Evolutionary Optimization of Satellite Formations with Topological Constraints

David Hinckley
Dr. Darren Hitt
Motivation: NASA MMS Mission

NASA's Magnetospheric Multi-Scale Mission (MMS) consisting of a formation of four satellites
Trajectory Optimization Challenges

• Topological constraints on satellite formation
  • accounting for four satellites
  • “quality” of formation
  • size of formation

• Orbit perturbations
  • oblateness effects
  • atmospheric drag (near perigee)
  • radiation pressure
  • other sources

• Robust design for deployment conditions
  • Location/anomaly
  • Initial configuration
Optimization Strategy – Evolutionary Computing

Conjecture
Owing to the topological constraint on the multi-satellite formation and the system’s dynamical complexity, evolutionary approaches for trajectory optimization may be more robust and offer improved performance over classical optimization methods.

Goal of this Study
An evolutionary computing approach is utilized to solving a class of problems involving topological constraints on a satellite formation imposed on a specified region of interest along the reference orbit.
MMS Reference Orbit & Region of Interest
MMS Reference Orbit & Region of Interest (cont’d)

- Perigee 1.2 $R_{⊕}$
- Apogee 12 $R_{⊕}$
- Eccentricity 0.82
- Inclination 28°
- ROI: $\approx ±20° \approx ±23,500$s centered about apogee
- $\leq 2$ impulsive maneuvers performed at $±90°$ anomaly; corrective maneuvers at perigee not performed for practical reasons of speed and communication
Evolutionary Algorithms

- Bio-inspired optimization methods that draw upon the concepts of evolution, mutation, recombination, and fitness
- For this problem, candidate solutions are the formation impulse maneuvers
- Differential Evolution is the EA used for this work
- Candidate solutions are made through weighted vector combinations
Topological Metrics

- Tetrahedron Quality $Q$
  \[ Q = \frac{V}{V_{\text{reg}}}, \quad 0 \leq Q \leq 1 \]

- Average Tetrahedron Side-Length $L$

- “Fitness” is a weighted balance of $Q$ and $L$
Test Cases

Case 1: MMS orbit; linear deployment configuration at -90° true anomaly

- Linear separation pf 100 m
- Target $L$ of 10 km and 160 km
- Impulses performed at ±90°
Sample Result
Test Cases (cont’d)

Case 2: MMS orbit; tetrahedral deployment configuration at -90° true anomaly

• Regular tetrahedron configuration
• Impulses performed at ±90°
• Target $L$ of 10 km and 160 km
• Initial $L$ of 6 km and 130 km
1-Impulse vs. 2-Impulse (Quality)
1-Impulse vs. 2-Impulse (Average Side-Length)
Formation Comparison – Highest Peak vs. Lowest Deviation

Highest Peak Quality

- Quality = 0.99
- Quality = 0.56

Lowest Quality Deviation

- Quality = 0.90
- Quality = 0.83
QUESTIONS?
Efficient Cyclization Methodology for Biologically Relevant Precursors

Rachael Carmichael
National space grant director’s meeting
March 2016
Sustainable Chemistry

Increased focus on minimizing hazardous chemical waste and cost reduction.

- Build complexity with as few steps as possible
  - Design tandem or cascade reaction sequences
- Consider environmental impact
  - Simplify purification process
  - Eliminate toxic or heavy metals

Interesting [6-5-6] Core

• Target an important class of biologically active molecules having a common framework

![Chemical structures with names](attachment:chemical_structures.png)

hirsutellone B  
taiwaniaquinol D  
gibberellic acid

• Develop method to efficiently synthesize [6-5-6] skeleton
  • Readily access pertinent natural products and their derivatives

Tandem Diels-Alder Nazarov Cyclization

- **Diels-Alder cyclization**
  - Awarded Nobel prize in 1950

\[
\text{Dienophile} + \text{Diene} \rightarrow \text{Cyclohexene} \rightarrow \text{Acetylene} + \text{Diene} \rightarrow \text{Aromatic Ring}
\]

- **Design route towards [6-5-6] advanced intermediates**
  - Utilize diynone starting materials as the dienophile

Regio-control Through β–silyl Effect

Proposed mechanism:

Elimination of silyl group allows for control over double bond location.
### Catalyst Screening

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>T (°C)</th>
<th>t [h]</th>
<th>Yield [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnCl₂</td>
<td>23</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>BF₃·Et₂O</td>
<td>-17</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>SnCl₄</td>
<td>-78</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>TiCl₄</td>
<td>-78</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>FeCl₃</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>AlCl₃</td>
<td>0</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>EtAlCl₂</td>
<td>23</td>
<td>30</td>
<td>64</td>
</tr>
<tr>
<td>Me₂AlCl</td>
<td>23</td>
<td>1.5</td>
<td>78</td>
</tr>
<tr>
<td>In(OTf)₃</td>
<td>23</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>BCl₃</td>
<td>-5</td>
<td>10 min</td>
<td>58</td>
</tr>
</tbody>
</table>
Major Isomer
Major Isomer
Symmetric Examples

- Silane Derivatives
  - Demonstrate method versatility
  - Consistent stereochemical and regiochemical outcome

- Non-silane derivatives
  - Methyl and phenyl substituents
  - Formation of vicinal quaternary carbons

<table>
<thead>
<tr>
<th>Diynone</th>
<th>Product</th>
<th>Yield (%)</th>
<th>Isomeric Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diynone1" /></td>
<td><img src="image2" alt="Product1" /></td>
<td>78</td>
<td>21:1</td>
</tr>
<tr>
<td><img src="image3" alt="Diynone2" /></td>
<td><img src="image4" alt="Product2" /></td>
<td>65</td>
<td>&gt;99:1</td>
</tr>
<tr>
<td><img src="image5" alt="Diynone3" /></td>
<td><img src="image6" alt="Product3" /></td>
<td>54</td>
<td>7:1.4:1:1</td>
</tr>
<tr>
<td><img src="image7" alt="Diynone4" /></td>
<td><img src="image8" alt="Product4" /></td>
<td>35</td>
<td>15:1</td>
</tr>
<tr>
<td><img src="image9" alt="Diynone5" /></td>
<td><img src="image10" alt="Product5" /></td>
<td>27</td>
<td>&gt;20:1</td>
</tr>
</tbody>
</table>

R. A. Carmichael, W. A. Chalifoux (February 2016) Submitted to Angewandte Chemie International
Asymmetric Examples

• Silane group always eliminates to give double bond

\[
\text{TMS} \quad \begin{array}{c}
\text{O} \\
\text{C} \\
\text{C} \\
\text{C} \\
\text{R}
\end{array} \quad \text{catalyst} \quad \begin{array}{c}
\text{O} \\
\text{C} \\
\text{C} \\
\text{C} \\
\text{R}
\end{array} \quad + \quad \begin{array}{c}
\text{O} \\
\text{C} \\
\text{C} \\
\text{C} \\
\text{R}
\end{array} \quad \rightarrow \quad \begin{array}{c}
\text{O} \\
\text{H} \\
\text{R}
\end{array}
\]

43% 35% 31% 46% 26%
Asymmetric: Multi-diene

- Control product formation at low temperatures

- Apply low temperature conditions to asymmetric reactions
  - Silane substituted alkyne undergoes Diels-Alder cyclization first

Fillion, E; Fishlock, D. J. Am. Chem. Soc. 2005, 127, 13144-13145
Future Endeavors

Optimize and complete asymmetric substrate scope
Develop enantioselective assay

- Apply method to the synthesis of an important target molecule
- Work with collaborators to screen compounds for high priority viruses

Fillion, E; Fishlock, D. J. Am. Chem. Soc. 2005, 127, 13144-13145
Special Thanks to....

- Dr. Wesley Chalifoux
- Chalifoux lab
- Nevada NASA Space Grant
- University of Nevada, Reno
Questions?
Effect of Coherent Structures on Energetic Particle Intensity in the Solar Wind

Jeff Tessein
University of Delaware
Outline

• Background
• Instrumentation
• Results
• Analysis of Results
Background
Space Weather

Joyce et al., Space Weather, 2015

• GPS guidance (tractors, ships)
• Racing pigeons

Image credit: NASA
Discontinuities

A change in the magnitude and/or direction of the fields.
Solar Energetic Particles (SEP)

Classical picture since 1990s: two main mechanisms

Reames, SSR, 1999
PVI

• Used to locate discontinuities
• Useful for comparison with simulation

\[ S^{(2)} = \frac{|\Delta \mathbf{B}|^2}{\Sigma^2} \]

\[ \Sigma^2 = \langle |\Delta \mathbf{B}|^2 \rangle \]

\( \Delta \mathbf{B} \) is increment \( \mathbf{B}(t + \tau) - \mathbf{B}(t) \)

(Greco et al. 2008)

Greco et al. PRE 2009

Instrumentation
Advanced Composition Explorer (1997)

Stone et al., SSR, 1998, Gold et al., SSR, 1998
Data Analysis

• Conditional statistics, superposed epoch analysis
• Sum over 8 energy channels of ACE/EPAM/LEMS
• ACE MAG/SWEPAM reduced to 5 minute temporal resolution for comparison with EPAM
• **How do magnetic field discontinuities affect energetic particle intensity?**

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Measurement</th>
<th>Energy Range</th>
<th>Cadence</th>
<th>Time Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE/EPAM/LEMS30</td>
<td>Ion Flux</td>
<td>0.046-4.7 MeV</td>
<td>5 minutes</td>
<td>1998-23 to 2001-050</td>
</tr>
<tr>
<td>ACE/EPAM/LEMS120</td>
<td>Ion Flux</td>
<td>0.047-4.78 MeV</td>
<td>5 minutes</td>
<td>1998-23 to 2010-258</td>
</tr>
<tr>
<td>ACE/SWEPAM &amp; MAG</td>
<td>Plasma Parameters &amp; Magnetic Field</td>
<td>0.26-36 keV</td>
<td>64 seconds</td>
<td>1998-23 to 2010-258</td>
</tr>
<tr>
<td>ACE/MAG</td>
<td>Magnetic Field</td>
<td>N/A</td>
<td>16 seconds</td>
<td>1998-23 to 2010-258</td>
</tr>
</tbody>
</table>

*aTime format is (year)-(day of year)*
Results
Stronger Discontinuities Associated with Higher Average Energetic Particle Flux

Shock exclusion: 12 hours of data removed on either side of the shock

Tessein et al., ApJL, 2013
Average Energetic Particle Flux Peaks Near Discontinuities

- Shock neighborhoods included
- Shock neighborhoods excluded

Superposed Epoch Analysis, 322 Shocks from ACE list

PVI > 8 trace is messy. Different mechanism or poorer statistics?

Tessein et al., ApJL, 2013
Analysis of Results
What leads to these results?

1. Presence of shocks not in the list
2. Extended shock acceleration events
3. Edge events
What leads to these results?

1. Presence of shocks not in the list
2. Extended shock acceleration events – Will not produce a peak
3. Edge events – Possible flux tube boundary or local acceleration site

Edge Events

Possible Flux Tube Boundary

High PVI denotes likely boundary

Filled tube

Empty tube

Compression

Conclusions

• Energetic particle flux associated with magnetic structures
• Structures are likely flux tube boundaries
• Local acceleration possible
• There are implications for shocked regions
Additional Slides
Intermittency

Matthaeus et al. 2015: The degree to which nonlinearly interacting fluctuations may be expected to give rise to structure in space and in time

Increment: \( \delta v_r(x) = \hat{r} \cdot [v(x + r) - v(x)] \)

Structure function: \( S^{(p)}(r) = \langle \delta v_r^p \rangle \)

Anselmet et al., JFM, 1984; Biskamp & Müller, PoP, 2000; Sorriso-Valvo et al., GRL, 1999
Upstream Events in LEMS120

Haggerty et al., GRL, 1999

Coherent Structures - Heating

- Increased ion temperature in or near strong coherent structures

Wu et al., ApJL, 2013

Osman et al., ApJL, 2011

Osman et al., PRL, 2012
Problems with LEMS30

Elevated noise floor

Haggerty et al., ASR, 2006

X-ray contamination

Marhavilas et al., P&SS, 2015
Shock Lists

• Not all shocks appear in the ACE list
• Use CfA Interplanetary Shock Database to complete list of shocks
Flare Acceleration

Diffusive Shock Acceleration

Treumann & Jaroschek, arXiv, 2008


ACE Science Center
Kurtosis: \( \kappa(r) = \frac{\langle \delta v_r^4 \rangle}{\langle \delta v_r^2 \rangle^2} \)
Signed Percent Difference

- Non-Gaussian distribution of energetic particle flux changes
- Statistical manifestation of thousands of PVI events showing small changes in energetic particle flux

Weak shocks

Average energetic particle profiles for questionable shocks, strong shocks and PVI > 8 discontinuities (with shock neighborhoods included). There is no evidence of strong energetic particle flux increases associated with questionable shocks.

Tessein et al., ApJL, 2013
Complex Time-Intensity Profiles in Shock Acceleration

Matsumoto et al., Science, 2015

Trapping in magnetic O-points


Unshocked region

Shocked region
Magnetic Reconnection

Osman et al., PRL 2014: 87%–92% of all reconnection exhausts and about 9% of all current sheets are concentrated within the highest 1% of PVI values.
Coherent Structures - Dissipation

• Most of the dissipation contained in a small percentage of the total volume (coherent structures)

Wan et al., PRL 2012
Coherent Structures - Instabilities

- Increased temperature and PVI associated with instability thresholds

Servidio et al., ApJL, 2014

Osman et al., PRL, 2012
Prevalence of Coherent Structures in Shocked Regions

PVI can be thought of as a proxy for turbulence level
Caveat: Typically 1/5 of IP shocks are reverse shocks

Tangential Discontinuity (TD)

Burlaga & Ness 1969
Discontinuities

• A sudden change in the magnitude and/or direction of a field

• Various classifications, e.g. TD, RD

• Flux tube vs. in situ generation

• Coherent structures – Localized region of strong current (current sheet, magnetic discontinuity)

TD: Burlaga & Ness, SP, 1969

Kelvin-Helmholtz: Karimabadi et al., PoP, 2013
Shock PVI

Histogram of the PVI value at 498 shocks. The shock-associated PVI value was obtained by taking the five nearest measurements to the shock (the nearest neighbor plus two on either side). Note that the distribution peaks for PVI < 2, which is a relatively low PVI value.
Complications of SEP Sources: Longitudinal spreading

Complications of SEP Sources: Possible Resolution


Complications of SEP Sources: Dropouts

Mazur et al., ApJL, 2000
Coherent Structures and Energetic Particles

Matthaeus et al., PRL, 1984

Drake et al., Nature, 2006

Acceleration Downstream of Shocks

Matsumoto et al., Science, 2015
Tessein et al., ApJL, 2013

Trapping in magnetic O-points

Location of PVI Events

Unshocked region

Shocked region

Matsumoto et al., Science, 2015
Lagged Cross Correlation

Correlation peaks at zero lag: Magnetic field and energetic particle intensity are often changing simultaneously – evidence in support of interpreting flux tubes as pipes

\[
I'(t) = I(t) - \langle I \rangle \\
PVI'(t) = PVI(t) - \langle PVI \rangle ,
\]

\[
C(I', PVI') = \frac{\langle I'(t)PVI'(t+\tau) \rangle}{\sqrt{\sigma_I \sigma_{PVI}}}
\]

Diffusive Shock Acceleration

Treumann & Jaroschek, arXiv, 2008
Questions?