National Aeronautics and Space Administration

Precise and Efficient Formation Keeping at Earth-Sun L2 for Starshade Missions

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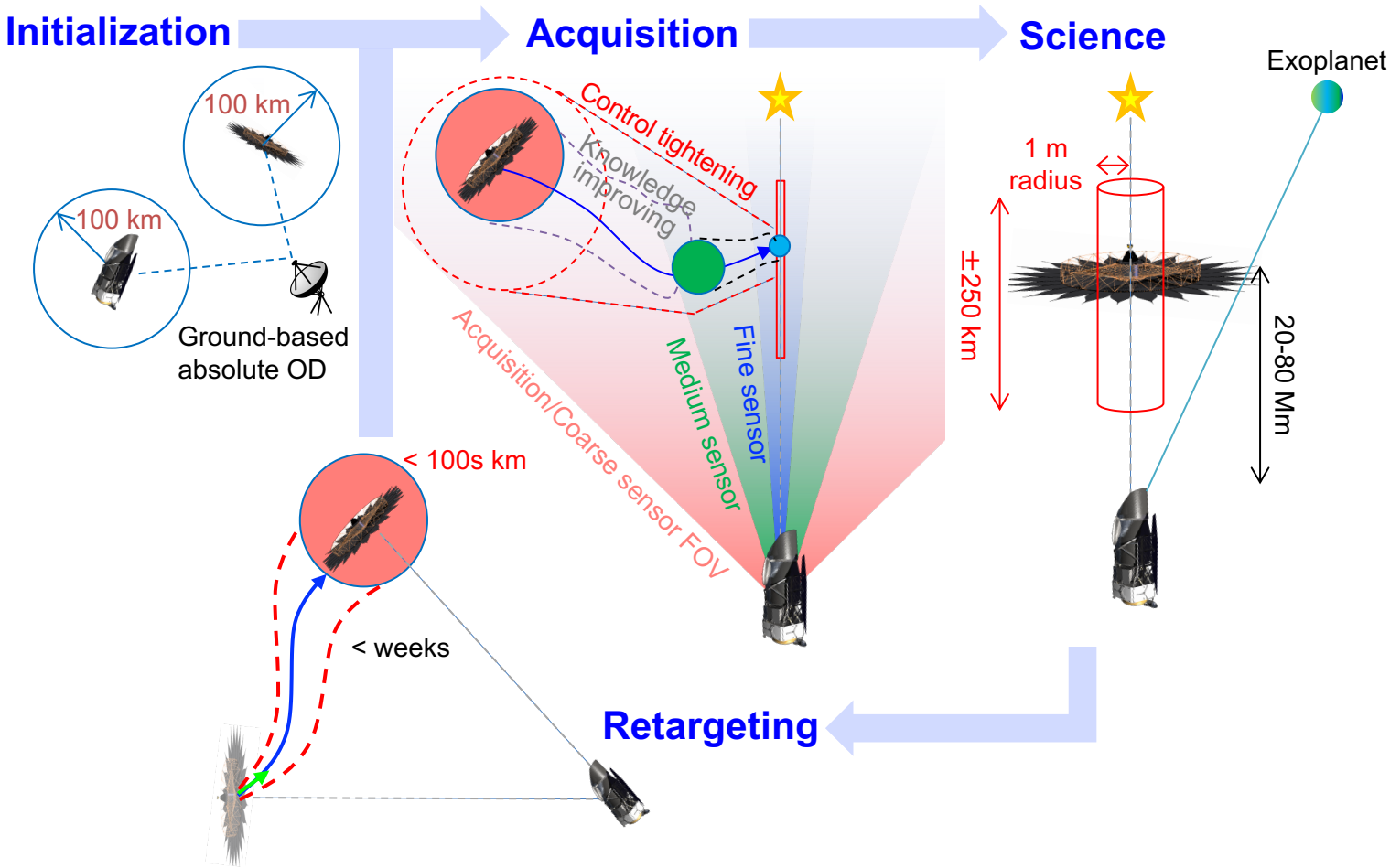
Introduction

Starshades: precisely shaped occulters flying in formation with telescope

➔ Allow direct imaging / spectroscopy of exo-Earths



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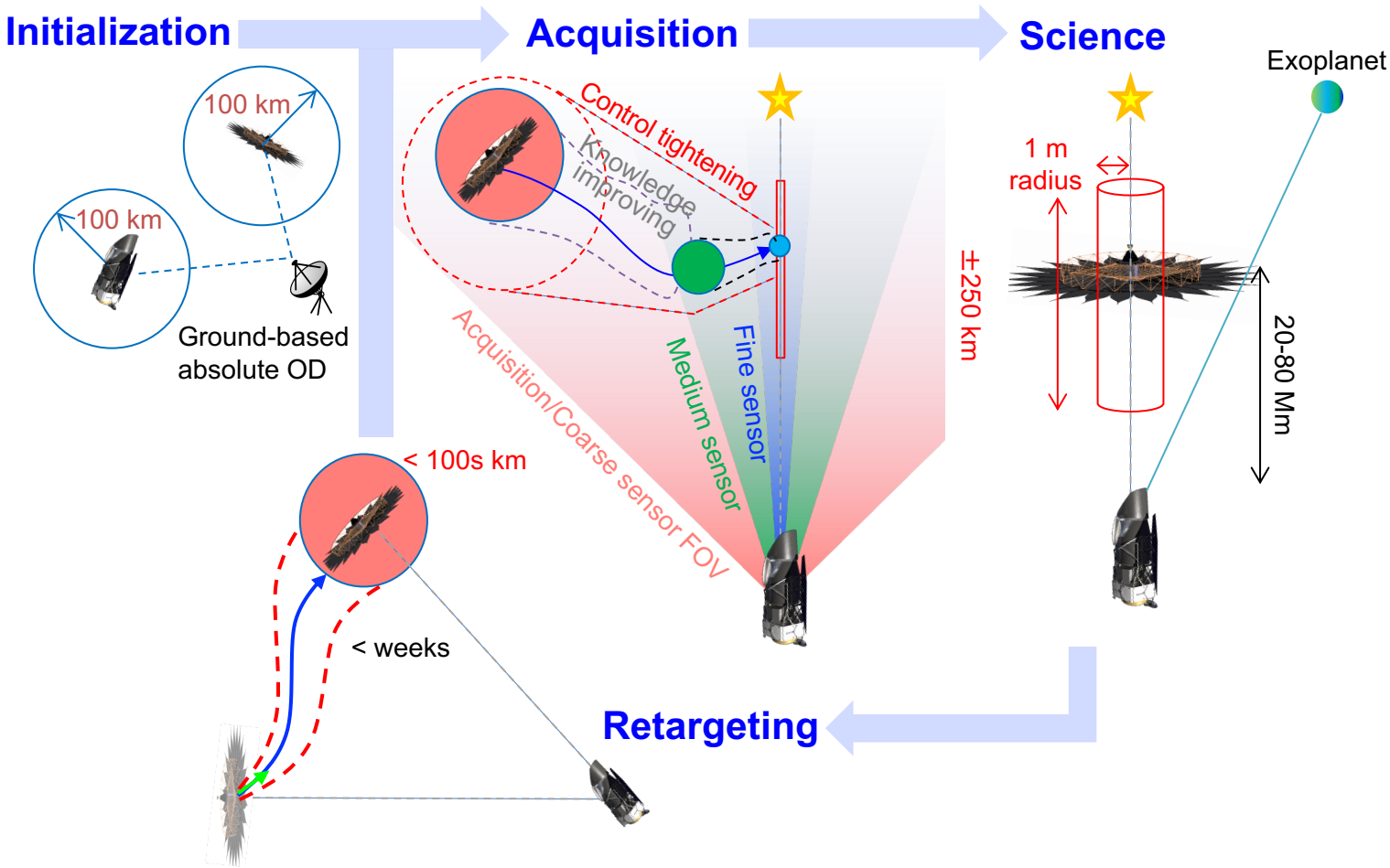
Introduction

Lateral sensing and control during **Science**: only technology challenge

➔ **Aim**: Demonstrate robust, meter-level, lateral formation keeping



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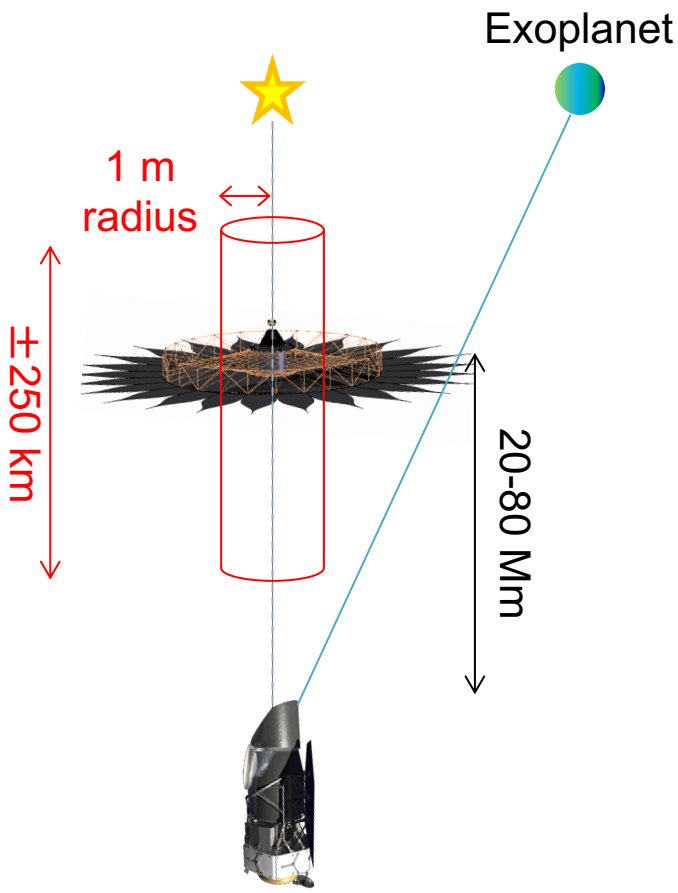

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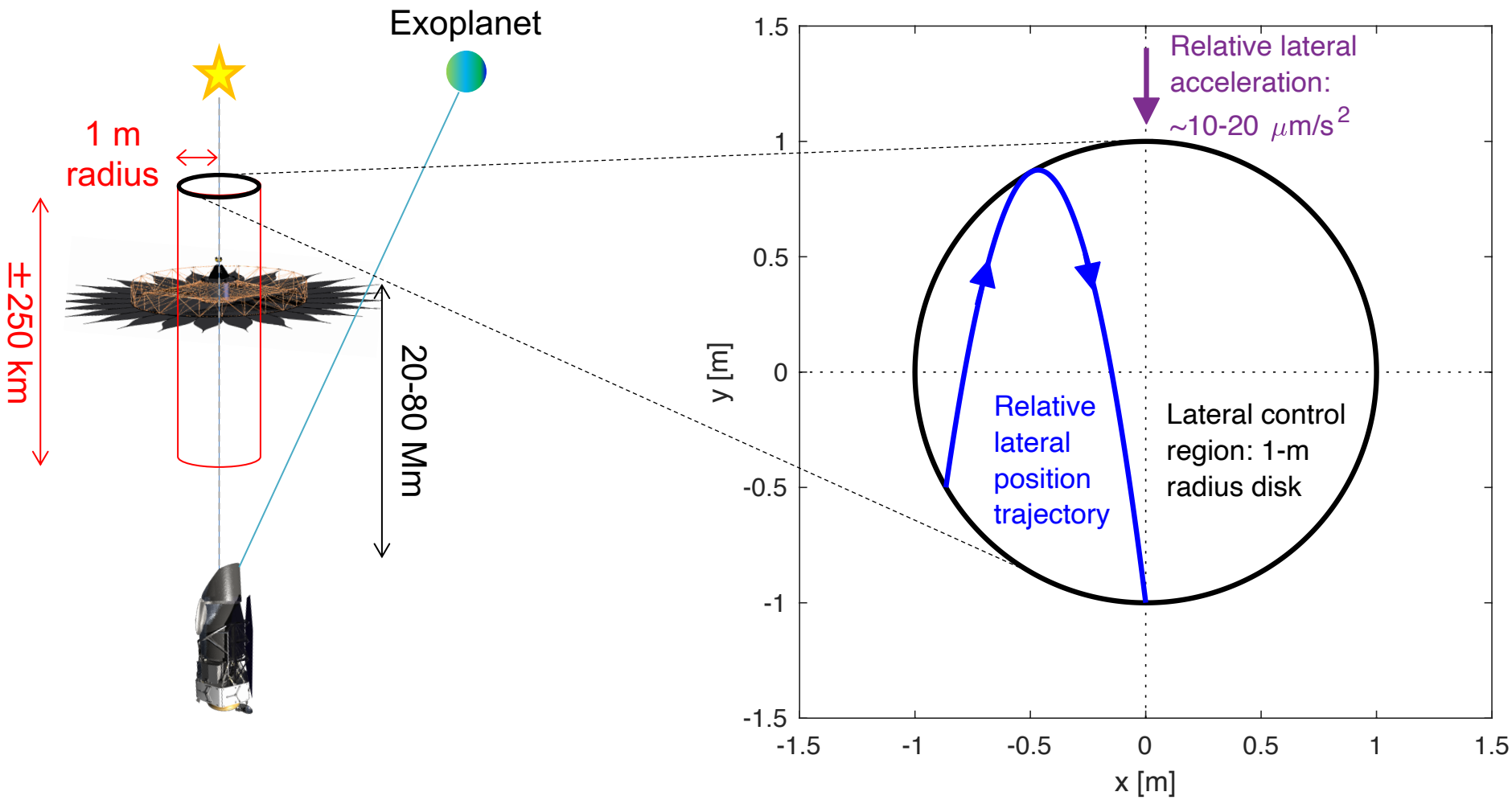

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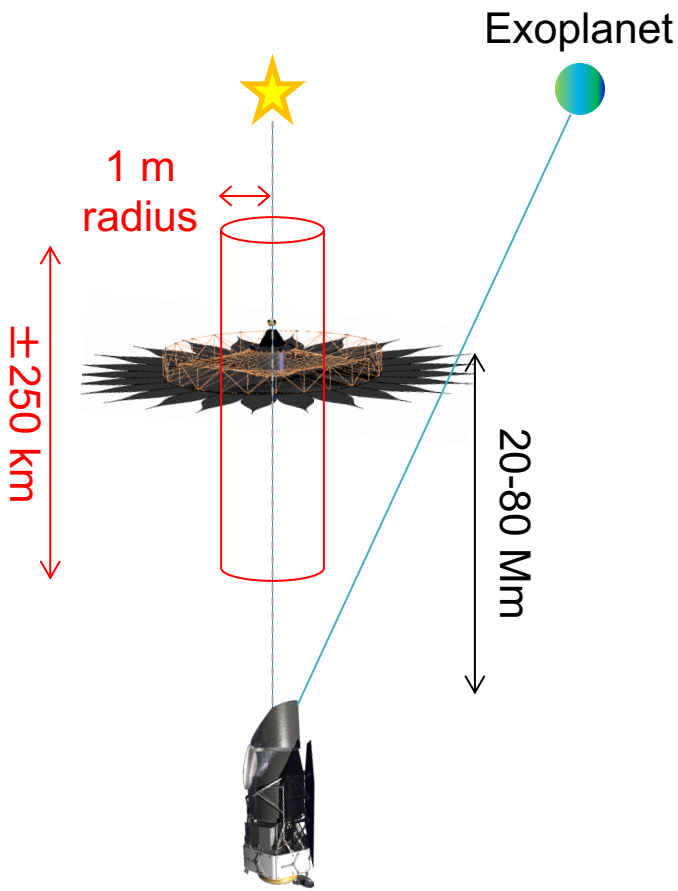

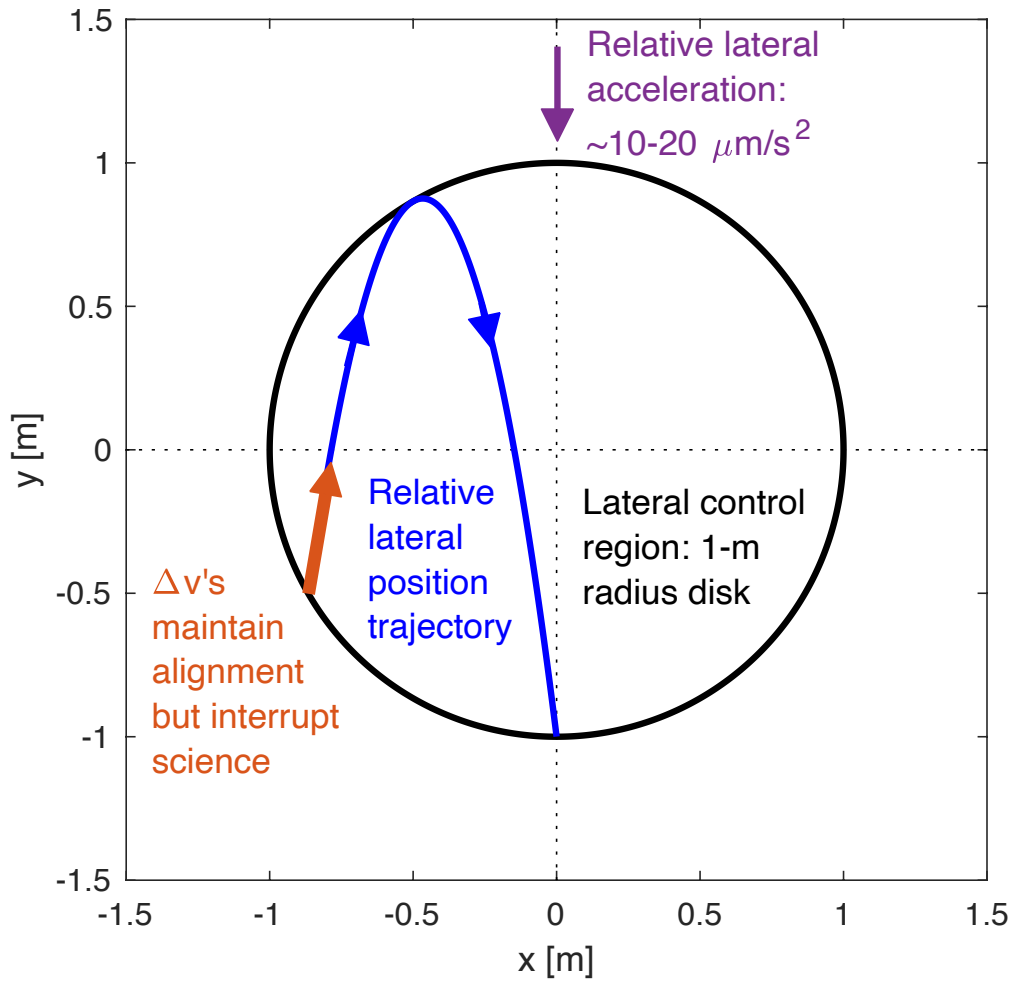

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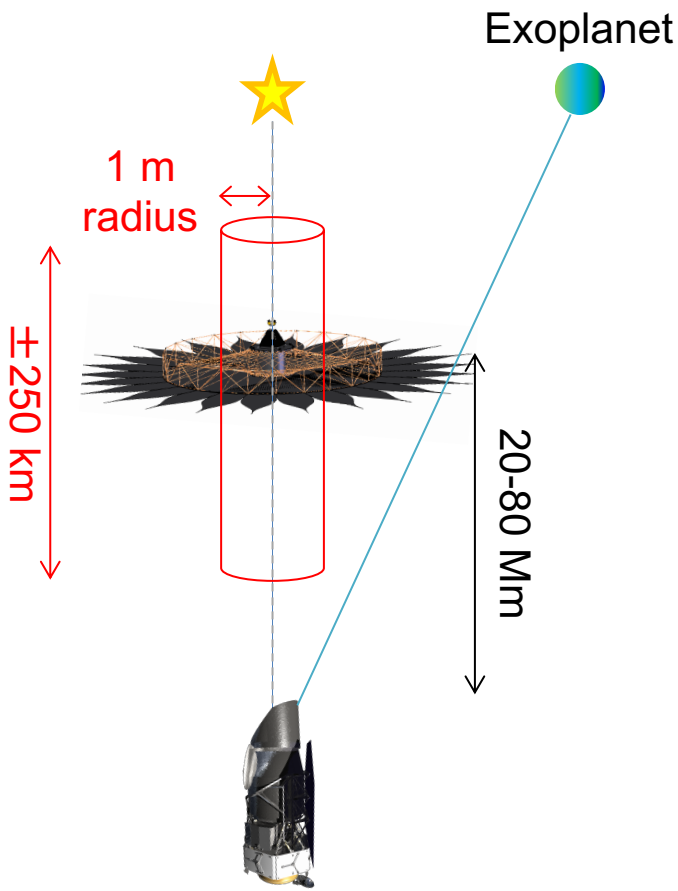

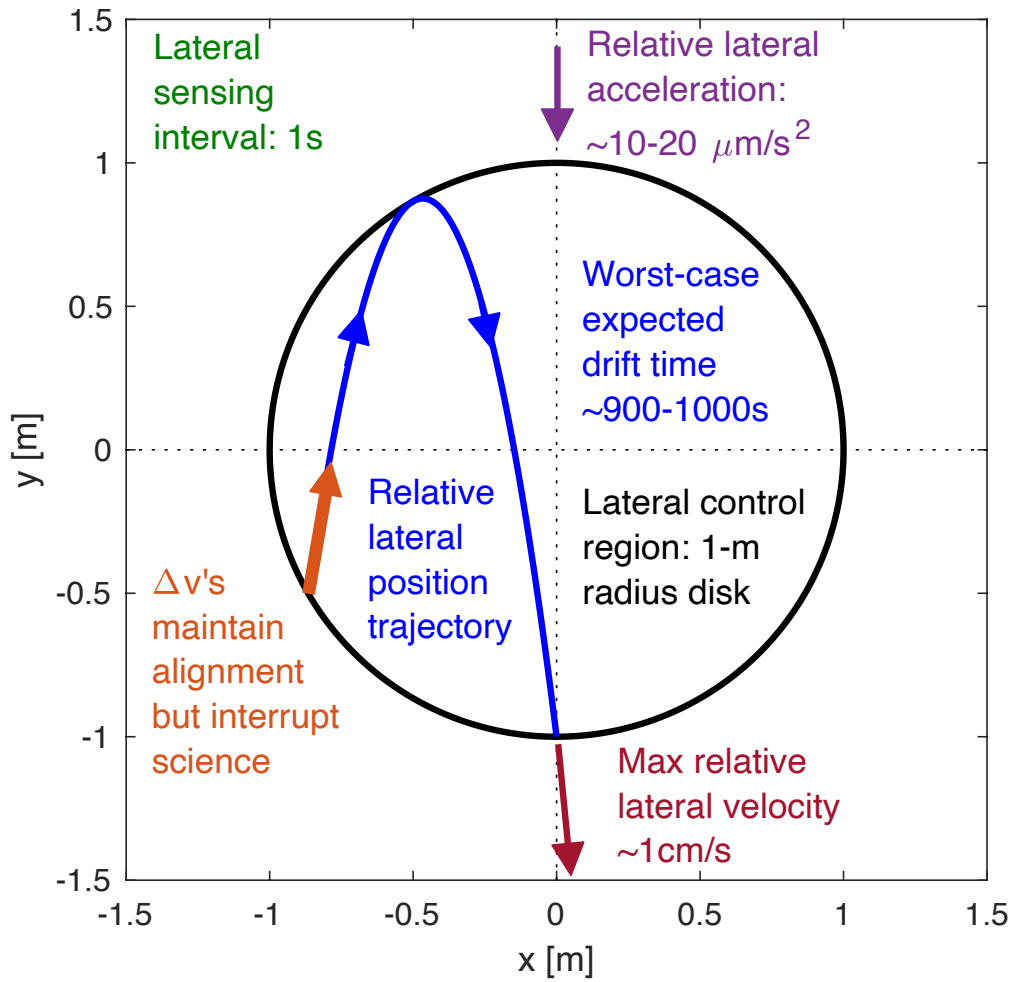

Approach

Incorporate lateral sensor model

- Model based on testbed-validated pupil-plane sensor scheme
- Least-squares matching between measurement and precomputed library

Develop GNC framework

- Robust two-axis circular deadbanding algorithm for lateral control
- Full GNC framework including estimation, control, and thrust allocation

Develop High-fidelity simulation environment

- Representative scenario of starshade flying in formation with WFIRST
- Conservative worst-case assumptions and initial conditions

Run Monte Carlo simulations

- Demonstrate successful control with required accuracy
- Demonstrate effectively optimal observational efficiency

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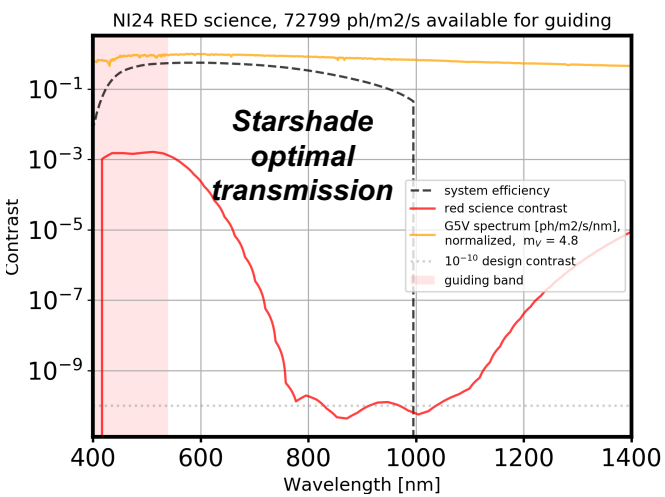
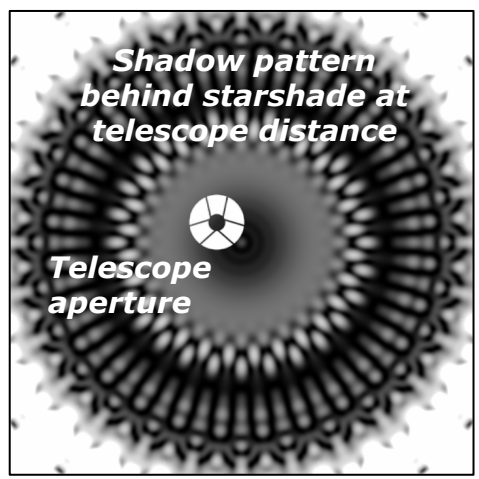
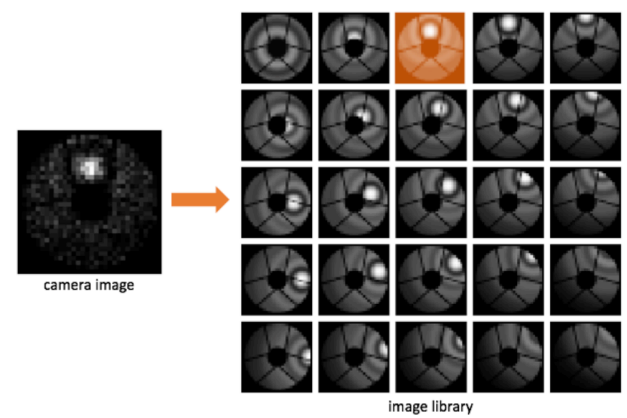
Lateral Sensing Approach

- Starshades designed to create very deep shadow in science band
  - Shadow brightens substantially (factor of ~10^6) outside science band
- Starshades converts flat incident wavefront into complex pattern
  - This pattern encodes positional information
- Pupil plane sensor in telescope images this residual diffracted starlight
  - Precompute grid shadow images corresponding to lateral offsets
  - Can determine relative offset between Starshade and telescope







M. Bottom et al., *Proc. SPIE*, Vol. 10400, 2017

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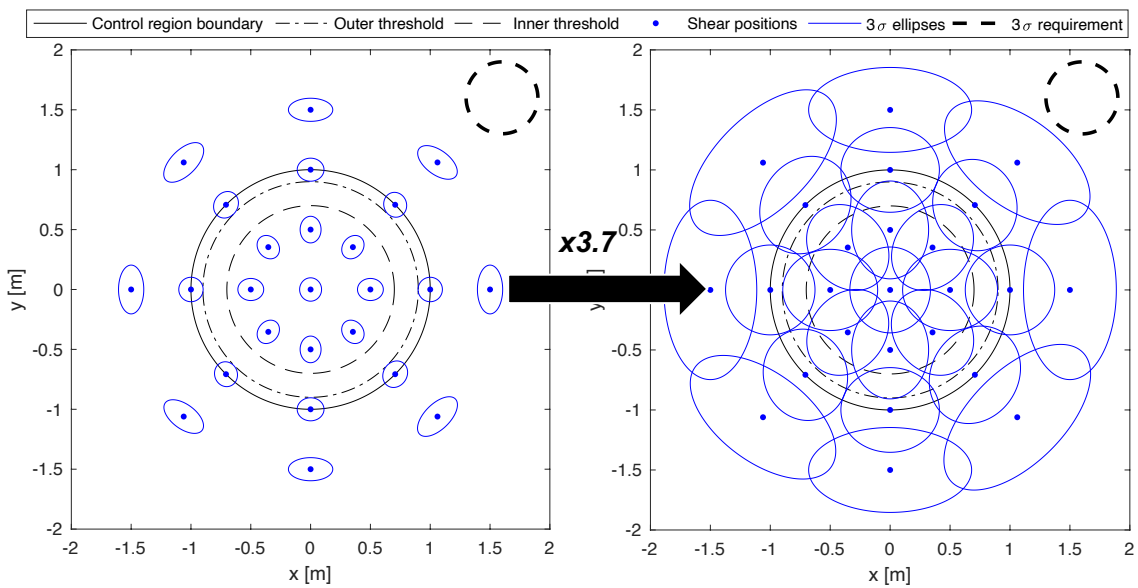
Lateral Sensor Model

- **Validated lateral sensor**
  - Sensor was validated analytically, numerically, and experimentally
  - Well within 30cm requirement for stars 12-75x fainter than faintest target

- **Sensor model for formation flying simulations**
  - Extremely conservative model: error scaled such that always ≥ 30 cm, 3σ
  - Performance depends on lateral position of starshade

Testbed-validated sensor model (stars 12-75x fainter than faintest target)



Extremely conservative model used in formation flying simulations

T. Flinois et al., "S5: Starshade Technology to TRL5 - Milestone 4 Final Report", 2019

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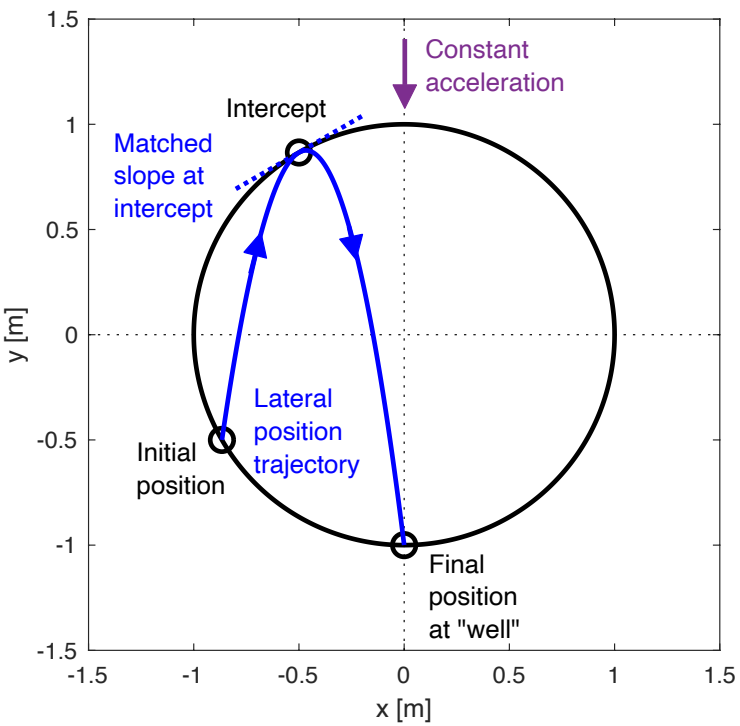
Lateral Control

- Two-dimensional disk-deadbanding algorithm, developed for S5



- Max drift time requires initial position at “well”

➔ **Always seek trajectory that targets well**

- Given initial & final position: maximize drift time

➔ **Intercept point tangent to boundary**

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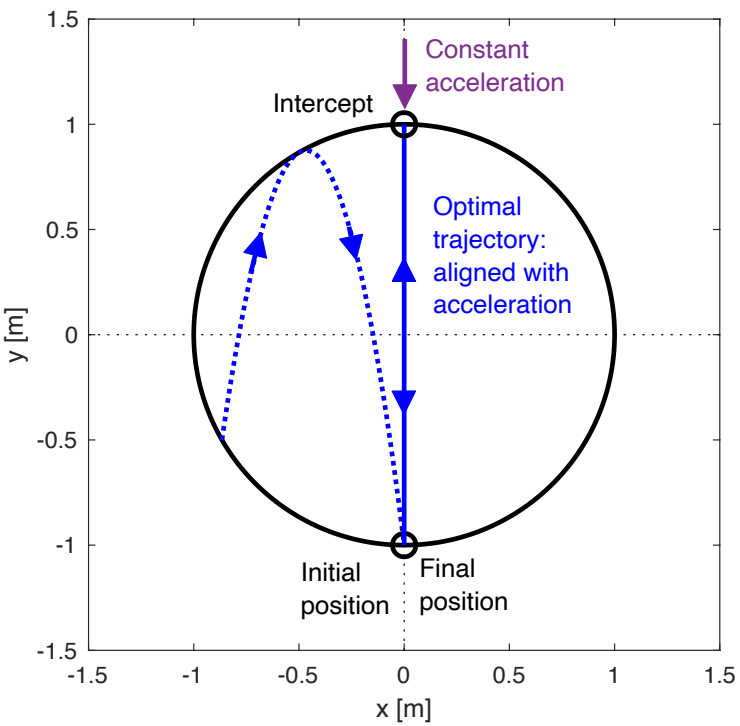
Lateral Control

- Two-dimensional disk-deadbanding algorithm, developed for S5
- Provides effectively optimal observational efficiency (max drift time)



- Naturally converges to globally optimal trajectory
- Only requires a single algorithm
- No nonlinear switching required

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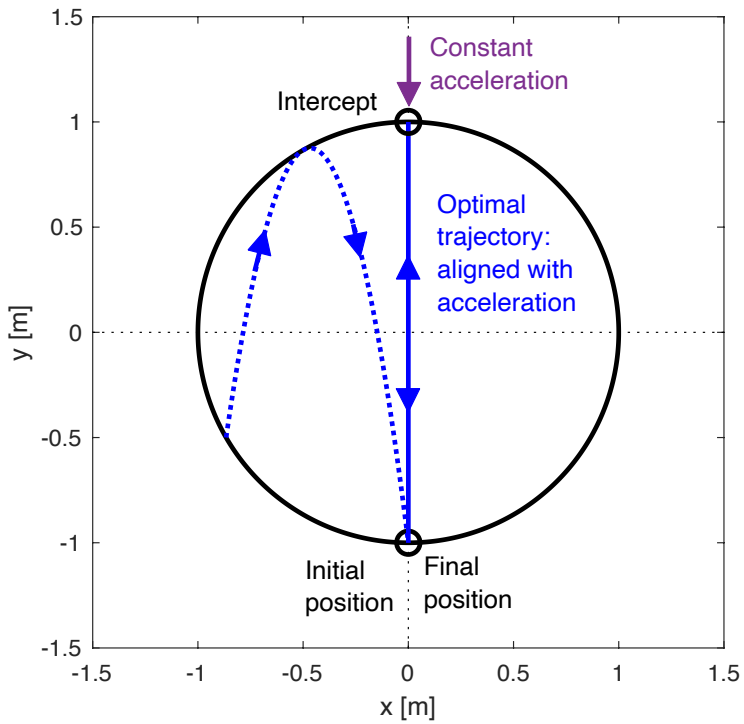
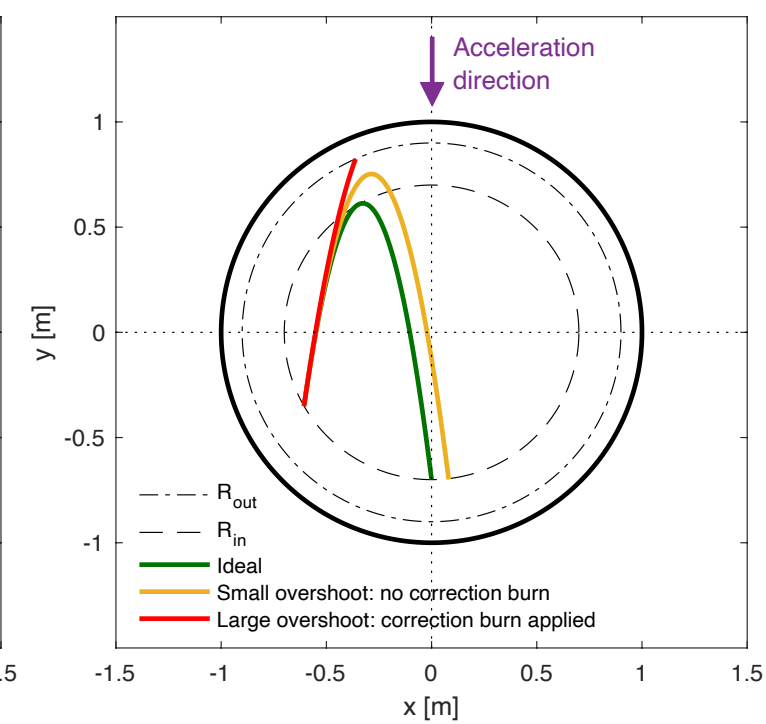
Lateral Control

- Two-dimensional disk-deadbanding algorithm, developed for S5
- Provides effectively optimal observational efficiency (max drift time)
- Double threshold approach: allows small overshoots





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Lateral Control

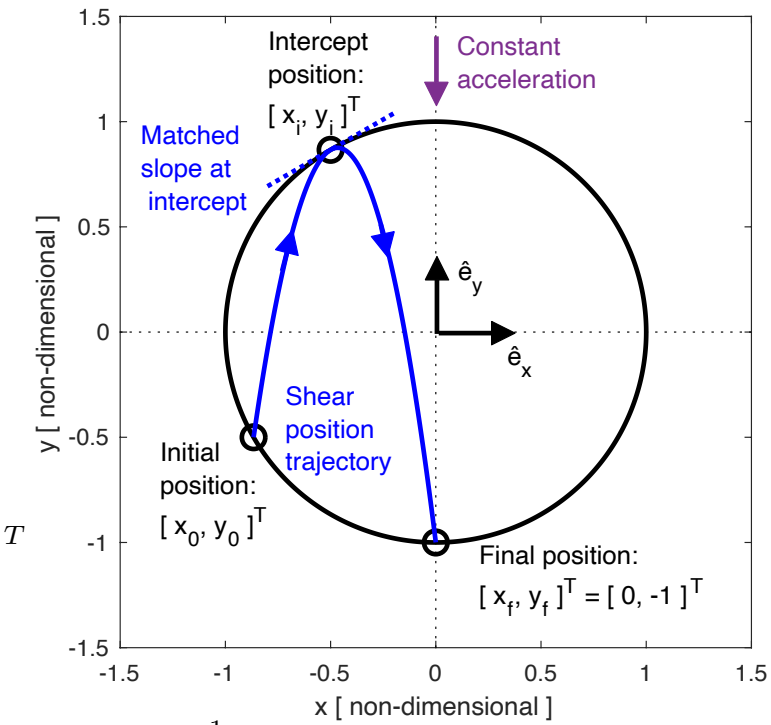
- **Nondimensionalize:**
  - Lengths / R_d (circle radius)
  - Velocities / $\sqrt{aR_d}$
  - Time / $\sqrt{R_d/a}$

- **Dynamics:**
  - Velocity: $[u(t), v(t)]^T = [u_0, -t + v_0]^T$
  - Position: $[x(t), y(t)]^T = \left[u_0 t + x_0, -t^2/2 + v_0 t + y_0\right]^T$

- **Trajectory:**
  - Intercept: $[x_i, y_i]^T = \begin{cases} [x_0, y_0]^T, & \text{for } y_0 > \frac{1}{2} \\ \frac{1}{\sqrt{2}}\left[-\sqrt{1+y_0}, \quad \sqrt{1-y_0}\right]^T, & \text{for } y_0 < \frac{1}{2} \end{cases}$
  - Initial velocity: $\boxed{[u_0, v_0]^T = \left[\frac{1}{\sqrt{2}}\sqrt{y_i\,(1-y_i)}, \quad v_i + t_i\right]^T}$

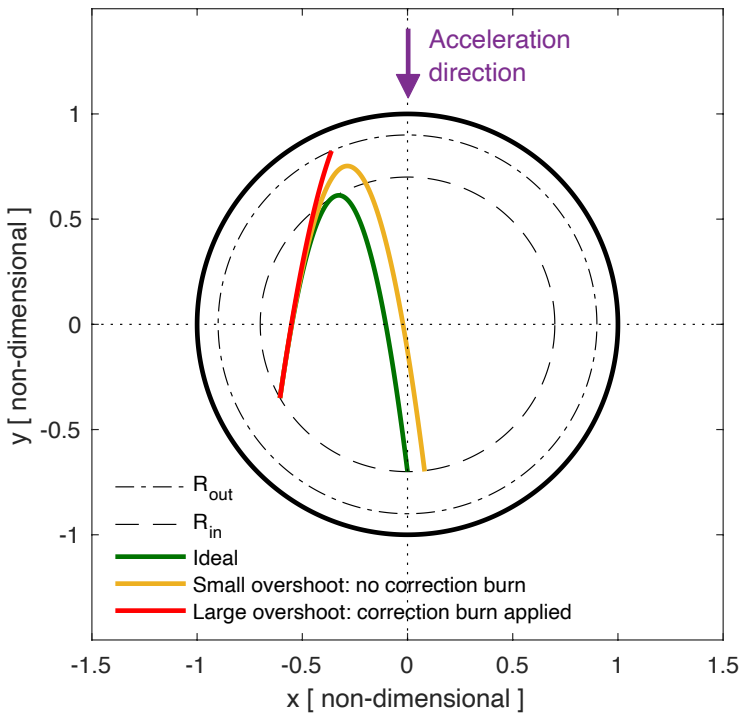
where: $v_i = -u_0 x_i / y_i$

$t_i = (x_i - x_0)/u_0$



Lateral Control

- **Outer threshold criteria:**
  - $\|\hat{\mathbf{r}}\| > R_{\text{out}}$ → Out of circle
  - $\hat{\mathbf{r}} \cdot \hat{\mathbf{v}} > 0$ → Getting further out
- **Inner threshold:**
  - $\|\hat{\mathbf{r}}\| > R_{\text{in}}$ → Out of circle
  - $\hat{\mathbf{r}} \cdot \hat{\mathbf{v}} > 0$ → Getting further out
  - $\hat{\mathbf{r}} \cdot \hat{\mathbf{a}} > 0.$ → In "bottom" half of circle



Remaining GNC algorithms

- **Estimation**
  - 3DOF relative position, velocity, acceleration
  - Constant acceleration model, justified at deadbanding timescales
  - No measurement during burns (burn time <1s)
  - Burns modelled as process uncertainties (different Q matrix)

- **Longitudinal control**
  - Not required in most cases due to loose control requirement (±250km)
  - Implemented “rate damping” if required: slows drift towards boundary edge

- **Thrust Allocation**
  - QPCAP 6DOF thrust allocation algorithm used
  - Developed at JPL, flight-proven e.g. used on Mars Science Laboratory
  - Assumes (constant) attitude during burns despite spin and thruster delay

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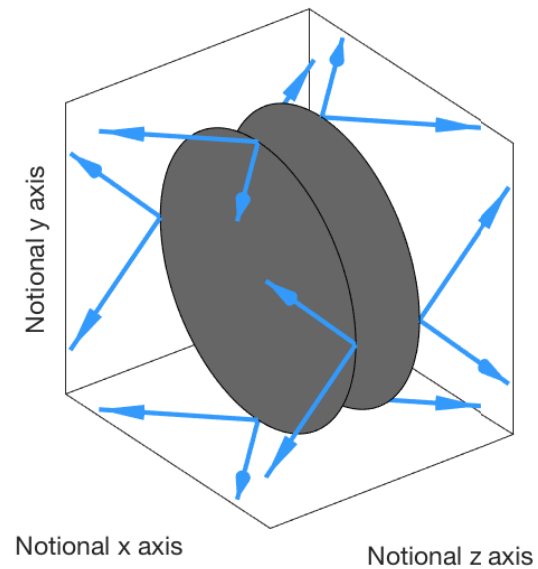
High-fidelity environment

- **Orbital dynamics** of starshade and telescope
  - Sun, Earth, Moon, solar system planets, solar radiation pressure (SRP) (JPL SPICE library)
  - Validated with JPL high-fidelity mission design tool (JPL MONTE)

- **Prescribed attitude** of starshade
  - Expected worst-case attitude motion prescribed
  - Spinning and precessing with spin axis at 1° offset from line of sight
  - Affects thrust allocation and SRP force

- **Thruster models**
  - 16-thruster configuration
  - Models based on flight-qualified bipropellant 22N thrusters
  - Conservative thruster execution errors and delays



Thruster configuration

- **Sensor models**
  - Extremely conservative lateral sensor already introduced
  - Longitudinal sensor based on S-band ranging with ±500m 3σ accuracy

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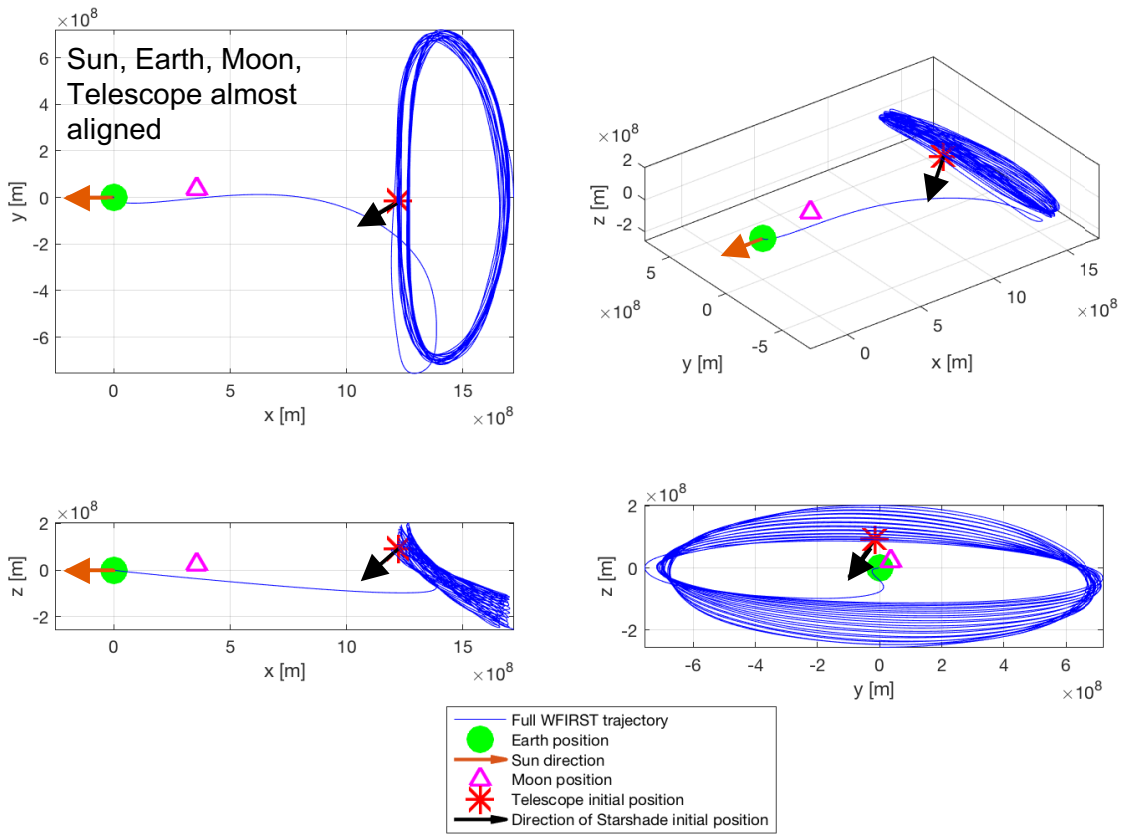
Initial conditions

- Maximize relative lateral acceleration
- **Earth gravity:** driving influence for *relative* dynamics
- **Worst-case formation geometry:**
  - Closest to Earth/Sun
  - Max starshade-telescope range
  - Formation "Earth angle" for max disturbance: 40° -45°



WFIRST representative Lissajous orbit at Earth-Sun L2 and ignition conditions used for simulations

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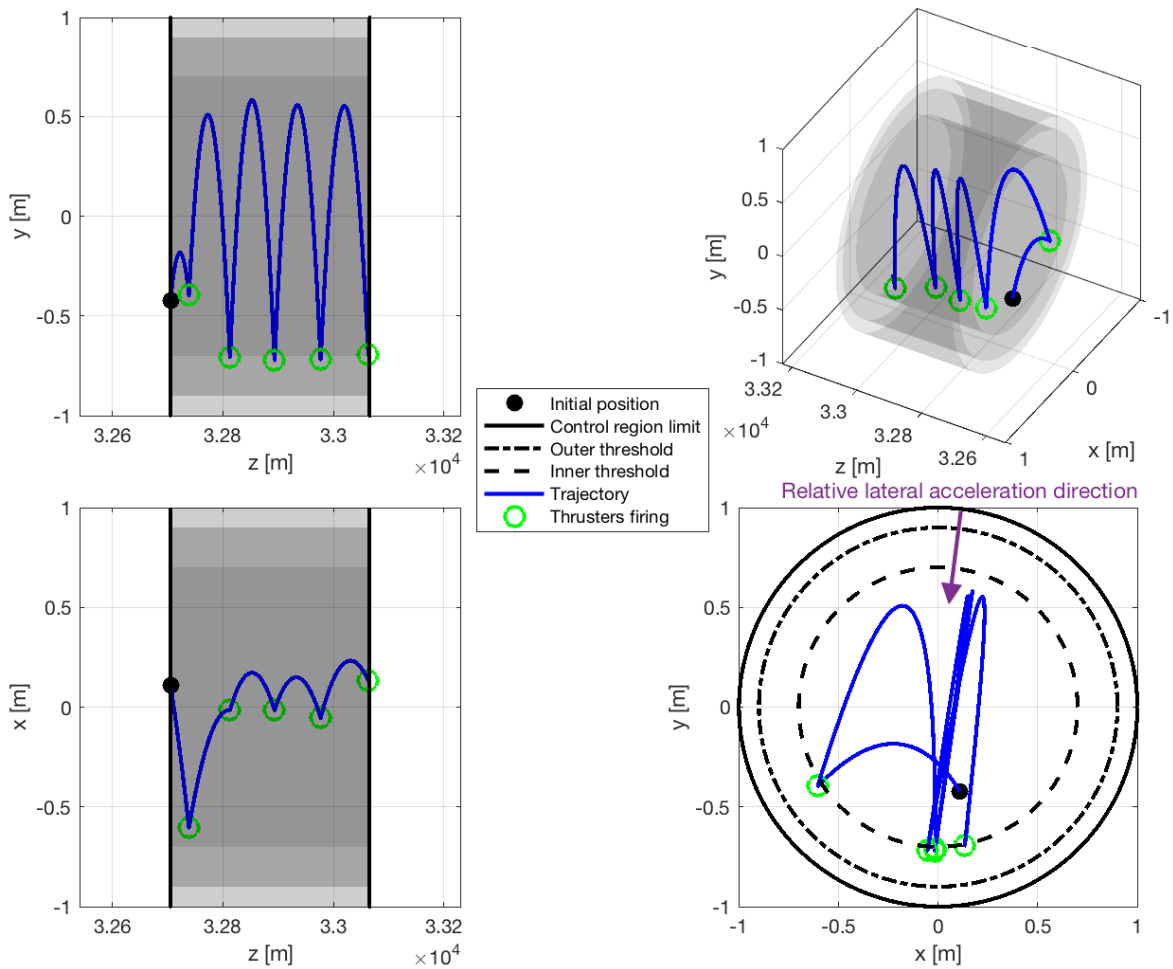
Monte Carlo simulations

Control requirements met for all simulations:

➔ 1-m radius lateral

➔ ±250 km longitudinal



Typical formation flying trajectory over a one hour period

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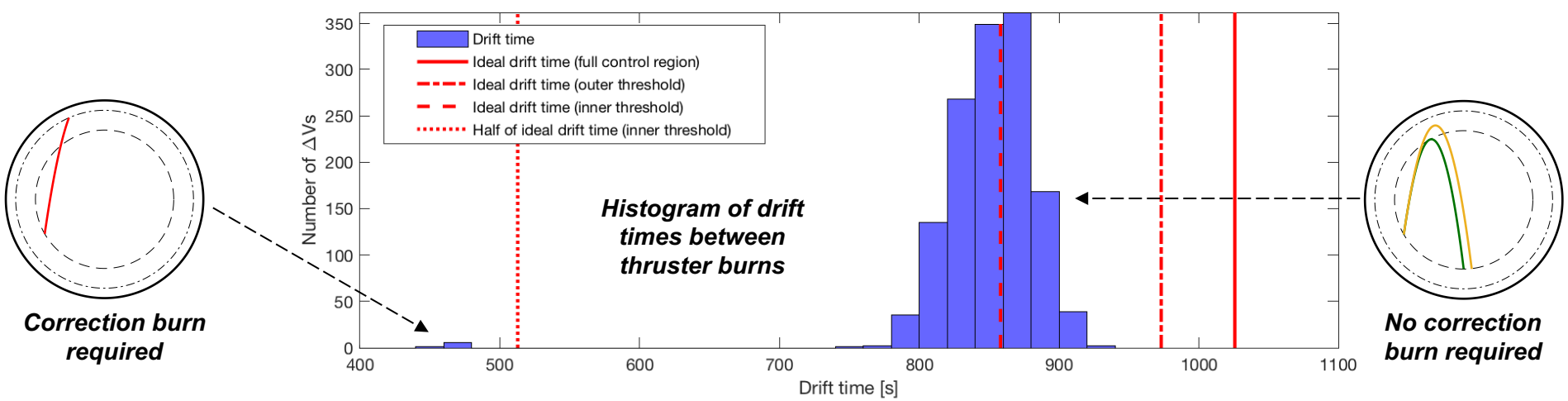
Monte Carlo simulations

- **Effectively optimal drift time**
  - Mean drift time ~ ideal given relative acceleration and control tuning
- **High observational efficiency**
  - Mean drift time for worst-case disturbance ~ 850s (science frames 10-100s)
- **Threshold sizing → Compromise between:**
  - Nominal drift time
  - Risk of correction burn



Conclusions

- **Developed GNC framework for starshade formation keeping at L2**
  - Includes testbed validated pupil-plane image-matching fine lateral sensor
  - Includes circular deadbanding algorithm: maintains starshade in 1-m circle

- **Showed robustness and essentially optimal observational efficiency**
  - Stressing lateral acceleration for WFIRST starshade rendezvous scenario
  - High-fidelity simulation environment
  - Conservative assumptions throughout

BACKUP

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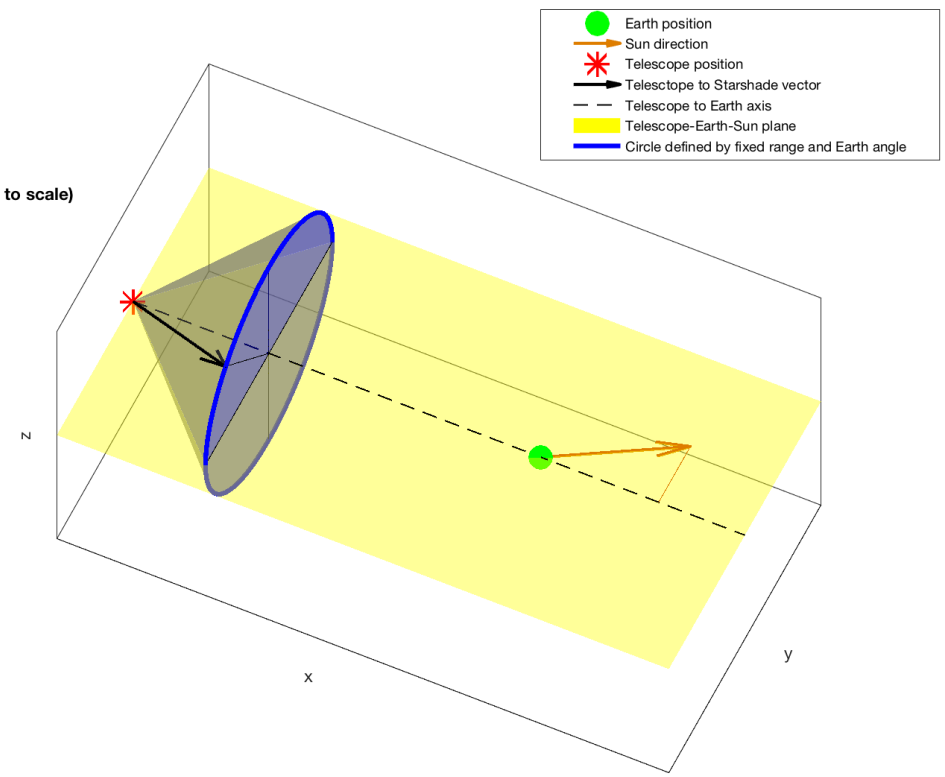
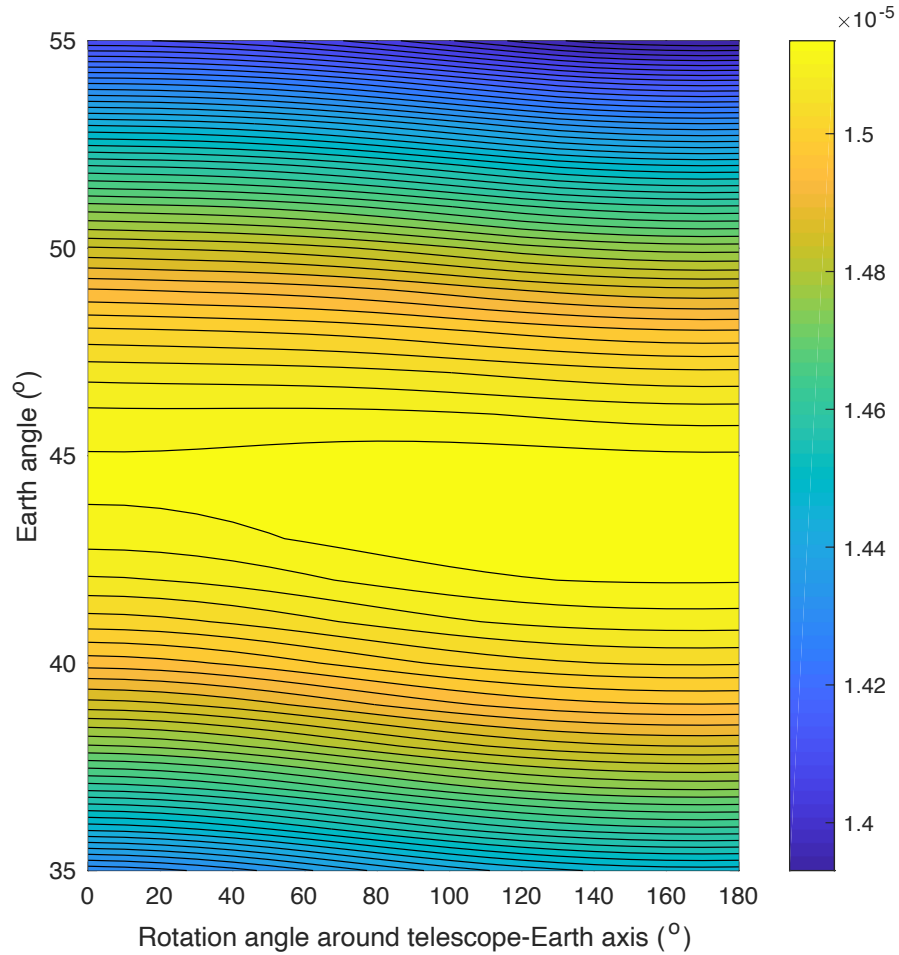
Initial conditions

(Not to scale)





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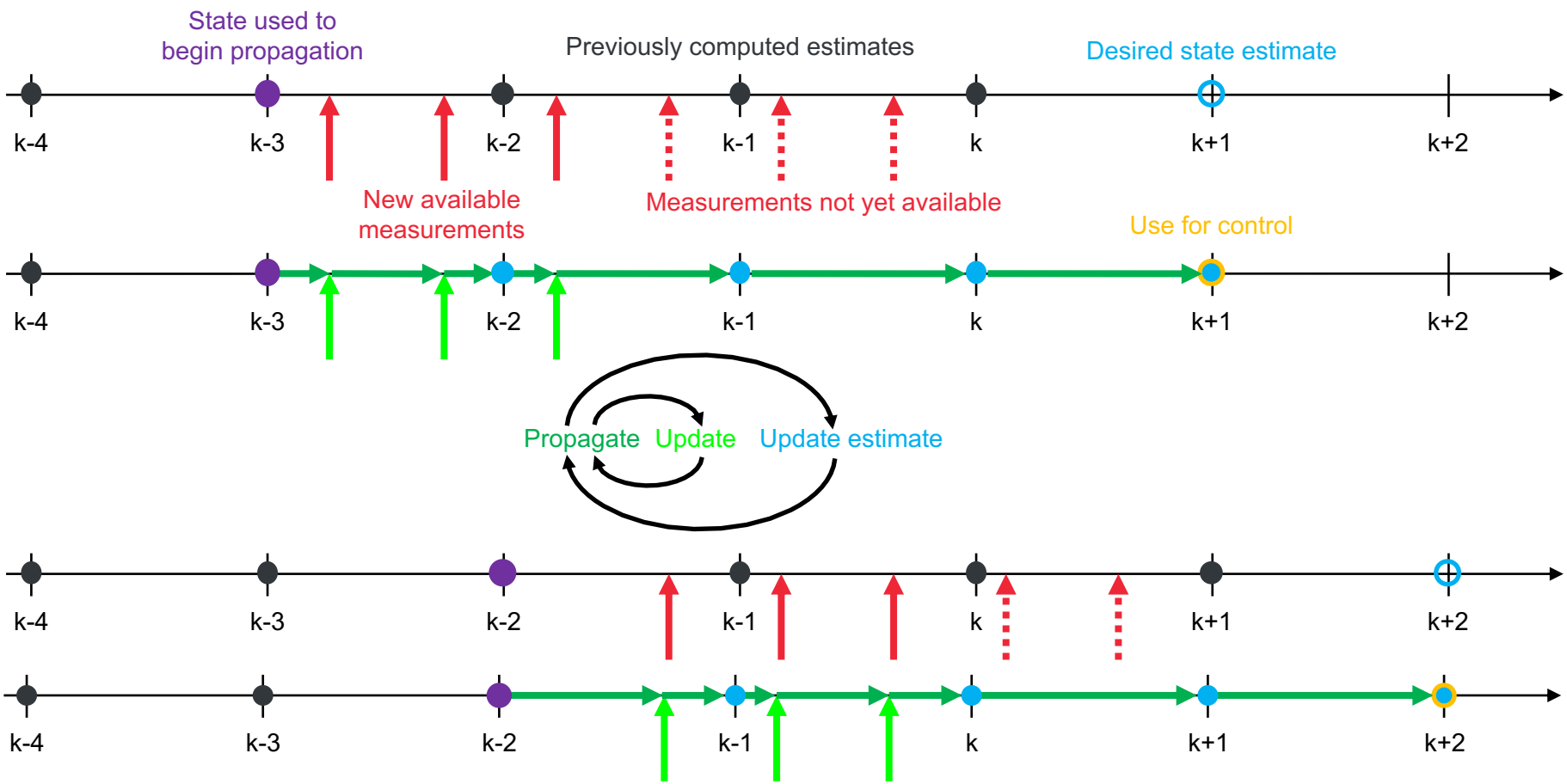
Estimation



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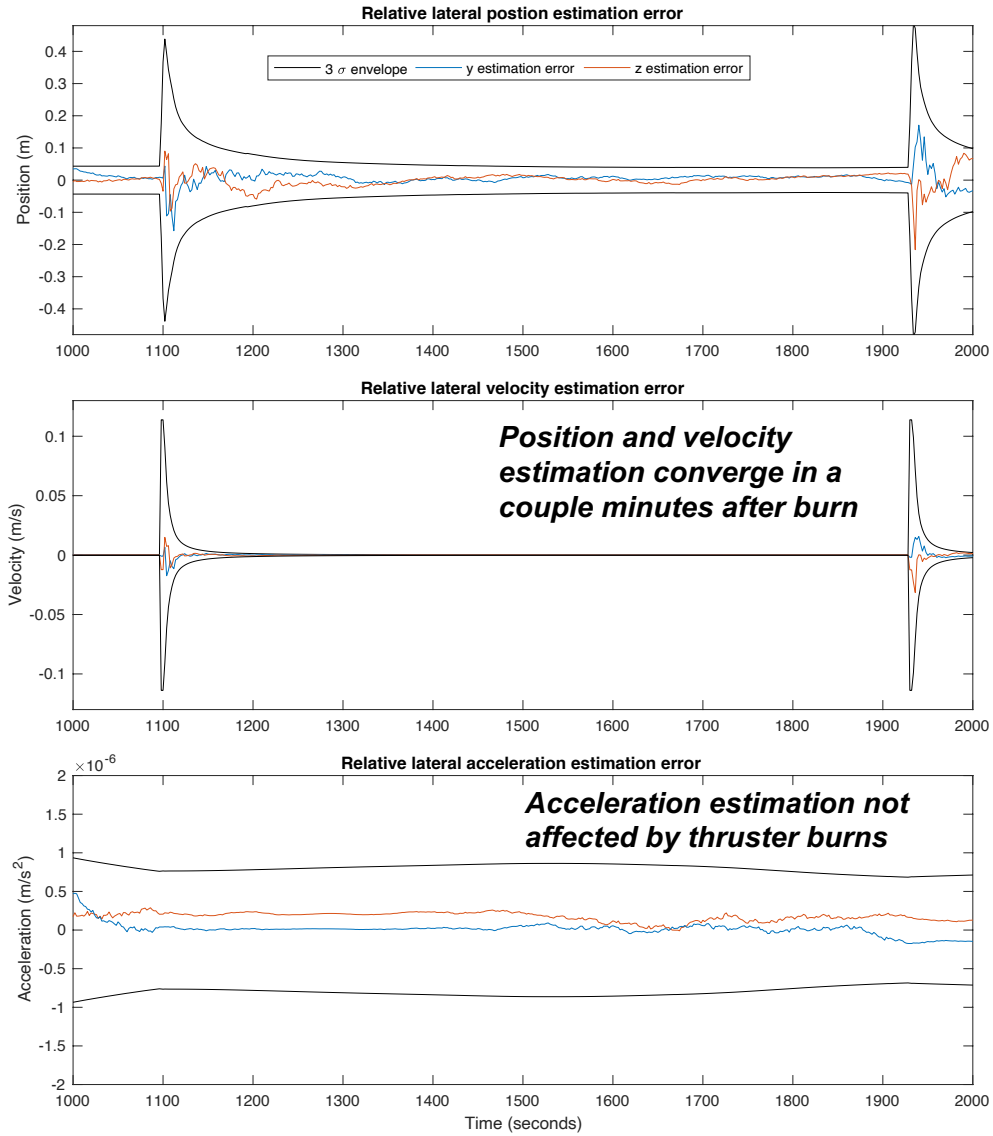
Estimation

- Estimation of 3DOF relative **position, velocity, acceleration**
- Kalman filter: **constant acceleration model,** justified at deadbanding timescales
- **No measurement during burns** (burn time <1s)
- Burns modelled as **process uncertainties** (different Q matrix)



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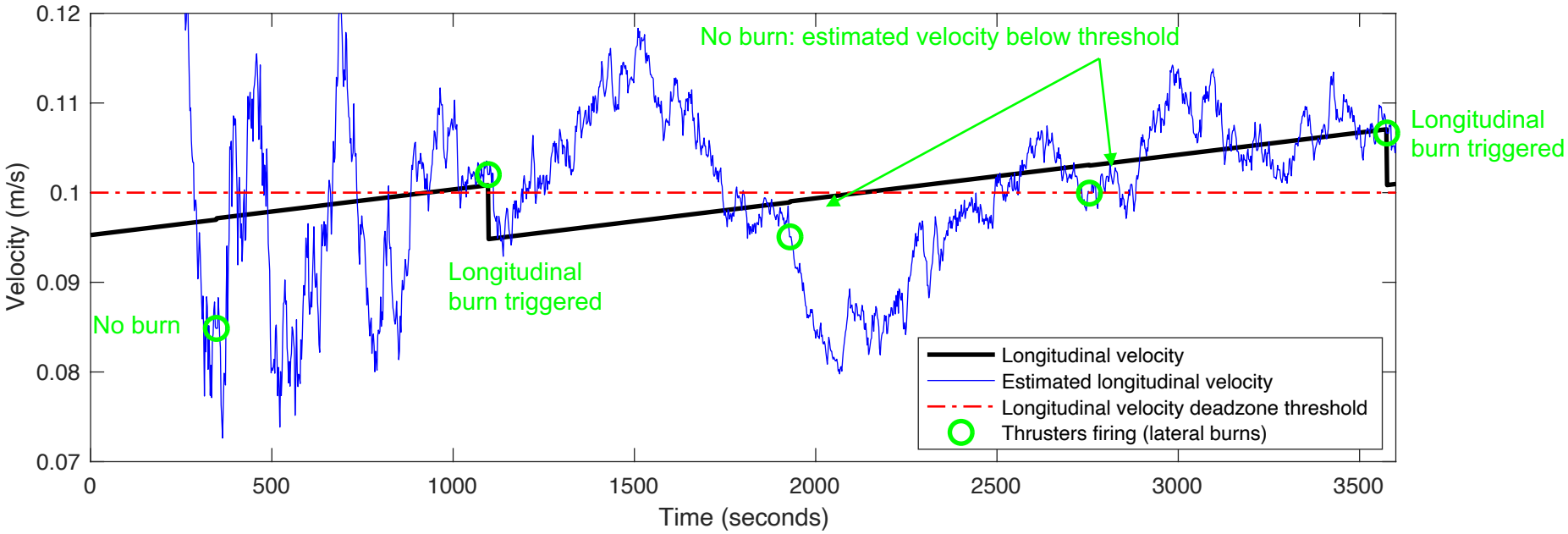
Longitudinal control

- **Not required in most cases** due to loose control requirement (±250km)

- Control strategy: "**rate damping**"
  - **Synchronize longitudinal burns**: maintain high observational efficiency
  - Only trigger burn above threshold (0.1 m/s)
  - Cap maximum magnitude of longitudinal burn (50% of lateral burn)



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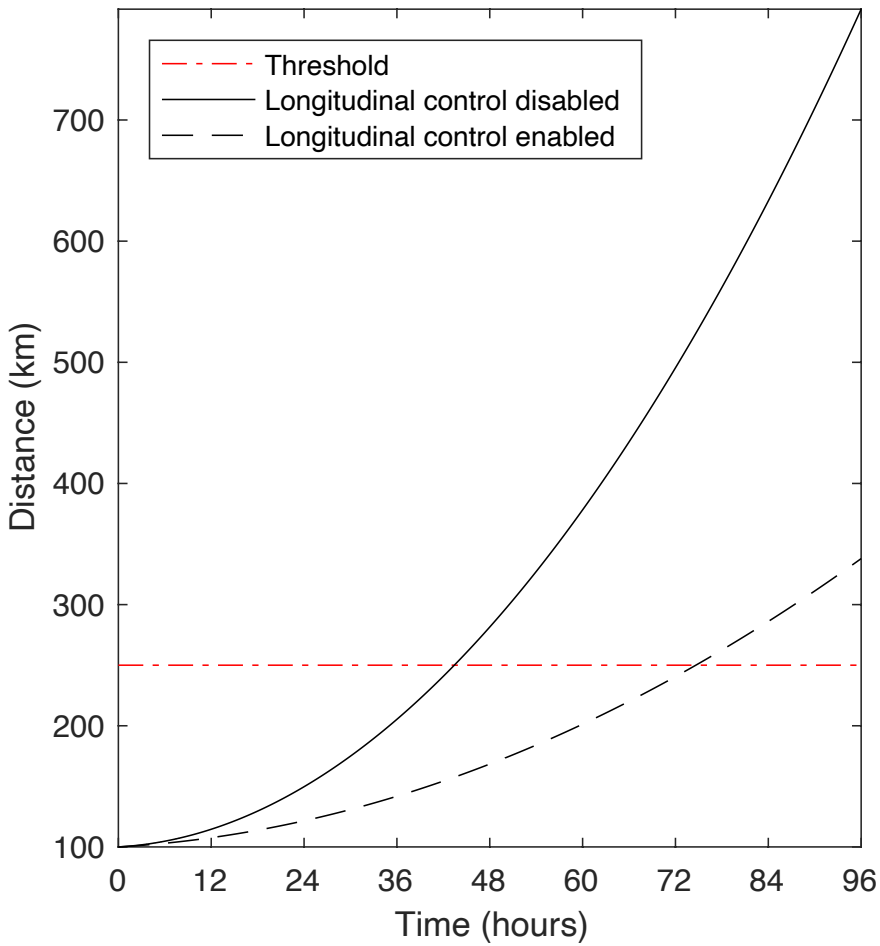
Longitudinal control

- **Longitudinal burn conditions:**
  - Synchronized with lateral burns
  - Only triggered above 0.1m/s relative velocity
  - Never larger than 50% of corresponding lateral burn

- **Conservative example:**
  - Initial error: 100km in acceleration direction
  - Initial velocity error: 0.1m/s in acceleration dir.
  - Longitudinal and lateral accelerations comparable (11um/s vs 15.2um/s)



➔ **Increase drift time by 30h or 72%**

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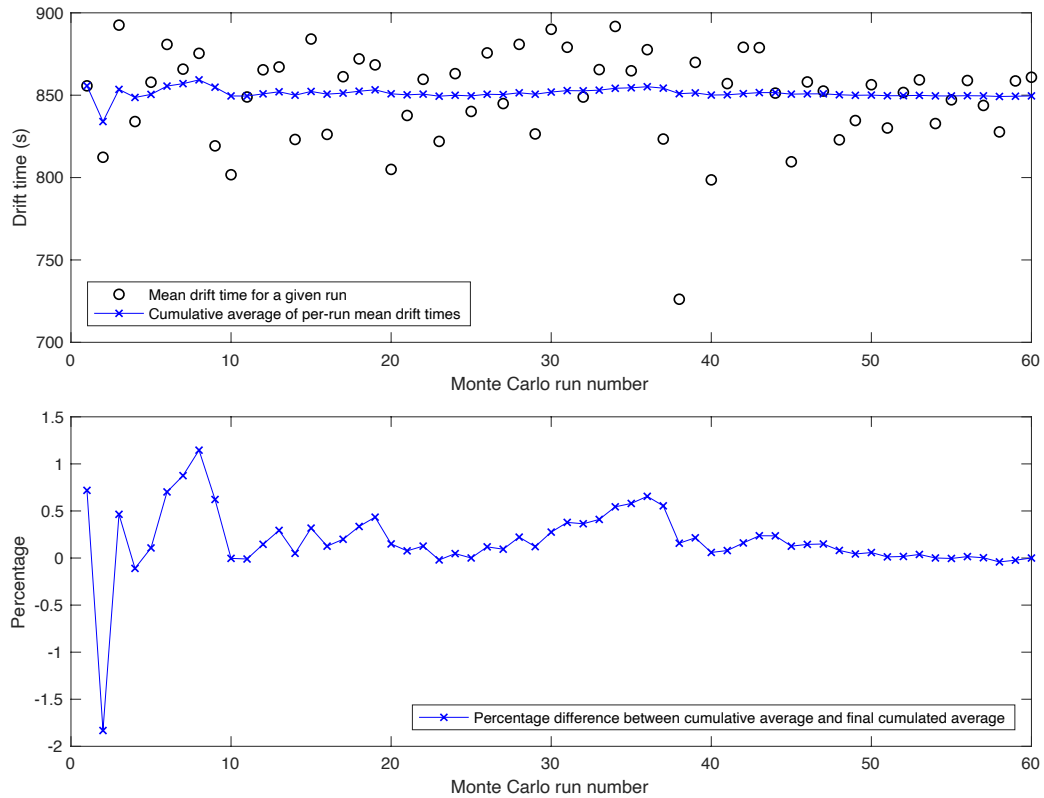
Monte Carlo simulations

- **60 simulations of 6h each**

➔ Converged statistics
  - Within each Monte Carlo
  - For full set of simulations

- **Variation within each run:**
  - Individual burn errors
  - Individual measurement errors

- **Variation from run to run:**
  - Biases (mass uncertainty, thruster biases, clock drift rates, etc.)
  - Initial conditions in state and estimation



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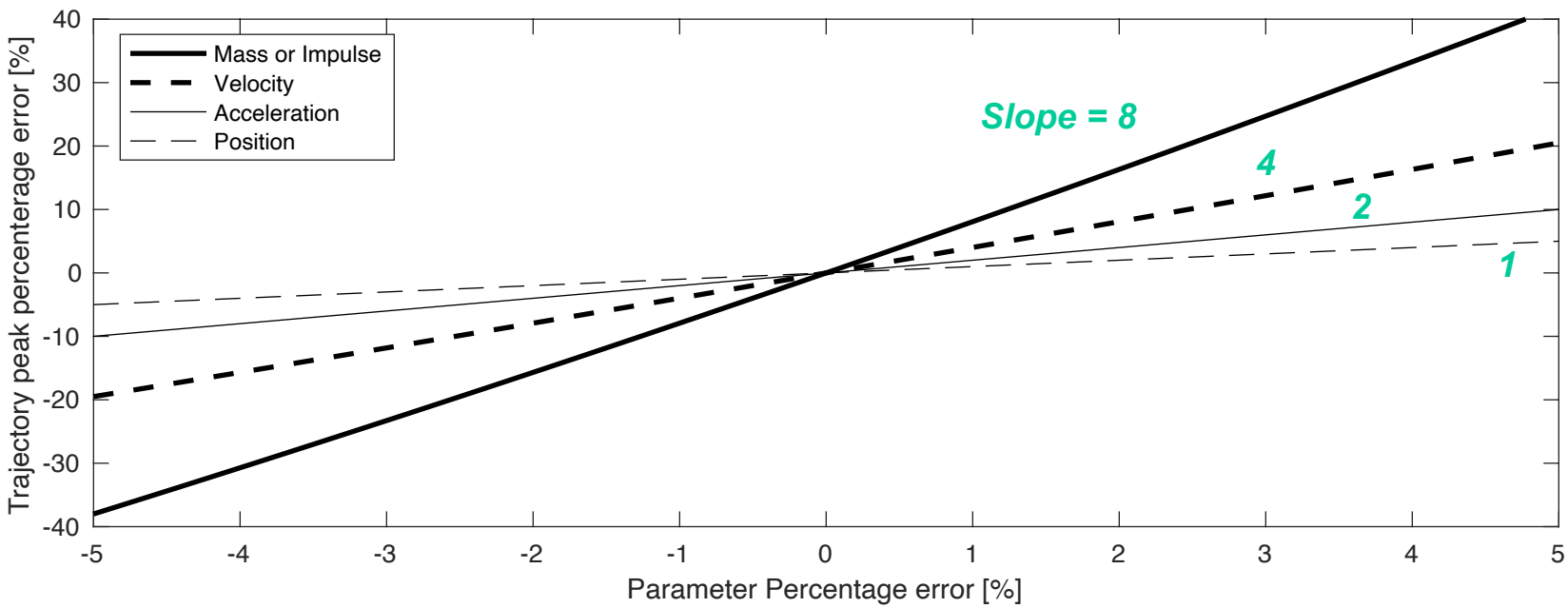
Error sensitivity analysis

- Driving error sources: mass estimation error, Δv realization error
- Δv error due to individual thrusters averages out

➔ **<u>mass estimation driving error source</u>**



Formation flying parameters

Parameter	Known/ Unknown on board	Value	Units
Time			
Single Monte Carlo run final time	N/A	6	h
SPICE ephemeris time step	N/A	360	s
Attitude dynamics time step	N/A	0.5	s
Attitude control time step	Known	0.5	s
Position dynamics time step	N/A	1	s
Position control time step	Known	1	s
Spacecraft physical properties			
Starshade spacecraft dry mass	Known	1200	kg
Starshade propellant mass	Known	100	kg
Propellant mass uncertainty (3σ)	Unknown	50	kg
Starshade hub diameter	Known	10	m
Starshade petal area (24 petals)	Known	10.66	m^2
Starshade surface absorptivity	Known	92	%
Starshade surface specular reflectivity	Known	4	%
Starshade surface diffusive reflectivity	Known	4	%
X principal moment of inertia	Known	42390	$kg.m^2$
Y principal moment of inertia	Known	21289	$kg.m^2$
Z principal moment of inertia	Known	21289	$kg.m^2$

Kept constant within a given Monte Carlo run but varies from run to run

Varies during each simulation

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Formation flying parameters

Parameter	Known/ Unknown on board	Value	Units
Actuator models			
Nominal angle of thruster to Starshade spin axis	Known	45	°
Nominal individual thruster force	Known	22	N
Individual thruster thrust magnitude bias (3σ)	Known	1	%
Individual thruster thrust angle bias (3σ)	Known	1	°
Individual thruster thrust magnitude bias (3σ)	Unknown	2	%
Individual thruster thrust angle bias (3σ)	Unknown	0.75	°
Individual thruster thrust magnitude variation (each burn) (3σ)	Unknown	1	%
Individual thruster thrust angle variation (each burn) (3σ)	Unknown	0.1	°
Thruster minimum on time real value	Unknown	5	ms
Thruster minimum on time assumed on board	Known	5.25	ms
Thruster on-time quantization	Known	0.5	ms
Delay between command and start of thrust assumed on board	Known	1	s
Variation in delay between command and start of thrust (3σ)	Unknown	50	ms
Sensor models			
Best shear measurement accuracy across all shear positions (3σ)	Known	0.3	m
Range measurement accuracy (3σ)	Known	±500	m
Attitude measurement accuracy (3σ)	Known	20	arcsec
Angular rate measurement accuracy (3σ)	Known	0.01	°/s
Nominal shear/range measurement sample time	Known	1	s
Shear/range measurement average sample time uncertainty (3σ)	Unknown	10	ms
Shear/range measurement sample time noise (3σ)	Unknown	3	ms
Shear/range measurement time-tagging uncertainty (3σ)	Unknown	100	ms
Shear/range measurement systematic delay	Unknown	1	s

Kept constant within a given Monte Carlo run but varies from run to run

Varies during each simulation

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Formation flying parameters

Parameter	Known/ Unknown on board	Value	Units
Position control			
Longitudinal Δv magnitude cap	Known	50	% of lateral Δv
Longitudinal Δv deadzone	Known	[-0.1 , 0.1]	m/s
Full longitundinal control region	Known	±250	km
Lateral control region radius	Known	1	m
Lateral control region threshold radii	Known	[0.7 , 0.9]	m
Estimation			
Initial acceleration uncertainty per axis (3σ)	Known	3	$\mu m/s^2$
Initial longitudinal velocity estimation uncertainty (3σ)	Known	0.2	m/s
Initial lateral velocity estimation uncertainty per axis (3σ)	Known	0.3	mm/s
Initial longitudinal position estimation uncertainty (3σ)	Known	500	m
Initial lateral position estiamtion uncertainty per axis (3σ)	Known	0.3	m
Position dynamics			
Telescope - Starshade nominal distance	Unknown	38.8	Mm
Earth - Telescope - Starshade nominal angle	Unknown	43.5	°
Initial longitudinal velocity uncertainty (3σ)	Unknown	0.2	m/s
Initial lateral velocity uncertainty per axis (3σ)	Unknown	7.5	mm/s
Initial longitudinal position uncertainty (3σ)	Unknown	150	km
Initial lateral position uncertainty per axis (3σ)	Unknown	0.7	m
Attitude dynamics			
Starshade spin rate	Unknown	2	°/s
Starshade spin axis offset from Starshade-telescope axis	Unknown	1	°
Starshade axis precession rate	Unknown	~ 4	°/s

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