LISSAJOUS Orbit Control for the Deep Space Climate Observatory Sun-Earth L1 Libration Point Mission

AAS 15-611

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Agenda for DSCOVR Lissajous Orbit Control

• DSCOVR Lissajous Orbit Overview
• DSCOVR Stationkeeping
• SEZ Avoidance Maneuvers
  – 6-month Z-control
  – 3-month Z-control
• SEZ Avoidance Considerations
• SEZ Avoidance Fuel Budget
• SEZ Avoidance and Stationkeeping
DSCOVR Lissajous Orbit Requirements

- DSCOVR Lissajous Orbit sized such that orbit track never extends beyond 15 degrees from Earth-Sun line (as seen from Earth)
- Requiring delta-V maneuvers, control orbit to obey a Solar Exclusion Zone (SEZ) cone of half-angle 4 degrees about the Earth-Sun line
  - Spacecraft should never be less than 4 degrees from solar center as seen from Earth
- Following Lissajous Orbit Insertion (LOI), DSCOVR should be in an opening phase that just skirts the 4-degree SEZ
  - Maximizes time to the point where a closing Lissajous will require avoidance maneuvers to keep it out of the SEZ
- Stationkeeping maneuvers should take no more than 15 minutes
DSCOVR: Numerically Integrated Lissajous Orbit

Lissajous opening: evolution over 5 years from insertion on 7 June 2015

DSCOVR Sun-Earth L1 Lissajous Orbit
June 2015 to June 2020 (Sunward View)

RLP Z-axis

LOI

SEZ: 4.0 deg radius

Counter-clockwise Motion

Rotating Libration Point Frame YZ-plane Projection

6/19/2020 2.0 deg zone

C.E. Roberts
DSCOVR Lissajous Orbit Stationkeeping

- Collinear LPOs are inherently unstable; stationkeeping maneuvers needed at intervals to prevent escape
- Delta-Vs needed to correct perturbative effects grow exponentially with time
  - Doubling time constant is ~16 days
- SK maneuvers impart a positive or negative change to orbital energy to prevent orbital decay and subsequent escape, either Earth-ward or Sun-ward, respectively
- SK maneuvers can be designed in variety of ways; discussed are techniques developed, studied or used for ACE, SOHO, and WIND, and will be used for DSCOVR
  - Delta-V direction along the RLP frame +X or −X axis
  - Delta-V direction along the RLP frame +Y or −Y axis
  - Techniques work also if delta-V is directed off-axis
    - For DSCOVR, off-axis variants could be up to ~12 degrees off respective axis
    - Depending on chosen technique, DSCOVR may need to be slewed to burn attitude to align given thruster set with delta-V direction
      - Slews could be up to 180 degrees
DSCOVR: ‘X-control’ Stationkeeping Schematic

DEP = DSCOVR Earth Point attitude (body +X-axis (HGA bore-sight) points to Earth
DSCOVR: ‘Y-control’ Stationkeeping (RLP XZ View)

**RLP XY Plane Projection of Orbit**

- **Blue arrows:** classic RLP Y-axis control; S/C Z-axis brought parallel to RLP Y-axis.
- **Red Arrows:** Z-mode attitude variant; S/C Z-axis rotated about X-axis to be parallel to RLP XY plane.

**Looking down from NEP**

- Clock-wise Motion
- **Red Arrows:** Angles to Earth may be exaggerated (max. of ≈ 12 deg)

To Earth
SEZ Avoidance Maneuvers

- SEZ avoidance technique is known quantity; was used for ACE
- DSCOVR Lissajous track will violate the 4 deg SEZ in late 2019 if SEZ avoidance not implemented
- To avoid violation, an SEZ avoidance strategy should begin by the rev prior to the rev that would violate
- Location of these maneuvers: at or very near to the RLP $z$-dot = 0.0 km/s point (northern and southern extremum points of the orbit)
- Use one of two main strategies:
  - Maneuver once per rev, always at the same extremum point (~6 month intervals)
  - Maneuver twice per rev, once at each extremum point (~3 mo. intervals)
- Delta-V cost is proportional to $A_z$; for this orbit, about 26 TO 27 m/sec/year
  - A burn of ~ 13 to 14 m/sec every 6 months
  - A burn of ~ 6.5 to 7 m/sec every 3 months
- Delta-V direction is normal to ecliptic plane
  - Toward South Ecliptic Pole (SEP) for burns on North side of orbit
  - Toward North Ecliptic Pole (NEP) for burns at south side of orbit
- ACE experience: 5 successful SEZ burns from 11/1999 to 7/2001
  - SEZ abolished by Science Working Team in latter 2001 to save fuel for very long extended mission
First Z-control Burn at +Z extremum on 4/28/2019

$\Delta V_z$ negative toward SEP

2-stage targeting achieves $-Z$ position then the $+Z$ position at RLP XZ plane

Repeat at each return to $+Z$ extremum

Performed in conjunction with SK $\Delta V_x$ for stability
DSCOVR: Frozen Lissajous Showing Precluded Phase Segments

Dotted trace indicates precluded segments of the Orbit
## Results for Case Controlling to SEV Angle ≥ 4.1 degrees

<table>
<thead>
<tr>
<th>#</th>
<th>Event</th>
<th>UTC Epoch</th>
<th>Delta-V (m/sec)</th>
<th>Elapsed Days from LOI</th>
<th>Elapsed Time Between Z-control burns</th>
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### Maneuver

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<th>Reference Frame</th>
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<th>Goal Variable</th>
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<td>Z-control</td>
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<td>ΔVz</td>
<td>Z = +112,000 ±100 km*</td>
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*at Northern Z-axis extremum*
Uncontrolled Orbit and 6-Month Z-Control SEV Angles

Red Trace: uncontrolled orbit
Blue Trace: 6-Month Z-control

[Graph showing DSCOVR 5-Year Lissajous SEV Angle Evolution]
DSCOVR: 3-Month Control Superimposed on 6-Month Control

Demonstrates equivalency of 6-month control and 3-month control

3 – Month Z-control burns at both the +Z and –Z extremums
DSCOVR: 3-Month Z-control Design through 5 Cycles

Results for Case Controlling to SEV Angle ≥ 4.0 degrees

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<tr>
<th>#</th>
<th>Event</th>
<th>UTC Epoch</th>
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**Maneuver**

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<td>SK</td>
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<td>Vx = 0.0 ±0.0001 km/sec</td>
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<td>Z-control</td>
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<td>Z = −136,465 ±100 km (South) Z = +116,000 ±100 km (North)</td>
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DSCOVR: 3-Month Control and 6-Month Control SEV Angles
DSCOVR SEZ Avoidance Considerations

- Either 3 month or 6 month control can be used; decision may involve Science Team
  - 3 month option may be preferred due to shorter burn duration (~15 min or less)
  - On the other hand, 6-month control reduces operations impact
- Use +Z-axis delta-V configuration (thrusters 9 and 10)
- Attitude re-orientation Slews will be necessary to orient body Z-axis to target ecliptic pole direction, and then back to Science attitude
  - Slews could be on the order of 180 deg each way, because science attitude has +Z-axis always pointing away from Earth-Sun line, roughly opposite to the needed direction for the SEZ burns
  - -Z-axis configuration thrusters (1,3,6,8) could in principle be used, but plume impingement issues being assessed
- Nominally, ample fuel should be available; not just thru 2020 but thru 2028 at least!
DSCOVR Fuel Usage Actuals and Lifetime Projections

- 51 kg out of a budgeted 74 kg used for Transfer and Lissajous Insertion
  - Leaves about 94 kg for remainder of mission
- SK expected to need no more than 2 kg yearly
  - With nominal performance, probably << 1 kg
- During first full year of SEZ avoidance, expecting to use 7.5 to 8 kg
- Annual fuel costs decline slowly as we ride down blowdown curve

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Notes:
1) Delta-H = momentum management
2) BOL/EOL = Beginning/End of Life
3) Actual usage to date (July 2015) highlighted yellow
SK maneuvers can be planned in tandem with Z-control burns
  – Plan SK before first SEZ burn for two-burn targeting
  – Or, include \( \Delta V_x \) component with the Z-control burn
  – Either way using 2 by 2 differential corrections targeting

Once Z-control burns initiated, they have potential to affect future SK burn magnitudes and frequency

Z-control burns are \( \sim \) 2 orders of magnitude larger than typical SK burns; any in-plane error from Z-control will affect future SK

If in-plane errors significant, they can be managed by planning an SK burn \( \sim \) 4 weeks later to do clean-up
  – Minimum interval needed to get good post-burn OD about 3 weeks
  – Going forward, may also need to increase overall SK frequency
Concluding Remarks

- Mission design analysis has shown that DSCOVR stationkeeping may be performed using either X-control or Y-control with variations of each:
  - Successful Lissajous Orbit Insertion-Correction burn was executed using X-control variant (staying in science attitude)
  - First SK burn planned for Sept. 15th; predictions show ~ 4 cm/sec
  - SK expected to consume no more than 2 kg per year; likely much less

- Analysis for SEZ avoidance shows that DSCOVR can follow in ACE’s foot-steps, using either 6-month or 3-month control:
  - 6-month finite burn estimates: ~ 30 min and ~ 4 kg per burn, initially
  - 3-month finite burn estimates: ~ 15 min and ~ 2 kg per burn, initially

- Finite burn fuel usage study shows fuel enough to last thru at least 2028

- Current analysis looking at controlling to a 2-degree SEZ