DEEP SPACE CLIMATE OBSERVATORY

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

AAS 15-611

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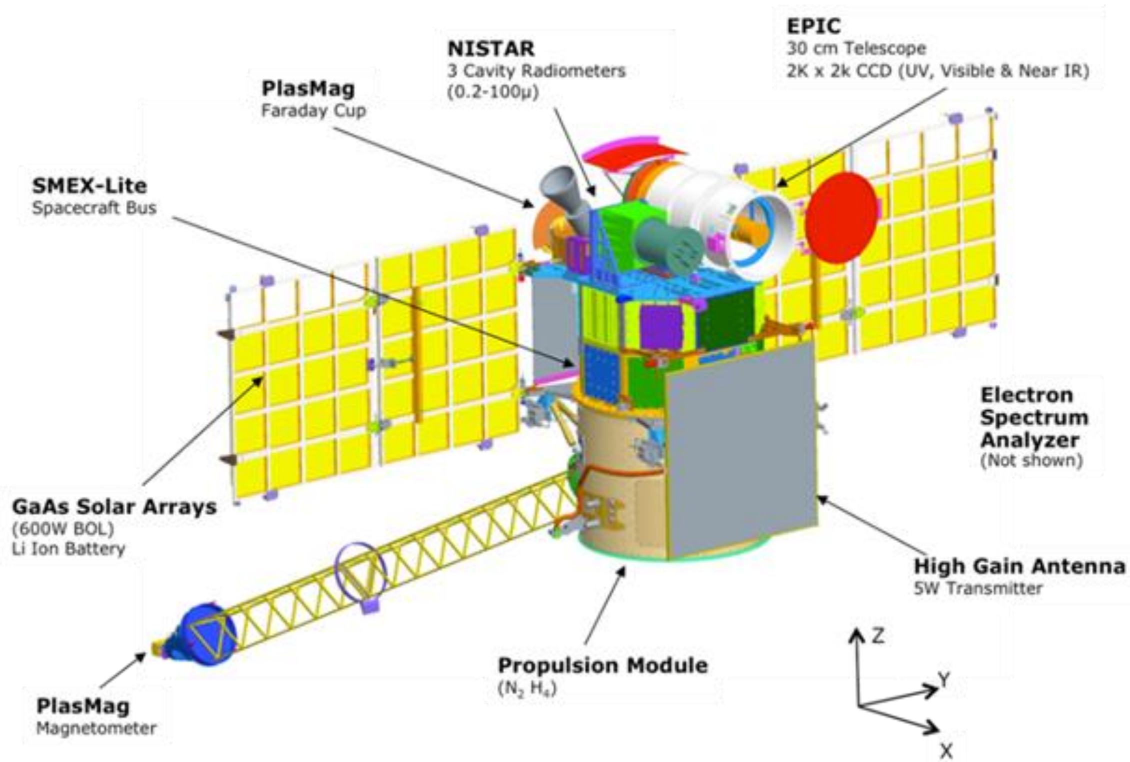

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Agenda for DSCOVR Lissajous Orbit Control

- 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

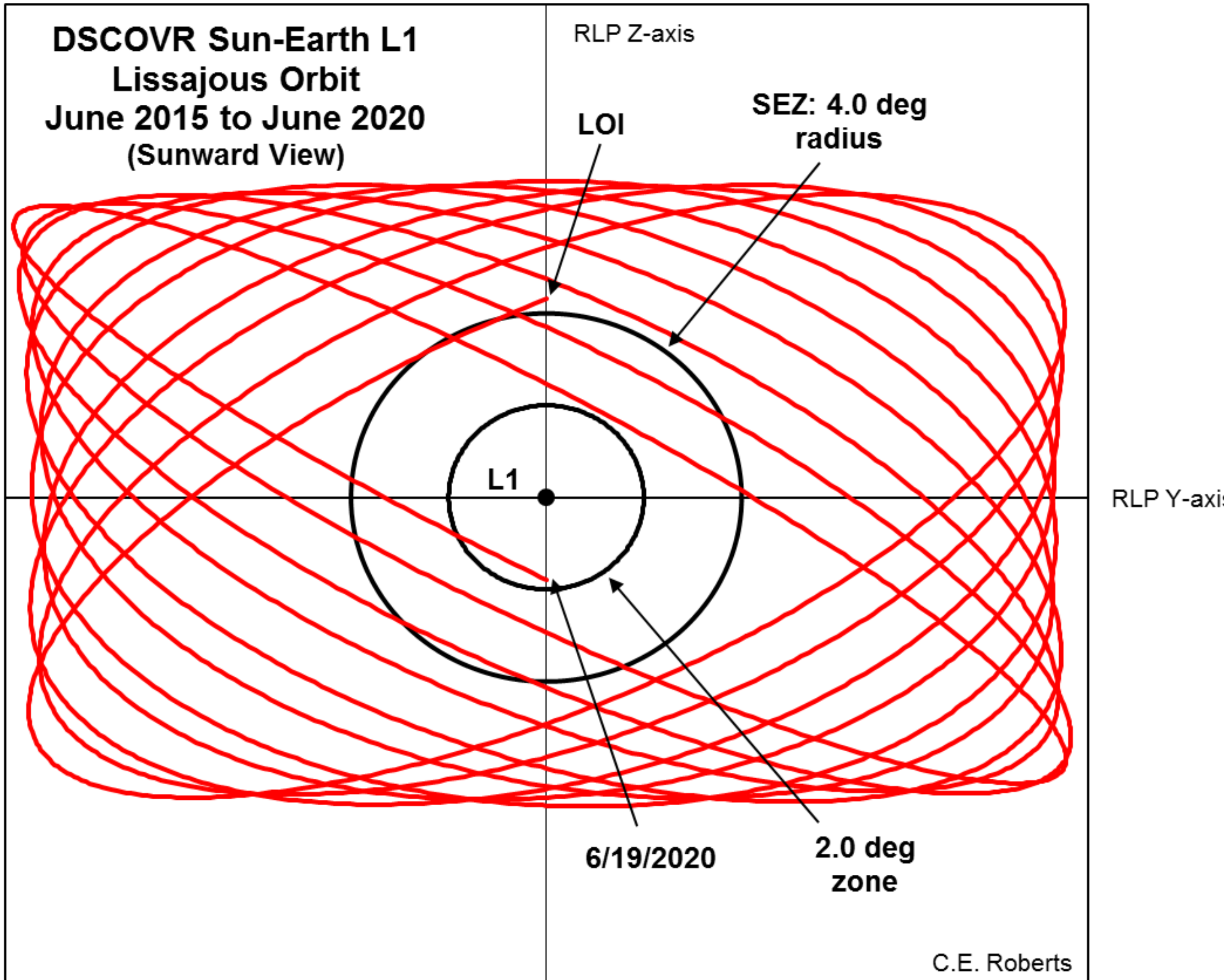
DSCOVR Lissajous Orbit Requirements

- 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

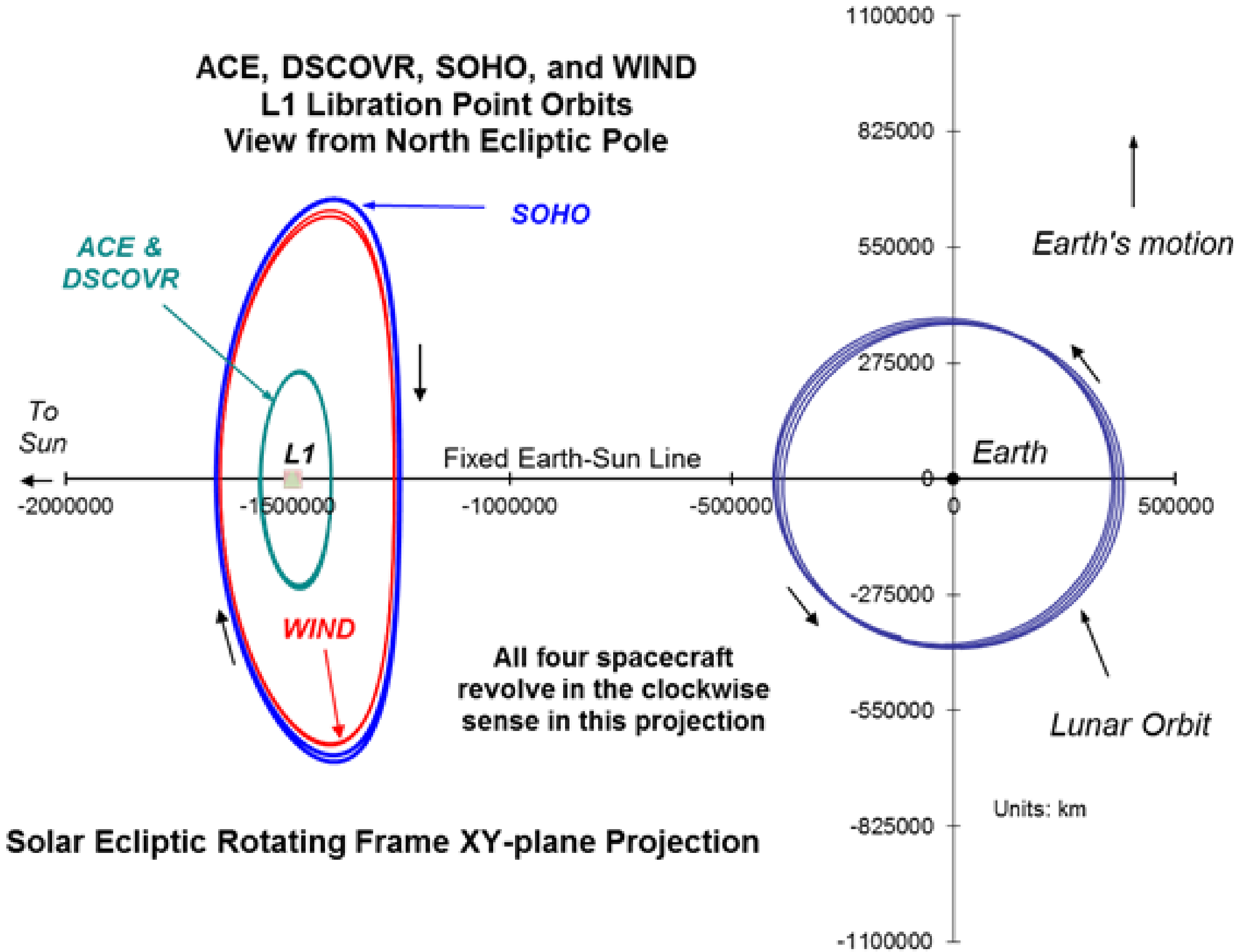
Lissajous opening: evolution over 5 years from insertion on 7 June 2015

Counter-clockwise Motion



Rotating Libration Point Frame YZ-plane Projection

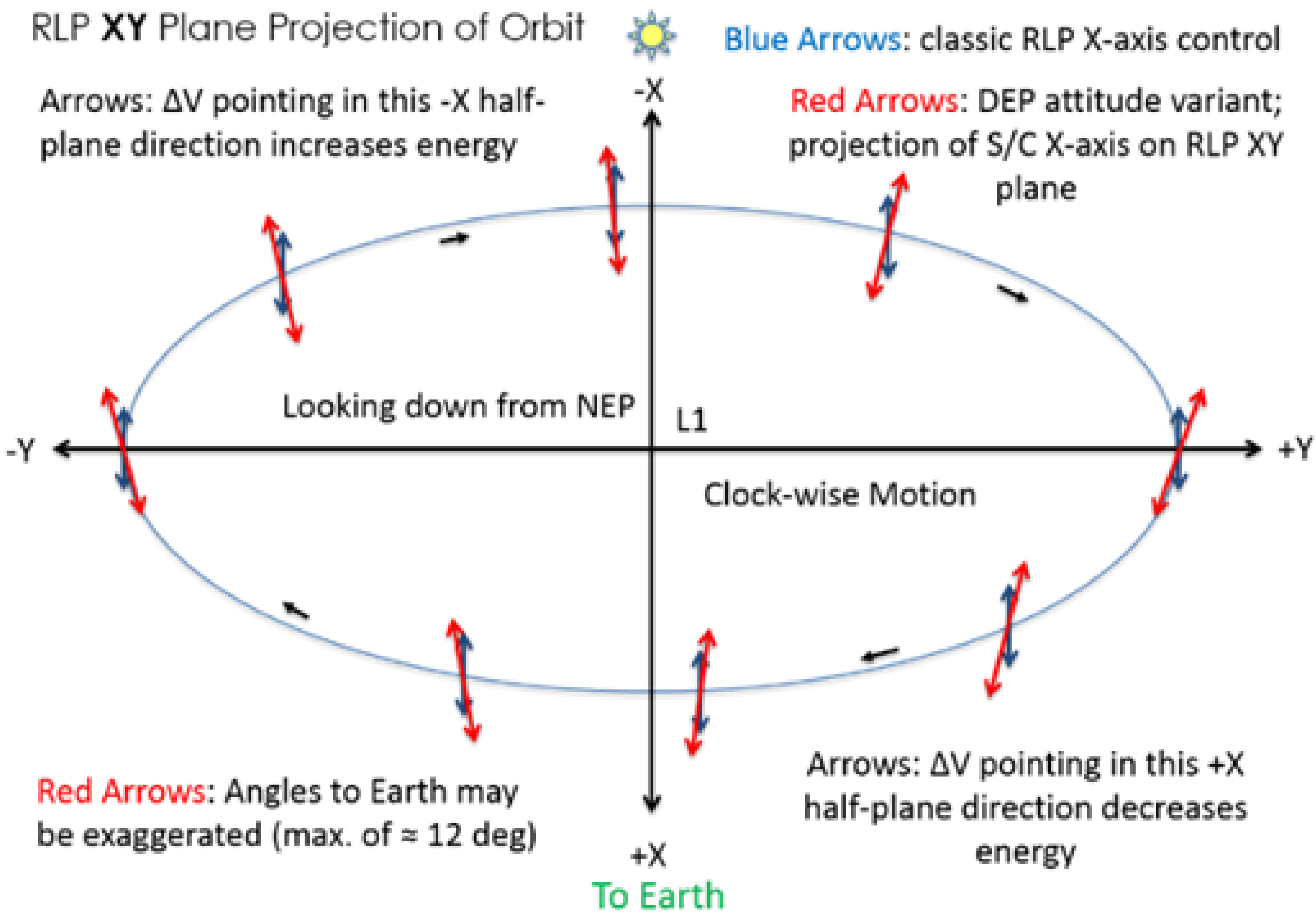
DSCOVR: View from NEP including ACE, WIND, SOHO



DSCOVR Lissajous Orbit Stationkeeping

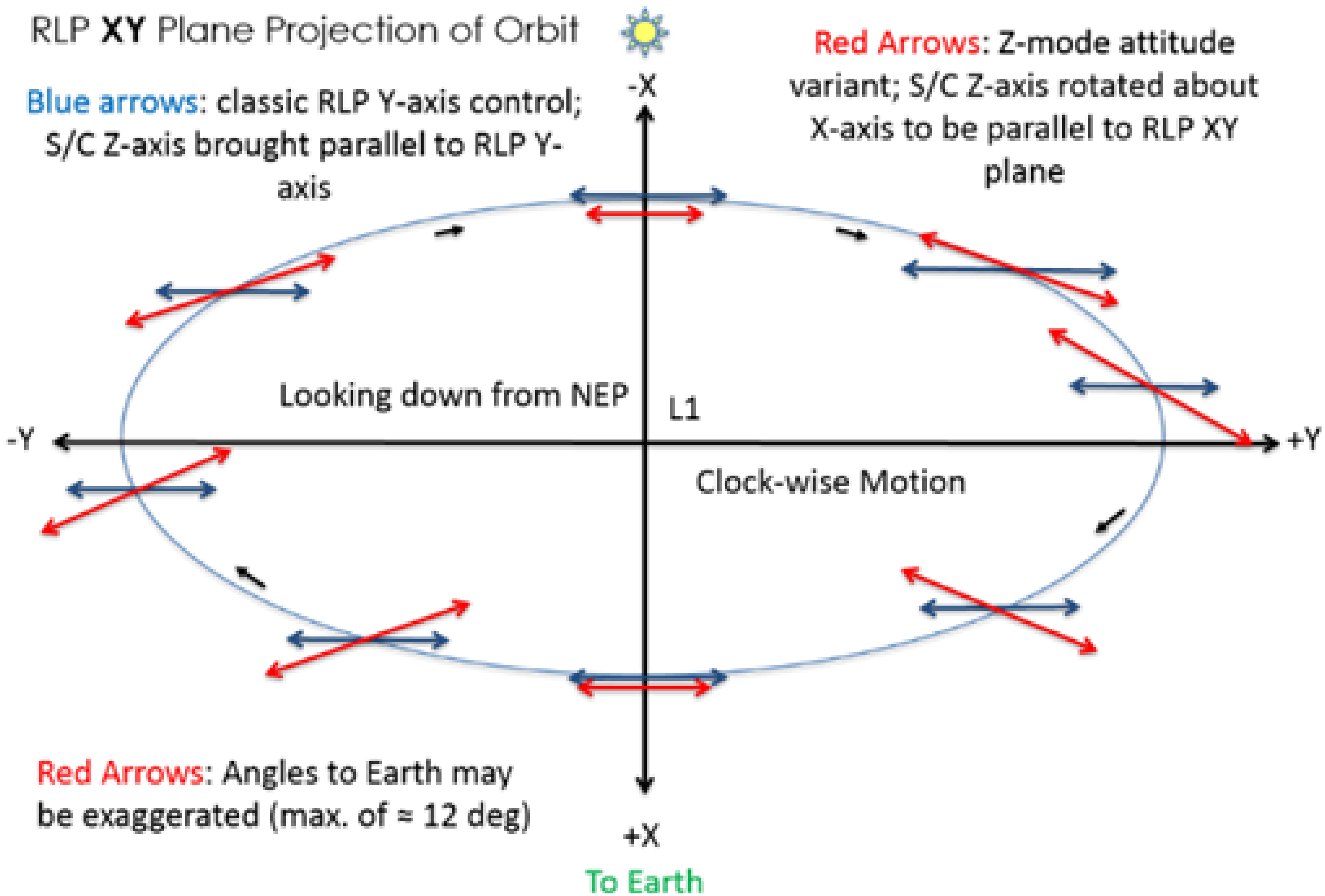
- Collinear LPOs are inherently unstable; stationkeeping maneuvers needed at intervals to prevent escape
- Delta-Vs needed to correct perturbative effects grow exponentially with time
  - Doubling time constant is ~16 days
- SK maneuvers impart a positive or negative change to orbital energy to prevent 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)



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 2001to save fuel for very long extended mission

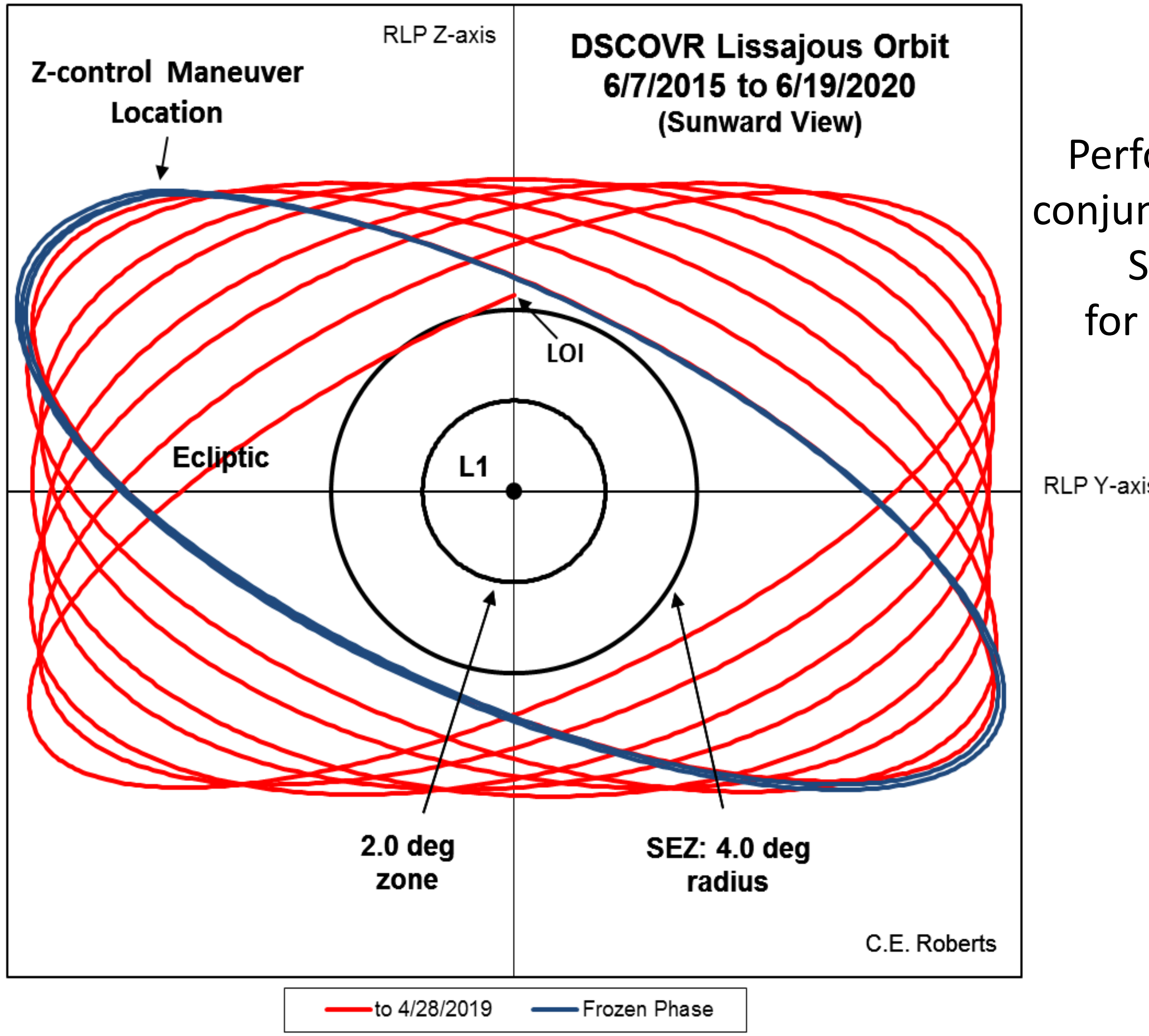
DSCOVR Lissajous with "Frozen Phase" Segment

First Z-control Burn at +Z extremum on 4/28/2019

ΔV_Z negative toward SEP

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

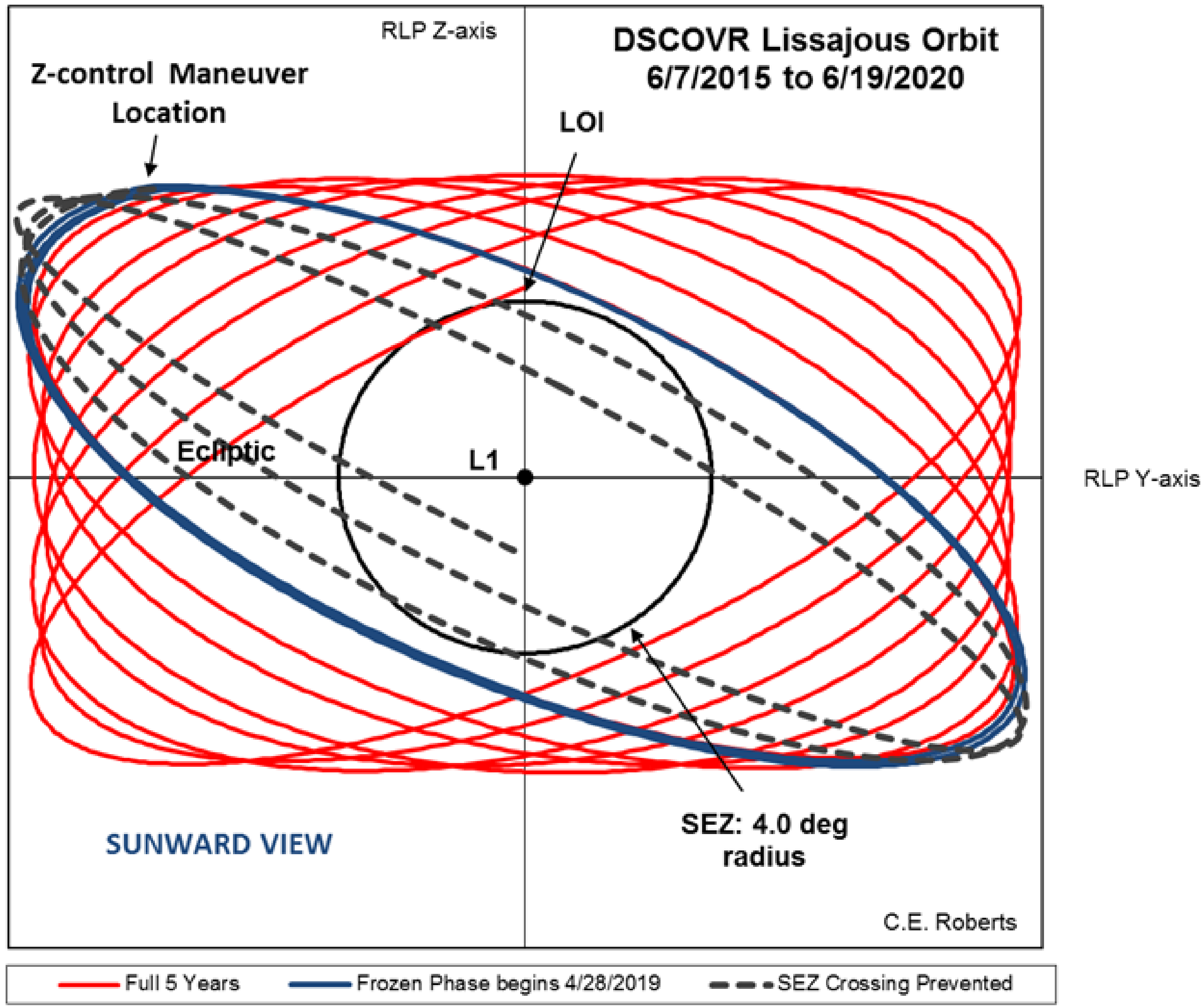
Repeat at each return to +Z extremum



Performed in conjunction with SK ΔV_X for stability

DSCOVR: Frozen Lissajous Showing Precluded Phase Segments

Dotted trace indicates precluded segments of the Orbit



DSCOVR: 6-Month Z-control Design through 4 Cycles

Results for Case Controlling to SEV Angle ≥ 4.1 degrees

#	Event	UTC Epoch	Delta-V (m/sec)	Elapsed Days from LOI	Elapsed Time Between Z-control burns
1	SK-1	7 April 2019	+0.166	1399.8	n/a
2	Z-control #1	28 April 2019	−10.53	1421.1	0
3	Z-control #2	23 Oct 2019	−13.89	1599.7	178.6
4	Z-control #3	13 April 2020	−12.72	1772.6	172.9
5	SK-2	18 Sept 2020	−0.077	1928.8	n/a
6	Z-control #4	10 Oct 2020	−14.38	1951.3	178.7

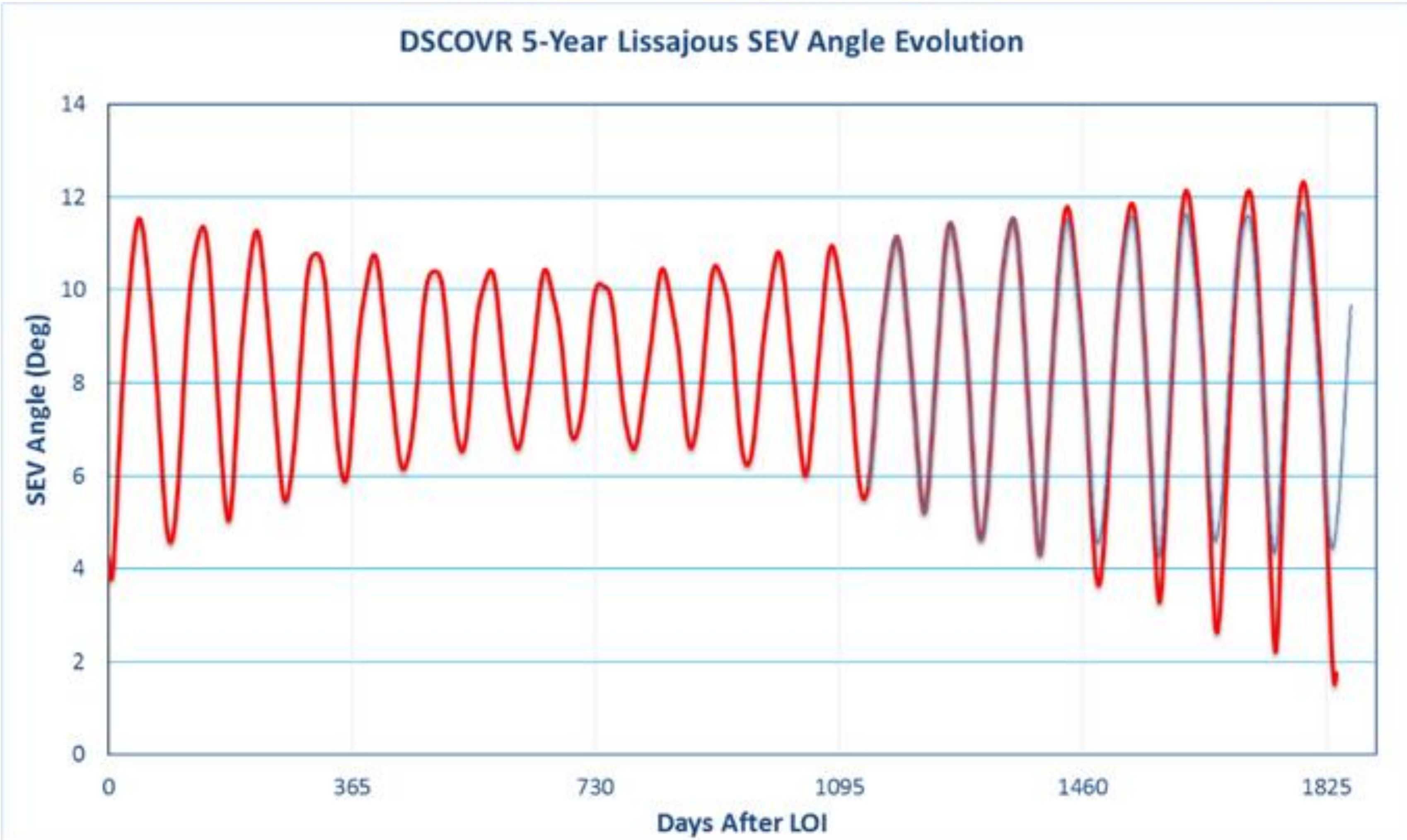
Maneuver	Reference Frame	Targeting Variable	Goal Variable
SK	RLP	ΔVx	Vx = 0.0 ±0.0001 km/sec
Z-control	RLP	ΔVz	Z = +112,000 ±100 km*

*at Northern Z-axis extremum

Uncontrolled Orbit and 6-Month Z-Control SEV Angles

Red Trace: uncontrolled orbit

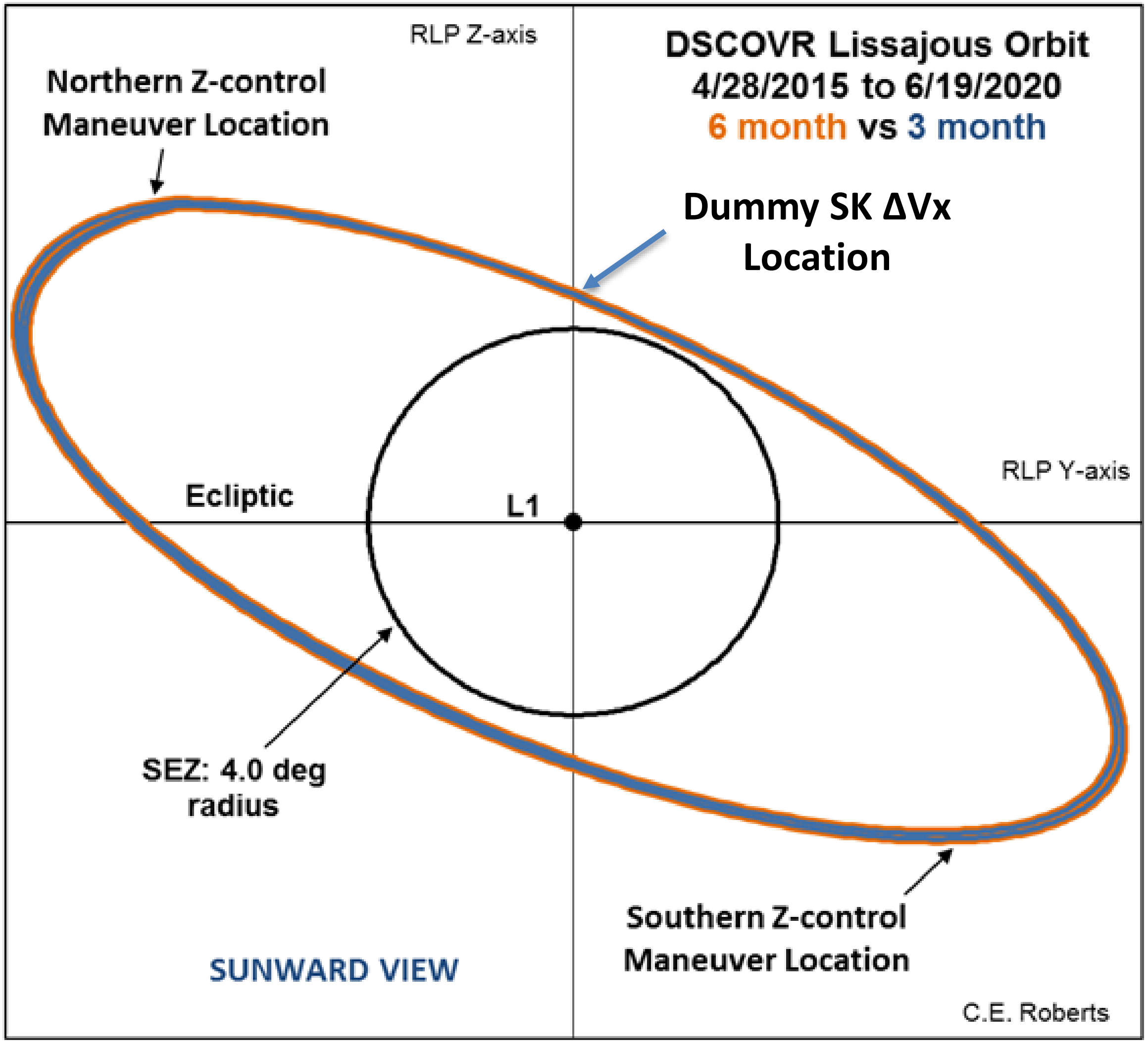
Blue Trace: 6-Month Z-control



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



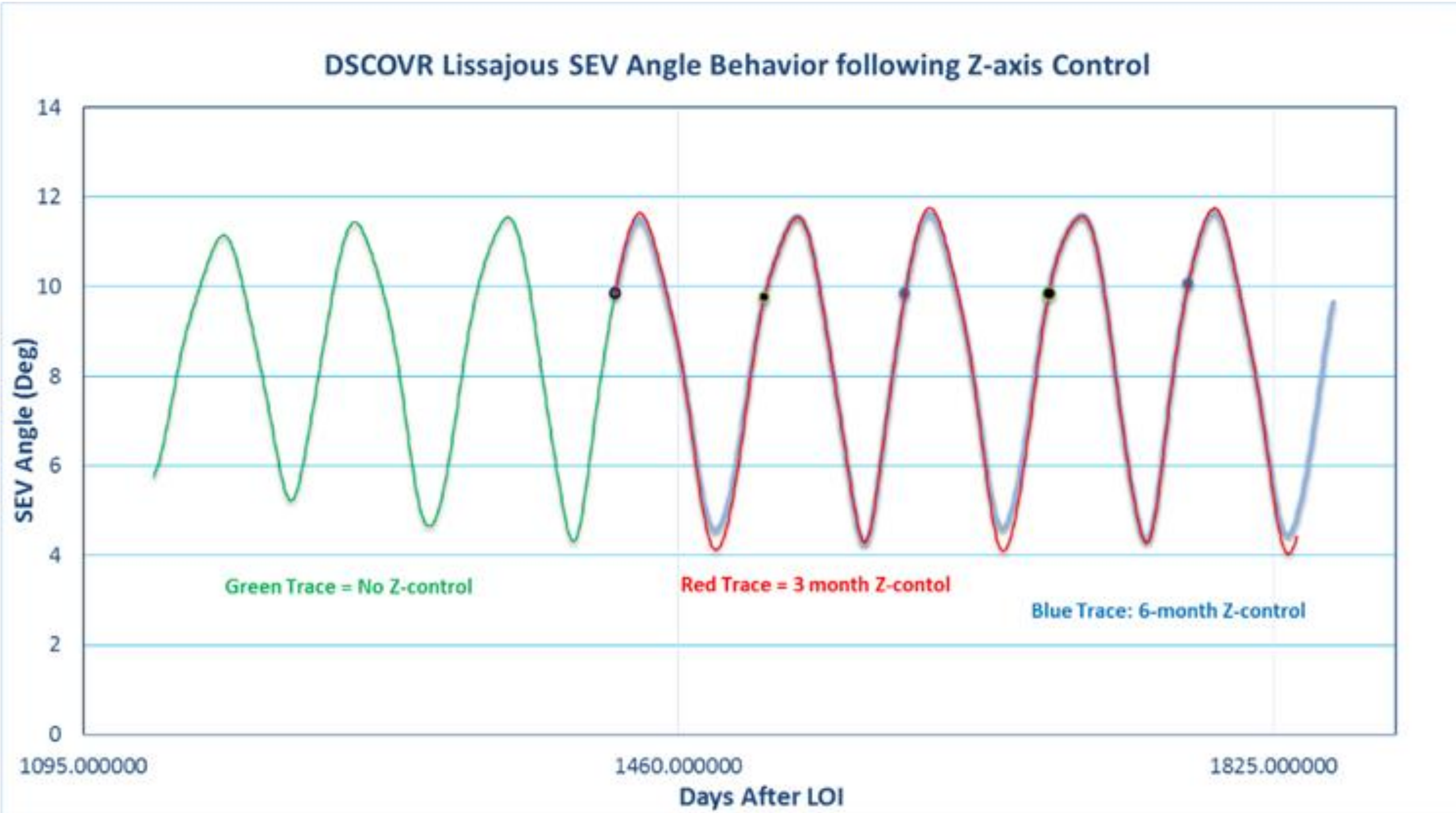
DSCOVR: 3-Month Z-control Design through 5 Cycles

Results for Case Controlling to SEV Angle ≥ 4.0 degrees

#	Event	UTC Epoch	Delta-V (m/sec)	Elapsed Days from LOI	Elapsed Time Between Z-control burns
1	SK-1	7 April 2019	+0.110	1399.8	-
2	Z-control #1	28 April 2019	−6.53	1421.1	0
3	Z-control #2	29 July 2019	+6.58	1512.7	91.6
4	Z-control #3	23 Oct 2019	−6.60	1599.2	86.5
5	Z-control #4	19 Jan 2020	+6.50	1687.1	87.9
6	Z-control #5	13 April 2020	−6.70	1772.2	85.1

Maneuver	Reference Frame	Targeting Variable	Goal Variable
SK	RLP	ΔVx	Vx = 0.0 ±0.0001 km/sec
Z-control	RLP	ΔVz	Z = −136,465 ±100 km (South) Z = +116,000 ±100 km (North)

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!

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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

Year #	BOL	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Year	5 Yr Budget	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
MCC-1	15	0.15													
MCC-2	2.5	0.6													
LOI	51	49.7													
LOIc	5.5	0.5													
SK	12	2	1.8	1.8	1.8	1.5	1.5	1.4	1.3	1.2	1.1	1	0.9	0.8	0.7
SEZ Control	11	0	0	0	4	7.6	6.9	6.3	5.9	5.4	5	4.6	4.2	3.8	0
Delta-H	2	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
EOL /Margin	43	—	—	—	—	—	—	—	—	—	—	—	—	—	6
Unusable	3	—	—	—	—	—	—	—	—	—	—	—	—	—	3
Consumed	n/a	53.35	2.2	2.2	6.2	9.5	8.8	8.1	7.6	7	6.5	6	5.5	5	7.1
Remaining	145	91.55	89.35	87.15	80.95	71.45	62.65	54.55	46.95	39.95	33.45	27.45	21.95	16.95	9.85

Notes: 1) Delta-H = momentum management
2) BOL/EOL = Beginning/End of Life
3) Actual usage to date (July 2015) highlighted yellow

DSCOVR SEZ Avoidance and Stationkeeping

- SK maneuvers can be planned in tandem with Z-control burns
  - Plan SK before first SEZ burn for two-burn targeting
  - Or, include ΔVx 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 ~ 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 ~ 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