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National Aeronautics and Space Administration

Orbital Maintenance for the Wide Field Infrared Survey Telescope: Effects of Solar Radiation Pressure and Navigation Accuracies on Stationkeeping

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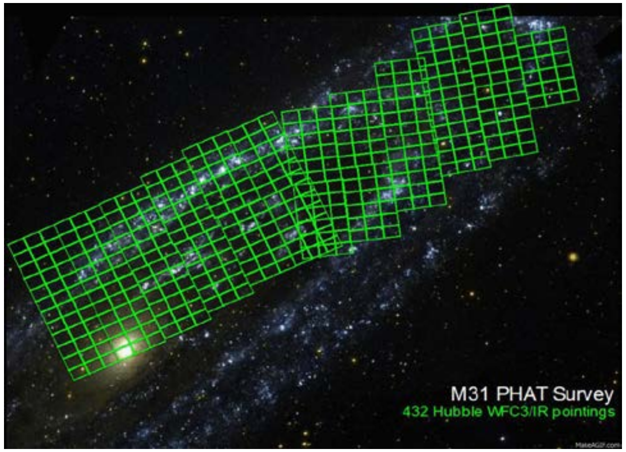
Outline

- Wide Field Infrared Survey Telescope (WFIRST)
- Force Models and Stationkeeping Strategy
- Modeling Solar Radiation Pressure (SRP)
- SRP Effect on Stationkeeping
- Navigation Errors Effect on Stationkeeping
- Conclusions and Future Work

Wide Field Infrared Survey Telescope

- Scheduled to launch in 2025 to an orbit about the Sun-Earth Libration Point 2 (SEL2)
- 2.4 meter primary mirror along with a Wide Field Instrument (WFI) will be used to scan up to 100x more sky than Hubble
- Coronograph Instrument (CGI) will be used to search for exoplanets

- Mission Objectives:
  - Explore exoplanets
  - Research into dark energy
  - Perform galactic and extragalactic surveys



Goal of the work

- WFIRST will be orbiting at Sun-Earth L2 around a Quasi-Halo orbit. To deal with the instability of the environment, and remain close to its nominal orbit, stationkeeping maneuvers will be performed every 21 days.
- Routine Momentum Unloads (MUs) will be performed to unload the stored momentum in the reaction wheels.
- The effect of Solar Radiation Pressure (SRP) on the stationkeeping Δv has been explored using different SRP models.
- The effect of Orbit Determination and Navigation errors, and maneuver execution errors on the stationkeeping Δv has also been explored.

Force Models

- **Circular Restricted Three Body Problem (RTBP)**

$$\ddot{\boldsymbol{R}} + 2\boldsymbol{\omega} \times \dot{\boldsymbol{R}} = \nabla\boldsymbol{\Omega} + \boldsymbol{a}_{srp},$$

where $\boldsymbol{R} = (X, Y, Z)$ is the location of the satellite, $\Omega = \frac{1}{2}(X^2 + Y^2) + \frac{1-\mu}{r_{ps}} + \frac{\mu}{r_{pe}}$ is the gravitational potential, and $\boldsymbol{a}_{srp} = (a_X, a_Y, a_Z)$ is the SRP acceleration.

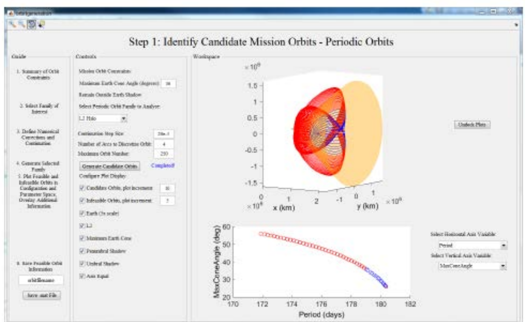
- **Point Mass Ephemeris Model**

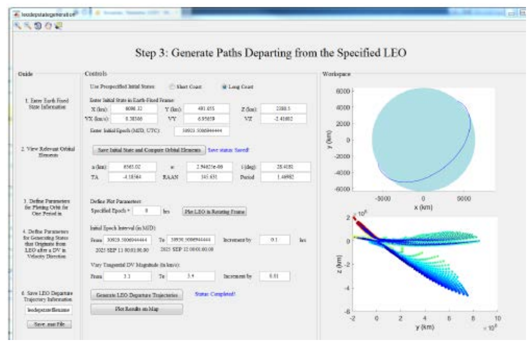
$$\ddot{\boldsymbol{R}}_{S,sc} = Gm_S \frac{\boldsymbol{R}_{S,sc}}{R_{S,sc}^3} + Gm_E \left(\frac{\boldsymbol{R}_{E,sc}}{R_{E,sc}^3} - \frac{\boldsymbol{R}_E}{R_E^3} \right) + Gm_M \left(\frac{\boldsymbol{R}_{M,sc}}{R_{M,sc}^3} - \frac{\boldsymbol{R}_M}{R_M^3} \right) + \boldsymbol{a}_{srp},$$

where $\boldsymbol{R} = (X, Y, Z)$ is the location of the satellite, $\boldsymbol{R_i} = (X_i, Y_i, Z_i)$ is the position of the Sun-Earth and Moon ($i = S, E, M$), and m_S, m_E, m_M their respective masses.

Adaptive Trajectory Design (ATD) module

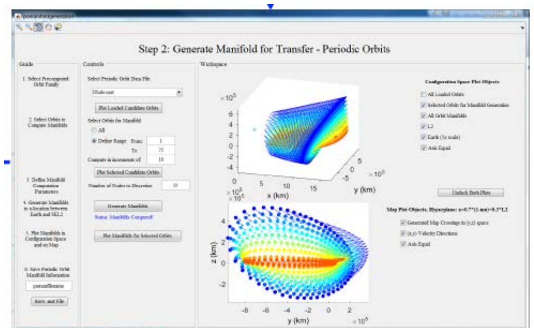
- The baseline trajectory for WFIRST has been computed with the ATD Module developed by Dr. Natasha Bosanac [1].

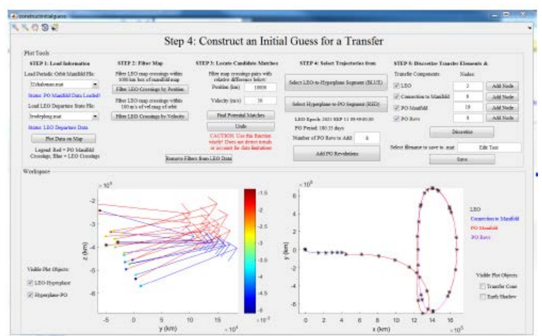


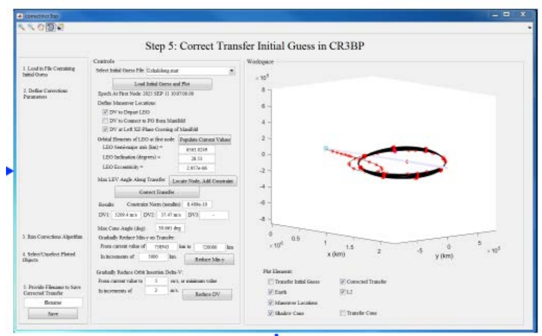


Main Steps:

1. Select candidate Halo orbit in CR3BP.
2. Find transfer from LEO to Halo in CR3BP.
3. Correct trajectory in CR3BP and Full Ephemeris.
4. Export to GMAT.



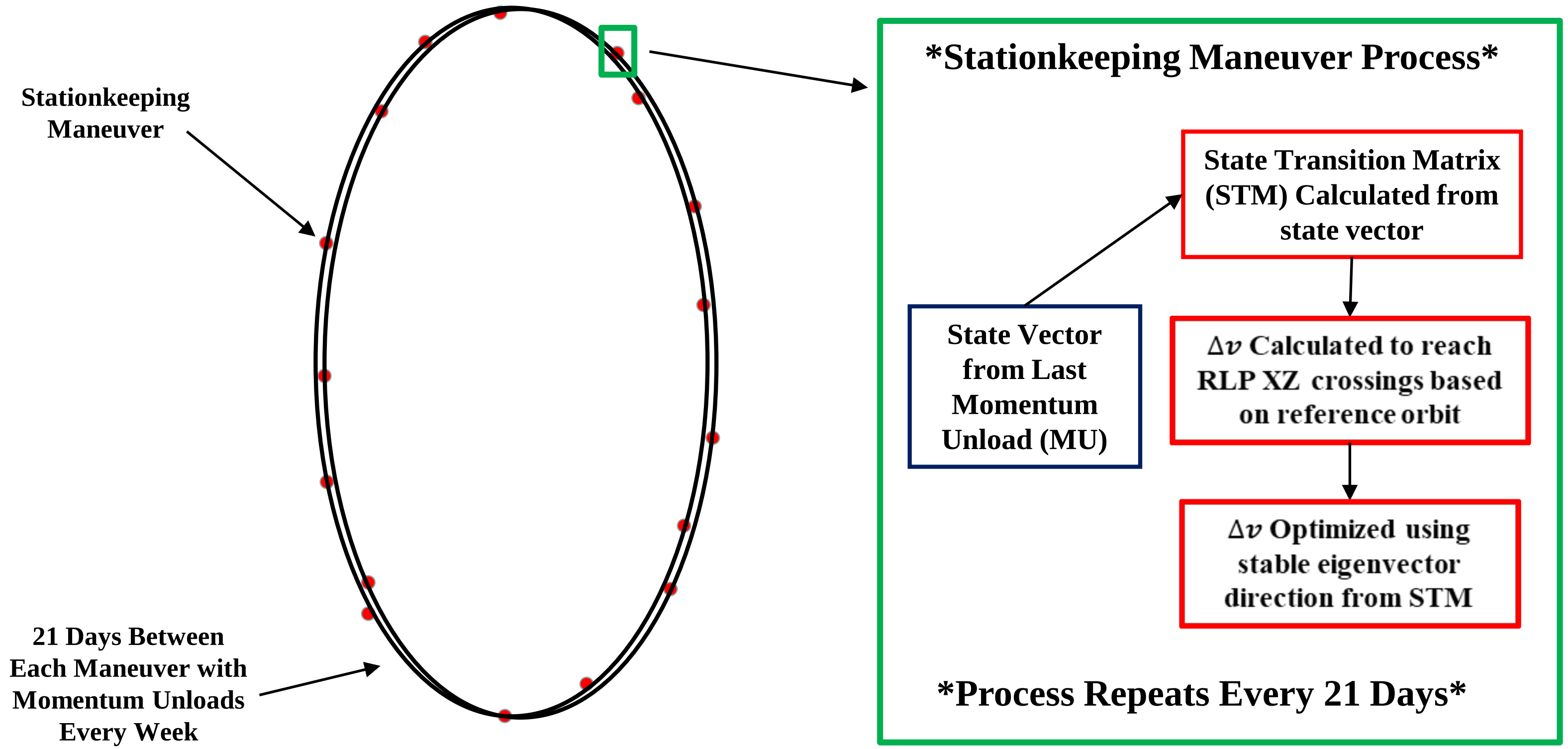




[1] N. Bosanac, C. M. Webster, K. Howell and D. C. Folta, *"Trajectory Design and Station-Keeping Analysis for the Wide Field Infrared Survey Telescope Mission",* in AAS/AIAA Astrodynamics Specialist Conference, 2017.

Stationkeeping Strategy

- We use information from the natural dynamics around a Halo orbit to determine the stationkeeping maneuver.



Solar Radiation Pressure Models

- **Cannonball Model** (simple) the satellite's shape is approximated by a sphere:

$$\boldsymbol{a}_{srp} = -\frac{P_{srp} C_r A_{sat}}{m_{sat}} \boldsymbol{r}_s.$$

- **N-plate Model** (intermediate) the satellite's shape is approximated by a set of flat plates, each one with different reflectivity properties:

$$\boldsymbol{a}_{srp} = -\frac{P_{srp}}{m_{sat}} \sum_{i=1}^{N} \left(A_i \langle \boldsymbol{n}_i, \boldsymbol{r}_s \rangle \left[(1 - \rho_s^i) \boldsymbol{n}_i + 2 \left(\rho_s^i \langle \boldsymbol{n}_i, \boldsymbol{r}_s \rangle + \frac{\rho_d^i}{3} \right) \boldsymbol{r}_s \right] H(\theta_i) \right).$$

- **Finite Element Model** (high-fidelity) a CAD model is used to approximate the satellite's shape and ray-tracing techniques are used to approximate the SRP acceleration:

$$\boldsymbol{a}_{srp} = -\frac{P_{srp}}{m_{sat}} \int_{\partial\Omega} A \langle \boldsymbol{n}, \boldsymbol{r}_s \rangle \left[(1 - \rho_s) \boldsymbol{n} + 2 \left(\rho_s \langle \boldsymbol{n}, \boldsymbol{r}_s \rangle + \frac{\rho_d}{3} \right) \boldsymbol{r}_s \right] d\Omega.$$

[2] A. Farres, D. C. Folta and C. Webster, "Using Spherical Harmonics to Model Solar Radiation Pressure Accelerations,“ in *AAS/AIAA Astrodynamics Specialist Conference*, 2017.

Comparison between SRP models

- The main difference between the Cannonball and the N-plate model is that it does not account for the satellite's attitude.
- The 14-plate approximation for WFIRST shows good agreement with the Finite Element approximation.

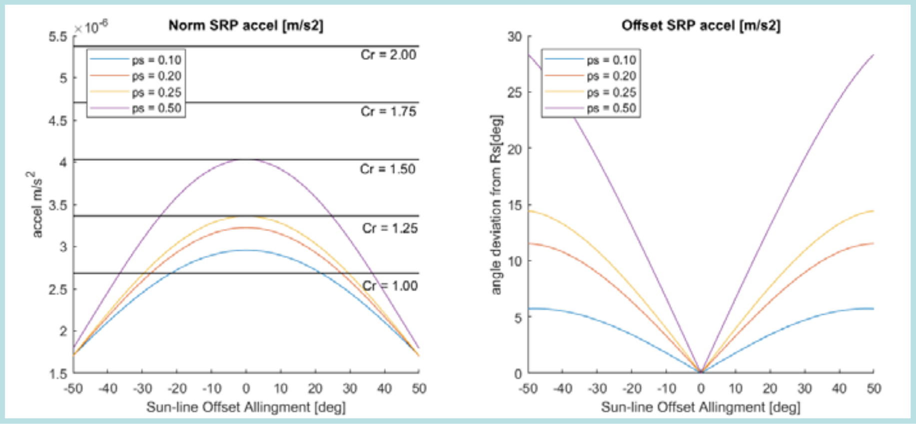


Fig 1: Cannonball vs 1-plate Model.

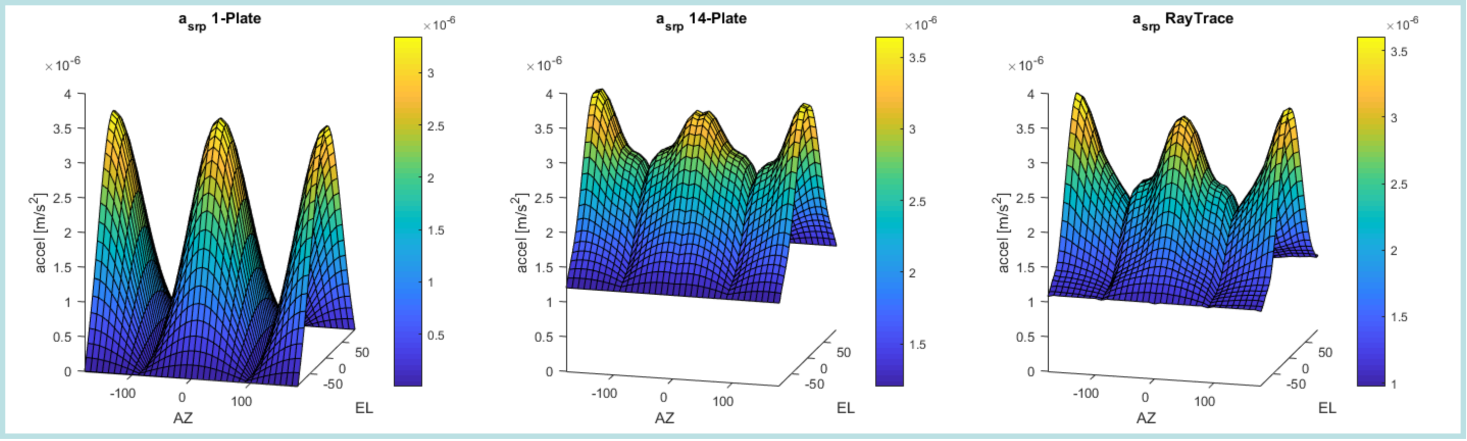


Fig 2: 1-plate vs 14-plate vs Finite Element

Effect of SRP on LPOs

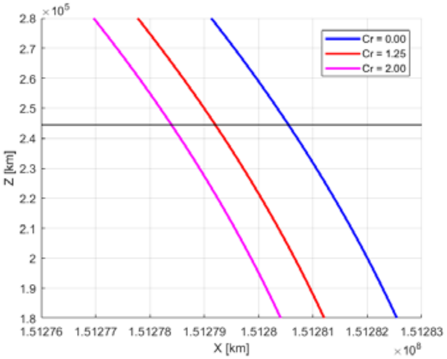
- The extra acceleration due to SRP essentially displaces the invariant objects toward the Sun.

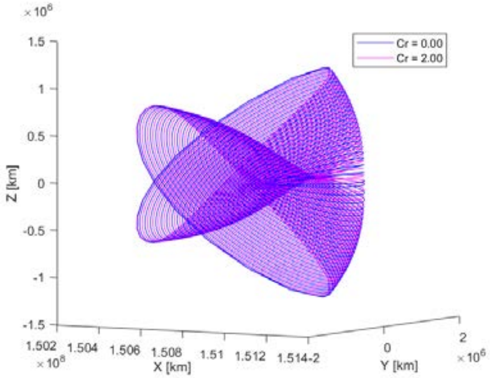
Table 1: Relationship between the location of L2 and Cr values.

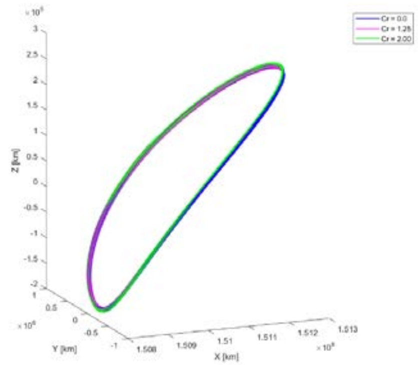
C_r	q_{srp}	L_2 location
$C_r^0 = 0.00$	0.0	151,105,099.17 km
$C_r^1 = 1.25$	5.7799×10^{-5}	151,104,145.49 km
$C_r^2 = 2.00$	9.2472×10^{-5}	151,103,573.97 km

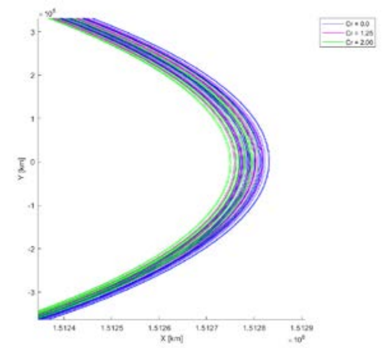
Table 2: Distance between L2 Halo orbits for different Cr values.

	$C_r^0 - C_r^1$	$C_r^0 - C_r^2$	$C_r^1 - C_r^2$
RTBP	1,300 km	2,000 km	800 km
Ephem	1,430 km	2,400 km	930 km









Effect of SRP on Stationkeeping

- Using the ATD module, two different reference orbits have been generated: one with $C_r = 0.0$ and another with $C_r = 2.0$.
- For each reference, orbit 5 simulations for stationkeeping over 5 years have been performed using three different C_r values ($C_r = 0.0, 1.25$ and 2.0) and different MUs sizes (1.3 mm/s and 13.3 mm/s).
- Results show that following the reference orbit with the same C_r value helps lower the total Δv cost.
- Increasing the size of the MUs increases the Δv cost, and the accuracy in SRP models is less relevant.

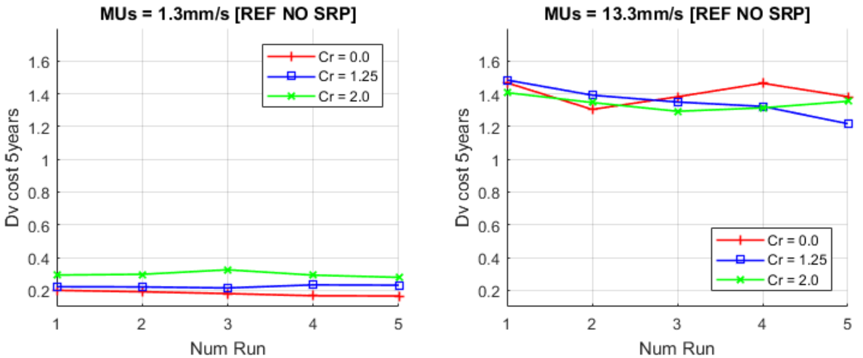


Fig 1. Total Δv cost for 5 years stationkeeping simulations using a No SRP reference trajectory for different Cr values.

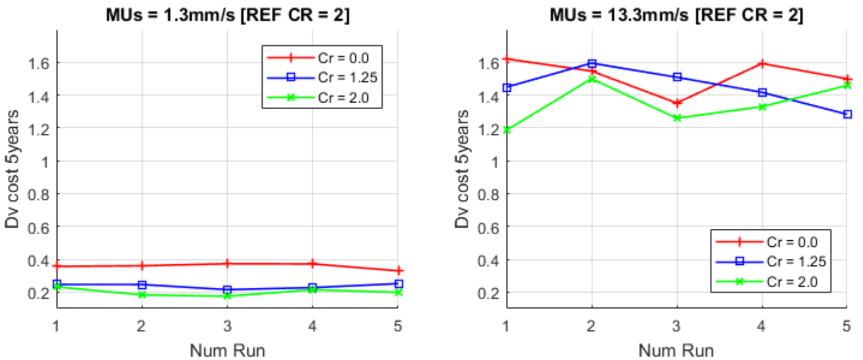


Fig 2. Total Δv cost for 5 years stationkeeping simulations using an SRP reference trajectory for different Cr values.

Effect of SRP on Stationkeeping

- Using a reference trajectory the same as in the previous examples ($C_r = 2.0$ with cannonball SRP).
- 5 simulations for stationkeeping over 5 years have been performed with different fixed offset angles and MUs sizes (1.3 mm/s and 13.3 mm/s).
- Results show that large offset angles result in larger total Δv cost.
- Increasing the size of the MUs increases the Δv cost, and the accuracy in SRP models is less relevant.
- Explorations with variable attitude will be done in the future.

Table 3: Total stationkeeping Δv cost with no MUs for a fixed plate offset.

Offset Angle	Total Δv
$\alpha = 0^o$	**0.1287 m/s**
$\alpha = 10^o$	**0.1355 m/s**
$\alpha = 20^o$	**0.1848 m/s**
$\alpha = 40^o$	**0.2754 m/s**

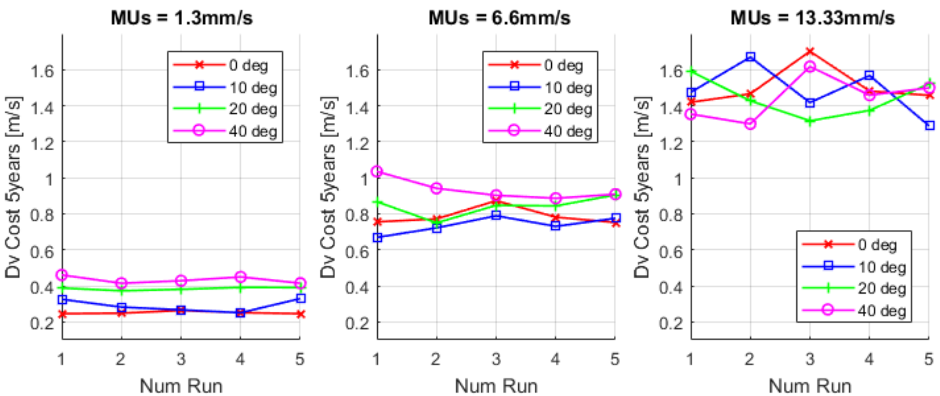
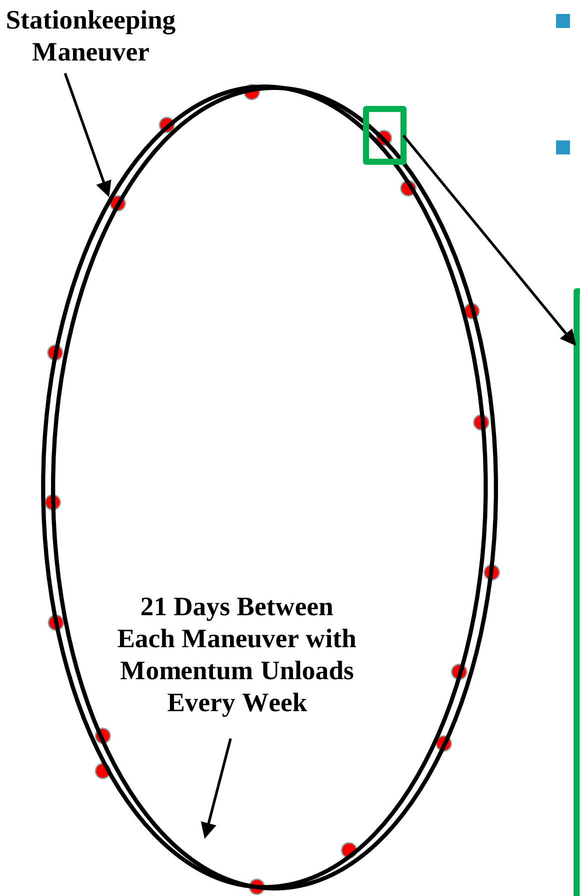


Fig 3. Total Δv cost for 5 years stationkeeping simulations using 1-plate model for SRP for different fixed offset angles.

Effects of Navigation Errors on Stationkeeping

- Currently NEN and DSN ground stations will be used for orbit determination.
- Having errors of 5 km on the steady-states and 5 cm/s on the velocity estimates.



Stationkeeping Maneuver Process

State Vector from Last Momentum Unload (MU) → **State Transition Matrix (STM) Calculated from state vector**

State Vector from Last Momentum Unload (MU) → **OD Error from Covariance Matrices applied to state vector**

State Transition Matrix (STM) Calculated from state vector → **Δv Calculated to reach RLP XZ crossings based on reference orbit** → **Δv Optimized using stable eigenvector direction from STM**

OD Error from Covariance Matrices applied to state vector and **Δv Optimized using stable eigenvector direction from STM** → **Stationkeeping Maneuver**:

<u>Stationkeeping Maneuver</u>
- **Uses OD Error State as Initial State**
- **Applies Optimized Δv and adds 5% to the magnitude (maneuver execution error)**

Process Repeats Every 21 Days

Effects of Navigation Errors on Stationkeeping

- Four different cases have been analyzed: with no SRP ($C_r = 0.0$) and SRP ($C_r = 2.0$), each one taking different MUs sizes (1.3 mm/s and 13.3 mm/s).
- 10 simulations using the cannonball model for SRP have been performed including random OD errors and maneuver execution errors for 1 year of stationkeeping.

Table 4. Stationkeeping Δv with Orbit Determination Errors and Cannonball SRP Model.

Analysis Case	C_r Value Used in Analysis and Reference Orbit	Momentum Unload Residual Δv (mm/s)	Maximum Position OD Error (km)	Maximum Velocity OD Error (cm/s)	Average Total Stationkeeping Δv for 1 Year (m/s)
1	0	1.33	9.57	3.22	1.12
2	0	13.33	12.81	3.83	1.20
3	2	1.33	13.72	4.04	1.06
4	2	13.33	10.75	4.53	1.16

Effects of Navigation Errors on Stationkeeping

- 8 different cases have been analyzed using a 1-plate model for SRP: taking different fixed offset angles, each one taking different MUs sizes (1.3 mm/s and 13.3 mm/s).

Table 5. Stationkeeping Δv with Orbit Determination Errors and N-Plate Model.

Analysis Case	1-Plate Offset Angle (°)	Momentum Unload Residual Δv (mm/s)	Maximum Position OD Error (km)	Maximum Velocity OD Error (cm/s)	Average Total Stationkeeping Δv for 1 Year (m/s)
1	0	1.33	8.43	3.14	0.92
2	0	13.33	10.62	4.09	0.99
3	10	1.33	11.31	4.62	0.91
4	10	13.33	9.82	3.87	0.97
5	20	1.33	7.64	4.17	0.89
6	20	13.33	16.27	4.54	1.02
7	40	1.33	10.94	3.75	0.88
8	40	13.33	12.03	4.03	0.95

Conclusions and Future Work

- We have analyzed how SRP acceleration uncertainties, the size of MUs and OD errors affect WFIRST's total Δv for stationkeeping.
- Simulations without OD errors: agreement between the SRP model and reference orbit help lower the Δv cost. Moreover, large MUs increase the total Δv.
- Simulations with OD errors: the OD errors introduced are similar in size to the individual stationkeeping maneuvers. Better navigation errors (either using more tracking or Onboard OD) may reduce the total stationkeeping maneuver Δv.
- The total stationkeeping Δv increased significantly when OD errors were introduced vs. when just looking at SRP and MU sizes.
- In the future, using a variable attitude profile for WFIRST, the effects of SRP can fully be studied as WFIRST moves through its orbit with different orientations.

Questions ?

Thank you for your attention