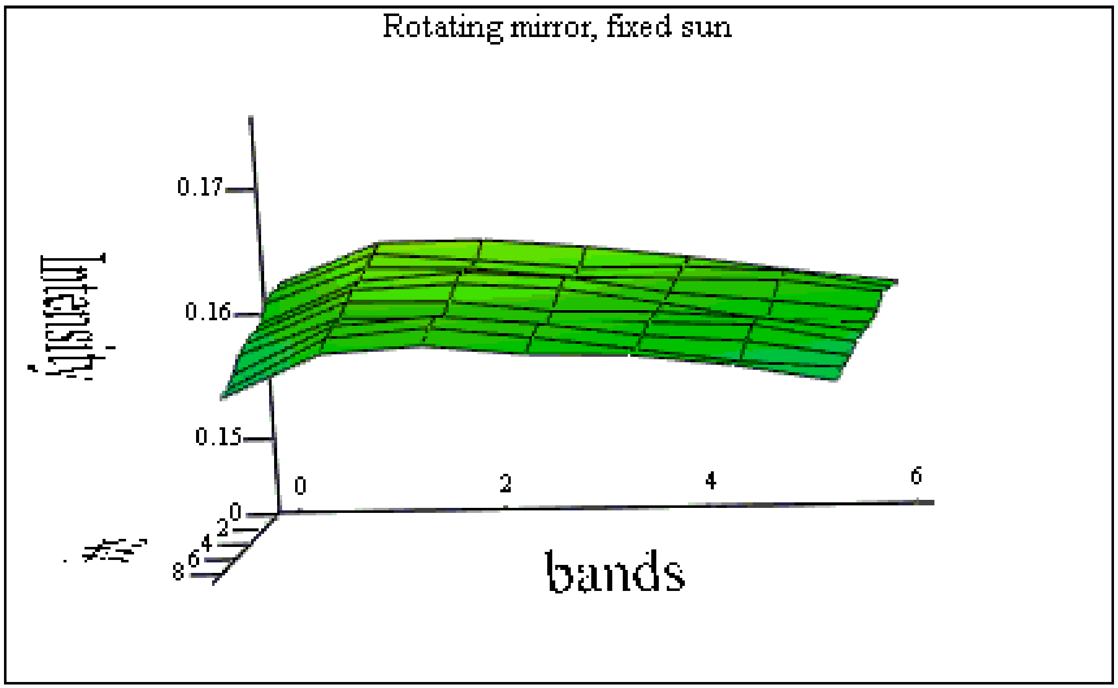
Detector Projection onto (Moving) Scan Mirror and Solar Diffuser



Focal plane intensity variations moving mirror, fixed sun angle

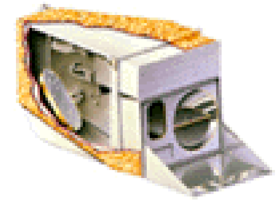


FRAME = 0 $\qquad$ $fname_{FRAME}$ = "C:\MODIS\s3_to_s2\December divide by rr and cos to the 4\Dec_rr_31.0"

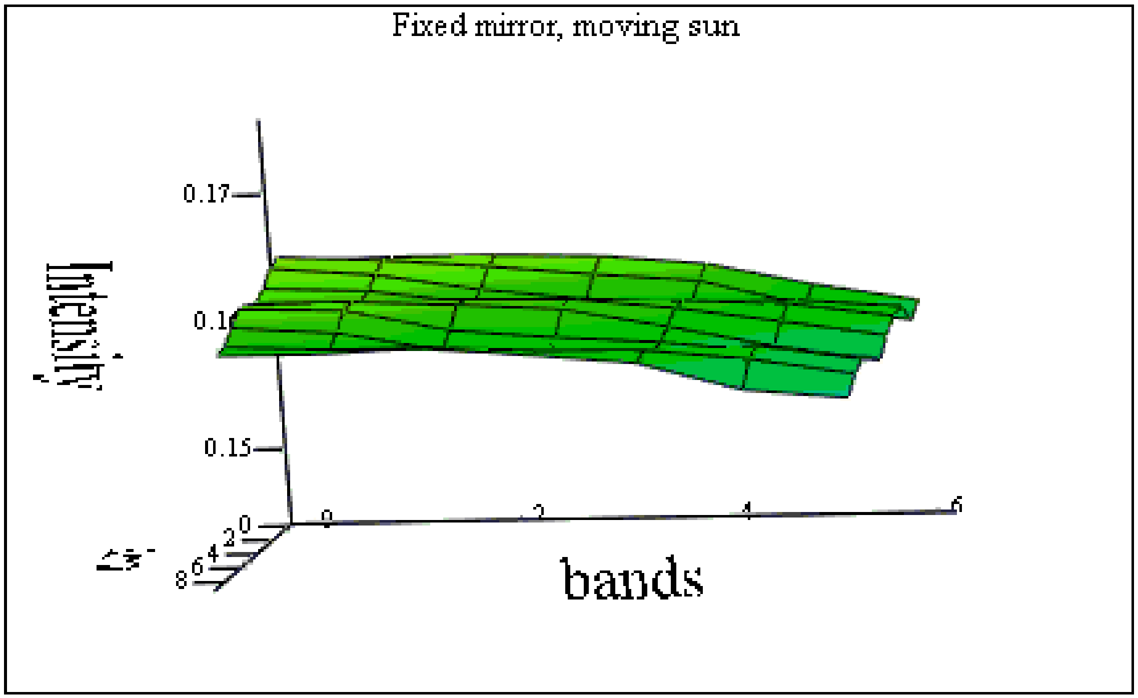


$E_{FRAME,20}$

Focal plane intensity variations fixed mirror, moving sun

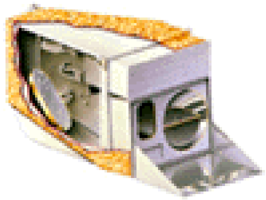


FRAME = 0

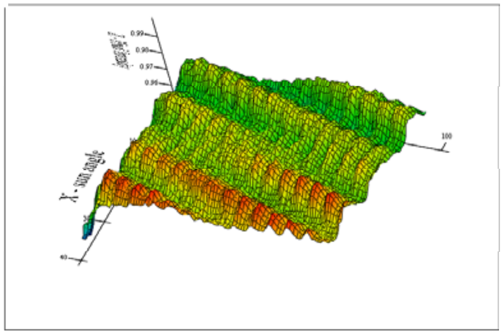


$E_{50,FRAME}$

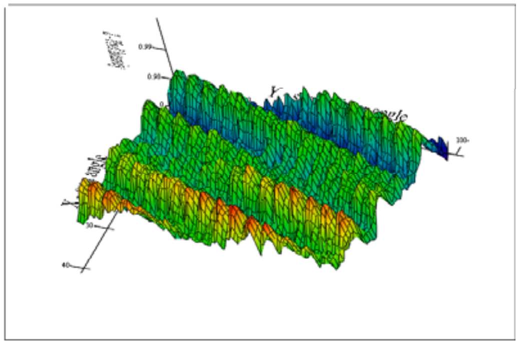
Summary of results



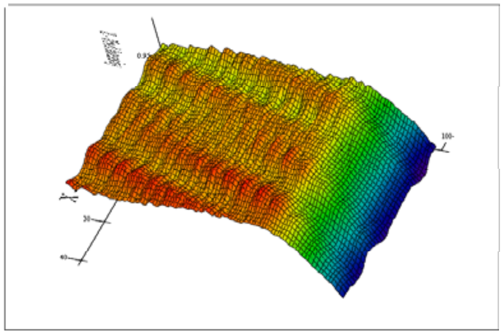
Middle Detector
band 10



Middle Detector
band 3

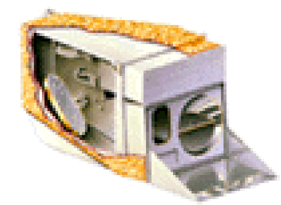


Middle Detector
band 12



Many more - for 7 bands and 10 detector locations per band.

Simulated (single mirror side) calibration



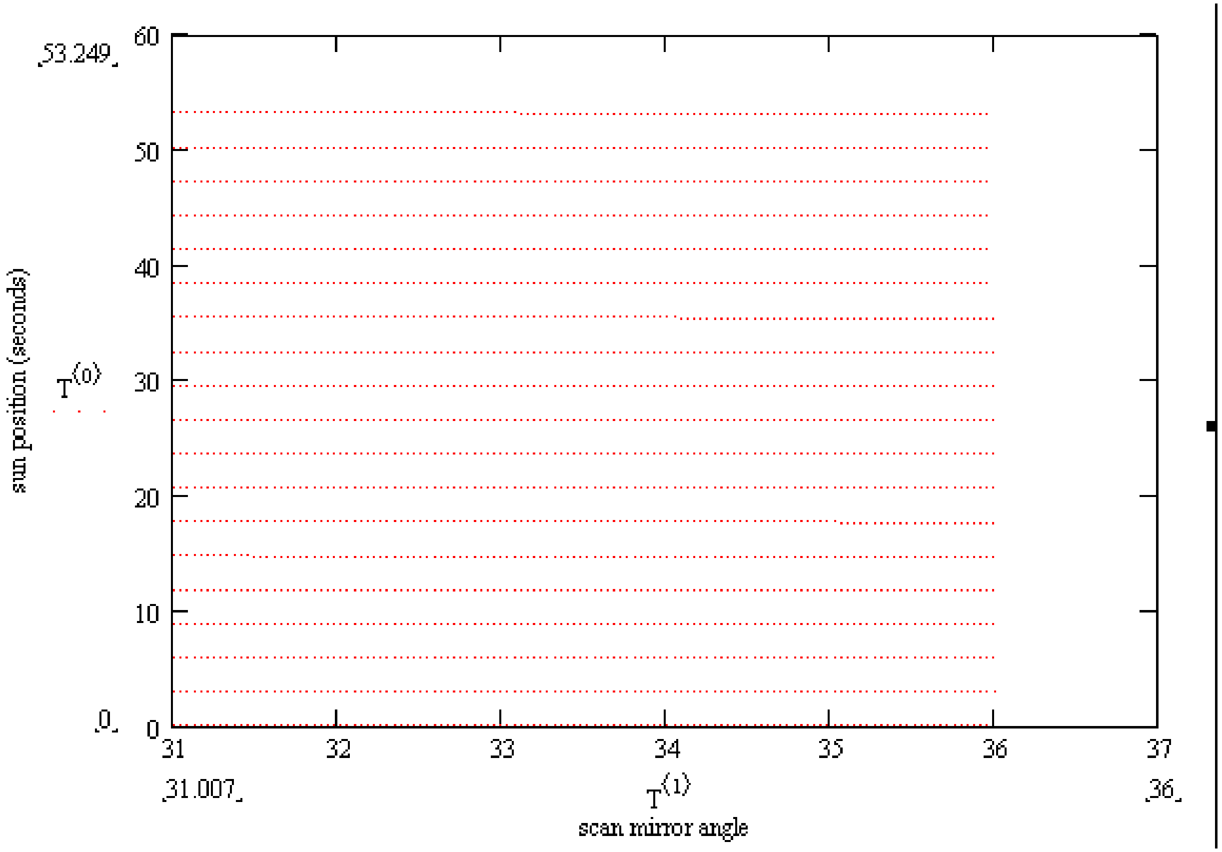
Coordinating the sun and scan mirror

- •5 degree mirror rotation (one complete revolution in 2.956 seconds or 36 to 31 degrees in CODE-V coordinates)
- •sun motion
- •frame rate

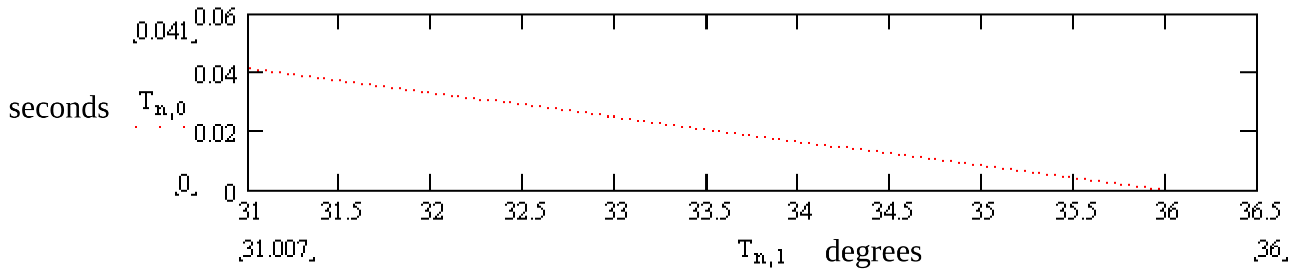
Produces

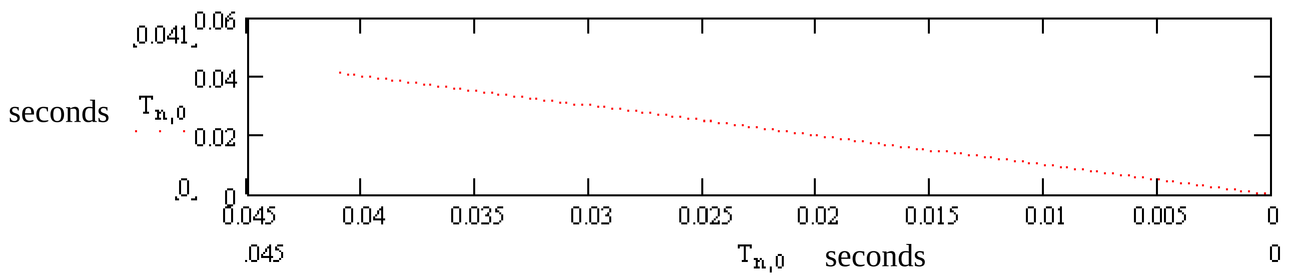
- •123 frames (in 0.041 seconds)
- •19 (single sided scan lines)

Frames and scans



First scan line and first 123 frames

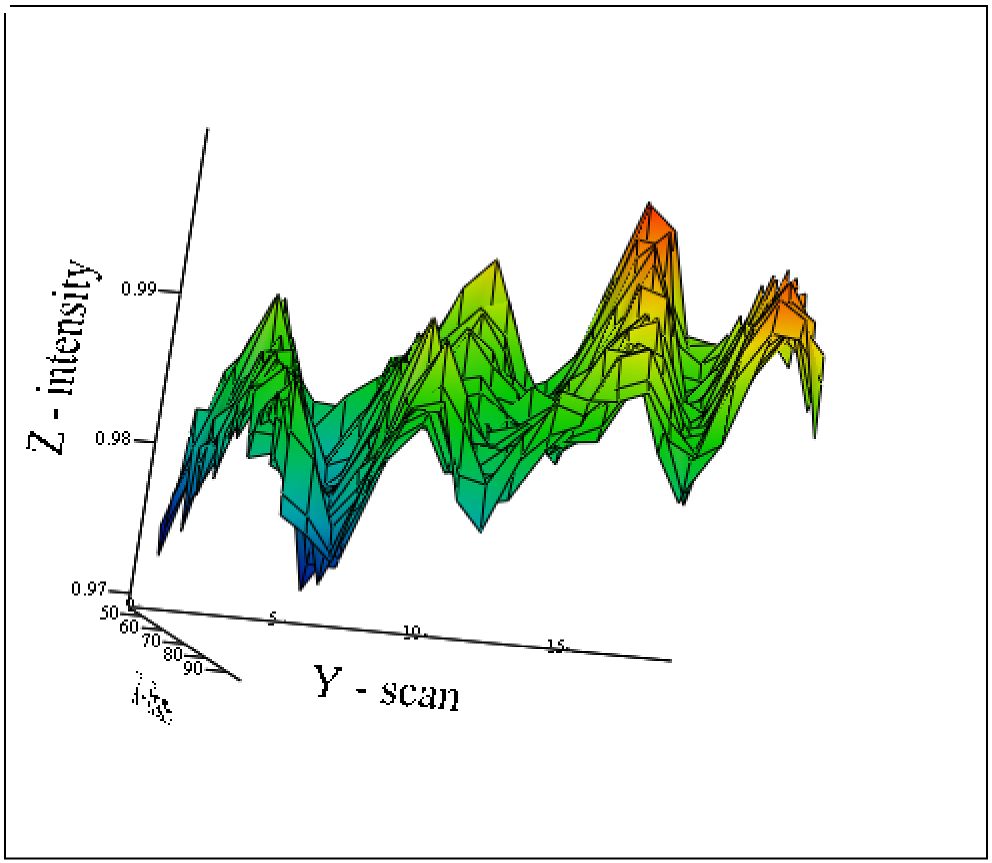




Only 50 middle frames are used in the calibration.

Need to synchronize modeled frames with actual frames and orbit.

Simulated signal for middle Detector band 12, 19 scans, 50 middle frames

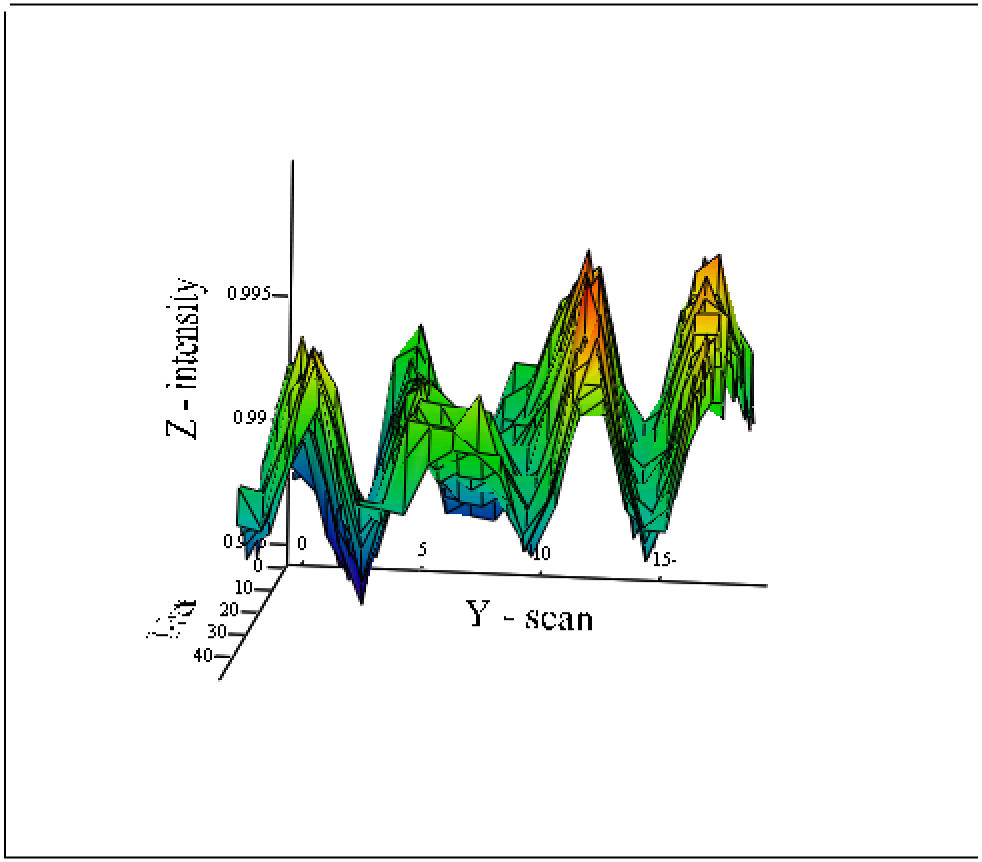


$\frac{dm}{max(dm)}$

Simulated result.

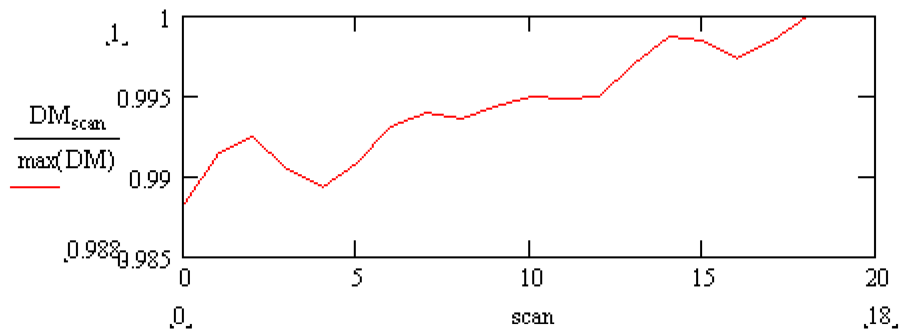
Real data

dmjack := READPRN("C:\MODIS\s3_to_s2\December divide by rr and cos to the 4\band12side1midpixel.txt")

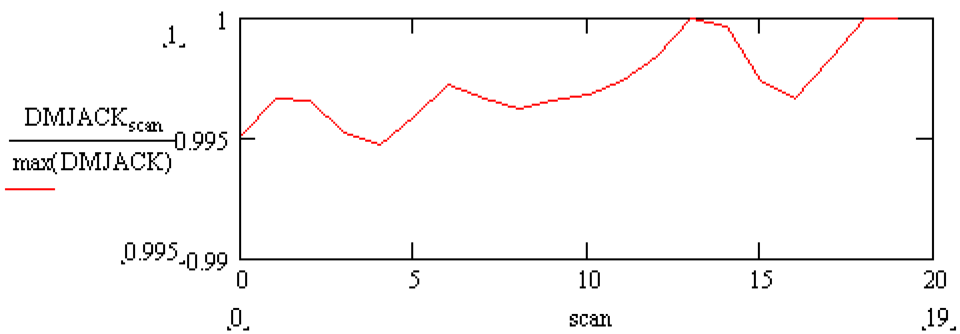


$$\frac{dmjack}{max(dmjack)}$$

Comparison of real and simulated 50 frame average data

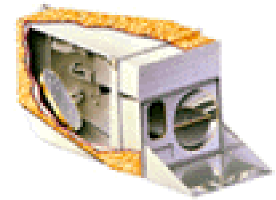


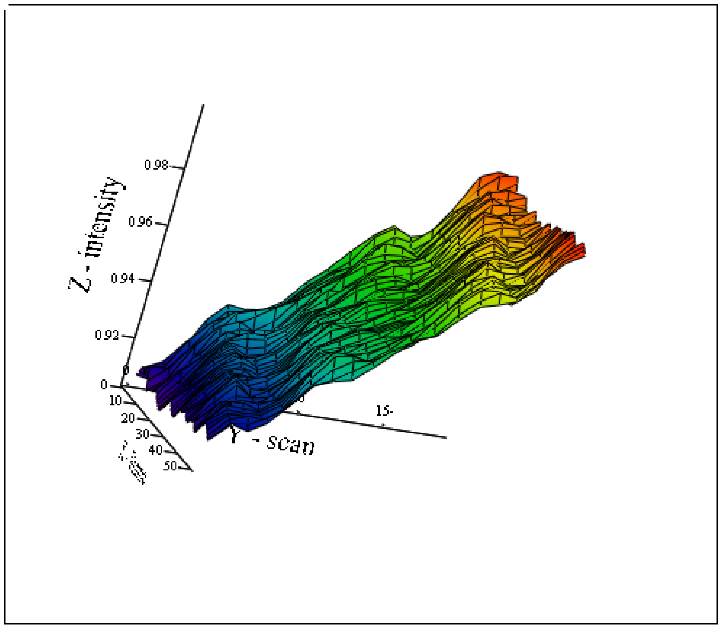
Simulated band 12 middle detector



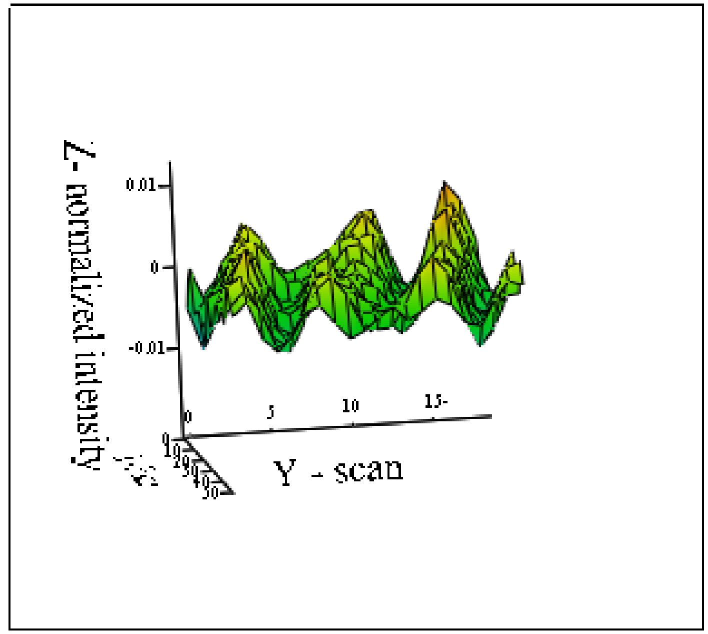
Real band 12 middle detector

$$\Delta E_4 = const. \cdot \frac{I \cdot \cos\theta_2 \cdot \Delta a_1 \cdot \cos\theta_1}{\pi \cdot r^2} \cdot \cos^4\theta_4 \cdot \frac{\Delta A}{h^2} \cdot \Delta a_4$$





$\frac{sub\_dm}{max(sub\_dm)}$



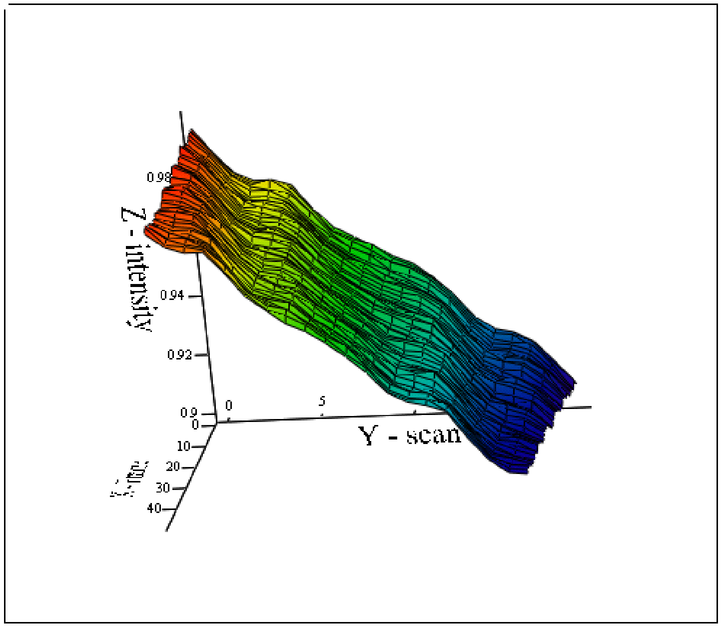
$(x, y, \Delta z)$

Simulated band 12 middle detector, with cosine factors.

Is it real or is it Memorx?
Band 12 mid detector with screen

PFM2002350.2100_dnsd_frame_band12_screen_close.txt

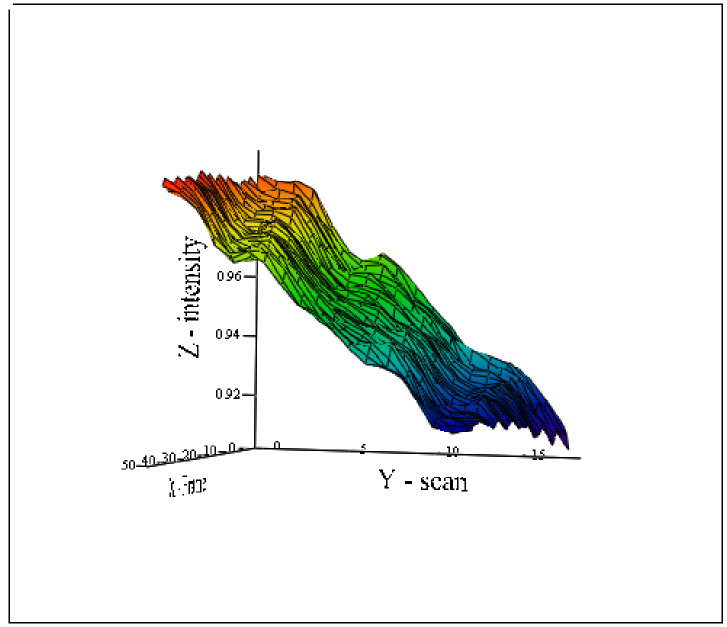
Real data



$\frac{dmjack\_sc\_closed}{max(dmjack\_sc\_closed)}$

Dec_rr_cos124V.mcd

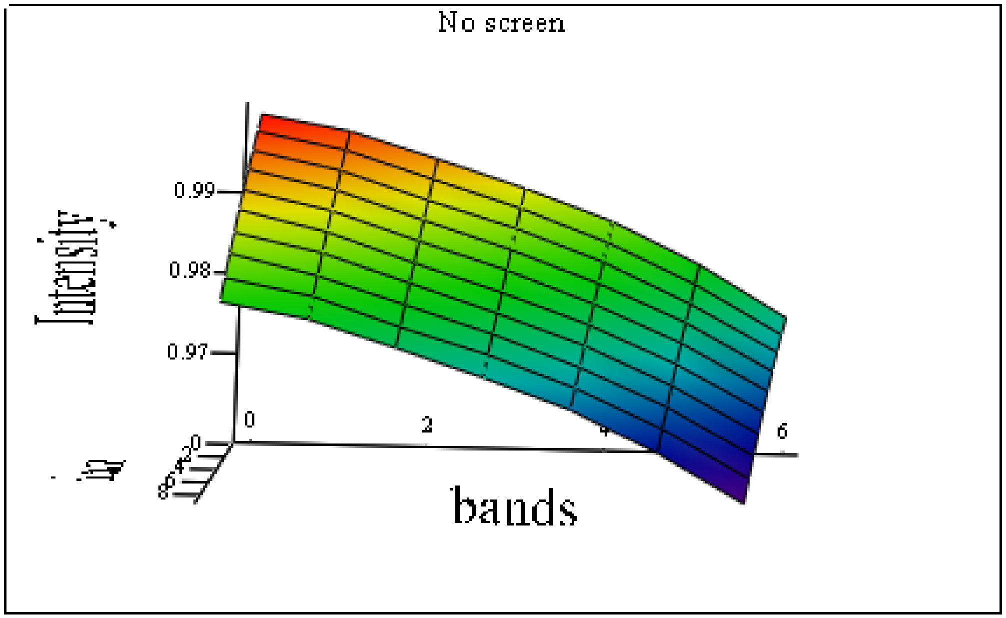
Simulated data



$\frac{sub\_dm}{max(sub\_dm)}$

Mirror_side_1_Sub_frame_1_Mid_detector_data_only						
Screen_close						
Band_12		Row: 50 frames data from each scan				
		Col: Scan number (from mirror side one only)				

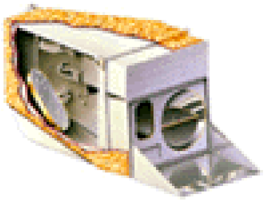
No screen VIS focal plane intensity



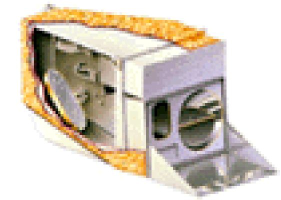
$$\frac{E_{50,FRAME}}{\max(E_{50,FRAME})}$$

One sun and one scan mirror position modeled result.

Solar diffuser modeling conclusion

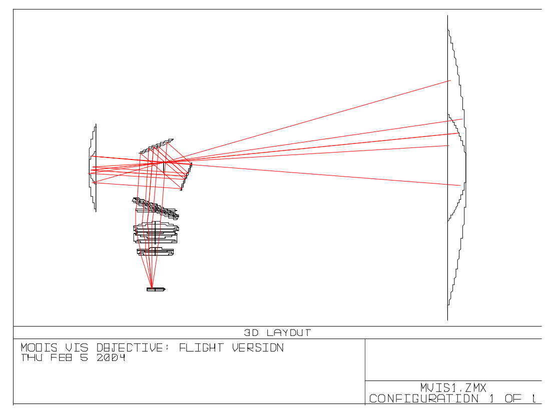


- Attenuation screen simulations and measurements headed for convergence
- May incorporate simulations directly into derived calibration coefficients
- *Historical note:*
  - *CONCLUSION from 2001 SPIE presentation was:*
  - *Speed up the computer runs!*



Polarization Modeling

The products of this effort will be used in a Polarization Ray Trace (PRT) model, that will be used to assist in the diagnosis and understanding of anomalous behavior in the MODIS TERRA instrument. Special attention shall be given to the spectral variations characteristic of the beam splitters and the band pass filters to ensure that they be accurately modeled, as it is suspected that these variations might contribute to or be responsible for the polarization sensitivity of MODIS and its temporal variation.



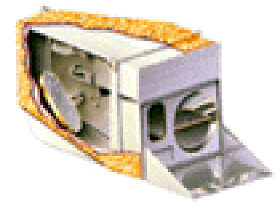
Assemble measured R(λ) & T(λ) polarization-component data for

- •scan mirrors,
- •VIS /NIR beamsplitters, and
- •(unpolarized data on) Band Pass Filters (BPF)
- •Visible path
- •NIR path

•Generate thin-film multi-layer coating designs for each component using realistic thin-film n & k material dispersion data.

•The goal is to reproduce the measured T & R values with sufficient fidelity and spectral resolution to permit the performance of the TERRA optical system to be accurately modeled.

Participants



PELLICORI OPTICAL CONSULTING

University of Miami (Ken Voss, Nordine Souaidia)

Goddard (Gerhard Meister)

SSAI (David Moyer)

Analysis of Aqua MODIS Prelaunch Polarization Measurements

January 15, 2004

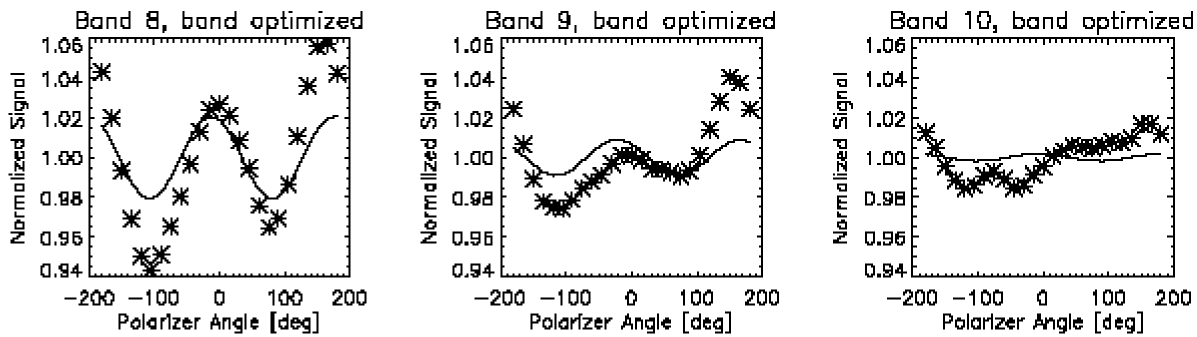
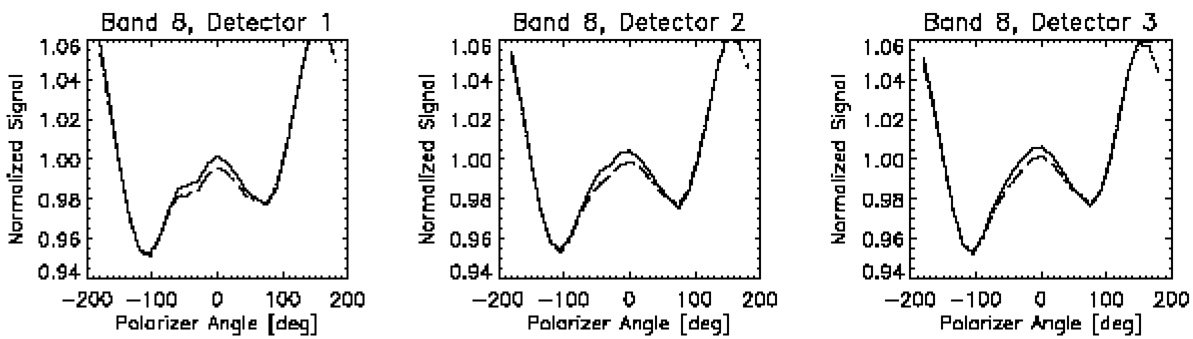
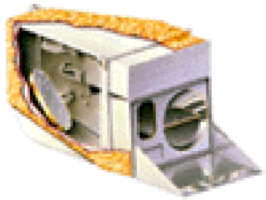


Figure 1: Polarization at a viewing angle of $-45°$, corresponding to an incidence angle on the scan mirror of $15.5°$. The stars show the band optimized prelaunch measurements, the solid line shows the two-cycle component.





Historical Note
First MODIS Polarization Ray Trace Model
(Perkin-Elmer circa 1990)

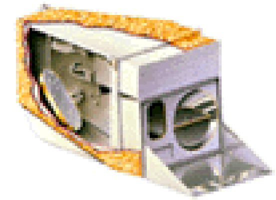
```
75
 0 0 0
   -300.0   1300.0   10.10101 !3,762.4,763,763.6,
48   405.5000      413.0000      420.5000
  438.0000      443.0000      448.0000
  460.0000      470.0000      480.0000
  485.0000      490.0000      495.0000
  515.0000      520.0000      525.0000
  545.0000      555.0000      565.0000
  560.0000      565.0000      570.0000
  645.5000      653.0000      660.5000
  655.0000      665.0000      675.0000
  676.0000      681.0000      686.0000
  745.0000      750.0000      755.0000
  857.5000      865.0000      872.5000
  870.0000      880.0000      890.0000
  890.5000      908.0000      925.5000
  931.0000      936.0000      941.0000
  940.0000      950.0000      960.0000
 0 2 0 0 2 2 3 099 4 59999

1.0                     1-air-air
1.0
1.0                     2-air-scanrx
thf4mtl   160.67
znsmtl     53.19
thf4mtl    80.33
znsmtl     53.19
thf4mtl   68.38
AGmtl      151.18
1.850       1.5                yttrium
1.52                         sub

1.0000                  3-air-gxbs1rx
thf4mtl   1536.57
znsmtl      23.91
thf4mtl      79.77
znsmtl      47.82
thf4mtl      79.77
znsmtl      47.82
thf4mtl      79.77
znsmtl      47.82
thf4mtl      79.77
znsmtl      47.82
thf4mtl      79.77
znsmtl      47.82
thf4mtl      79.77
znsmtl      47.82
thf4mtl      79.77
znsmtl      47.82
thf4mtl      79.77
znsmtl      54.22
thf4mtl      97.35
znsmtl      60.63
thf4mtl      97.35
znsmtl      60.63
thf4mtl      97.35
znsmtl      60.63
thf4mtl      97.35
znsmtl      60.63
thf4mtl      97.35
znsmtl      60.63
thf4mtl      97.35
znsmtl      60.63
thf4mtl      97. 53
znsmtl      60.63

thf4mtl      97.35
znsmtl      68.75
thf4mtl     122.10
znsmtl      76.87
thf4mtl     122.10
znsmtl      76.87
thf4mtl     122.10
znsmtl      76.87
thf4mtl     122.10
znsmtl      76.87
thf4mtl     122.10
znsmtl      76.87
thf4mtl     122.10
znsmtl      76.87
thf4mtl     122.10
znsmtl      76.87
thf4mtl     122.10
znsmtl      38.44
znsemtl      44.90
thf4mtl     157.77
znsemtl      89.80
thf4mtl     157.77
znsemtl      89.80
thf4mtl     157.77
znsemtl      89.80
thf4mtl     157.77
znsemtl      89.80
thf4mtl     157.77
znsemtl      89.80
thf4mtl     157.77
znsemtl      89.80
thf4mtl     157.77
znsemtl      44.90
2.4300
1.0                     4-air-bk7
bk7

bk7                     5-bk7-air
1.0
1.0000                  air-birsrx
1.5000    264.58
1.5200    260.12
1.5500    253.75
1.5800    247.71
1.6400    236.53
1.7000    226.40
1.7800    214.26
1.8800    200.92
2.0200    184.97
2.1300    174.20
2.2200    166.32
2.2800    161.47
2.3200    158.40
2.3600    155.45
2.3800    154.01
2.4000    152.61
2.4300
```



Coating Prescriptions

A strongly worded suggestion:

Must have ***full*** knowledge of as built coating prescriptions on all of the optical elements.

This means the

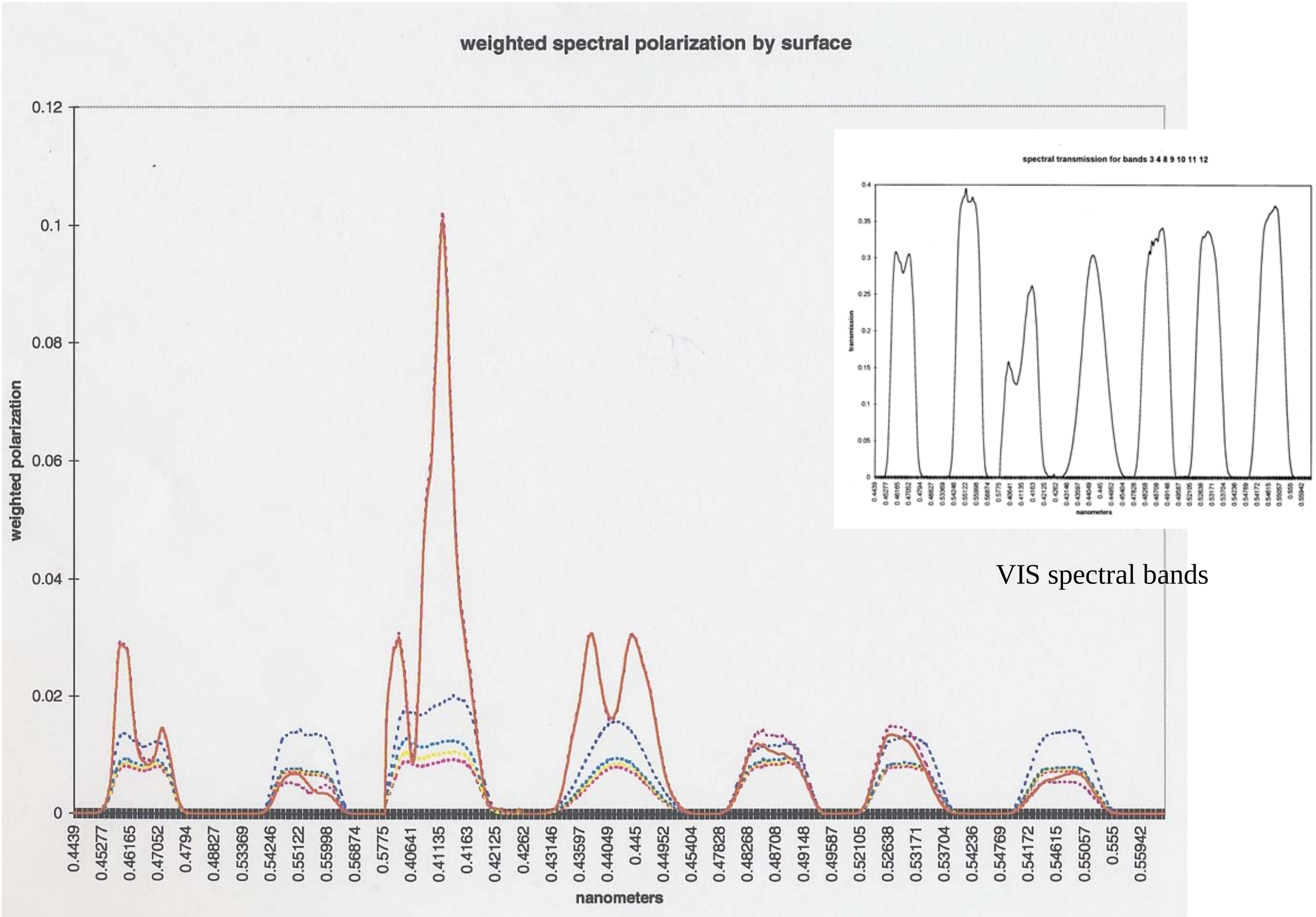
$$n(\lambda) + ik(\lambda)$$

for each layer in each coating.

Vendors will supply with NDA’s.

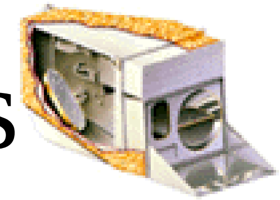
Goddard Polarization Modeling

circa 1997

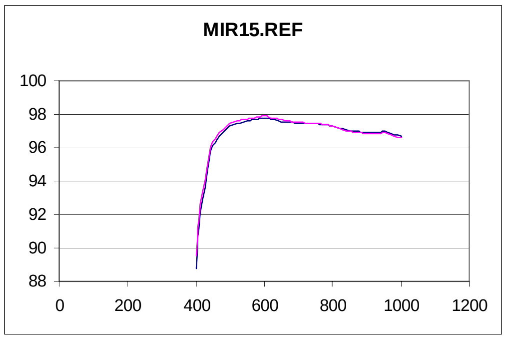


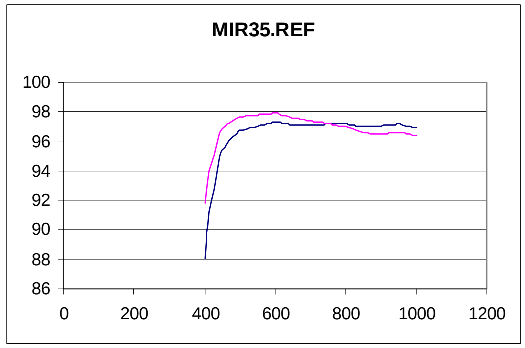
VIS spectral bands

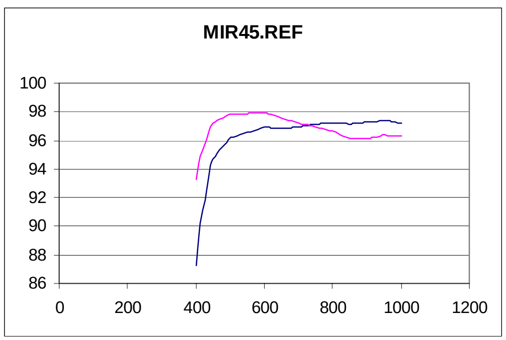
Measured Scan mirror values



Used measured surface reflectances or transmittances at one incidence angle







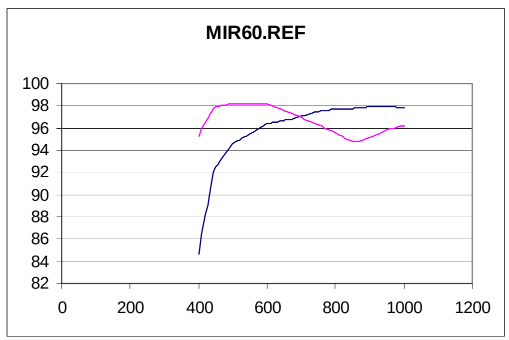
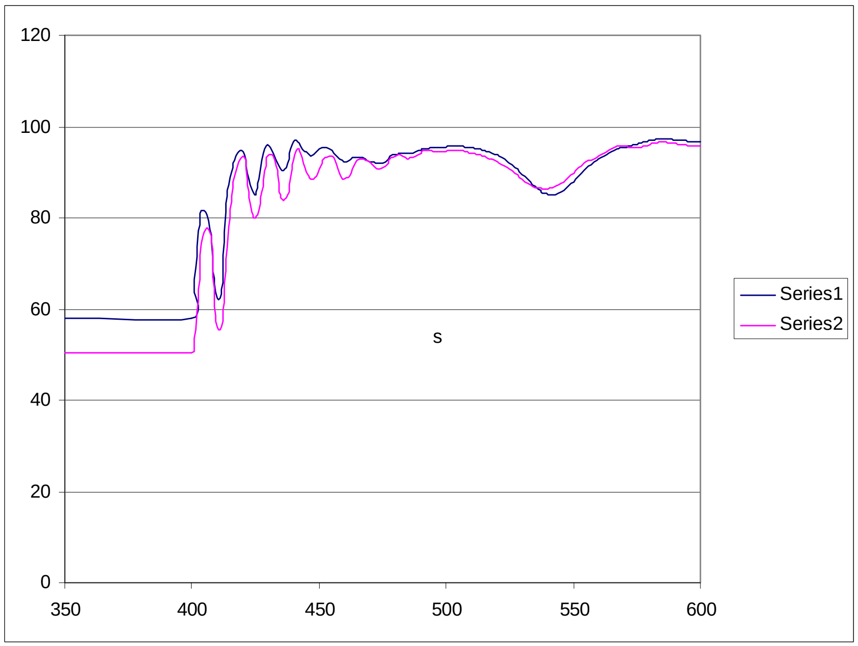


Table 1: Surfaces which effect the transmission and polarization in the visible light path. Surfaces without a name are dummy surfaces. Surface 23 represents all seven focal plane filters.

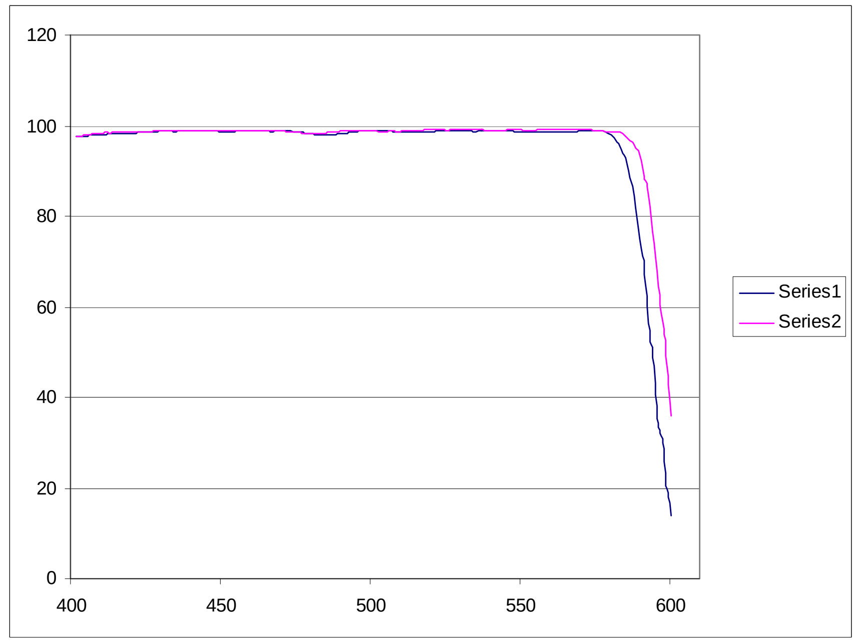
Surface #	Surface Incidence	Angle of (degrees)
1		0.0
2	Scan	45,60
3		0.0
4	Fold	45.0
5		0.0
6		0.0
7	Primary	9.22
8		1.985
9	Secondary	9.22
10		0.0
11	0.0	
12	Dichroic 1	22.5
13	Dichroic 2	22.5
14		22.5
15		15.2
16		0.0
17	E1	2.83E-3
18	E1	2.68E-3
19	E2	5.41E-3
20	E2	1.50E-3
21	E3	2.10E-3
22	E3	2.21E-3
23	Filters	2.45E-3

Dirchroic S and P reflectivities

DICH1_PFM_REFL



DICH2_PFM_REFL



<<<<<< Attached TEXT file named "DICH1.PFM.REFL" follows >>>>>>

DICHROIC NOTINV "OFC Dich: 400-700 nm Late SBRS Measurements, SN7: 12/96, 700-1.2um Early Measurements, PL3095-Q06183, SN6"

wavelength "vertical, p" "horizontal, s"

350 58.04 50.3

400 58.04 50.3

<<<<<< Attached TEXT file named "DICH2.PFM.REFL" follows >>>>>>

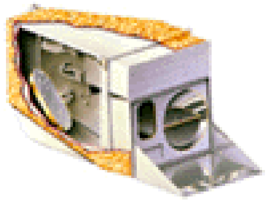
DICHROIC NOTINV BS 2 S/N 4-1 measured at 22.5 deg AOI on 7/26/93

WAVELENGTH (nm) P REFLECT (%) S REFLECT (%)

401.81 97.57 97.61

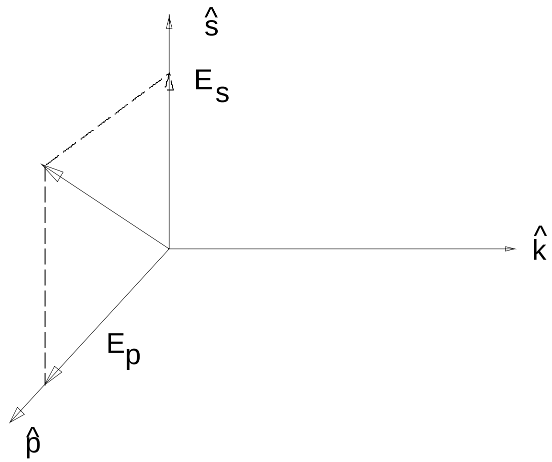
402.81 97.63 97.69

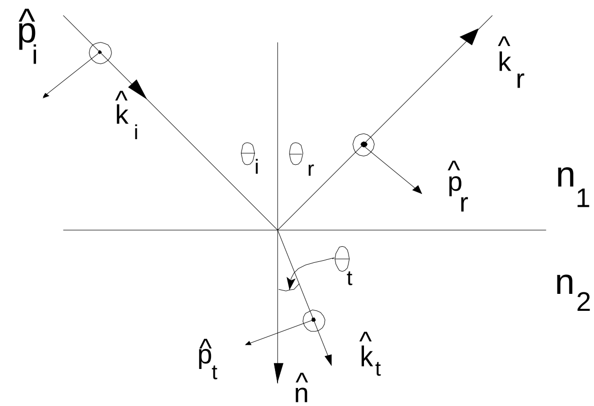
Polarization Ray Trace

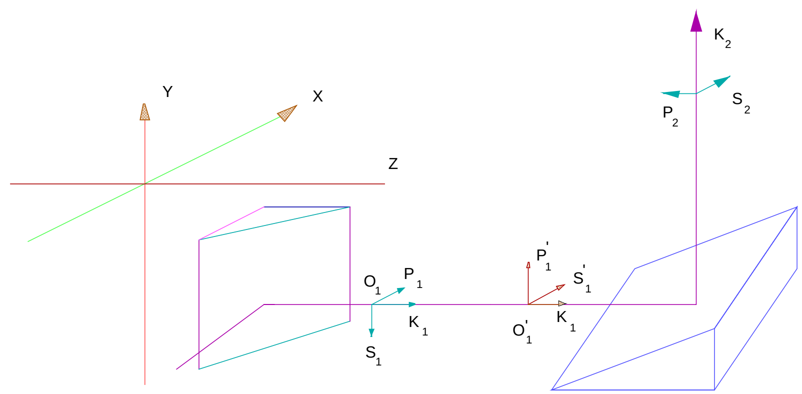


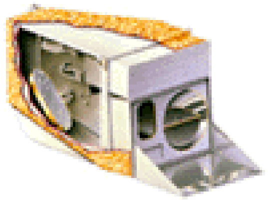
tutorial covered very quickly

Jones vector $\vec{E} = \begin{pmatrix} E_s \\ E_p \end{pmatrix}$

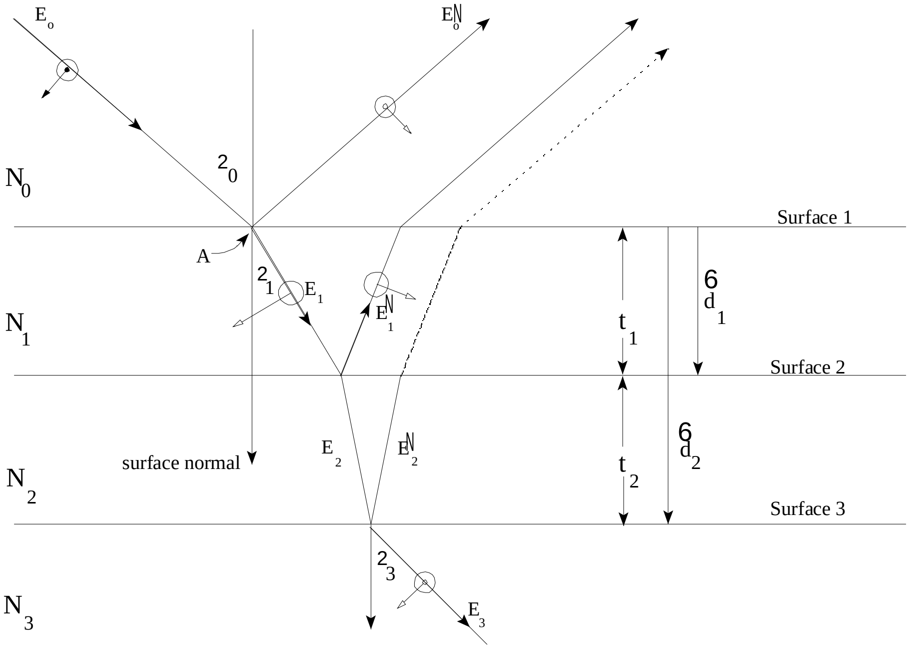








Film Stack

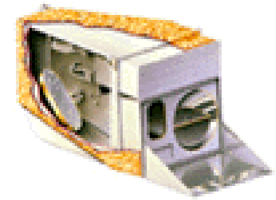


At each interface, within a film stack, the general form of the equations expressing continuity of the tangential components of the E and H fields is similar to the equations at the first interface.

$$(\vec{E}_1+\vec{E}'_1)\times\hat{n}=(\vec{E}_2+\vec{E}'_2)\times\hat{n}$$

$$(\vec{H}_1+\vec{H}'_1)\times\hat{n}=(\vec{H}_2+\vec{H}'_2)\times\hat{n}$$

$$\begin{pmatrix} \cos\left(\frac{2\pi}{\lambda}Nt\cos\theta\right) & -\frac{i}{\varsigma}\sin\left(\frac{2\pi}{\lambda}Nt\cos\theta\right) \\ -i\varsigma\sin\left(\frac{2\pi}{\lambda}Nt\cos\theta\right) & \cos\left(\frac{2\pi}{\lambda}Nt\cos\theta\right) \end{pmatrix}$$



Polarization ray trace

Associated with each ray is either a Jones or Stokes vector which is transformed by a series of matrix multiplications.

$$E_{m+1}(\theta) = S_m R_m S_{m-1} R_{m-1} \cdots S_2 R_2 S_1 R_1 E_1(\theta)$$

For any optical system with no birefringence

$$I(\theta) \sim \left|E(\theta)\right|^2 \sim const. + \cos^2(\theta + \varepsilon)$$

$$I(\theta) = \sum_{m=1}^{rays} I_m(\theta)$$

S 0.0 5.0 SILICA_SPECIAL

S 82.6262 18.6324755899 SAPHIR_SPECIAL

S -87.0204 7.5 SF11_SCHOTT

S 0.0 8.41706783452 SILICA_SPECIAL

S 0.0 1.5 BK7_SCHOTT

Stray Light around primary

The picture below shows three things.

A big circle which is the clear aperture of the primary.

A small circle which is the clear aperture of the stop. In the ray trace the stop is in the tangent plane of the primary. In actual hardware the stop would be clear aperture (the reflecting portion) of the primary mirror (I believe).

The intercept points of rays with the primary mirror surface. These rays were fired "backward" from the center of the visible focal plane and completely fill the first lens aperture (surface 25 of the aft-optics objective assembly). There are a total of 289 of these points of which 145 (50%) are inside the clear aperture of the primary.