National Aeronautics and Space Administration

S5: Starshade technology to TRL5

Milestone 4 : Lateral formation sensing & control

Thibault Flinois, Michael Bottom, Stefan Martin, Daniel Scharf, Megan Davis, Stuart Shaklan
Jet Propulsion Laboratory, California Institute of Technology
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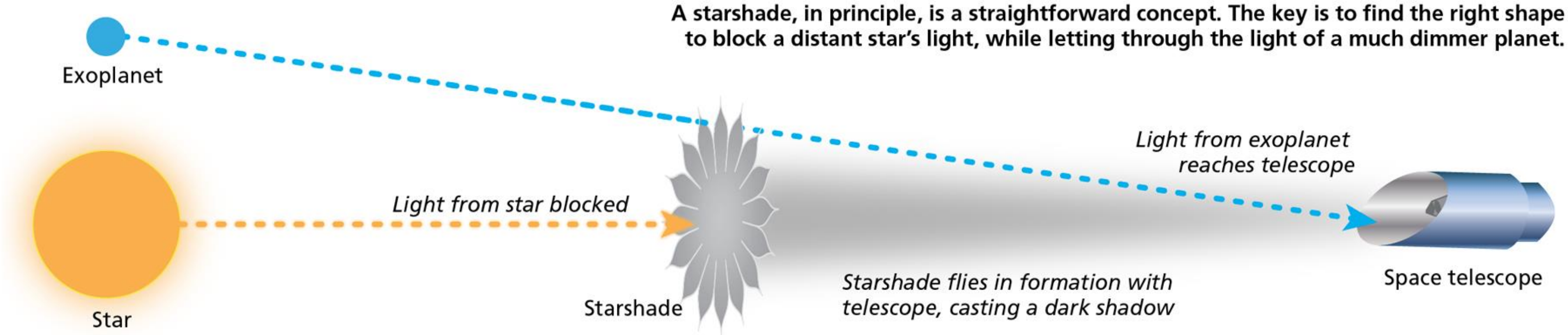
Introduction and overview

Starshades: stop the starlight from getting into your telescope

Create an “artificial eclipse” using a **~30 meter flower-shaped occulter**
…flying **20-80,000 km** in front of your telescope

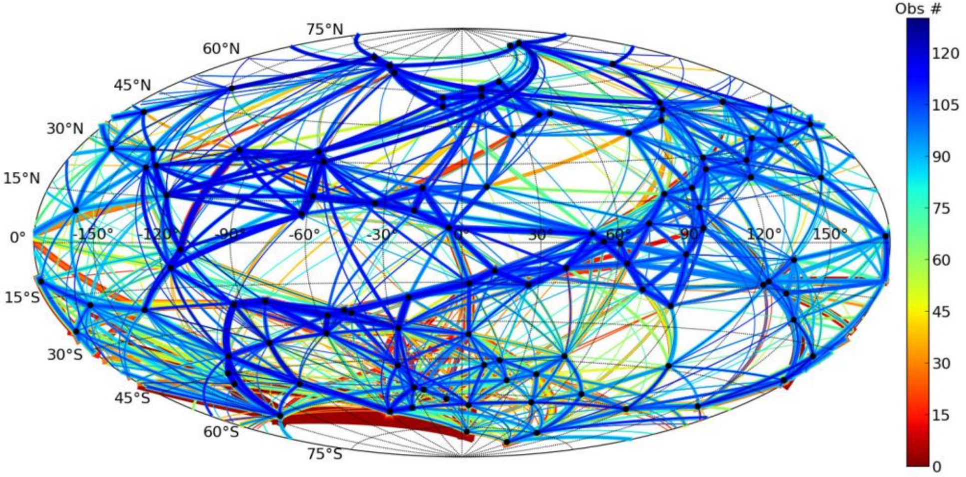


A starshade, in principle, is a straightforward concept. The key is to find the right shape to block a distant star’s light, while letting through the light of a much dimmer planet.

discovermagazine.com

Starshades operations concept

1. Starshades slews to target star
2. Starshade and telescope align themselves with the target star
3. Telescope detects planets around the target star
4. GOTO: 1) until you run out of fuel



Savransky et al. 2015

Why is it shaped like a flower?

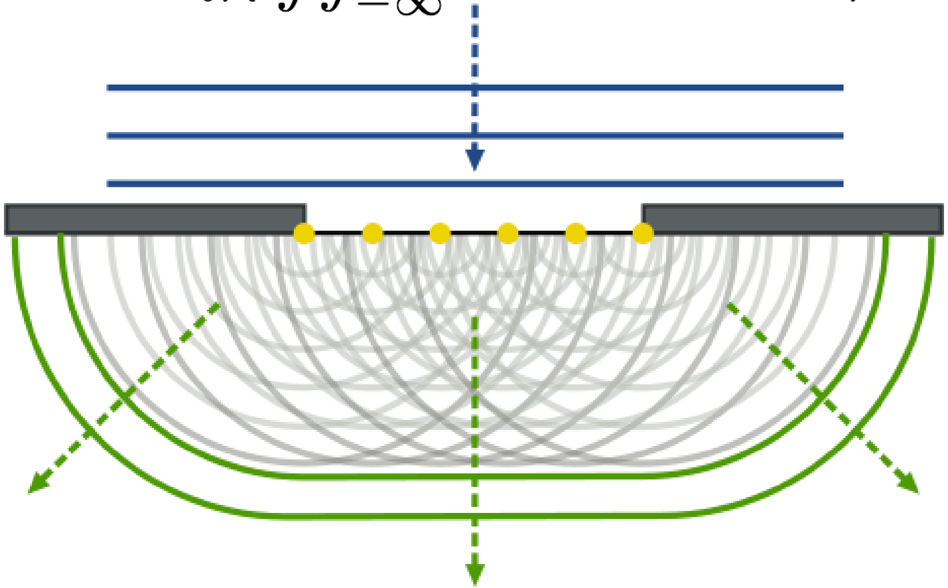
Huygens-Fresnel principle

Output electric field

Input electric field

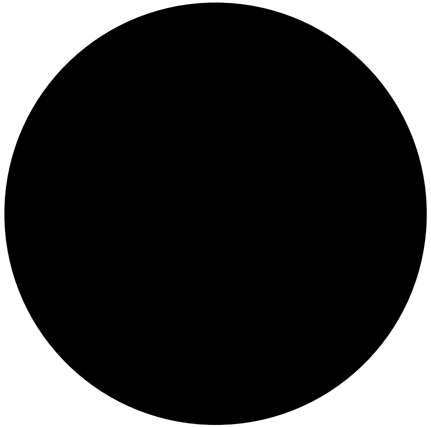
Spherical wavelets

$$U(x, y, z) = \frac{1}{i\lambda} \iint_{-\infty}^{+\infty} U(x', y', 0) \frac{e^{ikr}}{r} dx' dy'$$

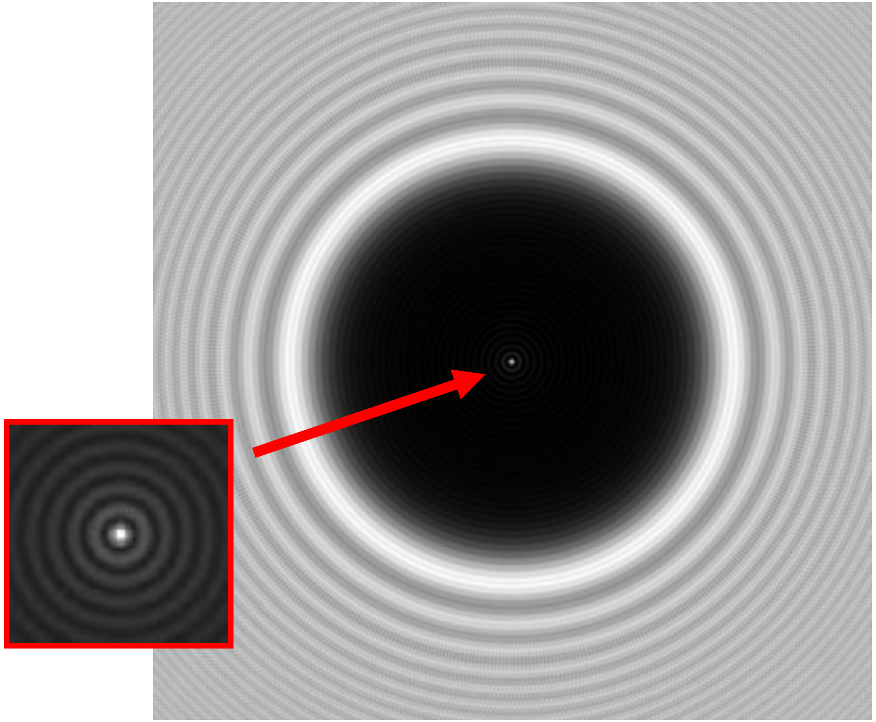


Why is it shaped like a flower?

The annoying Arago spot—a near-field diffraction effect



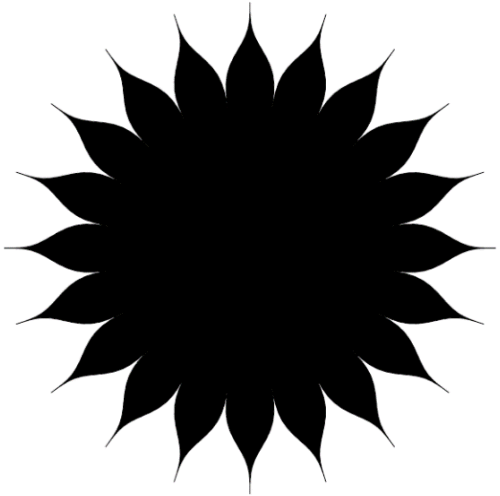
Occulting Aperture



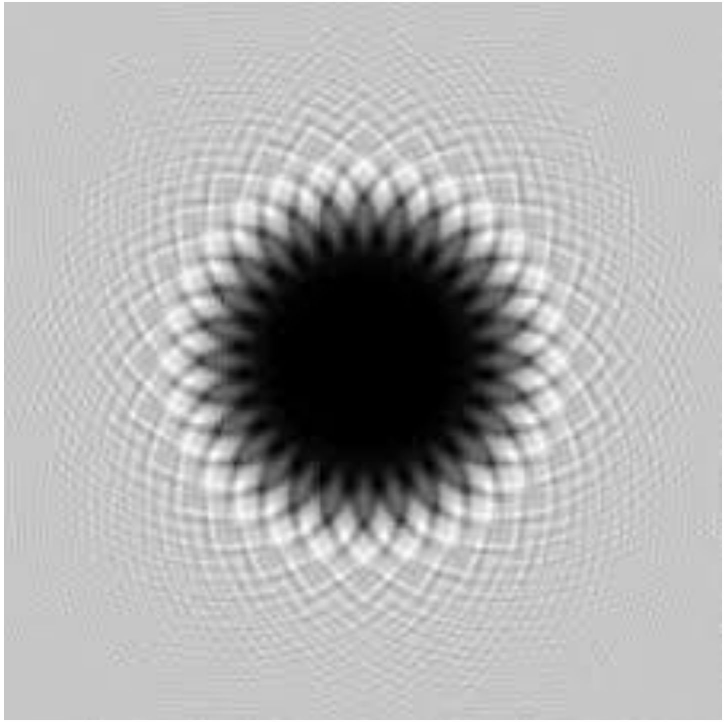
Beam intensity at intermediate distance

Why is it shaped like a flower?

Hypergaussian edges can suppress the Arago spot (W. Cash 2006)



Occulting Aperture



Beam intensity at intermediate distance

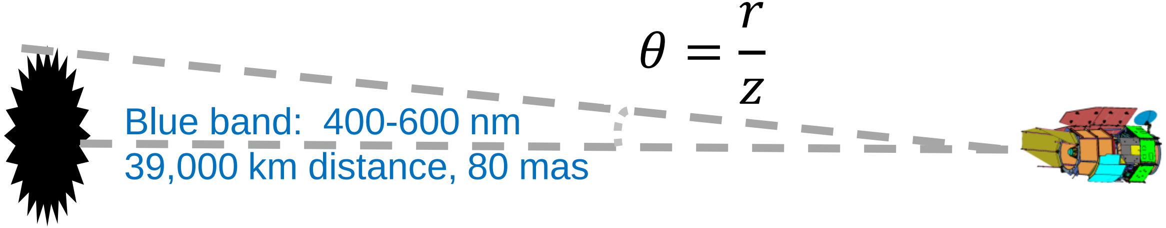
Starshades can only form a dark shadow over a finite bandpass.

They work at a fixed Fresnel number

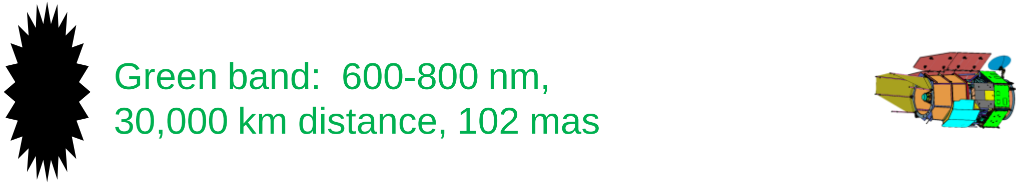
$$F = \frac{r^2}{\lambda z}$$

$$\theta = \frac{r}{z}$$

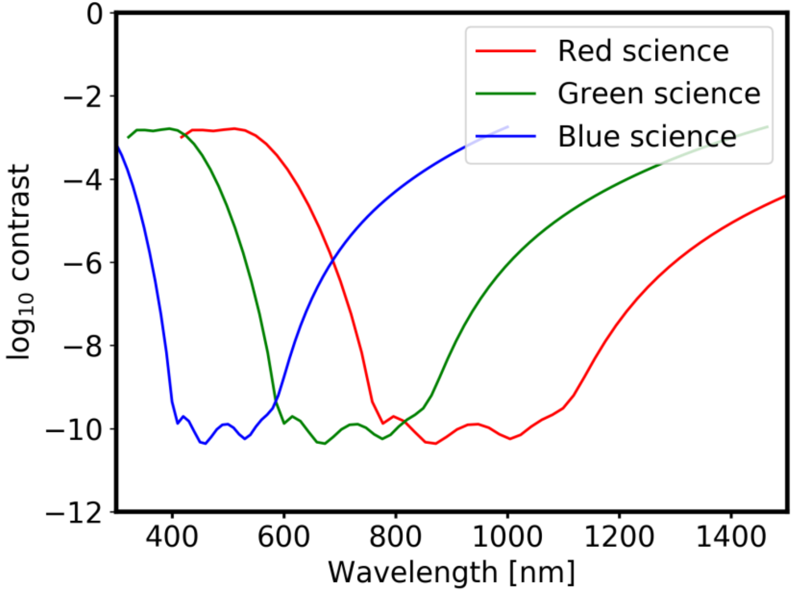
Better θ, But longer slews, no biomarkers



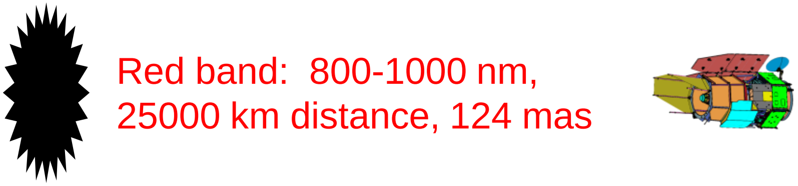
Blue band: 400-600 nm
39,000 km distance, 80 mas



Green band: 600-800 nm,
30,000 km distance, 102 mas



Good band for detecting H_2O, CH_4, etc, but poor access to the habitable zone.

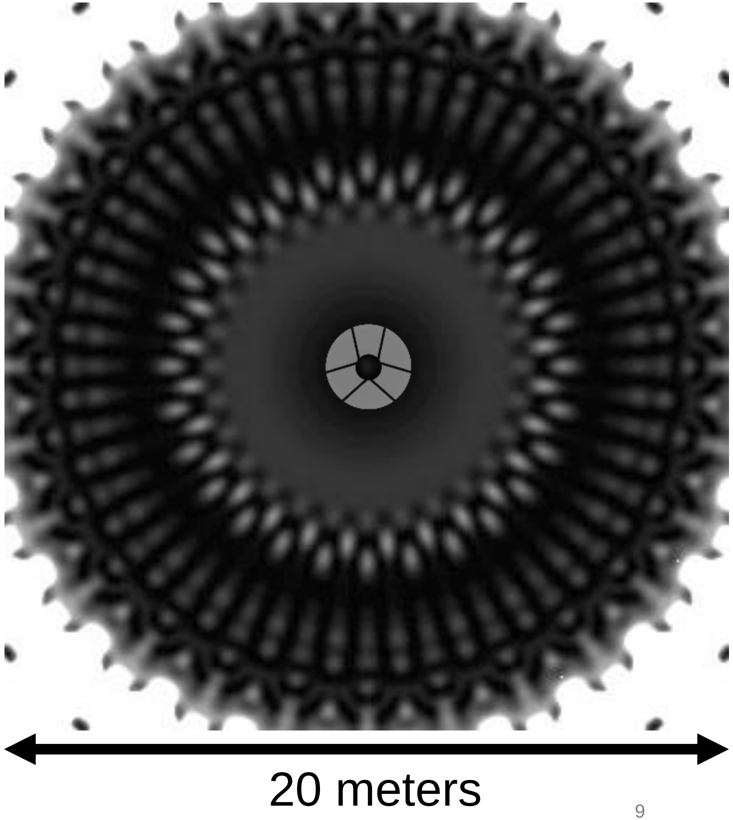


Red band: 800-1000 nm,
25000 km distance, 124 mas

Challenge: formation flying

Starshade and telescope must be aligned to within **1 meter** at **20-80000 km**

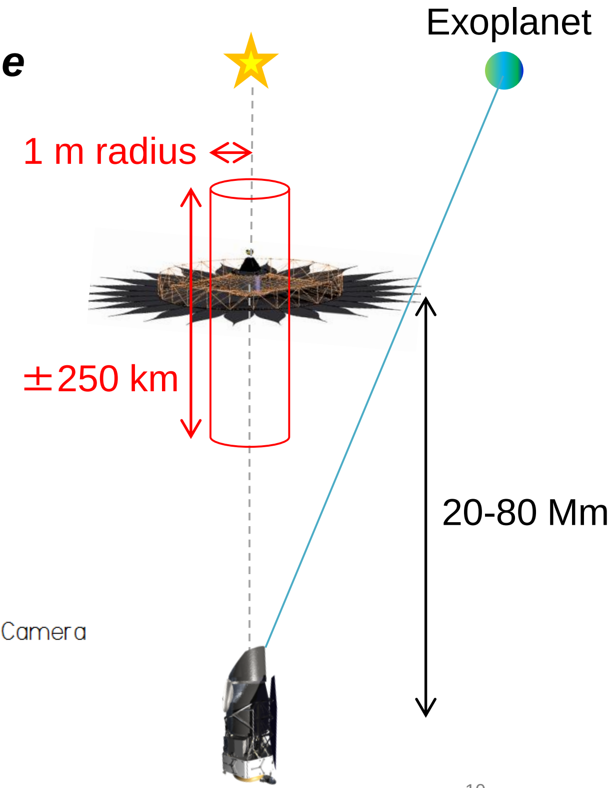
- The shadow is **only slightly wider** than the telescope aperture (**2.4 m** for WFIRST)
- Tolerances
  - **1 meter in shear (x, y)**
  - **250 km** in distance (z)
- (If WFIRST is the size of a pencil eraser, starshade is the size of a drink coaster 60 miles away)

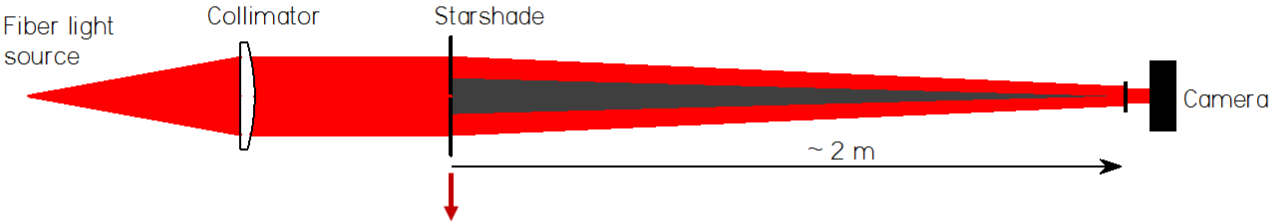


Starshade Formation Flying Milestone

S5 Technology Development Plan, Formation Flying Milestone

Starshade Lateral Alignment Testbed validates the sensor model by demonstrating lateral offset position accuracy to a flight equivalent of ± 30 cm. Control system simulation using validated sensor model demonstrates on-orbit lateral position control to within ± 1 m.





S5 Milestone and approach to TRL5

- **Starshade Lateral Alignment Testbed validates the sensor model by demonstrating lateral offset position accuracy to a flight equivalent of ± 30 cm**
  - Sensor performance is demonstrated using numerical simulations and analytic model
  - SLATE testbed validates the sensor model and demonstrates sensor function

- **Control system simulation using validated sensor model demonstrates on-orbit lateral position control to within ± 1 m**
  - A high-fidelity simulation of the space environment including the testbed-validated lateral sensor model is developed and validated
  - Robust control performance is demonstrated in Monte Carlo simulations

Milestone: Results Brief

Sensing

- Showed that the sensor performance predicted by validated simulations meets requirement with large margin
  - To reveal the sensor error, had to increase the stellar magnitudes by more than 2 and 4, thus the sensor was given a signal between 12x and 75x fainter than expected
- Validated the end-to-end sensing approach with results from the testbed
  - Testbed matched conservative (faint) SNR from flight simulations

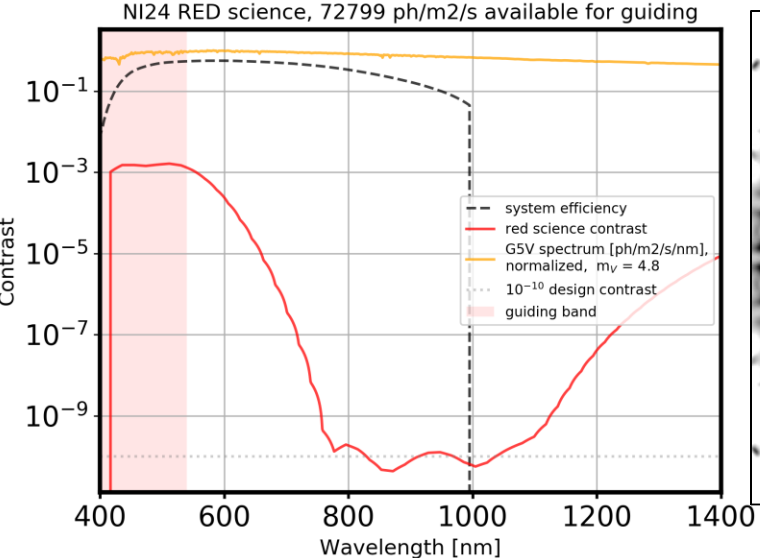
Control

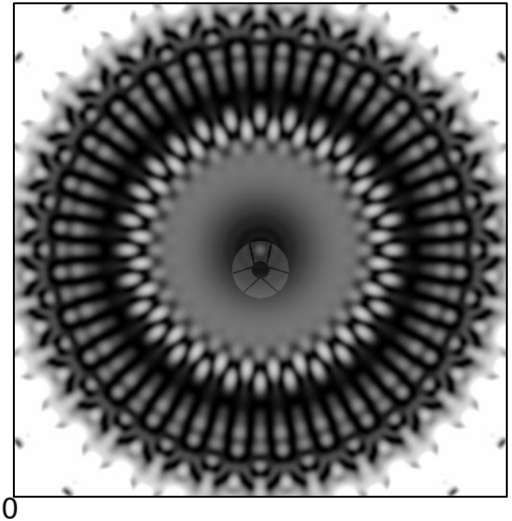
- Developed a high-fidelity simulation environment including testbed-validated lateral sensor model
- Demonstrated control of the starshade with the required accuracy over a realistic observation timescale
  - To demonstrate robust control, the sensor error was inflated far above the expected value to the flight equivalent of ± 30 cm called for in the milestone statement

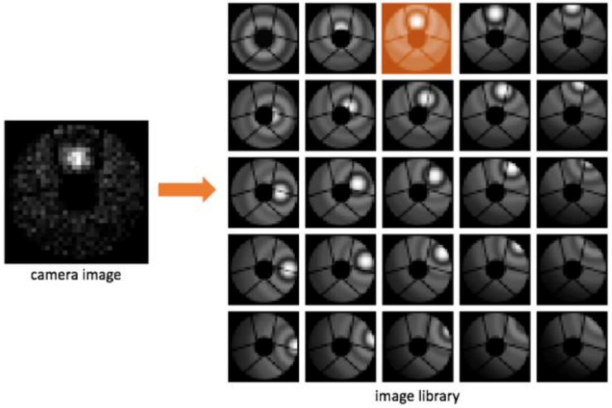
Lateral sensing

Lateral sensing overview

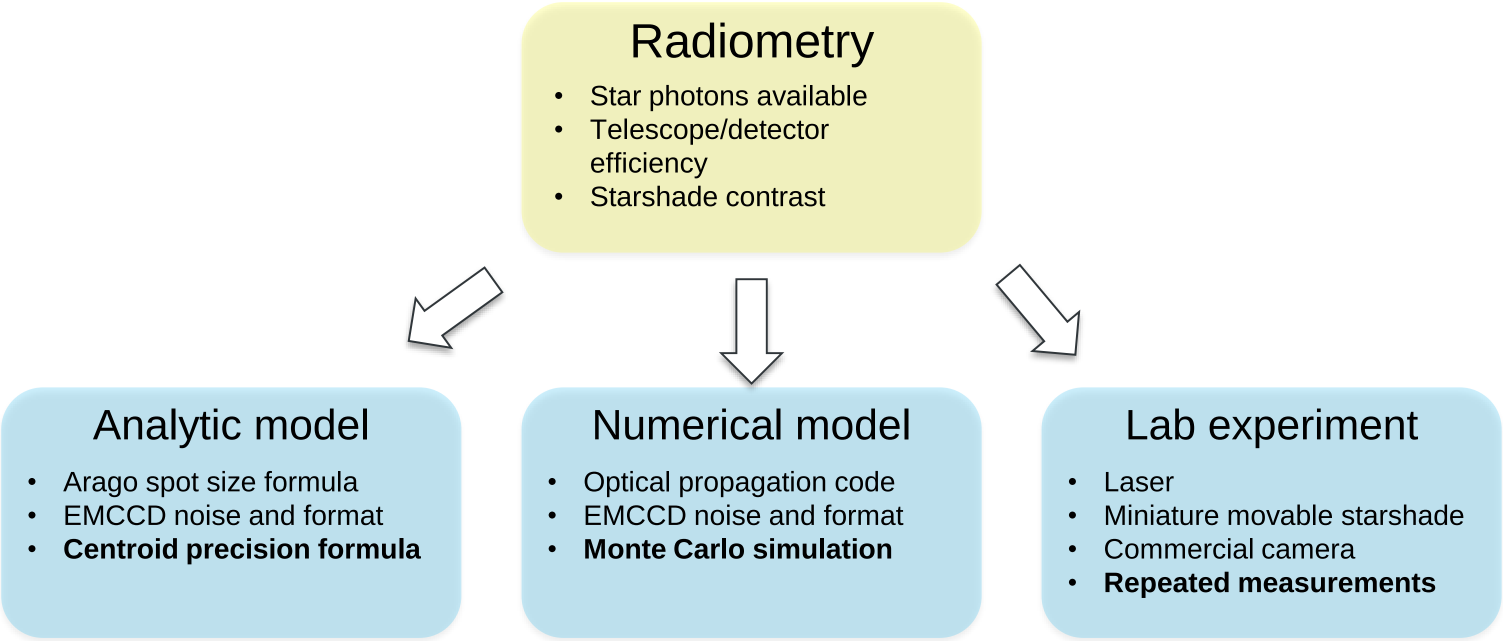
- Starshades create a very deep shadow in the design band, but this shadow brightens substantially (~10^6) outside these wavelengths
- The shadow has structure that encodes positional information
- Using a pupil sensor to image the shadow and a grid of precomputed shadow images, it is possible to determine the relative offset between the Starshade and telescope







Milestone demonstration overview



Radiometry

- Star photons available
- Telescope/detector efficiency
- Starshade contrast

Analytic model

- Arago spot size formula
- EMCCD noise and format
- **Centroid precision formula**

Numerical model

- Optical propagation code
- EMCCD noise and format
- **Monte Carlo simulation**

Lab experiment

- Laser
- Miniature movable starshade
- Commercial camera
- **Repeated measurements**

Radiometry

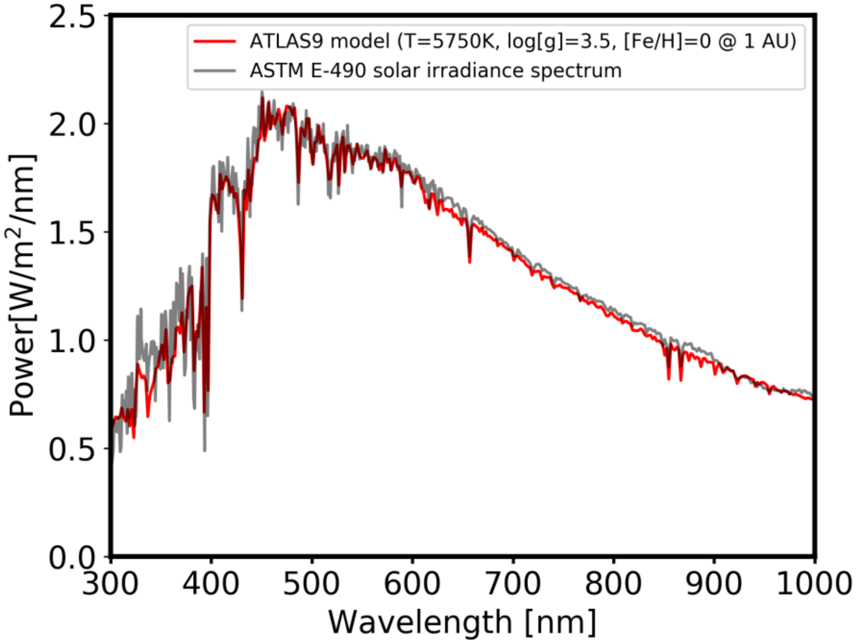
Main points

- A key question is how much light is detected by the pupil camera, the CGI low-order wavefront sensor (LOWFS)
- This depends on:
  - The stellar photon flux
  - The starshade contrast
  - The internal optical efficiency of the telescope
  - The detector efficiency

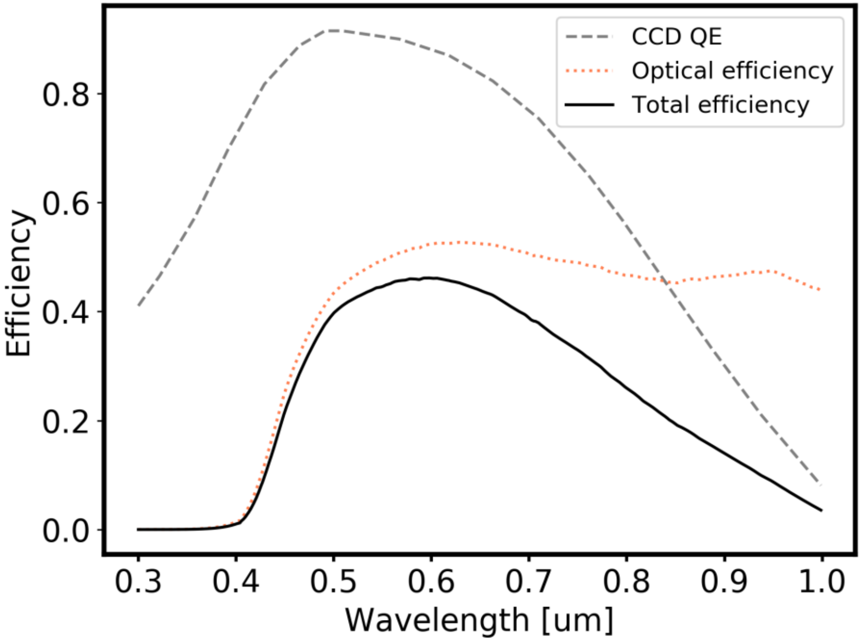
- This subsection will review how these numbers are determined

Radiometry

Stellar flux and internal telescope efficiency



Stellar models agree to ~few percent with measured solar irradiance and standard filter zeropoints



Optical efficiency was taken from the coronagraph optical designers, with further 10% loss assumed

Radiometry

Starshade contrast

- Formation flying does not depend on understanding contrast to extreme levels of accuracy. Formation flying operates at the **10^{-3} to 10^{-4}** level
- Starshade shadow contrast was computed using Eric Cady’s (JPL) flight starshade design code.
- The starshade design code is well validated and understood
  - Princeton testbed results validate the starshade optical model at better than the 10^{-10} contrast level

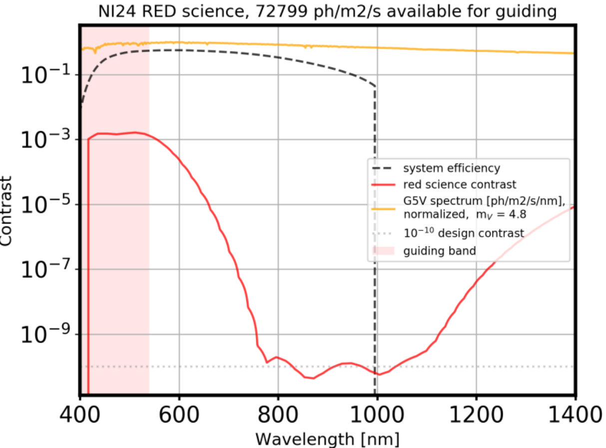
➢ Model is more than sufficiently accurate

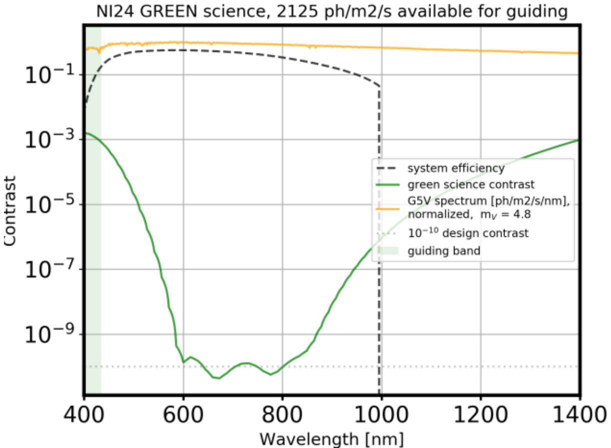
Ziemer et al 2018

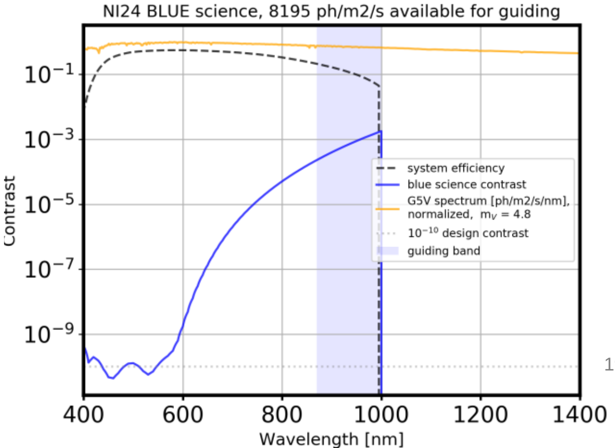
Radiometry

Summary

- Starlight, starshade, telescope, and detector all contribute to the photon budget
- Each of these terms is well understood
- Results will show formation flying performance is robust to efficiency changes
    - Main sensitivity is to change to starshade transmission


NI24 RED science, 72799 ph/m2/s available for guiding


NI24 GREEN science, 2125 ph/m2/s available for guiding


NI24 BLUE science, 8195 ph/m2/s available for guiding

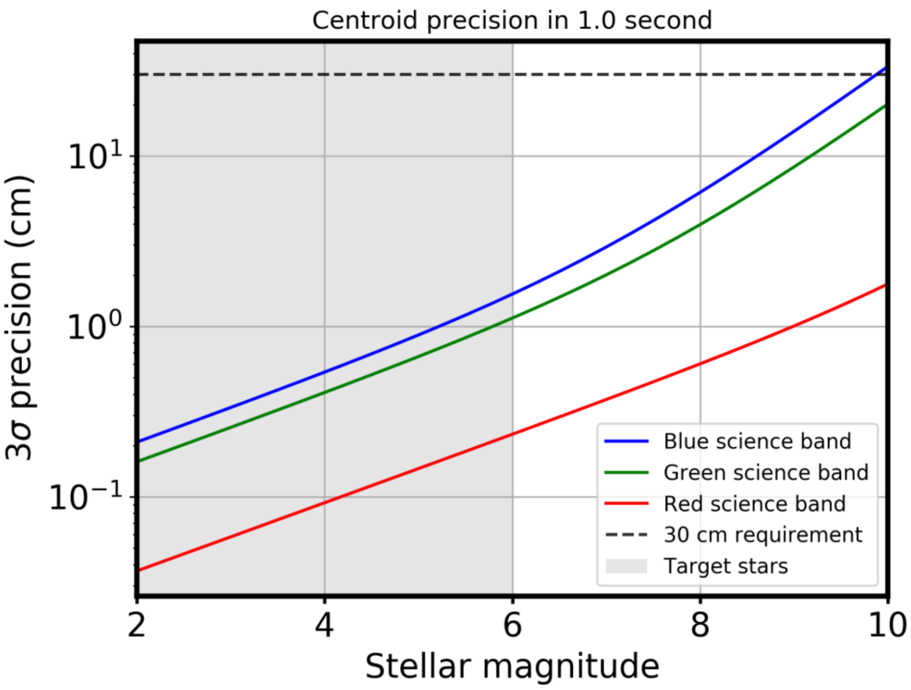
Analytic calculations

Centroid precision can be predicted from spot size and signal-to-noise ratio

- Assuming the shadow consists of just the Arago spot, can get a rough estimate of centroid precision using the standard centroid accuracy formula

$$\sigma_x = \frac{\mathrm{FWHM}}{c \cdot \mathrm{SNR}}$$

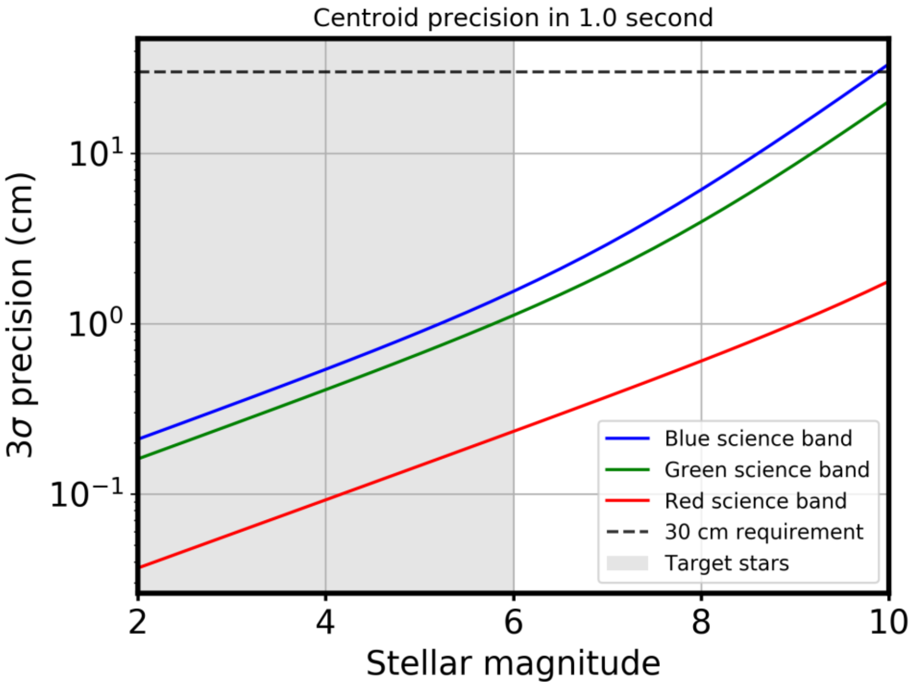
- sigma is in FWHM units, like pixels or meters. FWHM is the width of the spot
- The constant c depends on the exact shape of the PSF (or spot).
  - The theoretical limit is c=π
  - Often people (eg *Kepler* mission) use c=2
- This is a theoretical limit and other errors will get you first



Analytic calculations

Summary

- Analytic calculations indicate sensor should
  - **Easily exceed** the requirement at all target star magnitudes
  - **Achieve ~cm-level precision** for the faintest target stars
  - **Meet the requirement** at star magnitudes of up to ~10
- Caveats:
  - does not include effects like pupil obscuration, off-axis starshade shadow pattern, etc

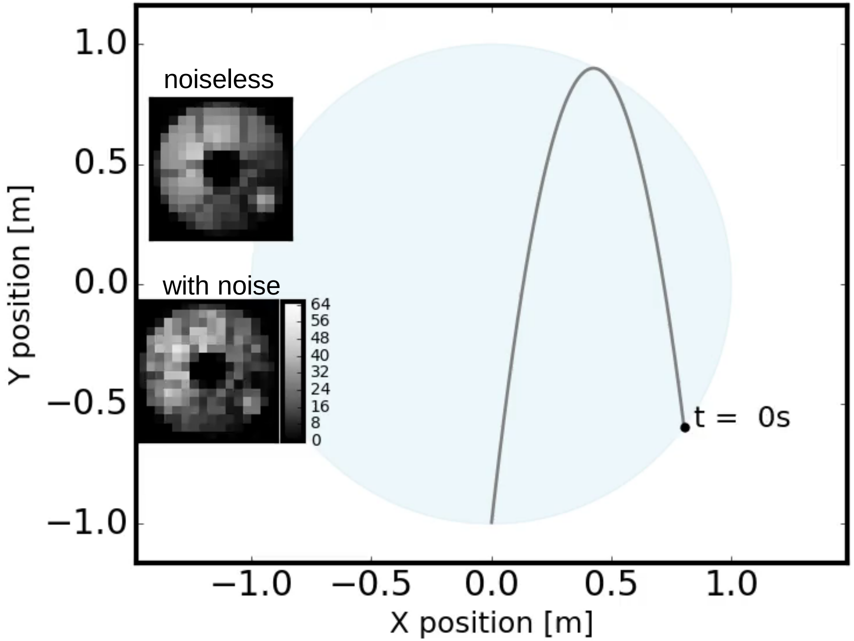


Numerical simulations

Main points

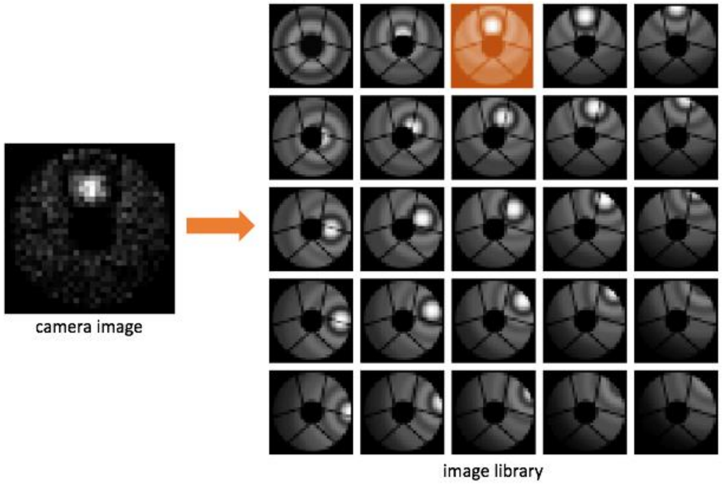
- Detailed numerical calculations are used to get a more accurate prediction of sensor performance
- Use optical propagation codes to move wave from star, to starshade, and through telescope
- Simulate realistic images on LOWFS, allowing for Monte Carlo experiments of sensor performance

red science band, 10th mag



(6th mag noisy case would have nearly undetectable difference with noiseless case)

Numerical simulations

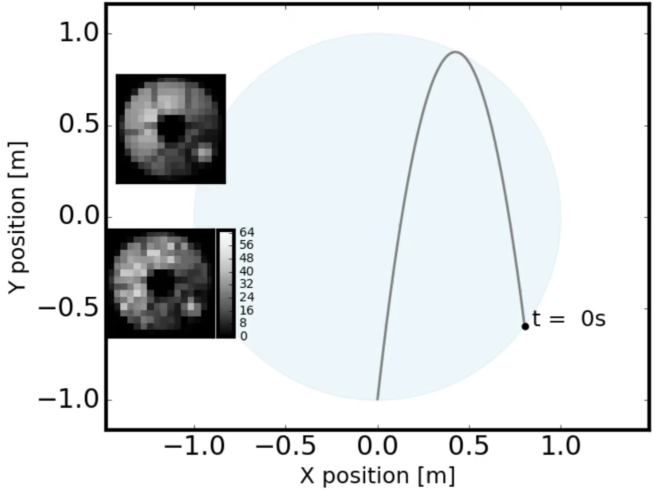


Monte Carlo simulations

1. Take noisy LOWFS image
    1. Equalize image (eg divide by mean)
2. Match to image library (2cm grid)
    1. Use least-squares matching algorithm
    2. Record matched position
3. Goto 1, repeat hundreds of times

- Analyze results to determine sensitivity at different star magnitudes
    - – *Note: exposure time is always 1 second, but this is overkill too*

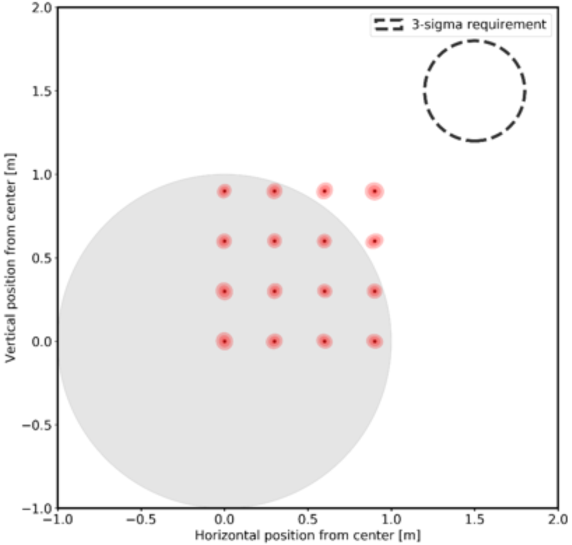
red science band, 10th mag



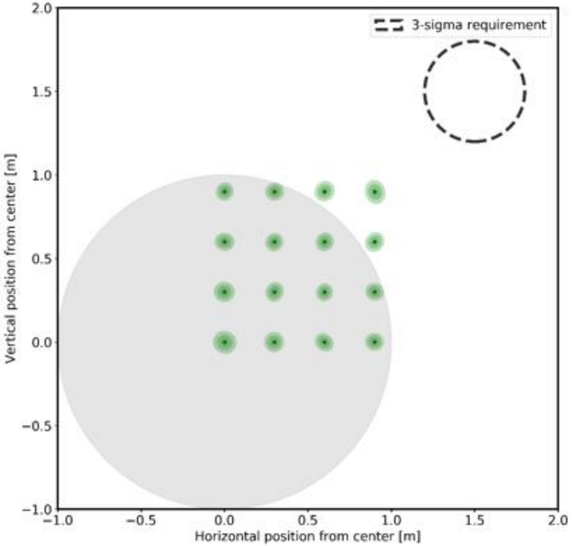
Numerical simulations: Results

- At target star magnitudes (<6th mag), 2cm grid never mismatches
  - Must increase magnitude until start getting some misses
- All science bands **easily beat the 30 cm (3σ) requirement by at least a factor of 3, on stars at least 10x fainter than any target star**

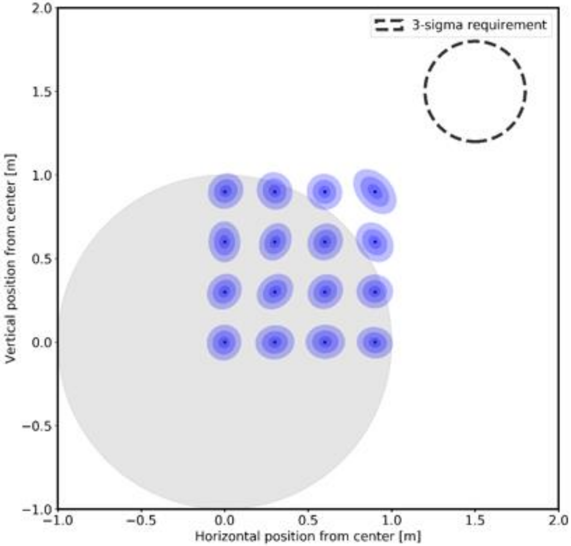
red science band, 10th mag, 1 sec
(75x fainter than faintest target)



green science band, 8th mag, 1 sec
(12x fainter than faintest target)



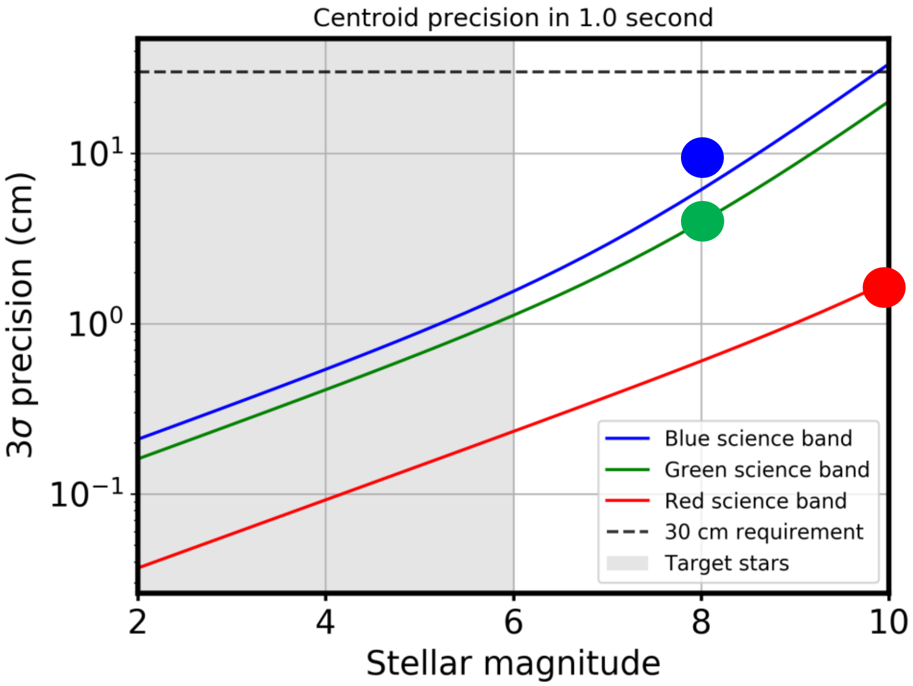
blue science band, 8th mag, 1 sec
(12x fainter than faintest target)



Numerical simulations: Results (2)

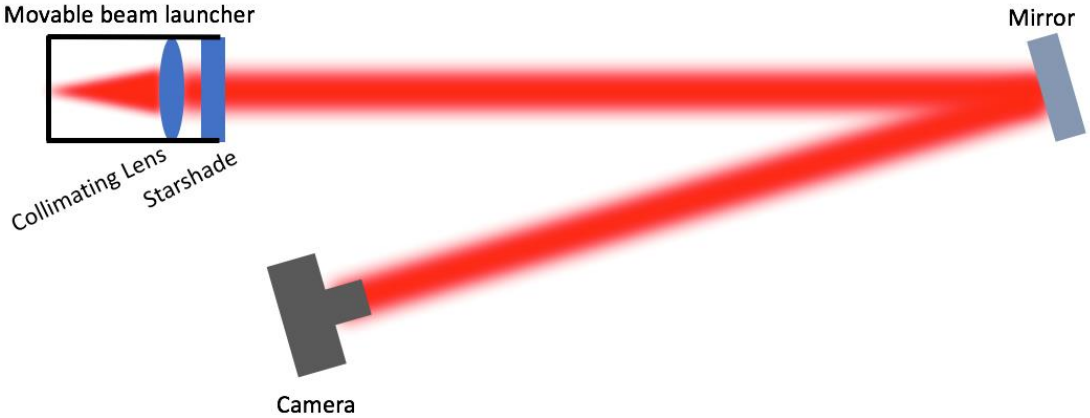
- Analytic and numerical simulations agree
- Blue band disagrees, probably because the (larger) spot is always partially obscured by the pupil

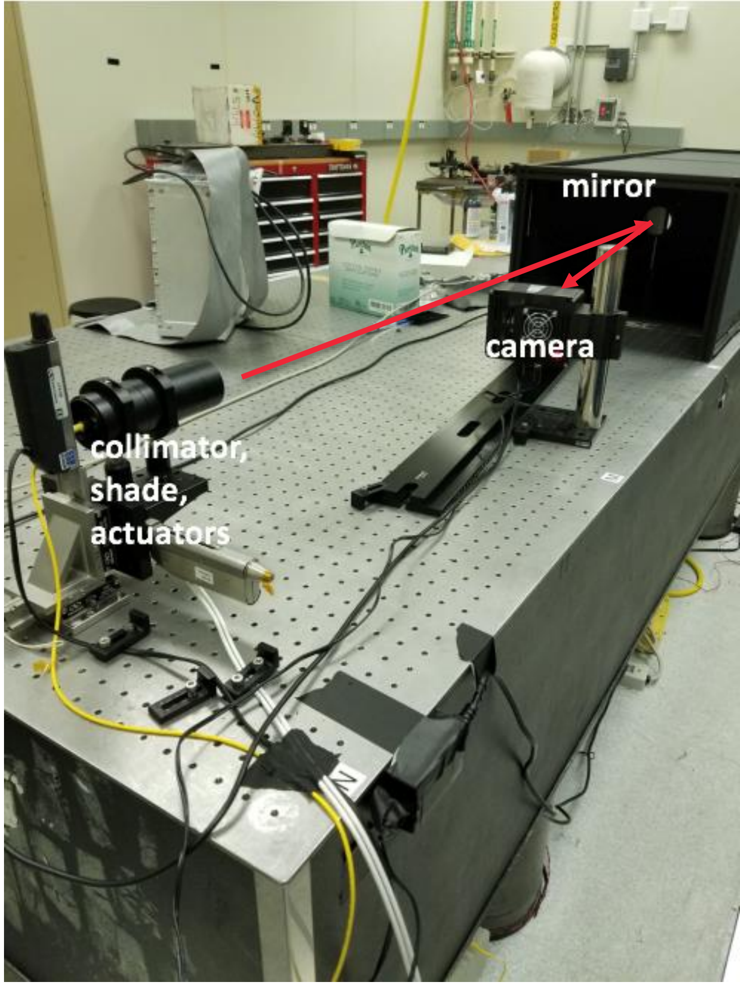
Science band	Star magnitude	Median 3σ error (cm)	Analytic 3σ error (cm)
Red	10.0	1.6	1.6
Green	8.0	3.6	3.9
Blue	8.0	9.7	6.1



Laboratory experiment

- Starshade Lateral Alignment Testbed (SLATE)
  - A movable beam launcher and starshade produce a realistic starshade shadow
  - A camera and software simulate the functionality of WFIRST-CGI LOWFS when used as a starshade alignment sensor
- The purpose of SLATE is to demonstrate the sensor function, testing the agreement between predicted performance and simulated performance, thus validating the sensor model





Laboratory experiment

Is SLATE a faithful reproduction of the space environment? ***NO, it's worse***

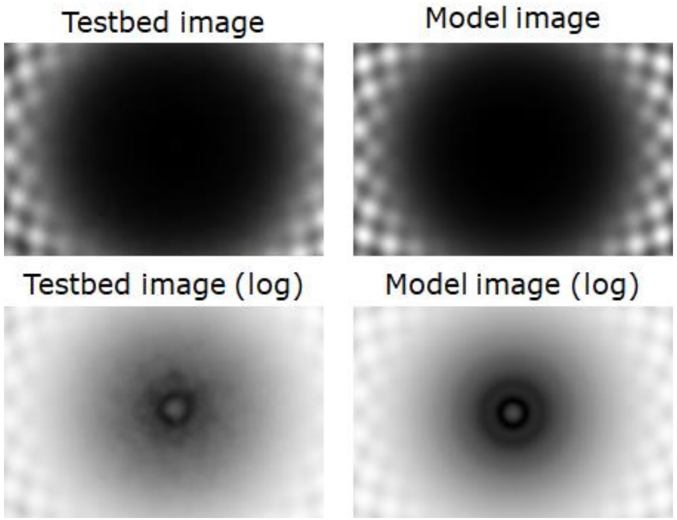
- Camera
  - **Noise 20 to >10000x** more than flight EMCCD
  - Bias and dark drift, flat field nonlinearities
- Optics
  - Significant wavefront error at the 10^{-4} contrast level (despite excellent optical surface quality)
  - Significant scatter
  - Some background light/variation
  - Wavefront error prevents testing at the largest Fresnel number, by producing excess scatter.
  - However this does not invalidate the tests since the error source is known and at lower Fresnel numbers, the system works.
- Philosophy
  - Match flight simulation SNR (not photon flux)
  - Match flight morphology (spot/pupil ratio)

Parameter	Flight expectation	SLATE testbed
Fresnel number	5-7	4.5
Light type	broadband starlight (50-100 nm filtered)	632 nm laser
Wavefront quality	~14nm wavefront error	>500 nm wavefront error
Beam apodization	None	Gaussian
Camera chip	e2v CCD201	SBIG KAF402-me
Camera read noise	2 electrons	40 electrons
Camera dark current	1.5e-4 electrons/pixel/sec	2 electrons/pixel/sec
Camera clock-induced charge	0.02 electrons	<1 electron
Camera flat field calibration	excellent	none
Arago spot FWHM	10 pixels /32x32 detector	10 pixels/ 32x32 pixels
Arago spot SNR	5/pixel in FWHM	5/pixel in FWHM

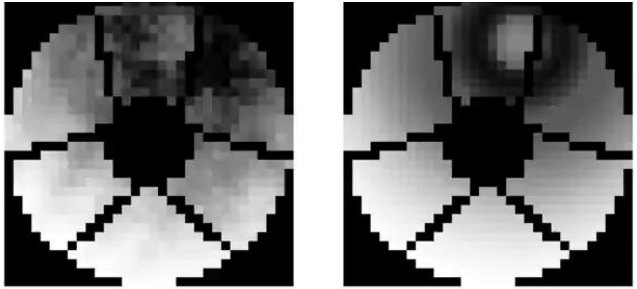
Lab experiment

Test design

- Create SLATE image library from optical model of lab
  - Contrast matches at ~20% level
    - Note this is just a check
- Match Arago spot size and SNR to space-like levels (flux >10x lower than target stars)
- Run sensor simulation
  - Command actuators to move to different points on trajectory
  - Match image to library
  - Get statistics of matched position



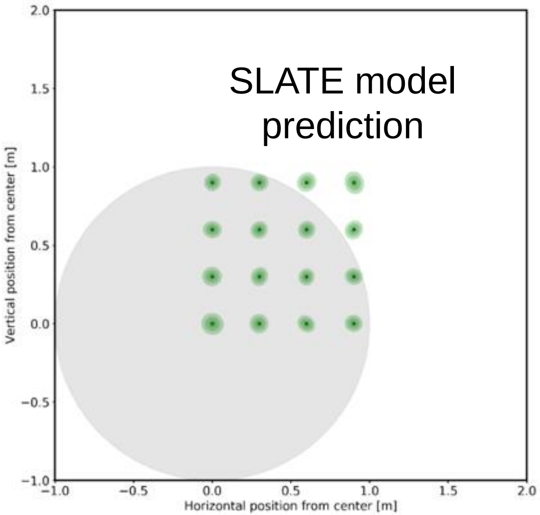
Position: (0.275,0.875), Setpoint: (0.0, 0.0)

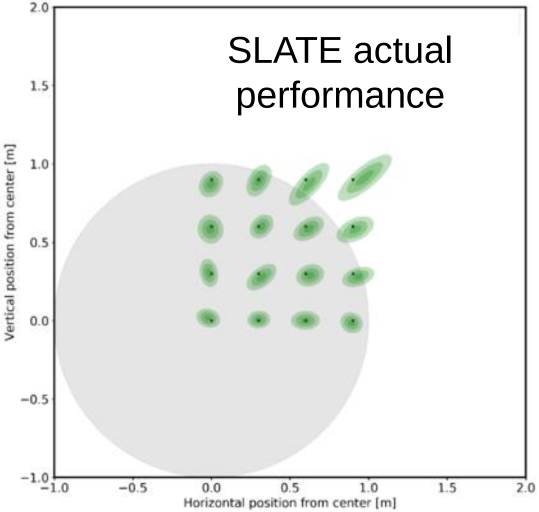


Lab experiment results

- Good agreement despite many non-idealities in testbed
- Reproduce numerical results to ~55%
- Main differences between model and testbed are flat fielding errors, background/scattered light, and pixel non-uniformity
- These all produce a worse performance than expected for an optically perfect testbed
- Thus, if the testbed model can be “flown” by the s/w, this satisfactorily validates the sensor

Sim 3σ (worst)	Sim 3σ (median)	SLATE 3σ (worst)	SLATE 3σ (median)
6.7 cm	4.0 cm	10.2 cm	6.2 cm





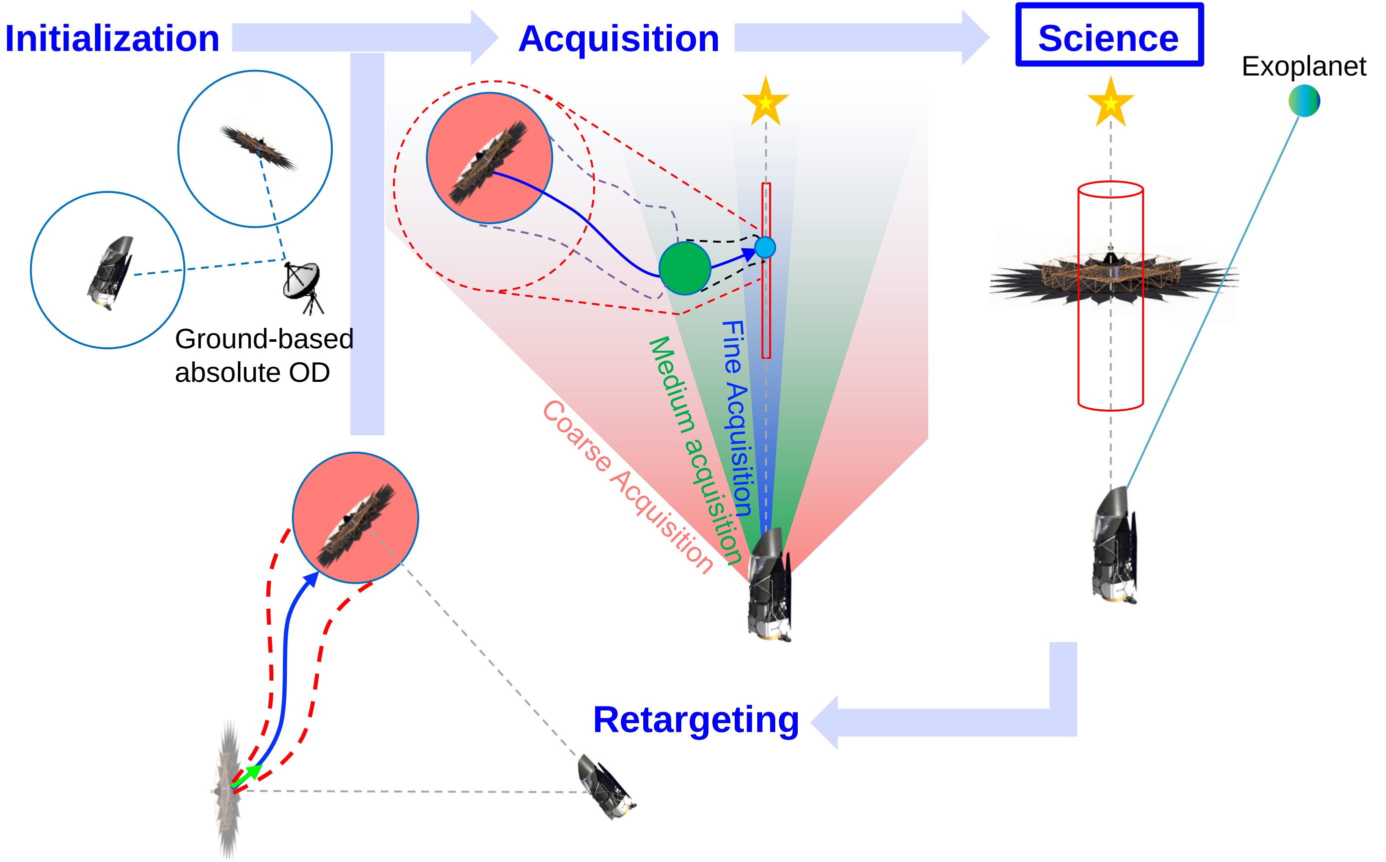
Conclusions

1. Flight simulations predict sensor performance well above what is needed, for all science bands, using stars ~12-75x fainter than the faintest target star

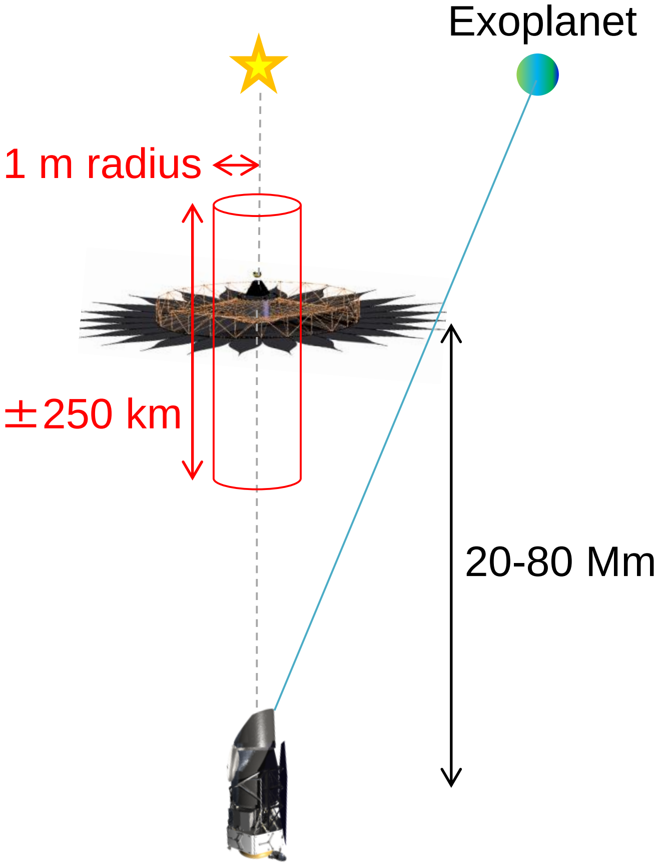
2. Laboratory experiments demonstrate good agreement with simulations of sensor performance

Formation flying simulations

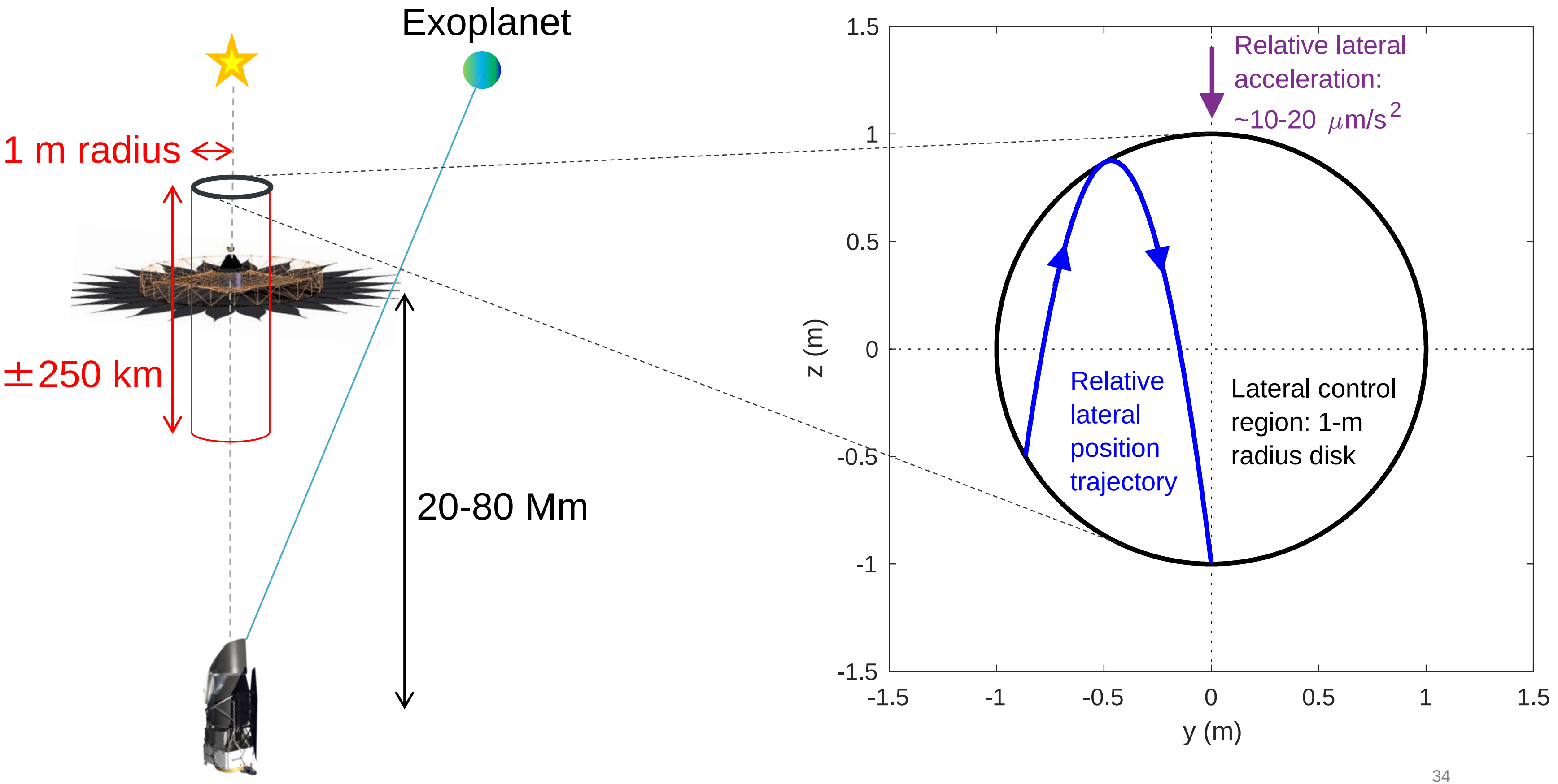
Formation flying overview



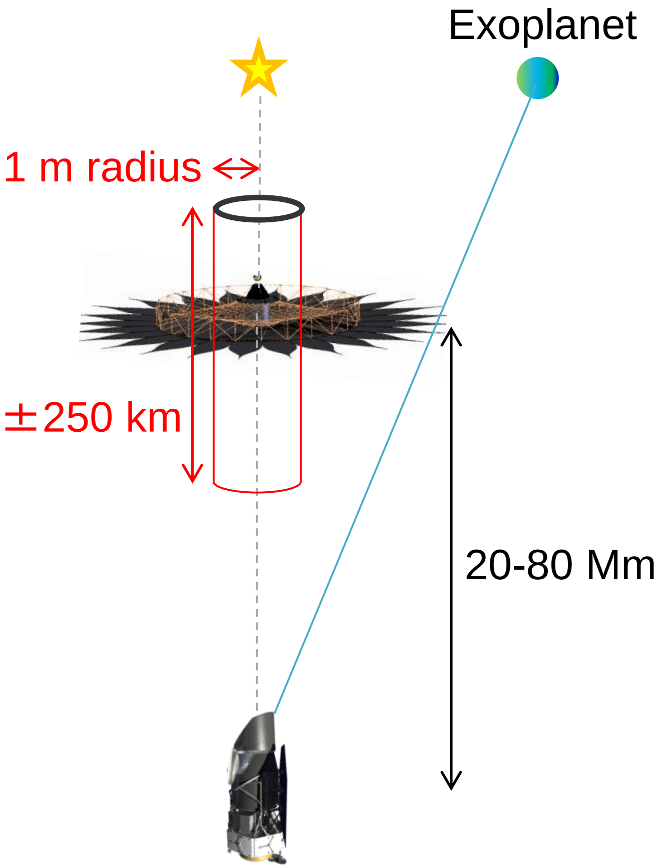
Formation flying overview

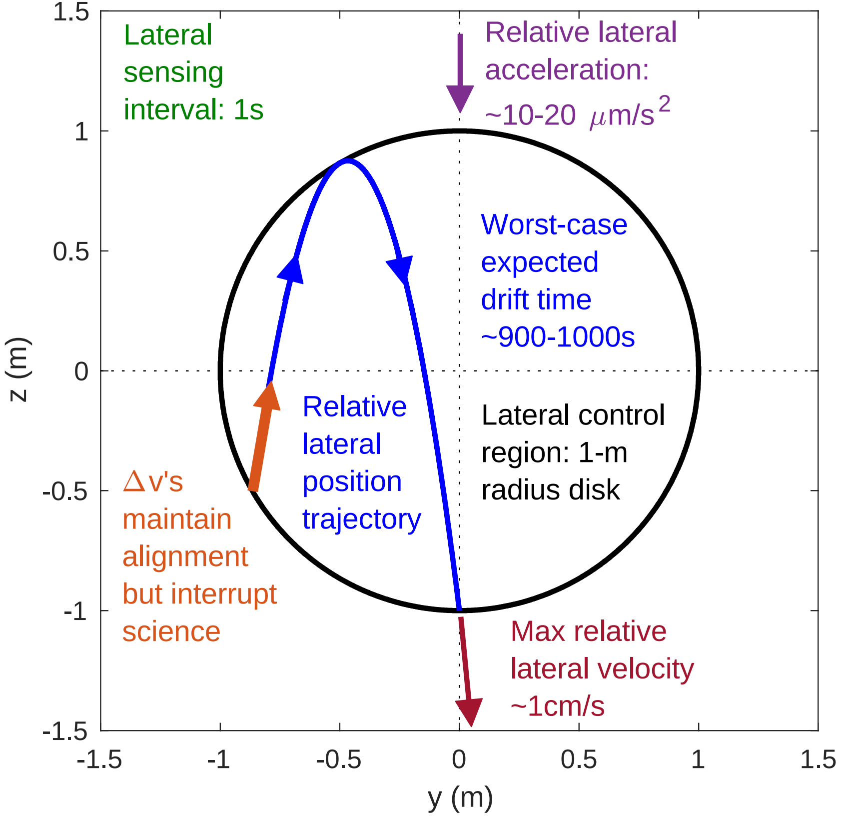


Formation flying overview

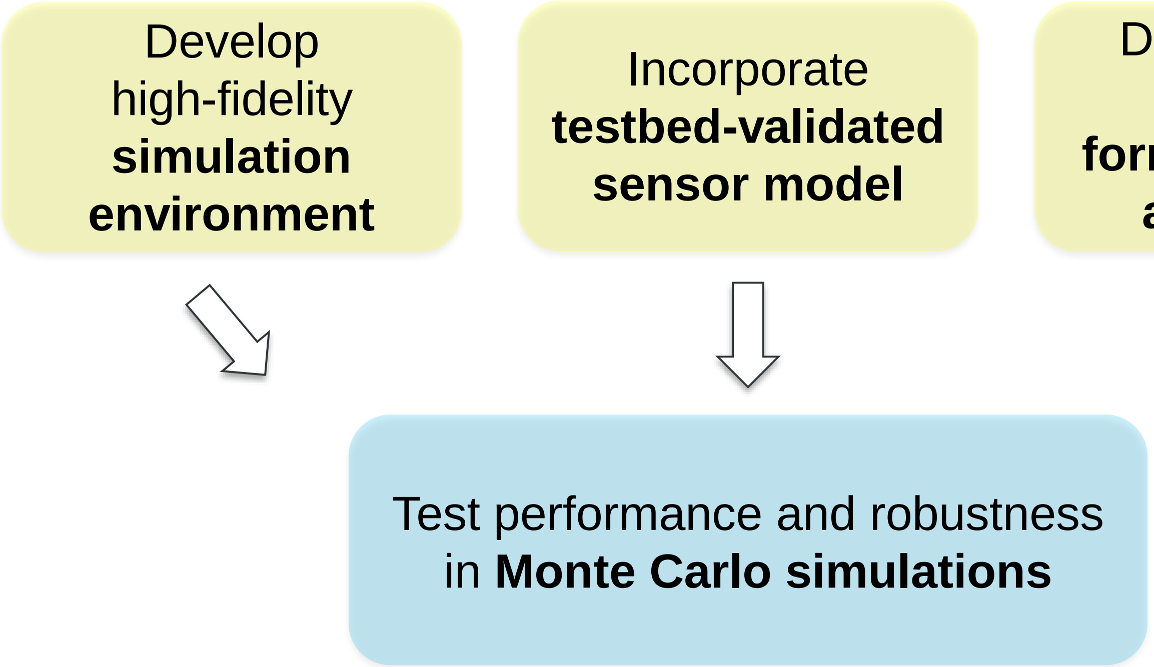


Formation flying overview





Formation flying overview



Develop high-fidelity **simulation environment**

Incorporate **testbed-validated sensor model**

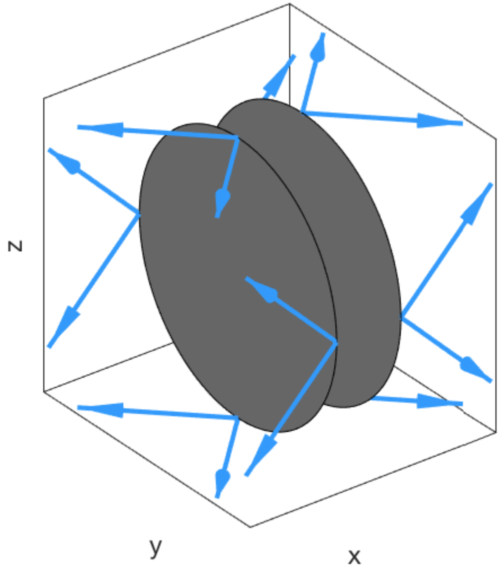
Develop flight traceable **formation-flying algorithms**

Test performance and robustness in **Monte Carlo simulations**

- ➔ Demonstrate successful **control with required accuracy**
- ➔ Demonstrate **observational efficiency**

Simulation fidelity

- **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

Initial conditions

- Maximize relative **lateral** acceleration

- **Earth gravity:** driving influence for *relative* dynamics

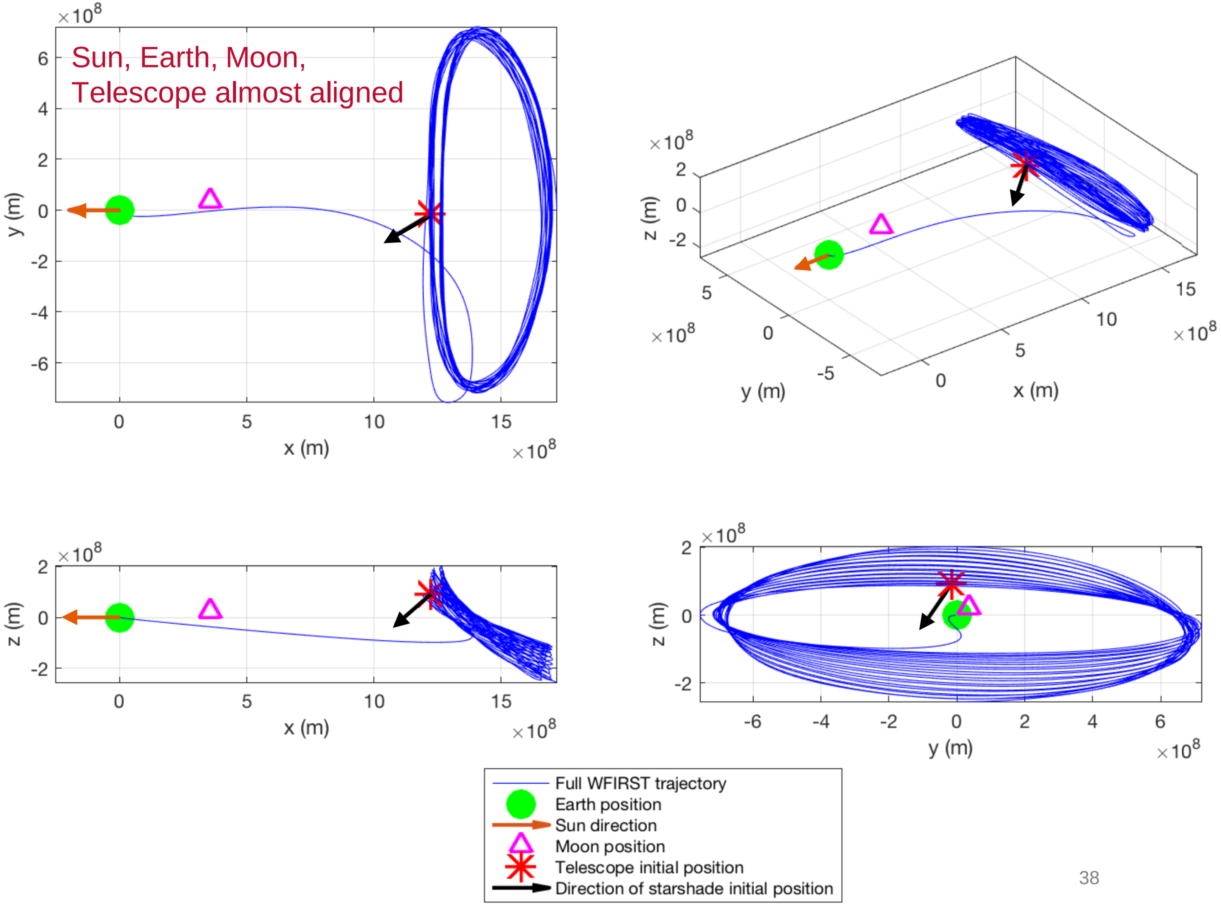
- **Worst-case formation geometry:**

➔ Closest to Earth/Sun

➔ Max starshade-telescope range

➔ Formation “Earth angle” for max disturbance: 40°-45°

WFIRST representative Lissajous orbit at Earth-Sun L2



Sensor models

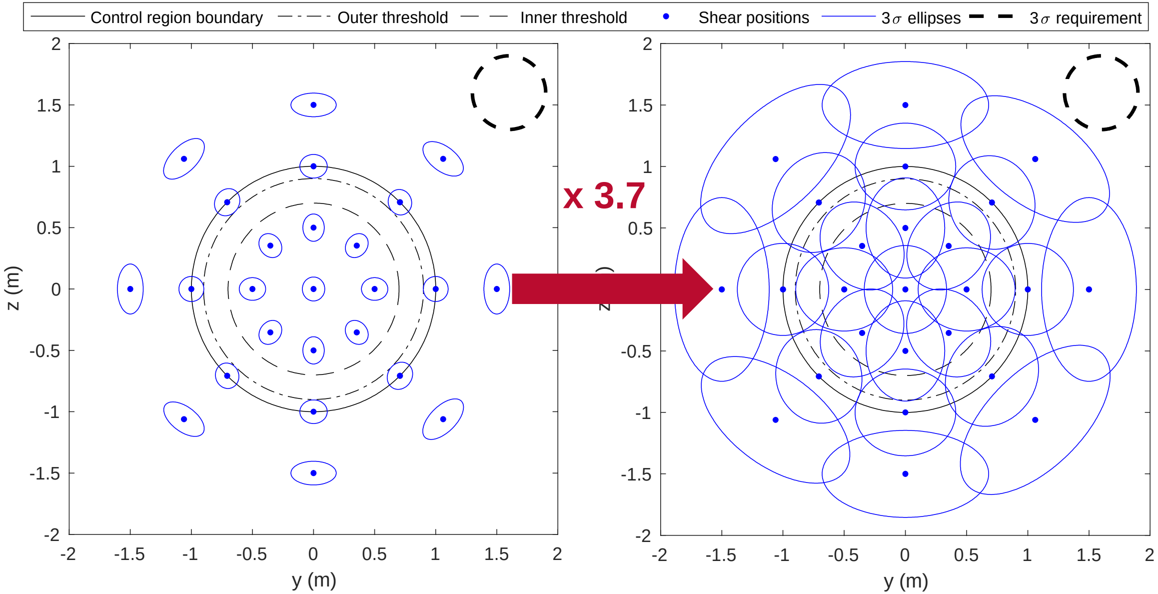
- Model based on **extremely conservative (scaled) sensor model**

➔ Assume performance is **no better than 30cm (3σ)**

- **Other errors**: Measurement time, time-tag, delays added

Testbed-validated sensor model for:

- *Blue band*
- *8th magnitude star (12x fainter than faintest target)*



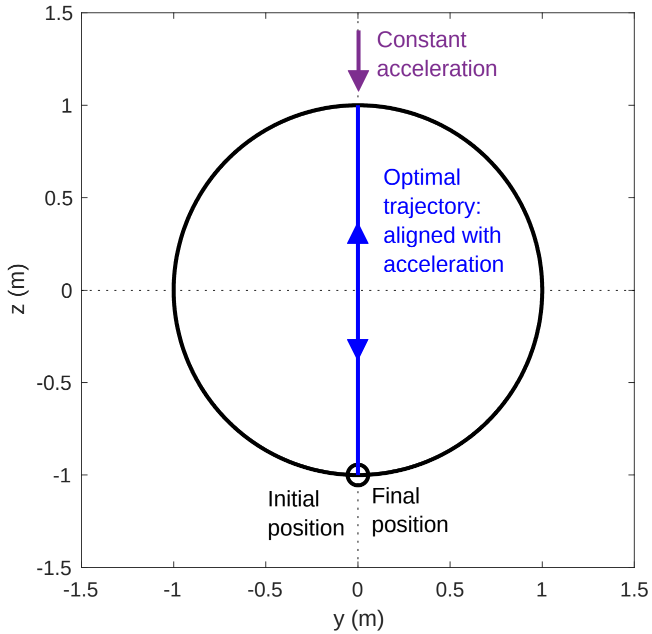
Extremely conservative model:

used in formation flying simulations

Lateral Control

- Typical deadbanding for attitude control /docking is “per-axis”

➔ **Developed two-dimensional disk-deadbanding algorithm**

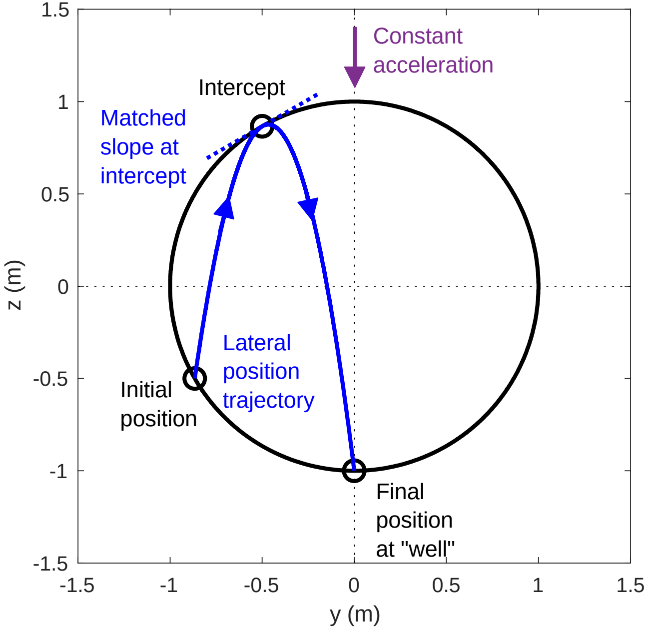


- Max drift time requires initial position at “well”

➔ **Seek trajectory that targets well**

Lateral Control

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



- Max drift time requires initial position at “well”

➔ **Always seek trajectory that targets well**

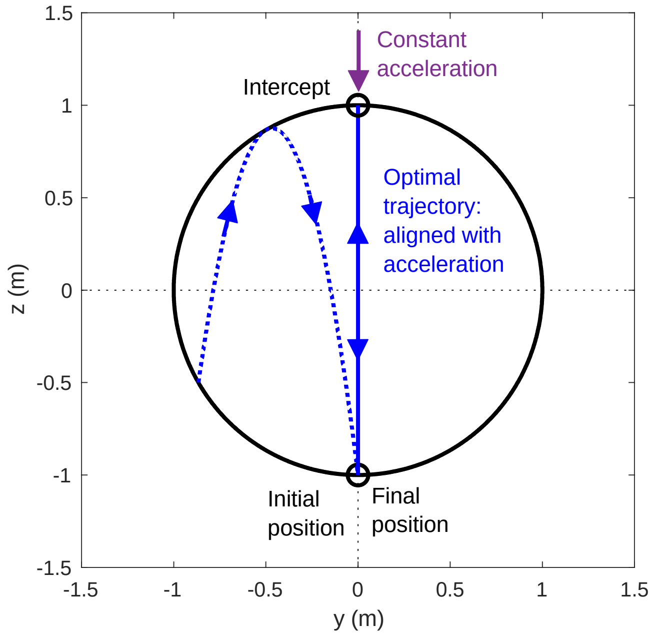
- Given initial & final position: maximize drift time

➔ **Intercept point tangent to boundary**

Lateral Control

- Typical deadbanding for attitude control /docking is “per-axis”

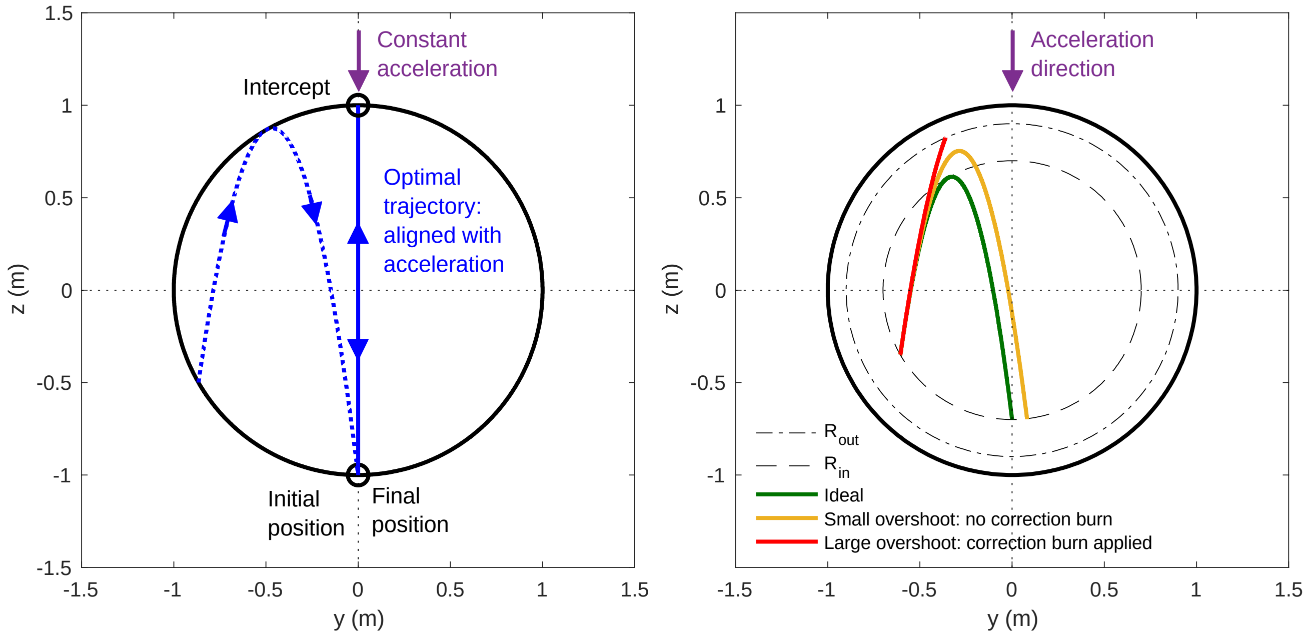
➔ **Developed two-dimensional disk-deadbanding algorithm**



- Converges to globally optimal trajectory
- Only requires a single algorithm
- Provides effectively optimal observational efficiency (long drift times)

Lateral Control

- **Double threshold approach**:
  - *Small* overshoots don’t trigger correction burns to maximize drift time
  - *Large* deviations are corrected to ensure control requirement is met

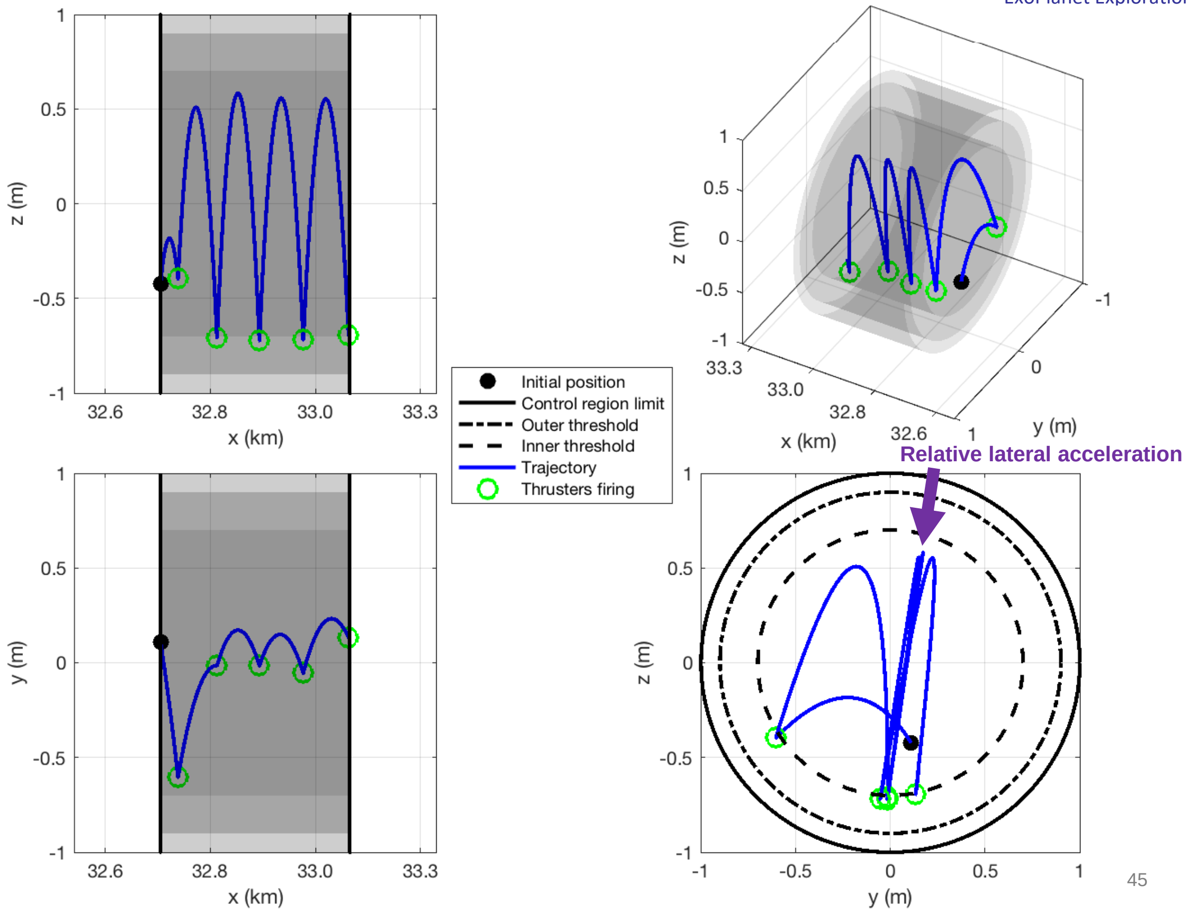


Remaining GNC algorithms

- **Estimation**
  - Filter state is 3DOF relative position, velocity, acceleration
  - Constant acceleration model, justified at deadbanding timescales
- **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**
  - Internally developed 6DOF thrust allocation algorithm used
  - Developed at JPL, flight-proven e.g. used on Mars Science Laboratory

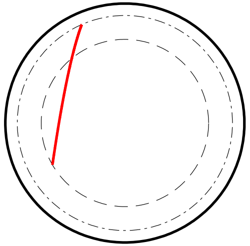
Results: Typical formation flying behavior

- **1-m radius control requirement met for all simulations**
- ±250 km longitudinal control requirement also met in all cases

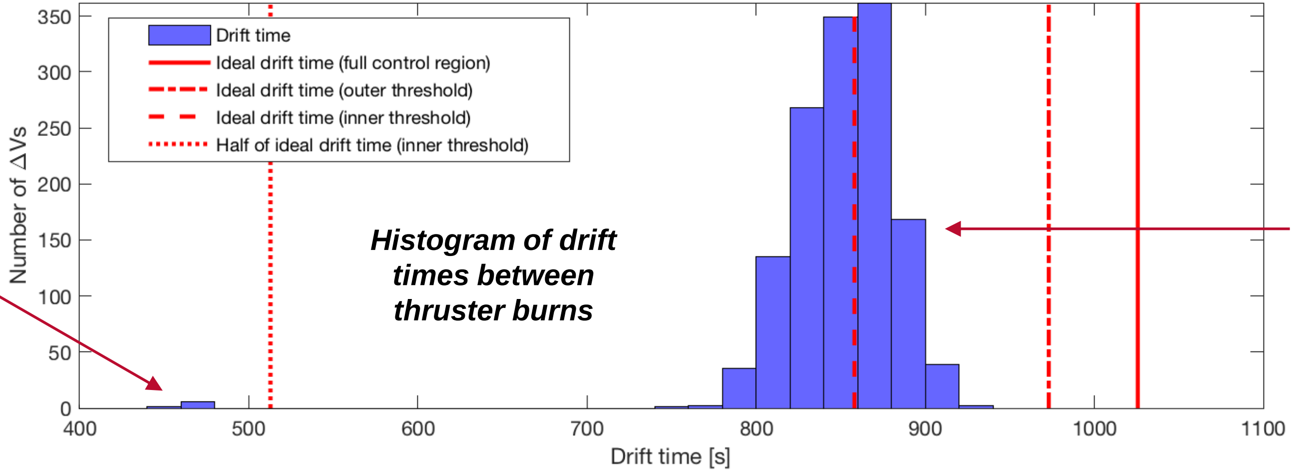


Results: Monte Carlo simulations statistics

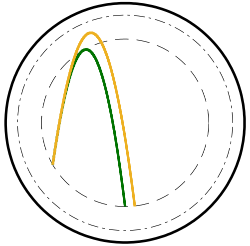
- **Effectively optimal drift time** given relative acceleration and control tuning
- **High observational efficiency:** Mean drift time for worst-case disturbance ~ 850s
- **Threshold sizing**: balance between nominal drift time and risk of correction burn



Correction burn required



Histogram of drift times between thruster burns



No correction burn required

Further simulations: robustness analysis

- Repeated Monte Carlo simulations with **HabEx**-like conditions:
  - Longer range (76.6Mm) → ~2x larger relative lateral acceleration
  - Larger dry mass (~6-7 tons)
  - Worst-case HabEx initial formation geometry

➔ **Approach robust to <u>environment</u>**

- Repeated Monte Carlo simulations **0.5Hz sensor measurement rate**

➔ **Approach not driven by <u>sensor measurements</u>**

- Identified driving disturbance: **<u>mass uncertainty</u>**
  - Only affects observational efficiency, not ability to meet milestone

➔ **Readily addressed with calibration**

Formation flying simulations summary

- Showed lateral sensing approach **enables formation flying for starshades**
- Developed control approach that allows **meeting requirements** with **effectively optimal observational efficiency**
- Confirmed **robustness** of flight-traceable GNC algorithms, even with conservative assumptions

Formation Flying Milestone: Conclusion

Starshade Lateral Alignment Testbed validates the sensor model by demonstrating lateral offset position accuracy to a flight equivalent of ± 30 cm.

➔ Developed a lateral sensing approach based on least squares image fitting

➔ Showed that analytical and numerical models predict excellent performance: 3x better than requirement on 10x fainter stars

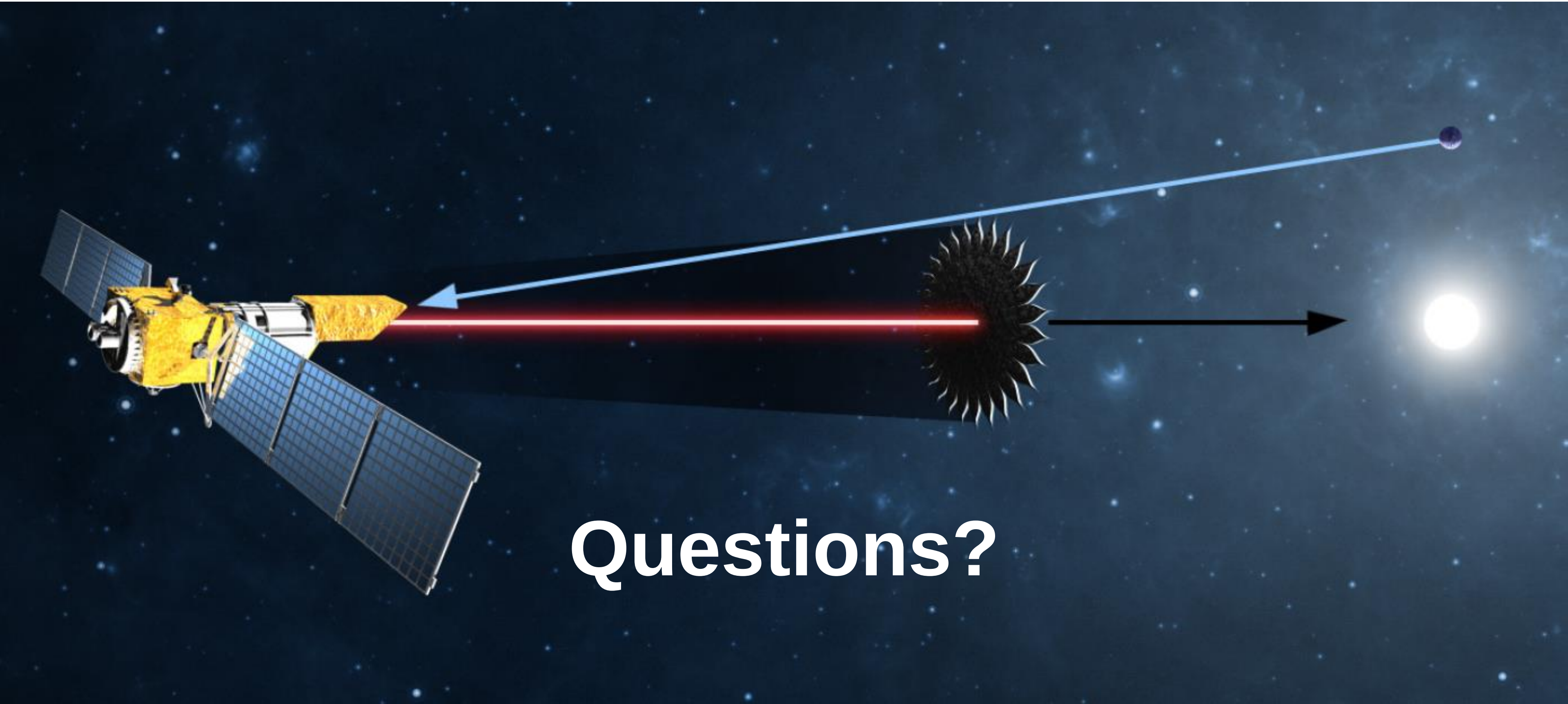
➔ Verified and validated formation sensing technique in SLATE hardware testbed

Control system simulation using validated sensor model demonstrates on-orbit lateral position control to within ± 1 m

➔ Created a high-fidelity model of the flight environment including a realistic sensor model with very conservative parameters

➔ Developed a control approach utilizing the sensor that meets formation flying requirements with effectively optimal observational efficiency

➔ Confirmed robustness of flight-traceable GNC algorithms, even with conservative assumptions



Questions?