Design of Nano-Satellite Cluster Formations for Bi-Directional Reflectance Distribution Function Estimations

Sreeja Nag
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Faculty Advisor: Prof. Olivier de Weck

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Bi-Directional Reflectance Function (BRDF) Estimations falls under the broad topic of Multi-Angular, Multi-Spectral Remote Sensing of the Earth.
Background

**BRDF Definition**

- Bi-directional reflectance distribution function
- Anisotropic (angle-dependent) and multispectral (near-solar spectrum) reflectance of clouds and ground surface
- \( R(\Theta_i, \Theta_r, \phi_i, \phi_r, \lambda) \)

**BRDF Geometry**

[Diagram of BRDF geometry with labels for \( \Theta_i, \Theta_r, \phi_i, \phi_r, \lambda \).]
Angular Challenge

BRDF Estimation by combining the consecutive measurements

**Problem:**
1. Restrictive plane with respect to the sun
2. Up to 10 minutes between measurements
Angular Challenge

BRDF Estimation by combining measurements over consecutive overpasses

**Problem:**
1. Restrictive plane with respect to the sun
2. Up 2 weeks between measurements

What is measured with a single satellite over time and/or multiple overpasses

What needs to be measured for BRDF estimation
BRDF Importance

Theoretical function, very important applications

Mentioned in many science and policy docs

- "Responding to the challenge of Climate and Environmental Change"; “enhance understanding of the role of CO2 in the global carbon cycle” – NAS Decadal Survey 2007
- “To provide data on variables (surface BRDF and albedo) that have wide application... (especially those) designed primarily for cloud and aerosol studies” - Ecosystems Structure and Biomass panel on Multi Angle Remote Sensing
BRDF Importance

BRDF effects on important applications such as **albedo**, radiative forcing, gross primary productivity is stark.

Image Credits: Arnold et. al, 2002

Figure uses thousands of angular measurement data from the airborne Cloud Absorption Radiometer taken during the ARMCAS campaign in 1998.
BRDF Importance

BRDF effects on important applications such as albedo radiative forcing, **gross primary productivity** is stark.

GPP => Extent to which vegetation acts as a Carbon Dioxide Sink

GPP α Photosynthetic Efficiency α BRDF corrected Photosynthetic Refractive Index

Image Credits: Hilker et. al., 2008
BRDF Importance

BRDF effects on important applications such as albedo radiative forcing, *gross primary productivity* is stark.

40% errors in current budget estimates shown in Canadell et al. 2007

Reduced to 10% errors using CHRIS multi-angular data shown in Hall and Tucker 2010
Monolithic Measurement Gaps

**Airborne**: Very accurate for local BRDF estimation e.g. Cloud Absorption Radiometer (CAR)

BUT no global or continuous coverage, expensive to scale up area and time

<table>
<thead>
<tr>
<th>BRDF-Science Metrics</th>
<th>Number of angles</th>
<th>Ground Pixel Size in km X km</th>
<th>Revisit Time (any view in days)</th>
<th>Spectral Range</th>
<th># of spectral bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolithic Measurement</td>
<td></td>
<td></td>
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</tbody>
</table>

**Geometrical Requirements**

**Spectral Requirements**

FLIGHT TRACK 4km

FOOTPRINT height
**Monolithic Measurement Gaps**

**Spaceborne:** Angular coverage through Large swath or FOV\(^1\), Fwd-Aft sensors\(^2\), autonomous maneuverability\(^3\)

BUT fall short in terms of science metric/s + nearing EOL

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</thead>
<tbody>
<tr>
<td>MODIS</td>
<td>1</td>
<td>0.25 to 1</td>
<td>~2 (16 day RGT)</td>
<td>0.4-14.4 µm</td>
<td>36</td>
</tr>
<tr>
<td>POLDER</td>
<td>14</td>
<td>6 X 7</td>
<td>~2 (16 day RGT)</td>
<td>0.42-0.9 µm</td>
<td>9</td>
</tr>
<tr>
<td>CERES</td>
<td>1</td>
<td>10 to 20</td>
<td>~2 (16 day RGT)</td>
<td>0.3-12 µm</td>
<td>3</td>
</tr>
<tr>
<td>MISR</td>
<td>9</td>
<td>0.275 to 1.1</td>
<td>9 (16 day RGT)</td>
<td>0.44-0.87 µm</td>
<td>4</td>
</tr>
<tr>
<td>ATSR</td>
<td>2</td>
<td>1 to 2</td>
<td>3-4</td>
<td>0.55–12 µm</td>
<td>7</td>
</tr>
<tr>
<td>ASTER</td>
<td>2</td>
<td>0.015 to 0.09</td>
<td>~2 (16 day RGT)</td>
<td>0.52–11.65 µm</td>
<td>14</td>
</tr>
<tr>
<td>CHRIS</td>
<td>5-15</td>
<td>0.017 to 0.5</td>
<td>As per command</td>
<td>0.415-1.05 µm</td>
<td>18-63</td>
</tr>
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</table>
Filling in the Monolithic Gaps

**Major Gap:** Angular undersampling ($\theta_s, \theta_r, \phi$)

**Potential Solution:** Clusters of nano-satellites since each sat will be small

**Additional advantages:**- 6U cubesats under development, Standard bus, Secondary payload launches, Cubesat GS network

**Disadvantages:**- Restrictive h-i combinations, mass/volume constraints

*Image Credits: Leonardo BRDF*
Build a Systems engineering (SE) model integrated with traditional BRDF Estimation models to finalize the ideal cluster architecture, satellite design, subsystem design and primary instrument.

**BRDF Systems Engineering -SE- Model**
(dependent on satellite subsystems)

**BRDF Science Evaluation Model**
(dependent on application)

Simulated measurements/sampling of the BRDF function

Errors in BRDF Estimation + other application specific metrics

INPUT

Estimated BRDF + errors; other application specific metrics

OUTPUT
**SE Model as an N2 Diagram**

**Cluster Geometry Module**
- Required states
- Sensor Capabilities
  - iFOV, FOV
- Intersat Comm Capabilities

**GNC Module**
- States + errors
- Co-reg Images for guidance

**Payload Module**
- Raw Images

**Onboard Processing Module**
- States + errors
- Range, Elevation for tracking
- Processed images

**Comm Module**
- Mass, Power, Volume
- MPV, data rate

**Complexity Module**
- Architecture “Size”
  - Relative Complexity
  - Mass, Cost

**Output: Metrics**
- Angular + Temporal Resolution
- Altitude

**Output: Metrics**
- TRL, Swath
- Spatial + Spectral Resolution
- Spectral Range

**Output: Metrics**
- SNR

**Output: Metrics**
- Image Download Rate

**Input**

**BRDF Measurement Requirements**
- Spatial resolution (< 500 m)
- Measurement Zenith Angles (< 60°)
- Measurement Azimuth (< 360°)
- Solar zenith Angles (< 80°)
- Spectral Resolution (>14 bands)
- Spectral Range (350-2300 nm)

**Nanosat Bus Requirements**
- Mass < 10 kg
- Cube < 10X20X30 cm
- Power < 25 W
- Altitude (400 – 800 km)
Cluster Geometry Models

- Linearized Hill Clohessy Wiltshire Equations
- Dual Spiral Equations
- Global Orbit Propagation Using STK
Cluster Geometry Models

LINEARIZED HILL CLOHESSY WILTSHIRE EQUATIONS

\[
x_k(t) = (R_E + h) \left[ \cos(\Phi_k + \alpha(t)) \sin\left(\frac{\pi}{2} - \delta(t)\right) - 1 \right]
\]

\[
y_k(t) = (R_E + h) \left[ \sin(\Phi_k + \alpha(t)) \sin\left(\frac{\pi}{2} - \delta(t)\right) \right]
\]

\[
z_k(t) = (R_E + h) \left[ \cos\left(\frac{\pi}{2} - \delta(t)\right) \right]
\]

String of Pearls (SOP)  Cross Track Scan (CTS)
Cluster Geometry Models

LINEARIZED HILL CLOHESSY WILTSHIRE EQUATIONS

Free Orbit Ellipse (FOE)
Cluster Geometry Models

Special Case for the Dual Spiral model:
Relative Analemma

\[ \sin \delta = \sin \alpha \sin nt \]
\[ \alpha = nt - \arctan(\cos i_R \tan nt) \]
\[ \Delta \Phi = \Phi_2 + \Phi_R - \Phi_1 \]
\[ \cos \Phi_1 = \frac{\cos i_2 - \cos i_1 \cos i_R}{\sin i_R \sin i_2} \]
\[ \cos \Phi_1 = \frac{\cos i_2 - \cos i_1 \cos i_R}{\sin i_R \sin i_2} \]
\[ \cos i_R = \cos i_1 \cos i_2 + \sin i_1 \sin i_2 \cos \Delta N \]
\[ \Phi_R = (T_2 - T_1)n + \Delta \Phi \]

DUAL SPIRAL EQUATIONS

String of Pearls (SOP)

Cross Track Scan (CTS)

Model Fidelity/Reliability

Computational Ease of Tradespace

Exploration and Optimization
Global Orbit Propagation Using STK

Trajectories in the LVLH frame of orbits propagated for one day.
Cluster Geometry Models

Target (yellow) imaged at multiple angles by cluster (green), MISR (pink)

GLOBAL ORBIT PROPAGATION USING STK

MISR

FF Cluster

Model Fidelity/Reliability

Computational Ease of Tradespace

Exploration and Optimization
Cluster Geometry Models

GLOBAL ORBIT PROPAGATION USING STK

Target (yellow) imaged at multiple angles by cluster (green), MISR (pink)
• **Snow environment** selected because of lack of aerosol effects, less clouds, important for climate change, melt season needs >1 day temporal repeat, availability of campaign.

• Used BRDF data as “truth” from the ARCTAS (Arctic) campaign at Elson Lagoon (71.3 N, 156.4 W), Alaska, which was studied by the NASA P-3B carrying the Cloud Absorption Radiometer (CAR).

• Data available at all 360 azimuth and 90 zenith angles, so **easy to select any angular sampling combination** for trades.

• Used the **RossThick-LiSparse (RLTS) model** because it is linear, suited for spatial scales, used for MODIS products and tested appropriate for snow [Lyapustin et al, 2010]
Snow Albedo Application

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Snow Albedo Application

KEY TRADE VARIABLES: Cluster Geometry (HCW-FOE), FOE Orientation (22deg to LVLH-XY), # Rings (2-4), # Satellites (5, 9, 13), Angle subtended by rings at chief orbit (20-60deg), Orbit Orientation (normalized to Sun), Angular Coverage

INTEGRATED MODEL: Modified HCW for FF + RLTS for BRDF Estimation

KEY METRICS: RMS error wrt true BRDF, Albedo error wrt true black sky albedo

The Configuration

Measurement Angles

Inverted BRDF
KEY TRADE VARIABLES: Cluster Geometry (HCW-FOE), FOE Orientation (22deg to LVLH-XY), # Rings (2-4), # Satellites (5, 9, 13), Angle subtended by rings at chief orbit (20-60deg), Orbit Orientation (normalized to Sun), Angular Coverage

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BRDF and Black Sky Albedo errors compared to ‘Truth’/CAR Values as a function of #satellites

Important quantification of value to trade against cost of a growing cluster size!
Angular/Area variation for the BEST FOE geometry:
H = 600 km, N = 13 satellites in 4 rings
x0/z0 ratio = 0.4 = 21.8 deg
FOV assumed = 10 deg
Nominal boresight angle = 0, 20, 40, 50, 60 deg
Nominal azimuthal angle = Variation optimized per ring

ANGULAR SAMPLING
Required Boresight angle variation:

SPATIAL SAMPLING
Footprint Area variation:
Zenith/Azimuth variation for the **BEST FOE geometry**:

**ANGULAR SAMPLING**

**Required Boresight angle variation:**

**SPATIAL SAMPLING**

**Footprint Area variation:**
ACDS variation for the BEST FOE geometry:

H = 600 km, N = 13 satellites in 4 rings
x0/z0 ratio = 0.4 = 21.8 deg
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Required Slew Rate:

(I = 0.15 kg-m^2 assuming a cubic nanosat)

MAI-400 (Maryland Aerospace) RW

P ~ 3W
m < 0.7 kg
V ~ 0.5 cube
Max H = 11.8 mNms
Max T = 0.625 mNm
**Linearized HCW Analysis**

*ACDS variation for the BEST FOE geometry:*

- \( H = 600 \text{ km}, \ N = 13 \text{ satellites in 4 rings} \)
- \( x_0/z_0 \text{ ratio} = 0.4 = 21.8 \text{ deg} \)
- FOV assumed = 10 deg
- Nominal boresight angle = 0, 20, 40, 50, 60 deg
- Nominal azimuthal angle = Variation optimized per ring

**Required Angular Acceleration:**

- \( I = 0.15 \text{ kg-m}^2 \)
- assuming a cubic nanosat

**MAI-400**

- (Maryland Aerospace) RW
- P ~ 3W
- \( m < 0.7 \text{ kg} \)
- \( V \sim 0.5 \text{ cube} \)
- Max H = 11.8 mNms
- Max T = 0.625 mNm
Conclusions and Future Work

- **Proposed nanosatellite clusters in formation flight** with VNIR spectrometers to sample the BRDF function as a complement to existing monolithic data products
- Designed a physics-based, *integrated science + systems engineering model* for tradespace exploration to find the “optimal design” for the cluster geometry that will maximize specific BRDF science goals
- Identified *snow albedo* as a critical BRDF application
- Used the tradespaces to *quantify the significance on albedo and BRDF errors* of cluster geometry and orientation, # of Satellites, orbit orientation and azimuthal coverage. Showed that the optimal cluster configuration’s subsystem requirements (e.g. ADCS) is COTS supportable
- **Future Work** includes heuristic optimization of clusters (both modified linearized and global propagation) for albedo accuracy over mission lifetime (cluster dynamics and orbit maintenance). Other critical applications such as GPP will also be realized.
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Questions?