RSP/APS potential for validation of orbital surface BRDF measurements

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Knobelspiesse, K.D., B. Cairns, B. Schmid, M.O. Roman, and C.B. Schaaf (2008), Surface BRDF estimation from an aircraft compared to MODIS and ground estimates at the Southern Great Plains site, J. Geophys. Res., 113, D20105.
Outline

An alternate RSP/APS use: Validation of MODIS surface BRDF products

Surface BRDF
- Importance for climate modeling
- Definitions and terminology
- Current orbital estimation techniques
- Validation with ground radiometers

Our contribution: RSP measurements during ALIVE
- Experiment details, data sifting
- Estimating BRDF including multiple ground-atmosphere scattering
- Narrow spectral bandpass to broadband conversion

Results
- Validation
- APS potential for routine BRDF validation efforts

Concluding remarks
RSP and Glory-APS

Aerosol Polarimetry Sensor (APS)

- June launch on NASA Glory mission
- Also on Glory: a solar irradiance monitor

Research Scanning Polarimeter (RSP)

- Airborne prototype of APS

Main goal: Measure aerosols and clouds
... but we will use them to measure the surface

RSP and APS design

- Nine spectral channels, blue to infra-red (410 - 2250 nm)
- Scans along track (in the direction of motion) NOT an imager
- Polarized radiance - I,Q,U components of Stokes vector
- High (0.2%) accuracy for polarized radiances

Aerosol spectral bands: 410nm, 470nm, 555nm, 670nm, 865nm, 1590nm
Other bands: 960nm, 1880nm, 2250nm
Alternate use… surface albedo

IPCC 4AR (2007) summary for policymakers

Instruments such as MODIS, MISR and MERIS can characterize surface albedo… validation?
ALIVE field campaign

Test validation potential with field campaign data

ALIVE (Aerosol Lidar Validation Experiment)
  • DOE Southern Great Plains (SGP) site (near Ponca City, Oklahoma)
  • September, 2005
  • Surface type: rural pasture, late season crops, recently plowed fields

Compare albedo from

Satellite (MODIS)
  to
Aircraft (RSP)
  to
Ground (SGP radiometers)
What is albedo?

We must compare apples to apples…

Single view angle satellite (MODIS):
- global
- narrow spectral bands
- fit observations to albedo model
- must accumulate views
- must account for atmosphere

Multiple view angle aircraft (RSP):
- local
- narrow spectral bands
- fit observations to albedo model
- Multiple view angles instantaneously
- must account for atmosphere

Ground radiometers (BEFLUX):
- point
- broad spectral band
- Observe diffuse upwelling and downwelling, direct downwelling
How is albedo defined?

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Directional</th>
<th>Conical</th>
<th>Hemispherical</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Incoming/Reflected</strong></td>
<td>Bidirectional reflectance distribution function (BRDF)</td>
<td>Directional–conical CASE 2</td>
<td>Directional hemispherical reflectance (DHR)</td>
</tr>
<tr>
<td><strong>Directional</strong></td>
<td>Conical–directional CASE 4</td>
<td>Conical–hemispherical CASE 5</td>
<td>Conical–hemispherical CASE 6</td>
</tr>
<tr>
<td><strong>Conical</strong></td>
<td>Hemispherical–directional CASE 7</td>
<td>Hemispherical–conical CASE 8</td>
<td>Bihemispherical reflectance (BHR)</td>
</tr>
</tbody>
</table>

The labeling with ‘Case’ corresponds to the nomenclature of Nicodemus et al. (1977). Grey fields correspond to measurable quantities (Cases 5, 8), the others (Cases 1, 4, 6, 7, 9) denote conceptual quantities. Please refer to the text for the explanation on measurable and conceptual quantities.

How is BRDF defined?

\[
\text{BRDF}(\theta_s, \theta_v, \phi_s, \phi_v, \lambda) = \frac{dL(\theta_s, \theta_v, \phi_s, \phi_v, \lambda)}{dE(\theta_s, \phi_s, \lambda)} \text{[sr}^{-1}] 
\]

L = radiant flux per unit solid angle [W m\(^{-2}\) sr\(^{-1}\)]
E = irradiance [W m\(^{-2}\)]
\(\lambda\) = wavelength [nm]
\(\theta_s\) = solar zenith angle
\(\theta_v\) = view zenith angle
\(\phi_s\) = solar azimuth angle
\(\phi_v\) = view azimuth angle

BRDF is a theoretical property impossible to measure exactly
Often estimated by fitting observations to reflectance models
DHR and BHR can be estimated by integrating BRDF over view and solar geometries
How is DHR defined?

\[
\text{DHR}(\theta_s, \phi_s, \lambda) = \int_0^{2\pi} \int_0^{\pi/2} \text{BRDF}(\theta_s, \theta_v, \phi_s, \phi_v, \lambda) \cos(\theta_v) \sin(\theta_v) \, d\theta_v \, d\phi_v
\]

\(\lambda\) = wavelength [nm]

\(\theta_s\) = solar zenith angle

\(\phi_s\) = solar azimuth angle

\(\theta_v\) = view zenith angle

\(\phi_v\) = view azimuth angle

DHR is BRDF integrated over viewing geometry

This simplified form of BRDF is often the type used in climate models

A typical assumption (that we make) is that DHR is independent of \(\phi_s\), reasonable if surface properties have no preferred azimuth orientation

Also known as ‘black sky’ or planetary albedo
**How is BHR defined?**

\[
\text{BHR}(\lambda) = \frac{2\pi}{2\pi/2} \int \int \int \int \text{BRDF}(\theta_s, \theta_v, \phi_s, \phi_v, \lambda) \cos(\theta_v) \sin(\theta_v) \cos(\theta_s) \sin(\theta_s) \, \text{d}\theta_v \, \text{d}\phi_v \, \text{d}\theta_s \, \text{d}\phi_s
\]

- \(\lambda\) = wavelength [nm]
- \(\theta_s\) = solar zenith angle
- \(\phi_s\) = solar azimuth angle
- \(\theta_v\) = view zenith angle
- \(\phi_v\) = view azimuth angle

BHR is BRDF integrated over solar and viewing geometry.

BHR is measured by field radiometers.

We will work with \(\text{BHR}_{\text{iso}}\), which is BHR assuming completely diffuse (isotropic) downwelling irradiance.

Also known as ‘white sky’ or spherical albedo.
Why all these albedo types?

**MODIS & RSP**
- Fit observations to model
- Integrate geometrically
- Integrate spectrally

**BEFLUX**
- Estimate $\text{BHR}_{bb,iso}$ from diffuse ratios of upwelling and downwelling irradiance in cloudy conditions
- Determine DHR using $\text{BHR}_{bb,iso}$, direct and diffuse downwelling irradiance and diffuse upwelling irradiance

Characterizing the downwelling irradiance is difficult with varying instrument spatial and temporal scales
We use the MODIS MCD43 ‘collection five’ products

- BRDF estimated from 16 days of Terra & Aqua observations
- 500m spatial resolution, 7 narrow spectral bands (470-2130nm)
- BRDF model fitting splits surface interactions into three parts, i.e.

\[
\text{BRDF}(\theta_s, \theta_v, \phi_s, \phi_v, \lambda) = f_{iso}(\Lambda) + f_{vol}(\Lambda)K_{vol}(\theta_s, \theta_v, \phi) + f_{geo}(\Lambda)K_{geo}(\theta_s, \theta_v, \phi)
\]

- Where
  - \(\Lambda\) = instrument spectral band
  - \(\phi = \phi_v - \phi_s\)
  - \(f_{iso}\) = isotropic scaling parameter
  - \(f_{vol}\) = volumetric scaling parameter
  - \(f_{geo}\) = geometric scaling parameter
  - \(K_{vol}\) = Volumetric (dense vegetation) scattering kernel from Roujean et al. [1992] and Ross [1981]
  - \(K_{geo}\) = Geometric (sparse vegetation) scattering kernel from Wanner et al. [1995], Li and Strahler [1992] and reciprocal form in Lucht et al. [2000]

- This simplifies the BRDF to three parameters

The MCD43 product for each pixel are the three \(f\) scaling parameters
Best Estimate Flux (BEFLUX)

- Value Added Product (VAP) created from several radiometers
- Located in a pasture at the DOE’s Southern Great Plains (SGP) site in central Oklahoma, USA

Adapted from:
Table 1. Low Altitude ALIVE Flight Segments Used for Surface Characterization

<table>
<thead>
<tr>
<th></th>
<th>JRF3</th>
<th>JRF4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>09/16/2005</td>
<td>09/16/2005</td>
</tr>
<tr>
<td>Start time, UTC#</td>
<td>16:32:25</td>
<td>22:09:32</td>
</tr>
<tr>
<td>Number of RSP scans</td>
<td>270</td>
<td>41</td>
</tr>
<tr>
<td>J-31 Altitude above sea level*</td>
<td>510 m</td>
<td>475 m</td>
</tr>
<tr>
<td>Relative sensor-solar azimuth</td>
<td>$-45^\circ$</td>
<td>$156^\circ$</td>
</tr>
<tr>
<td>Solar zenith angle</td>
<td>$43^\circ$</td>
<td>$62^\circ$</td>
</tr>
<tr>
<td>AERONET $\tau_a(\lambda = 500$ nm)</td>
<td>0.07</td>
<td>0.05</td>
</tr>
<tr>
<td>AATS-14 $\tau_a(\lambda = 499$ nm)</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>sky conditions</td>
<td>clear</td>
<td>clear</td>
</tr>
</tbody>
</table>

* SGP height above seal level is about 315m

# local time was five hours earlier
RSP observations were fit to the MODIS BRDF models

How to characterize scattering?

• Aerosol effect between aircraft and ground is minimal due to low altitude
• Aerosols above aircraft determined by onboard sun-photometer and high altitude RSP measurements

Doubling and Adding method describes atmospheric scattering, but…

Surface-atmosphere scattering depends on parameters we are attempting to retrieve

Solution: Iterative approach that initially estimates BRDF assuming no scattering
RSP and MODIS BRDF results

\[ \theta_s = 30^\circ \]
RSP and MODIS BRDF results

$\theta_s = 30^\circ$
Spectral integration

How to integrate spectral DHR and BHR to BEFLUX broadband values?

Method: linearly interpolate DHR or BHR, then integrate weighted by direct solar transmittance associated with previously modeled atmosphere.

$$DHR_{bb}(\theta_s) = \frac{\int_{400nm}^{2500nm} E_o(\lambda)t(\lambda)DHR(\theta_s, \lambda)d\lambda}{\int_{400nm}^{2500nm} E_o(\lambda)t(\lambda)d\lambda}$$

$$BHR_{bb} = \frac{\int_{400nm}^{2500nm} E_o(\lambda)t(\lambda)BHR(\lambda)d\lambda}{\int_{400nm}^{2500nm} E_o(\lambda)t(\lambda)d\lambda}$$
BHR results

MODIS $BHR_{bb} = 0.208$
RSP $BHR_{bb} = 0.185$
BEFLUX $BHR_{bb} = 0.185$
Normalized DHR:  
\[ nDHR_{bb}(\theta_s) = \frac{DHR_{bb}(\theta_s)}{DHR_{bb}(60^\circ)} \]
Results

BHR
- Highest values, and largest differences, in Near Infra Red (NIR)
- MODIS BHR\(_{bb}\) high bias with ‘all’ related to NIR band RSP doesn’t have

DHR
- Good agreement by all three when \(\theta_s<70^\circ\).
- Divergence between BEFLUX morning and afternoon DHR expresses variability

nDHR
- Good agreement by all three when \(\theta_s<70^\circ\), best with ‘all’ classes
Conclusion

• RSP, with its large number of viewing angles, validates the ability of MODIS to retrieve BRDF, DHR and BHR that agrees with ground radiometers when $\theta_s < 70^\circ$

• Validation is for ONE DAY at the SGP site only

• Largest potential problem is the spectral interpolation

Side note

How does ModelE describe surface albedo?

Is it time to consider using satellite derived albedo climatologies?
Thanks

I was supported during ALIVE by an NSF IGERT graduate student fellowship.

BEFLUX data are from the DOE’s Atmospheric Radiation Measurement Program (ARM). ARM also funded the ALIVE field campaign.

RSP participation during ALIVE was supported by NASA, who also provide MODIS data.

Knobelspiesse, K.D., B. Cairns, B. Schmid, M.O. Roman, and C.B. Schaaf (2008), Surface BRDF estimation from an aircraft compared to MODIS and ground estimates at the Southern Great Plains site, J. Geophys. Res., 113, D20105.
Yang (2006) compared parameterizations of MODIS to BEFLUX 

\( DHR_{bb}(\theta_s) \) found:

- BEFLUX \( DHR_{bb}(\theta_s) \) larger at high solar zenith angles (expected)
- BEFLUX \( DHR_{bb}(\theta_s) \) smaller at low solar zenith angles (unexpected)

Source of these differences?

- Spatial / temporal resolution?
- MODIS albedo computation?
  - Not enough view angles?
  - Atmospheric correction?
  - BRDF model appropriate?
- BEFLUX albedo computation?

RSP observations during the Aerosol Lidar Validation Experiment (ALIVE) can bridge the resolution and methodological gap.
Results

What about MODIS underestimation at low $\theta_s$ as in Yang [2006]?

- We don’t actually have BEFLUX data at low $\theta_s$...
- ...but neither did Yang. He fit a 3rd order polynomial to his data

What happens if we do the same?

So difference may be due to fitting technique, not data
Glory/APS, since it is in the ‘A-train’, could be used to regularly validate MODIS BRDF products, using these techniques

- Classification could be abandoned for downscaled pixel to pixel comparison
- Spectral integration could be avoided by directly comparing similar bands (550, 650, 860, 1640 & 2120nm)
Aerosol Lidar Validation Experiment (ALIVE)

- North-central Oklahoma (SGP site) in September, 2005
- Main goal: validation of aerosol vertical profiles from recently updated LIDAR instruments at SGP
- Jetstream-31 aircraft payload:
  - RSP
  - NASA Ames Airborne Tracking 14-channel Sun Photometer (AATS-14)
- Aircraft flew several low altitude flights, ideal for surface albedo characterization
RSP BRDF estimation

Observation at aircraft altitude modeled as follows
(neglecting geometry and integration notation)

\[
\rho^o = \rho^a + S
\]

\[
S = (t^\uparrow + T^\uparrow)\rho^g (t^\downarrow + T^\downarrow) + (t^\uparrow + T^\uparrow)\left[ \rho^g \sum_{i=1}^{\infty} (\rho^g \rho^{a*})^i \right] (t^\downarrow + T^\downarrow)
\]

- \(\rho^o\) = reflectance at aircraft altitude
- \(\rho^a\) = path reflectance;
- \(S\) = total reflectance due to ground interaction
- \(T\) = diffuse downwelling (\(\downarrow\)) or upwelling (\(\uparrow\))
- \(\rho^g \sum (\rho^g \rho^{a*})^i\) = multiple ground-atmosphere interaction

Measured by RSP
From doubling-adding model
Desired value

We are attempting to find \(\rho^g\)
Then fit it to BRDF models to retrieve kernel weights, \(f_i\)
RSP BRDF estimation

1. Estimate ground reflectance neglecting diffuse and multiple scattering

\[
\rho_1^g = \frac{\hat{S}}{t^\uparrow t^\downarrow} = \frac{\rho^o - \rho^a}{t^\uparrow t^\downarrow}
\]

\(\hat{S}\) is from measurements

2. Fit ground reflectance estimate to BRDF kernel model

\[\rho_1^g \approx \rho_1^{g,k} = f_{\text{iso},l} + f_{\text{vol},l} K_{\text{vol}} + f_{\text{geo},l} K_{\text{geo}}\]

3. Estimate S using modeled BRDF

\[S_1 = (t^\uparrow + T^\uparrow) \rho_1^{g,k} (t^\downarrow + T^\downarrow) + (t^\uparrow + T^\uparrow) \left[ \rho_1^{g,k} \sum_{i=1}^{\infty} \left( \rho_1^{g,k} \rho^a \right)^i \right] (t^\downarrow + T^\downarrow)\]

4. Compare measured and modeled S to get new ground reflectance

\[\rho_{p+1}^g = \left[ \frac{\hat{S}}{S_p} \right] \rho_p^{g,k} = \gamma_p \rho_p^{g,k}\]

5. Repeat steps 2-4 until \(\gamma\) approaches 1.0
Data Classification

Classification

- Reduce spatial resolution and coverage differences between instruments
- Different instruments may see different combinations of bare or pre-harvest fields, shrubs, and other land types
- Perhaps it is best to divide data by land surface type and compare this?

Classification criteria: Aerosol Resistant Vegetation Index (ARVI)

- Similar to NDVI but intended to account for aerosols, Kaufman and Tanre, [1992]
- Used after correction for gases, screening of high zenith angle data, and removal of boundary pixels.

Three classes

- ‘Soil’ representing low ARVI
- ‘Vegetation’ representing high ARVI
- ‘All’ representing all but extreme ARVI values

Classification performed on both RSP and MODIS data
Data Classification

Data were screened several ways, then classified broadly.
The Next Generation *RSP and APS*

**RSP and APS design**
- Nine spectral channels, blue to infra-red (410 - 2250 nm)
- Scans along track (in the direction of motion)
- Polarized radiance - I,Q,U components of Stokes vector
- High (0.2%) accuracy for polarized radiances

### Atmospheric transmission & RSP spectral sensitivity

**RSP Aerosol channels:**
- 410nm, 470nm, 555nm, 670nm, 865nm, 1590nm

**Other Channels:**
- 960nm, 1880nm, 2250nm

Circular polarization: two orders of magnitude smaller than linear polarization when source is unpolarized
The Next Generation: *RSP and APS*

Comparison with current instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Visible bands</th>
<th>IR bands</th>
<th>Multiple view angles</th>
<th>Polarized</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVHRR</td>
<td>0.63, 0.86(\mu m) (wide bands)</td>
<td>3.7(\mu m)</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>MODIS</td>
<td>0.47, 0.55, 0.65, 0.86(\mu m)</td>
<td>1.24, 1.64, 2.12(\mu m)</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>MISR</td>
<td>0.45, 0.56, 0.67, 0.87(\mu m)</td>
<td>no</td>
<td>9 from ±70°</td>
<td>no</td>
</tr>
<tr>
<td>POLDER</td>
<td>0.49, 0.67, 0.86(\mu m)</td>
<td>no</td>
<td>12 from ±60°</td>
<td>I,Q,U, Limited accuracy</td>
</tr>
<tr>
<td>APS</td>
<td>0.41, 0.44, 0.56, 0.67, 0.87(\mu m)</td>
<td>0.91, 1.37, 1.61, 2.20(\mu m)</td>
<td>~250 from +60° to -70°</td>
<td>I,Q,U, 0.2% accuracy</td>
</tr>
</tbody>
</table>
Another technique?


Present methodology for creating *true* BHR from DHR and BHR$_{iso}$.

Comparison could be made at the level of BEFLUX observations, with no further processing of ground radiometer data needed…