Modeling MODIS performance/radiometric ray tracing

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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 $\iff$ 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

• “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 $333.3 \times 10^{-6}$ 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.
MODIS attenuation screen
SD Screen Design

8.5% SCREEN

SOLID DOOR

SOLAR VIEW DOOR ASSEMBLY
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.

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

\[ E = \int_{\Omega} \int_{\lambda} \int_{t} \int_{a} I_{\lambda}(\theta, \phi) \cdot \cos \theta \cdot d\Omega \cdot da \cdot d\lambda \cdot dt. \]
Ray from focal plane to solar diffuser to pinhole(s)

\[ dE_4 = I_4 \cdot \cos \theta_4 \cdot d\Omega_4 \cdot da_4 \]

\[ I_4 = (\text{transmission loss}) \cdot I_3 \]

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

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

\[ \Delta E_4 = \text{const.} \cdot \frac{I \cdot da_4 \cdot dA}{\pi h^2} \cdot \frac{\cos \theta_4 \cdot \cos \theta_4 \cdot \cos^2 \theta_4}{r^2} \]
Energy incident on detector

Energy deposited on a detector by a single ray

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

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

Total Energy deposited on a detector

\[ E = \sum_{\text{all rays}} \Delta E_4 \]

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
Motion of pinhole images

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
frame_{FRAME} = "C:\MODIS\s3_to_s2\December divide by \pi and cos to the 4\Dec_{rr}_{31.0}"

Rotating mirror, fixed sun

Intensity

bands

E_{FRAME,20}
Focal plane intensity variations
fixed mirror, moving sun

FRAME = 0

Fixed mirror, moving sun

Intensity

bands

$E_{50,\text{FRAME}}$
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

Simulated result.
Real data

dmjack = READFN("C:\MODIS\a3_to_s2\December divide by rr and cos to the 4\band12\side1\midpixel.txt")
Comparison of real and simulated 50 frame average data

Simulated band 12 middle detector

Real band 12 middle detector
\[ \Delta E_4 = \text{const} \cdot \frac{I \cdot \cos \theta_2 \cdot \Delta a_1 \cdot \cos \theta_1 \cdot \cos^4 \theta_4 \cdot \Delta A}{\pi \cdot r^2 \cdot h^2 \cdot \Delta a_4} \]

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

Dec_rr_cos124V.mcd
Simulated data
No screen VIS focal plane intensity

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 $R(\lambda)$ & $T(\lambda)$ 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 $-45^\circ$, corresponding to an incidence angle on the scan mirror of $15.5^\circ$. 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)*

<table>
<thead>
<tr>
<th>Layer 1</th>
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</table>

**Ocean Color from MODIS Review**

February 11-12, 2004
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

weighted spectral polarization by surface

VIS spectral bands
Used measured surface reflectances or transmittances at one incidence angle.

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

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<th>Surface</th>
<th>Angle of</th>
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<td>Secondary</td>
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Dirchroic S and P reflectivities

DICH1_PFM_REFL

DICH2_PFM_REFL

<<<<< Attached TEXT file named "DICH1_PFM_REFL" follows >>>>>>
DICHRIOIC 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 >>>>>>
DICHRIOIC 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*  \( \tilde{E} = \begin{pmatrix} E_s \\ E_p \end{pmatrix} \)
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.

\[
\begin{align*}
(E_1 + E'_1) \times \hat{n} &= (E_2 + E'_2) \times \hat{n} \\
(H_1 + H'_1) \times \hat{n} &= (H_2 + H'_2) \times \hat{n}
\end{align*}
\]

\[
\begin{pmatrix}
\cos \left( \frac{2\pi}{\lambda} N t \cos \theta \right) & -i \frac{\xi}{\sqrt{\lambda}} \sin \left( \frac{2\pi}{\lambda} N t \cos \theta \right) \\
-i \xi \sin \left( \frac{2\pi}{\lambda} N t \cos \theta \right) & \cos \left( \frac{2\pi}{\lambda} N t \cos \theta \right)
\end{pmatrix}
\]
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

\[ I(\theta) \sim |E(\theta)|^2 \sim const. + \cos^2(\theta + \varepsilon) \]

\[ I(\theta) = \sum_{m=1}^{\text{rays}} I_m(\theta) \]

- 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.