Non-Resolved Satellite Attitude, Shape and Composition Analysis

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Paul Kervin – AFRL/RDSM
Doyle T. Hall – The Boeing Co.
Outline

- Motivation
- Review of attitude and shape analysis
  - Single-band photometry formulation
- Current and on-going research
  - Bayesian inference methodology
  - Multi-wavelength formulations
- Conclusions and future work
Motivation

• As angular extent of satellite decreases …
  – Smaller satellite
  – Greater slant range

• … resolution decreases, until the satellite is completely unresolved
  – LEO micro- and nano-satellites
  – GEO satellites
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Challenge: characterize unresolved satellites

Vastly more of these….
Non-Imaging Methods

• **Do not require** knowledge of satellite shape or attitude
  – But do require positions of sensor, object and illumination source(s)

• **Employ physics-based algorithms**
  – Developed with strong support from AFOSR
  – Some heritage in asteroid astronomy

• **Combine data from multiple sensors**
  – Space-based and/or ground-based
  – Implemented: single-band photometry
  – Current R&D: multi-band photometry + spectroscopy
Single-band Photometric Satellite Characterization

Satellite Characteristics

- Size
- Period
- Spin
- Attitude
- Shape
- Panel offset

Data reduction methods

Whole Object Brightness vs. Time
Multi-Wavelength Satellite Characterization

Satellite Characteristics

- Size
- Period
- Spin
- Composition
- Attitude
- Shape
- Panel offset
- Weathering

Multi-wavelength methods

Cleared for Public Release (Release # 377ABW-2014-0941, OPS-14-6873)
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Multi-site sensors (simultaneous)

Body parameters are albedo-area distributions. Given attitude parameters, solve for body albedo-area distributions. Integrate over all possible facet-normal orientations.

\[ L_s(t, \mathbf{p}_\text{Body}, \mathbf{p}_\text{Attitude}) = \int 4\pi \sum_{m=1}^{2} c A_m(n) K_{s,m}(t, n, \mathbf{p}_\text{Attitude}) \, dn \]

\[ s = 1 \ldots N \]

Observed object
Single-Band Rigid Body Theory: System of Equations

\[ L_s(t, p_{\text{Body}} , p_{\text{Attitude}} ) = \int_{4\pi} \left[ \sum_{m=1}^{2} aA_m(n) K_{s,m}(t, n, p_{\text{Attitude}}) \right] dn \]

Discrete data from multiple sensors: \( D = \{ s_i, t_i, L_i, \Delta L_i \} \)

Body parameters: \( p_{\text{Body}} = aA = \alpha \)

Attitude hypothesis: \( p_{\text{Attitude}} = H \)

Discrete grid of facet normal vectors spanning unit sphere, \( G \)

Add noise model, \( \eta \)

Impose non-negativity

\[ L = K(G,H) \times \alpha + \eta \]

\[ \alpha \geq 0 \]
Multi-facet Analysis of a Simulated Milled Aluminum Cube

Phase Angle = 85.0°

Diffuse

Specular

aA > 0 (color)

aA = 0 (gray)

Not detected (black)
Non-Rigid Body Theory: Block Diagonal System

Generalize body as assembly of articulating components

\[ L = K_1 K_2 \cdots K_n \times \alpha_1 \alpha_2 \cdots \eta + \eta \]

- Block-diagonal kernel matrix
- Multi-component facet albedo-area vector

\[ \alpha \geq 0 \]
Galaxy 12 GEO Satellite: Raven Small Telescope R-Band Photometry

Photometric Observations (10 nights from RME+ABQ Ravens)

- 27715_abq_2010_08_19
- 27715_abq_2010_08_21
- 27715_abq_2010_09_03
- 27715_rme_2010_10_20
- 27715_rme_2010_11_28
- 27715_rme_2010_11_30
- 27715_rme_2010_12_01
- 27715_rme_2010_12_03
- 27715_rme_2010_12_04
- 27715_rme_2010_12_05

Body Facet Analysis

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Galaxy 12 GEO Satellite:
Raven Small Telescope R-Band Photometry

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Body Facet Analysis

Spec A (SNR > 3)

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Galaxy 12 GEO Satellite:
Raven Small Telescope R-Band Photometry

Photometric Observations
(10 nights from RME+ABQ Ravens)

Dominated by body nadir-facing surface
Galaxy 12 GEO Satellite: Raven Small Telescope R-Band Photometry

Photometric Observations (10 nights from RME+ABQ Ravens)

Panel Facet Analysis

Cross-articulation offset (deg) →
Along-articulation offset (deg) →

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Galaxy 12 GEO Satellite: Raven Small Telescope R-Band Photometry

Photometric Observations (10 nights from RME+ABQ Ravens)

Solar panels with two offsets

Panel Facet Analysis

Along-articulation offset (deg) → Cross-articulation offset (deg) →
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• Current and on-going research
  – Bayesian inference methodology
  – Multi-wavelength formulations

• Conclusions and future work
Multi-hypothesis Attitude Analysis

enumerate attitude hypotheses for main-body + articulating components: \( \{H_h\} h = 1\ldots N_h \)

compare hypotheses using Bayesian inference methodology

\[
L = K(G,H_h) \times \alpha_h + \eta
\]

\( \alpha_h \geq 0 \)
Bayesian Inference Approach

• Bayesian evidence-based inference

• First level of inference: estimate solution vector
  – Infer optimal facet albedo-areas

• Second level of inference: optimize hyper-parameters
  – Infer optimal regularization strength(s)
  – Infer optimal facet-normal grid and wavelength grid resolutions

• Third level of inference: model comparison
  – Infer optimal attitude/articulation hypothesis
  – Compare relative likelihoods of attitude/articulation hypotheses
Galaxy 12 GEO Satellite:
Raven Small Telescope R-Band Photometry

Photometric Observations
(10 nights from RME+ABQ Ravens)

Bayesian evidence-based method rejects incorrect attitude hypotheses and provides optimal facet-grid resolutions.

<table>
<thead>
<tr>
<th>Attitude Hypothesis</th>
<th>Log-Evidence</th>
<th>N_{body} Grid</th>
<th>N_{panel} Grid</th>
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<td>nadir/inertial no panel</td>
<td>-5897</td>
<td>35</td>
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<td>solar/inertial solar panel</td>
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</tr>
</tbody>
</table>
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  – Single-band photometry formulation

• Current and on-going research
  – Bayesian inference methodology
  – Multi-wavelength formulations

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Multi-Wavelength Satellite Characterization

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Multi-wavelength methods
Three Different Multi-Wavelength Formulations

1. Multi-band facet estimation
   - Already implemented – just repetitively apply the current single-band approach to multiple spectral bands
   - All sensors must use a standardized photometric filter set
   - Incorporating spectroscopic data is not realistic

2. Facet material-area estimation
   - Relatively easy to formulate and implement
   - Requires library of lab-measured material BRDFs
   - Cannot address unknown or changing satellite materials

3. Facet albedo-area spectrum estimation
   - Can address unknown and changing satellite materials
   - More difficult to formulate and implement
   - Likely requires greater observational diversity

Advantages

Disadvantages
Facet Albedo-Area Spectrum Estimation

\[ L = K_h \times \alpha_h + \eta \quad \alpha_h \geq 0 \]

- Data vector contains photometric and spectroscopic measurements
- Non-iterative approach: requires absolute calibration for photometry and spectroscopy
- Iterative approach: absolute photometry + relative spectroscopy
Facet Albedo-Area Spectrum Estimation

\[ L = K_h \times \alpha_h + \eta \]

\[ \alpha_h \geq 0 \]

- Kernel elements are integrals over time and the interpolated wavelength grid
- Also must sum over all illumination sources
  - Point sources and/or extended sources
  - Sun, Earth, Moon, Lasers, etc.
- Formulation for integrating over the interpolated wavelength grid is straightforward but complicated
Facet Albedo-Area Spectrum Estimation

\[ L = K_h \times \alpha_h + \eta \quad \alpha_h \geq 0 \]

- Solution vector represents the albedo-areas of the facets at each wavelength grid point
- Can be used to derive relative facet albedo spectra
  - Compare to lab-based measurements for material identification
  - Monitor over time for space weathering effects
Conclusions

• Non-resolved satellite attitude and shape formulation extended to multi-wavelength data sets

• Multi-facet material-area analysis is easiest to implement
  – But relies on lab-measured material BRDFs….

• Multi-facet albedo-area spectra analysis more promising
  – Data intensive, but can address unknown/changing materials….

• Ongoing and future work:
  – Continue testing new algorithms against simulated and real data
  – Implement Bayesian evidence-based algorithms
  – Investigate random jump MCMC for multi-wavelength case
Backup Charts
Development of Theory

**Earliest formulation**
- Rigid body
- Reflected light (single-source)
  - Sunlight only
- Analytical BRDFs
  - Lambertian
  - Specular
- Multiple photometric sensors
  - Single spectral band
  - Short exposures
- Least-squares estimation

**Later formulations**
- Articulating body
- Reflected light (multi-source)
  - Sun, Earth, Moon, Laser
- Analytical and/or material BRDFs
  - Lambertian + specular
  - Lab-measured materials
- Multiple photometric sensors
  - Single spectral band
  - Short or long exposures
  - Max-like. estimation + L2 regularization

**Current formulation (in progress)**
- Articulating body
- Analytical and/or material BRDFs
  - Lambertian + multi-spectral
  - Lab-measured materials
- Reflected light (multi-source)
  - Sun, Earth, Moon, Laser
- Multiple optical sensors
  - Multi-band photometry and spectroscopy
  - Short or long exposures
- Bayesian estimation + L1 or L2 regularization
Assumptions: Single-band Rigid Body Analysis

1. Assumptions concerning measurements
   a. Whole-body brightnesses all measured in same spectral band
   b. Data are radiometrically calibrated with quantified uncertainties
   c. Reflected sunlight dominates
   d. Ancillary data are known (times of measurements, sensor/object/sun positions, illuminating solar irradiance, etc.)

2. Assumptions concerning satellite body
   a. Object is a rigid body
   b. Object is convex (i.e., neglect effects of concavities)
   c. Object outer surface can be decomposed into flat, opaque facets
   d. Facet BRDFs are sum of Lambertian and specular components

3. Assumptions concerning satellite attitudes
   a. Attitude model applies to all measurements (e.g., nadir/velocity stabilization) throughout entire observation period
   b. Stabilized attitude control system limit-cycle motions are negligible
Relaxed Assumptions: Multi-Wavelength Non-Rigid Body Analysis

1. Assumptions concerning measurements
   a. Whole-body brightnesses from multi-band photometry + spectroscopy
   b. Photometry is radiometrically calibrated with uncertainties; spectroscopy provides relative measurements with uncertainties
   c. Reflected light dominates (including Sun, Laser, Earth, and/or Moon)
   d. Ancillary data are known (times of measurements, positions, solar irradiance, etc.)

2. Assumptions concerning satellite body
   a. Object is an assembly of articulating rigid bodies
   b. Object is convex (i.e., neglect effects of concavities)
   c. Object outer surface can be decomposed into flat, opaque facets
   d. Facet BRDFs are a sum of analytical functions and/or lab-measured materials

3. Assumptions concerning satellite attitudes
   a. Hypothesized attitude models each apply to all measurements (e.g., nadir/velocity stabilization) throughout entire observation period
   b. Stabilized attitude control system limit-cycle motions are negligible
Multi-Band Non-Rigid Body Theory: Kernel Equations

\[ K_{j,m}(t, \lambda, n, o, s_j) = \begin{cases} \text{Kernel function for BRDF } m, \\ \text{facet normal } n, \text{ observer direction } o, \\ \text{and light-source } j \text{ in direction } s_j \end{cases} \]

Average over the exposure durations and spectral band responses:

\[ K_{i,j,m}(n, o, s) = \frac{1}{T_i} \left\{ \int_{t_i}^{t_i+T_i} dt \left[ \int_0^\infty d\lambda \, R_i(\lambda) K_m(t, \lambda, n, o, s) \right] \right\} \]

Sum over the light sources and integrate over their solid angles:

\[ K_{i,m}(n, o) = \sum_{j=1}^{N_j} \int_{\Omega_j} ds \, K_{i,m}(n, o, s) \]
Challenges with Current Multi-Wavelength Formulation

• CPU requirements are rapidly growing
  – Due to growing matrix system sizes
  – Also from non-negativity constraint

• Matrix system size: $N_{Data} \times (N_{facet-grid} \times N_{\lambda-grid})$

• Data vectors:
  – Photometric only: $N_{Data} \sim 10^4$ or less
  – Photometric + spectroscopic: $N_{Data} >> 10^4$

• Facet grids:
  – Single rigid body: $N_{facet-grid} \sim$ few x $10^2$ or less
  – Main bus + solar panel: $N_{facet-grid} \sim 10^3$
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  – Bayesian inference methodology
  – Markov Chain approach

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Markov Chain Approach*

• Random Jump Markov Chain Monte Carlo (RJMCMC)*
  – Bayesian MCMC formulation extended to address problems where:
  – “The number of things you don’t know is one of the things you don’t know.” (Green, 1994)

• Potentially appropriate for finding the number of dominant facets of an unknown object
  – Can also use other shape primitives
  – Spheres, hemispheres, cylinders, cones, etc.

• Can be CPU intensive
  – Needs tuning for optimal performance
  – But could be competitive because of growing matrix-system sizes

* See Hastie & Green (2011), Green & Hastie (2009), and Green (1994)