

# MINIATURE DISTRIBUTED OCCULTER TELESCOPE (MDOT)

## A SUBSCALE STARSHADE MISSION IN EARTH ORBIT

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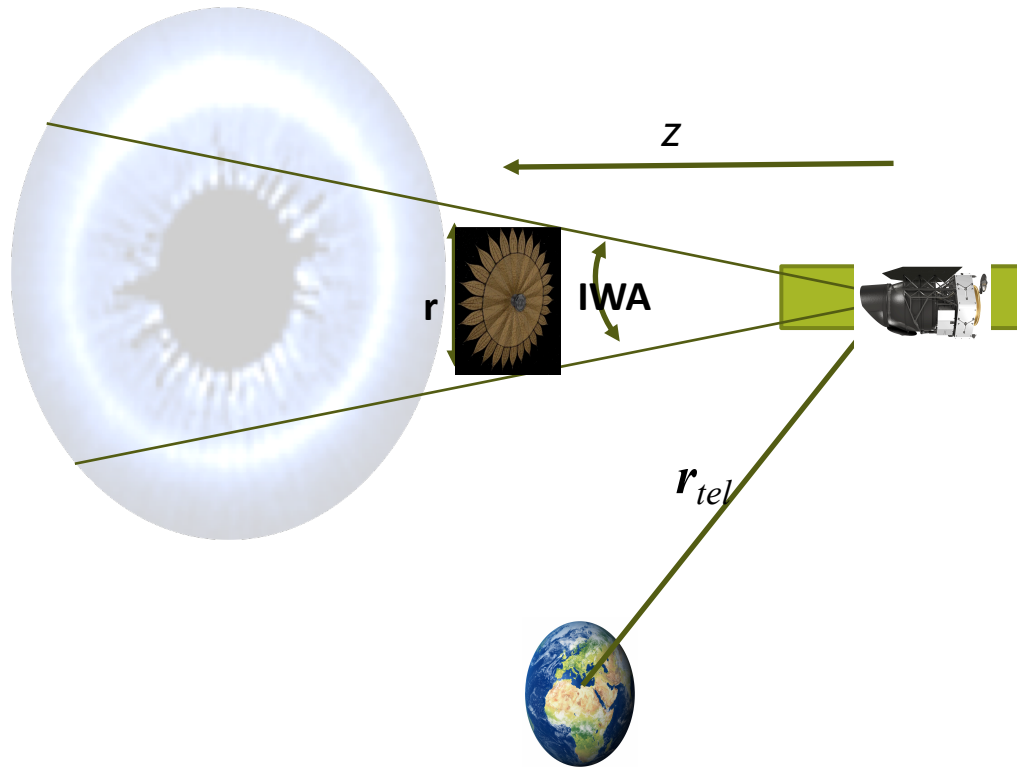
Stanford University

Ames Mission Design Center

JPL    Tendeg LLC



# Starshade scaling laws



Geometry: Inner Working Angle

$$IWA > \frac{r}{z}$$

Diffraction: Fresnel number

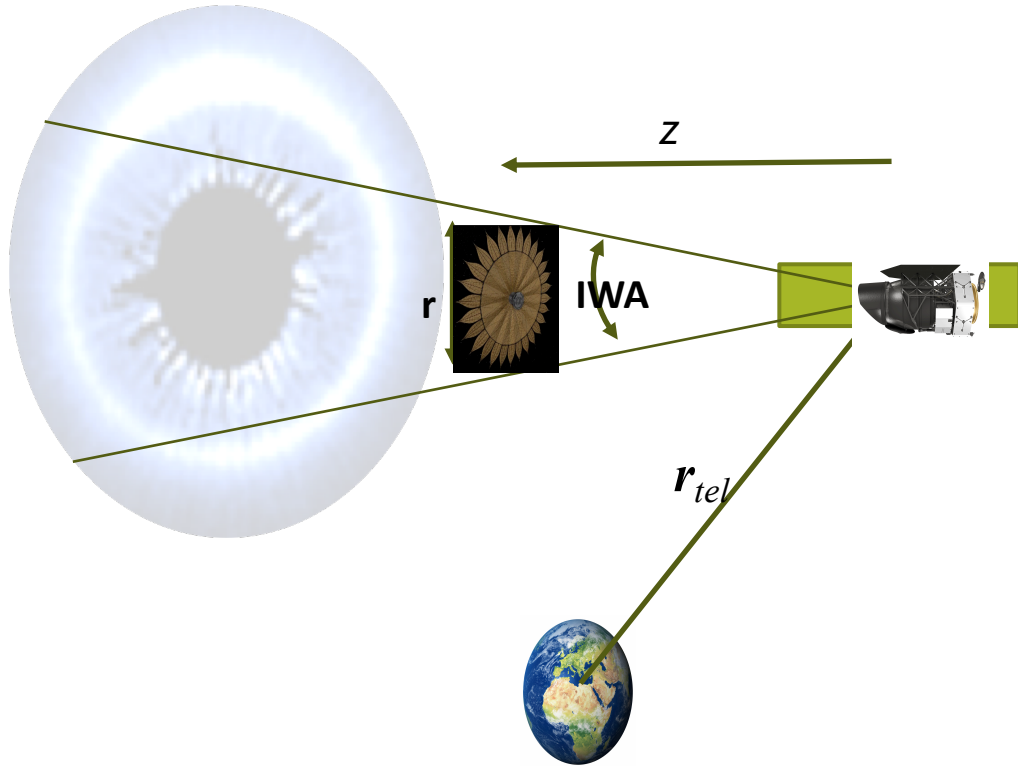
$$F < \frac{r^2}{z\lambda}$$

# Starshade scaling laws

Joint constraint

$$r = \frac{F\lambda}{IWA}$$

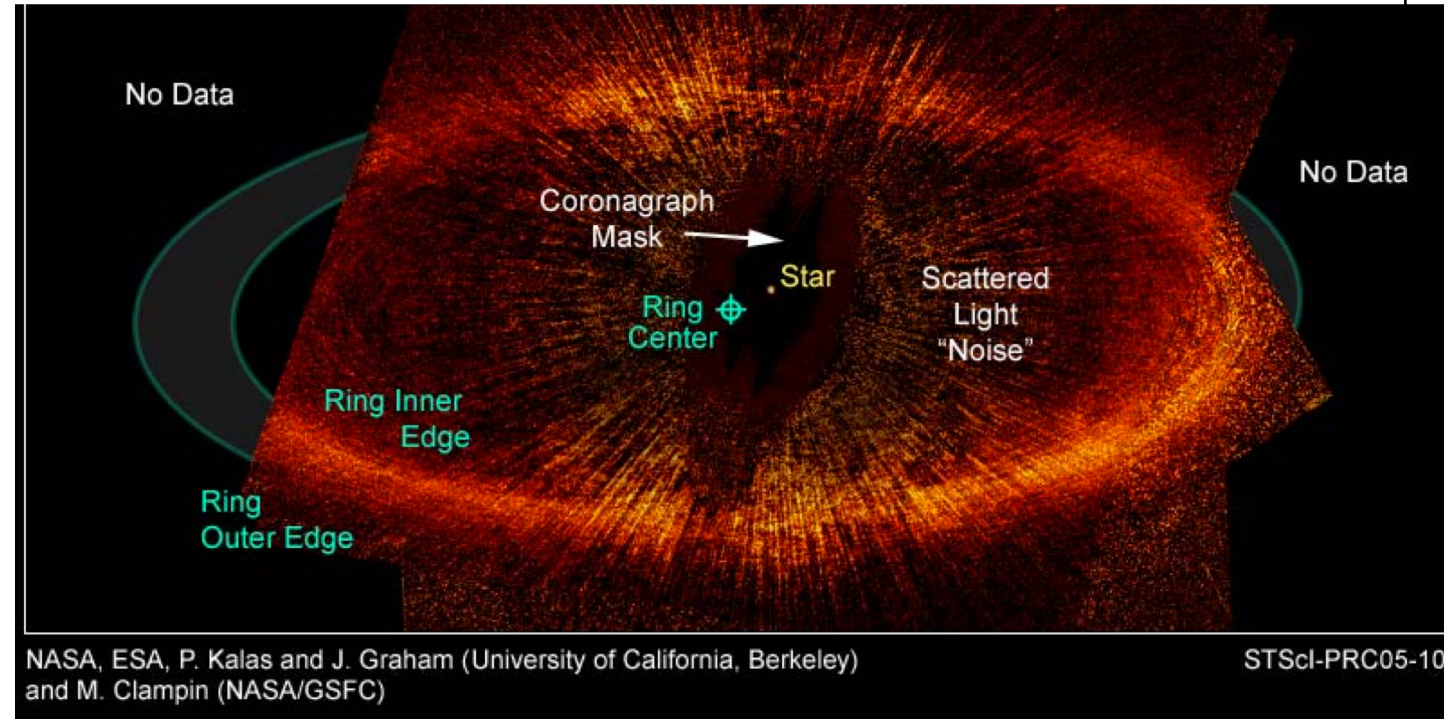
$$z = \frac{F\lambda}{IWA^2}$$



	IWA	Fresnel F	Wavelen $\lambda$	Radius R	Distance z	Contrast	D <sub>tel</sub>
Classic	0.1"	14	1000 nm	28	59,000 km	10 <sup>-10</sup>	2.4 m
Mini	0.6"	10	300 nm	1.5	350 km	10 <sup>-7</sup>	0.1 m

# Science objectives: circumstellar debris disks

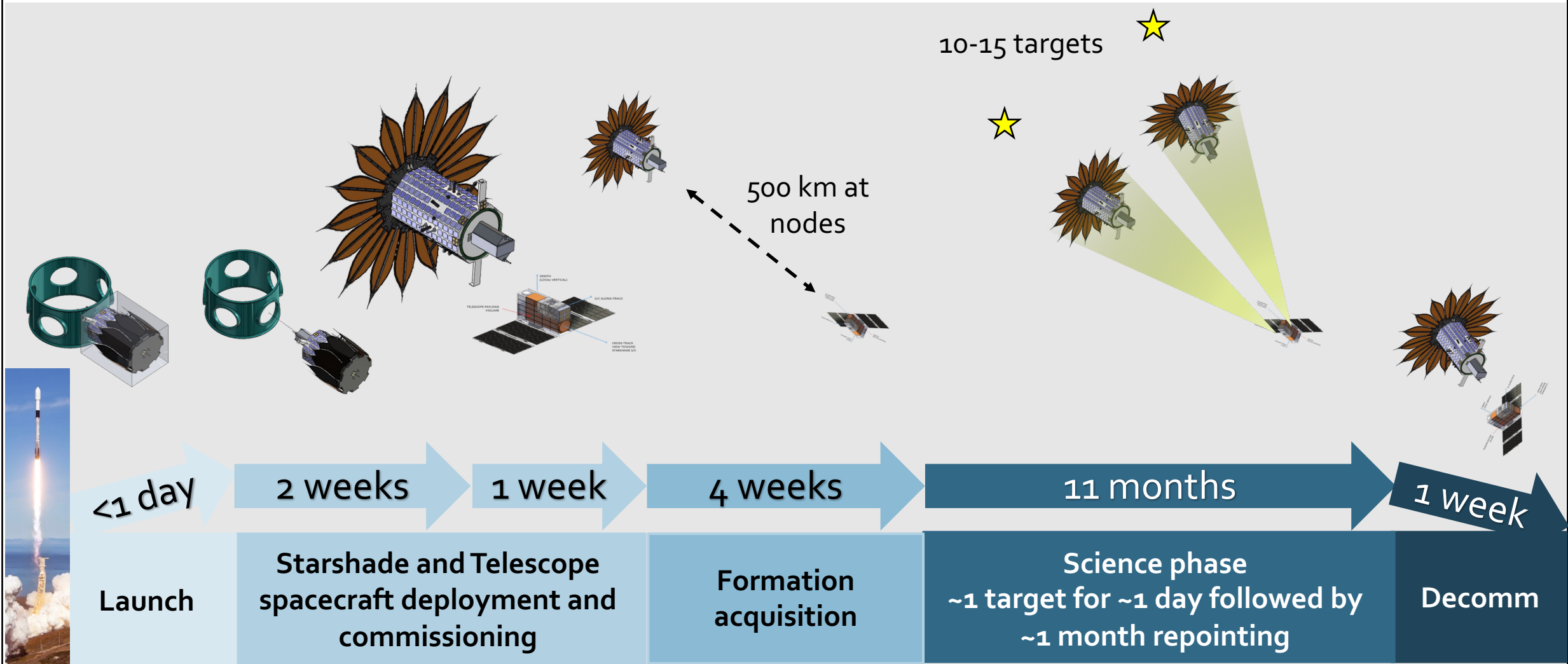
- Objective 1: Characterize known bright outer (10-1000 AU) debris disks at short wavelengths
- Objective 2: Measure visible to IR brightness ratio for stars with disks known through thermal emission
- Objective 3: Detect or constrain inner (<5 AU) zodiacal dust equivalents



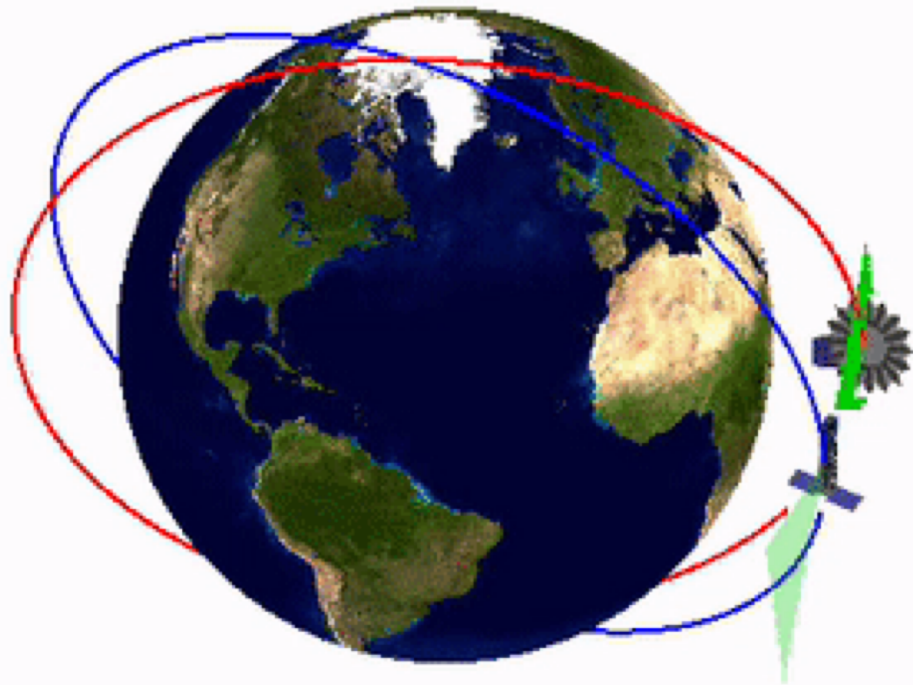
Hubble image of Fomalhaut ring (20")



# Concept of Operations

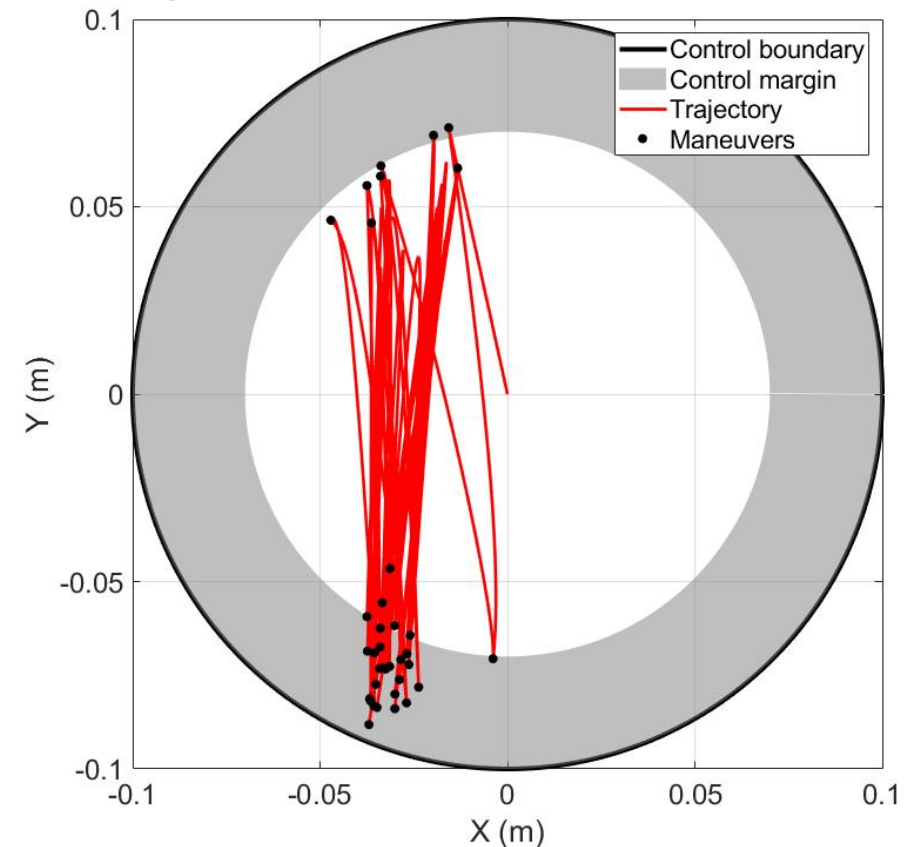


# Spacecraft in sun-synchronous orbits

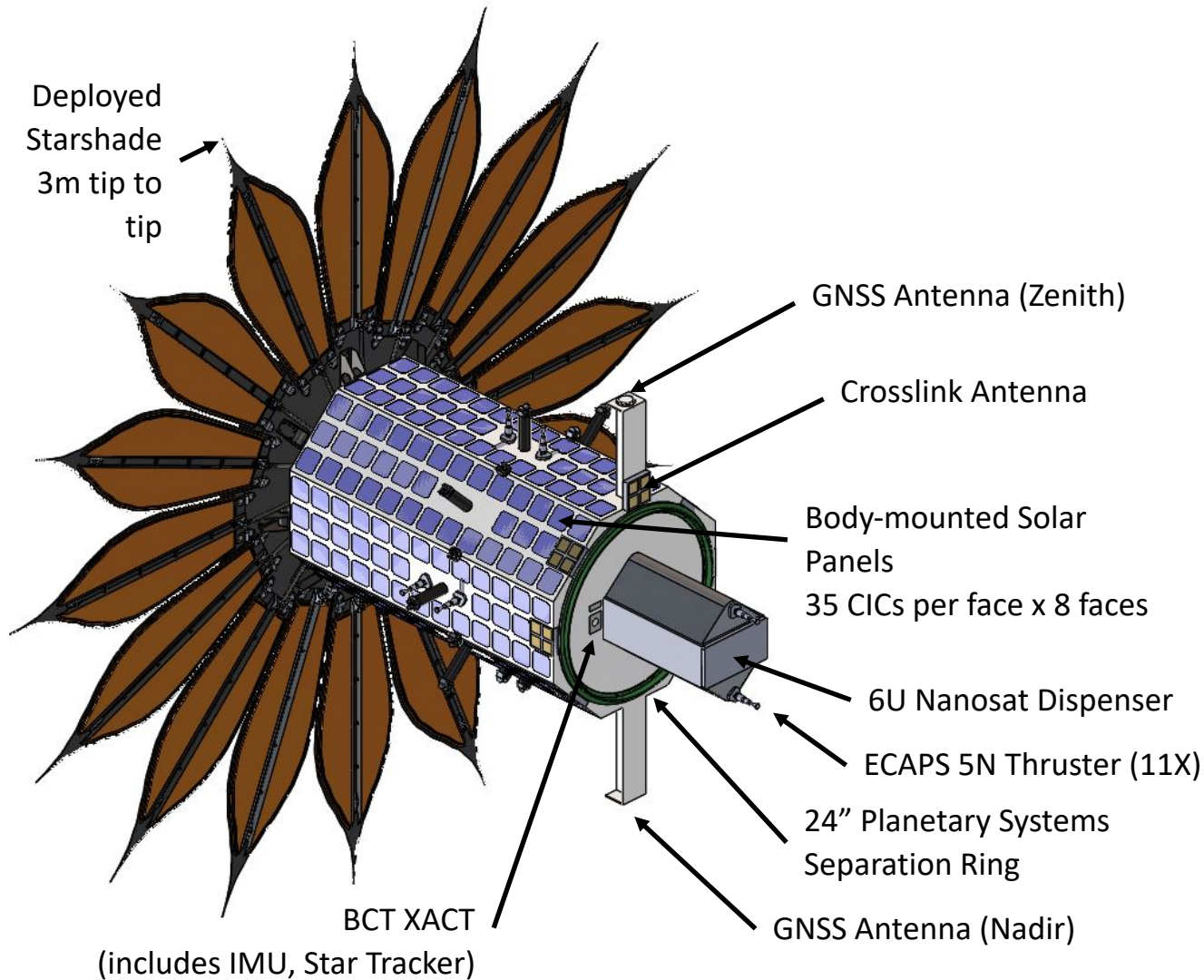


Observations: multiple 3-5 minute exposures during node crossings in shadow

Positional accuracy w thruster firings during typical 5-minute exposure  
GNSS navigation

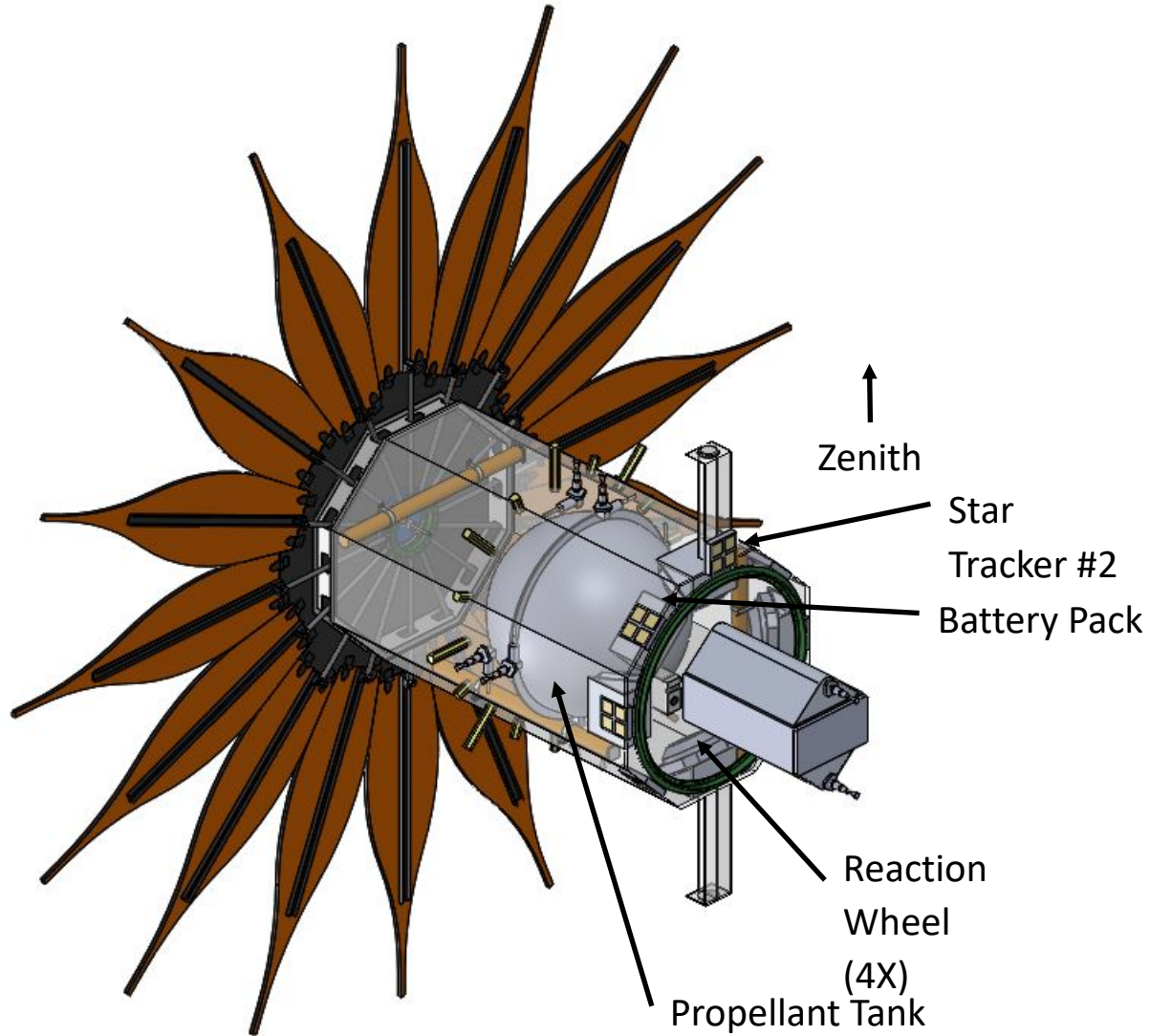


# mDOT: smallsat starshade spacecraft



Resource	CBE
Dry Mass (kg)	138
Prop Mass (kg) (81.2 kg for delta-V)	96
Total delta-V	940 m/s
Solar Power (W) - EOL	177
Battery Power (Whr)	345.6
Relative Position Navigation Accuracy (RMS)	<b>2 cm (3D)</b>
Relative Position Ctrl Accuracy (MAX)	<b>10 cm (R,T)</b>
Pointing Control Accuracy (deg)	0.002
Pointing Knowledge Accuracy (deg)	0.002
Starshade diameter	3 m

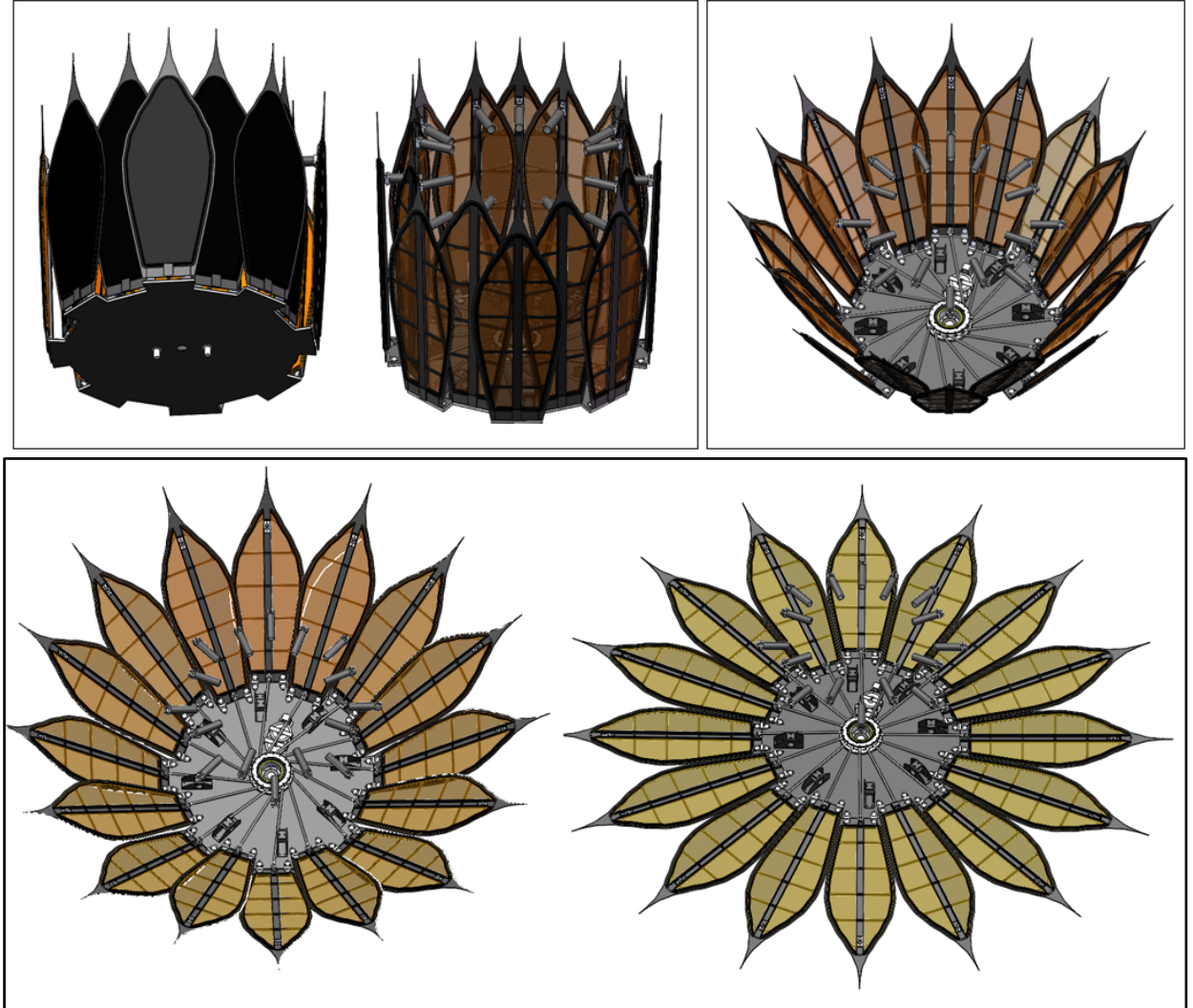
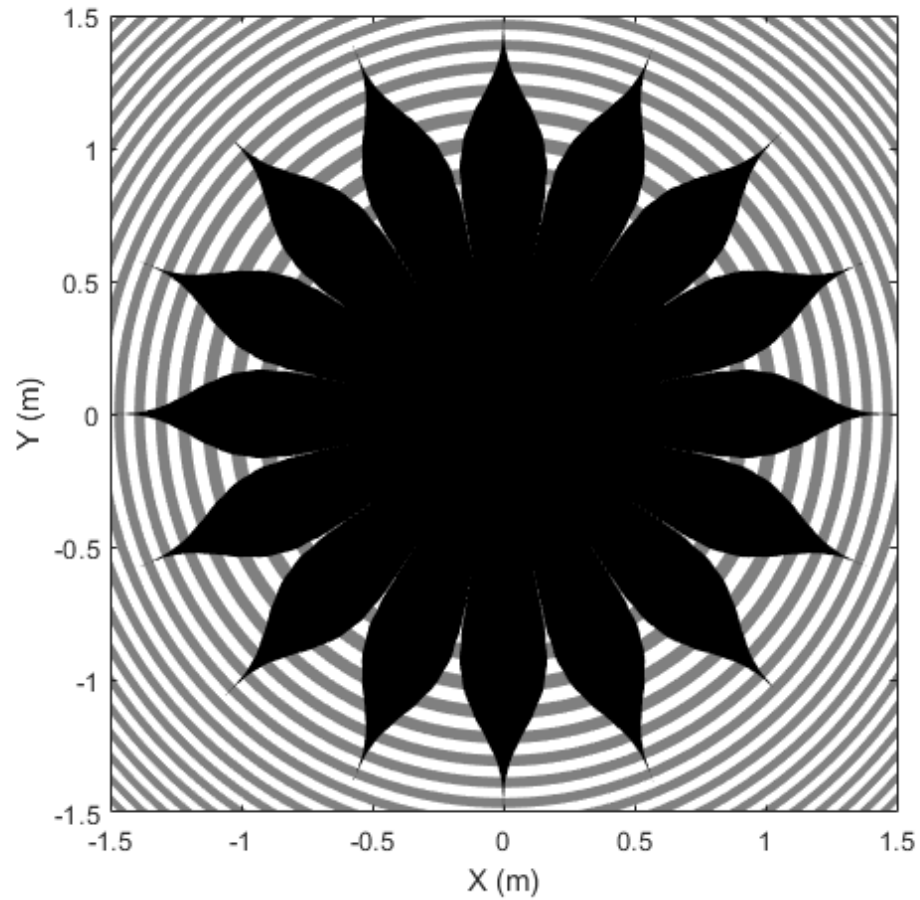
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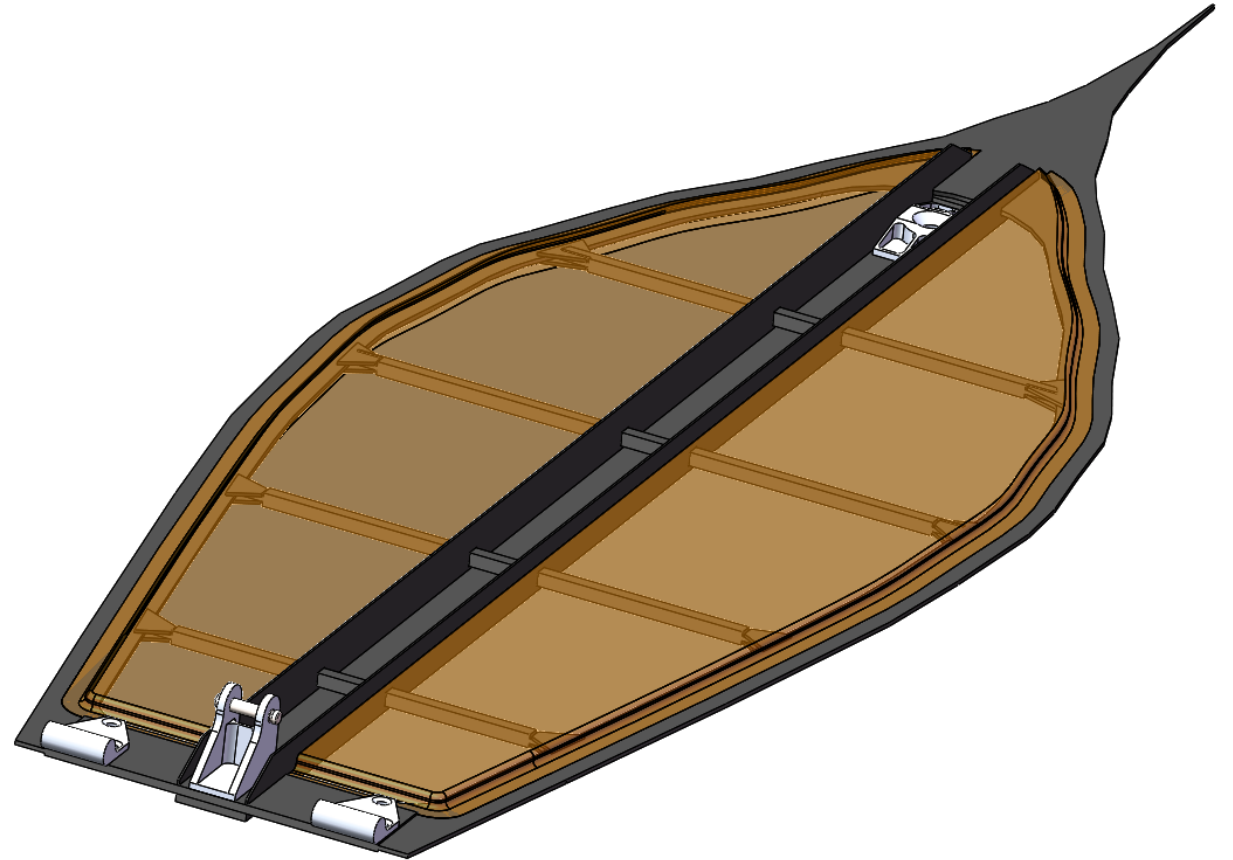


# Starshade suppression level $10^{-7}$

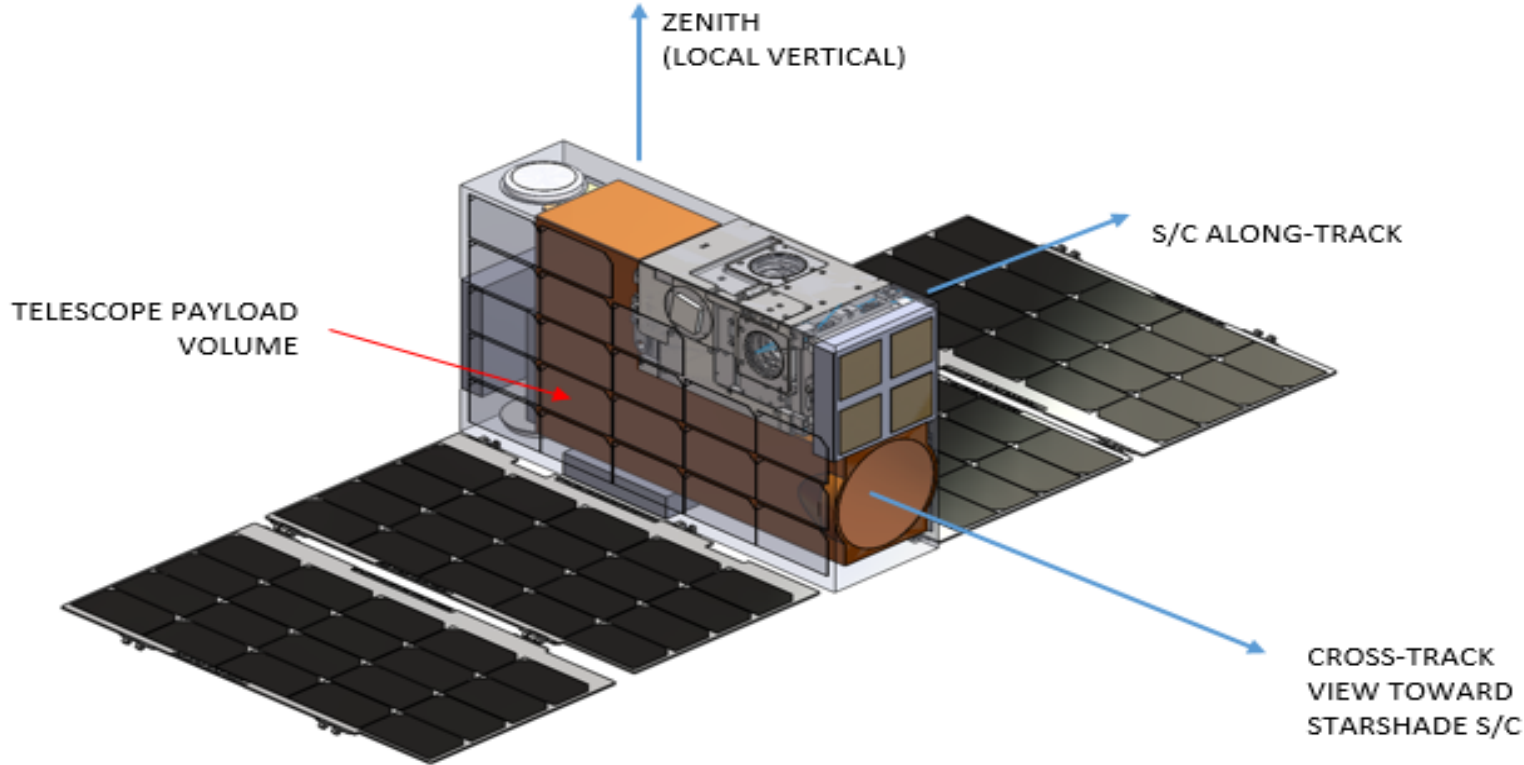


# Starshade petals (Tendeg LLC)

- Carbon fiber spine and battens
- Carbon fiber + amorphous foil optical edge
- Kapton petal material
- Typical tolerance ~2 mm



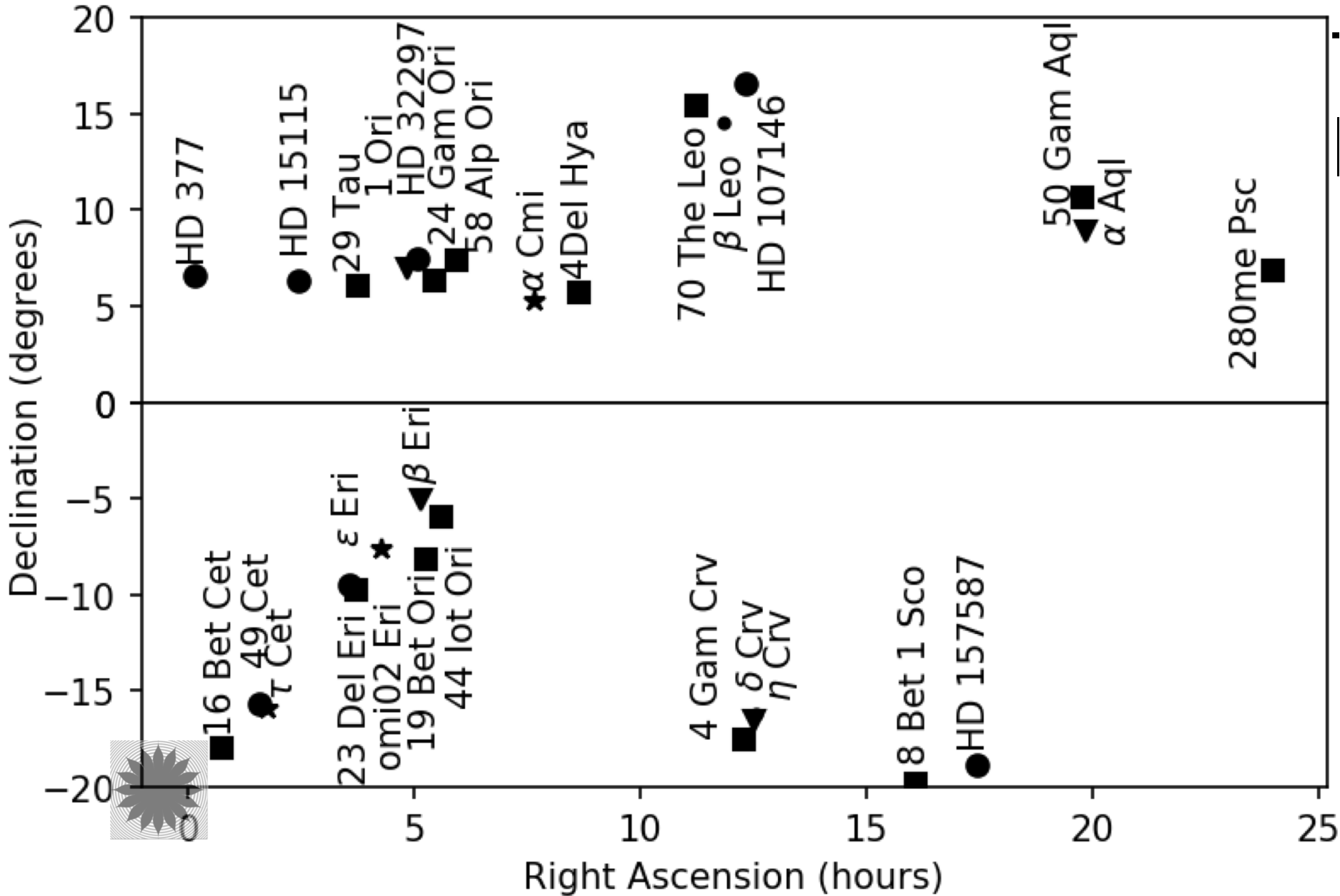
# mDOT: 6U Telescope spacecraft



Resource	CBE
Mass (kg)	12
Total delta-V	N/A
Solar Power (W) - EOL	10
Battery Power (W)	45
Pointing accuracy	2 cm (3D)
Telescope	9.2 cm
Image stability	0.2"
Image resolution	1"
Detector	2 x CMOS
Wavelength	B (450 nm)



# mDOT Targets



• Surface brightness sensitivity ~22 magnitudes per square arcsecond  
1-10 5-minute passes per target



# Simulations and Delta-V Budget

- **Mission profile**

- 98deg, LTAN of noon, 600km
- 15 targets (<5min single observations)
- Up to 50min cumulative observations
- Lifetime of about 1 year
- Declinations from 5 to 16 degrees
- State-of-the-art force modeling

- **GNC errors ( $3\sigma$ )**

- Absolute navigation: 1.5 m and 3 mm/s
- Relative navigation: 3cm, 0.03 mm/s
- Maneuver execution errors: 5%
- Process noise: only J2 considered in GNC

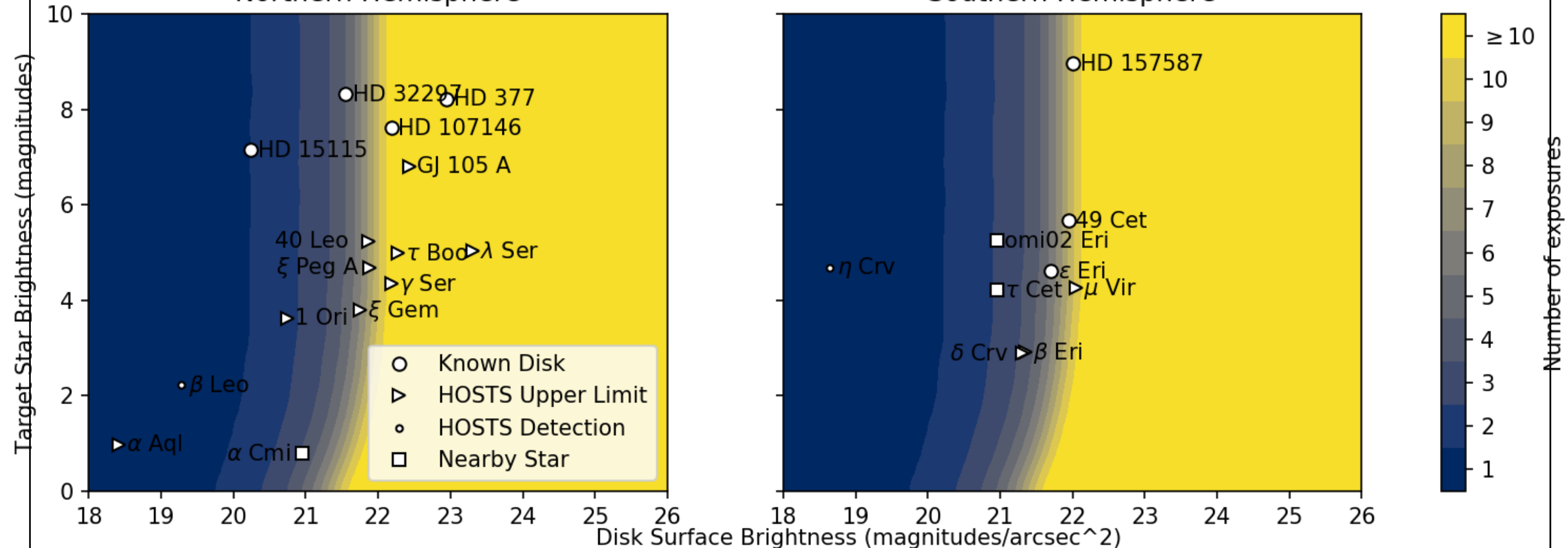
Source	Amount (m/s)
Formation acquisition	275
Science phase	375
Observations	115
Reconf to same target	91
Reconf to other target	169
Safe modes	25
De-orbiting	50
Margin (23%)	215
<b>Total</b>	<b>940</b>
Propulsion system	ECAPS (Green)
Specific impulse	240 s
Amount of propellant	81.2 kg
Thrusters	11x 5N

# Sensitivity vs exposure time

mDot 5 $\sigma$  detection thresholds at the IWA

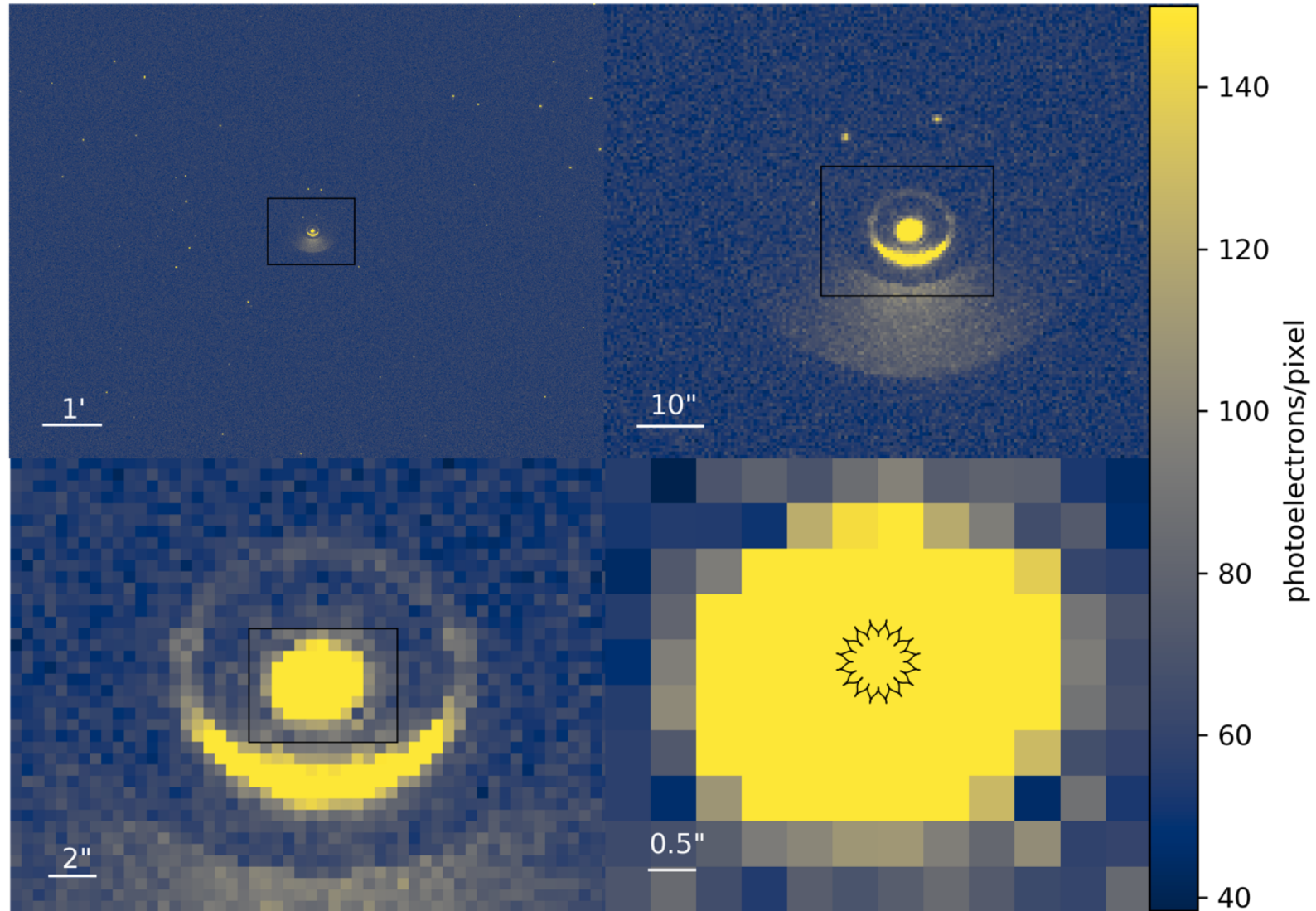
Northern Hemisphere

Southern Hemisphere

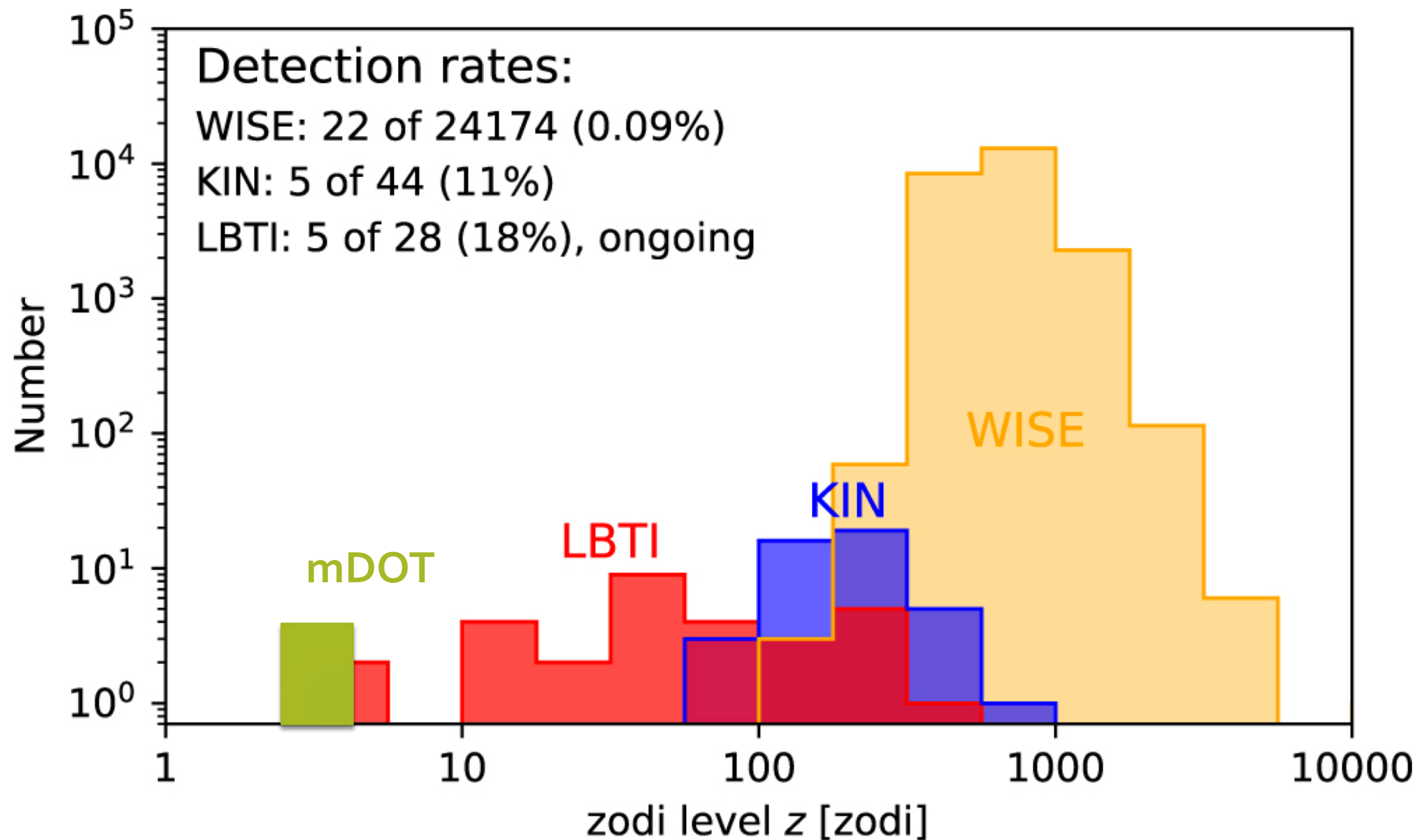


Surface brightness sensitivity ~22 magnitudes per square arcsecond  
1-10 5-minute passes per target

# mDOT observations of Epsilon Eridani



# 1-sigma sensitivity to zodiacal (<5 AU) dust



# Status

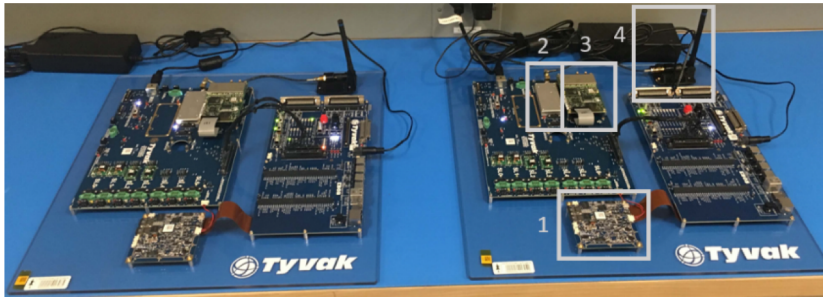
- This version of mDot is science-driven, not a pure technology demonstration
  - Design choices emphasized lowering cost and maximizing science potential
- Astrophysics small satellite study completed
  - Parametric estimate \$48M
- Didn't submit a mission proposal for 2019 call
- Refining project plan for 2021

# Conclusion and Future

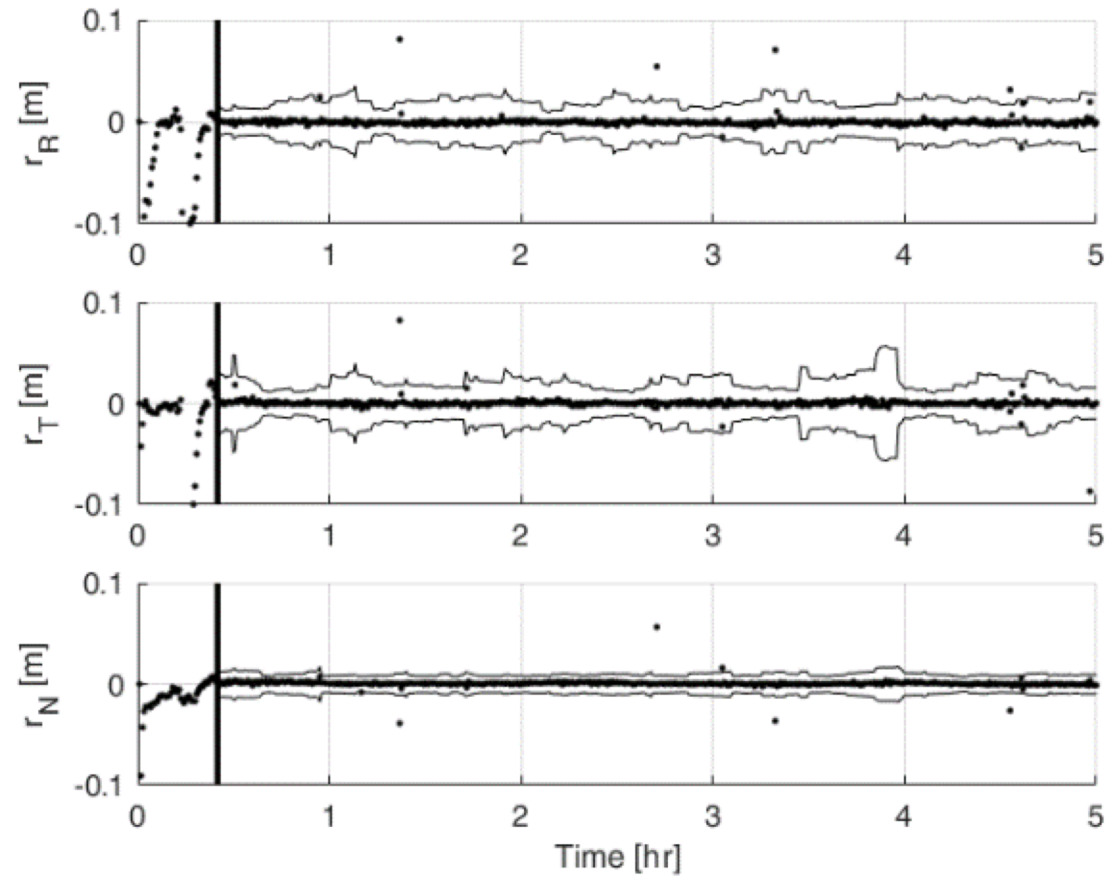
- Small starshade concepts in Earth orbit are feasible science missions and technology demonstrations
- Point design closes with healthy technical margins...mass, power, data
- Technology readiness level and risks have been assessed...and can be mitigated
  - Most systems TRL 7
  - Starshade manufacture and deployment, precision navigation, green thrusters TRL 5
- Future work and trades
  - Lower-cost mission implementation options (e.g., commercial partner)
  - Higher-capability versions with 20-30 cm telescope for exoplanet imaging
  - Dedicated technology demonstration features (navigation, performance)
  - Planning a workshop for early 2020



# Precise (cm-level) Relative Navigation using GNSS

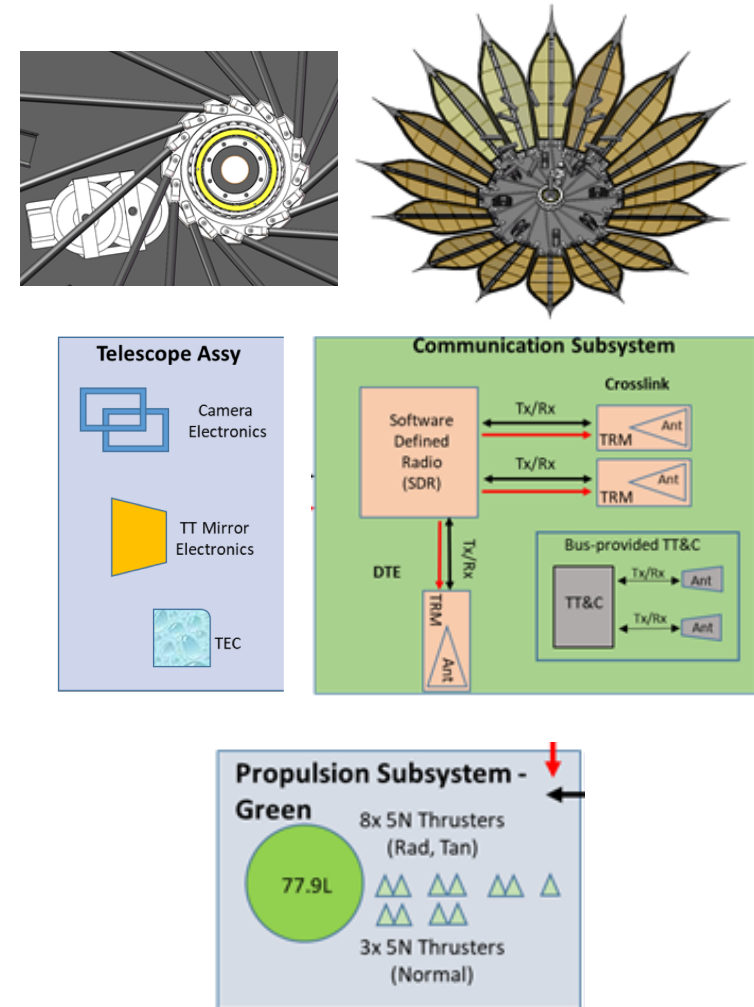


Relative State	Statistics
x	$0.19 \pm 9.96$ mm
y	$0.60 \pm 9.72$ mm
z	$0.84 \pm 0.84$ mm
vx	$-0.015 \pm 0.013$ mm/s
vy	$0.019 \pm 0.023$ mm/s
vz	$-0.009 \pm 0.008$ mm/s

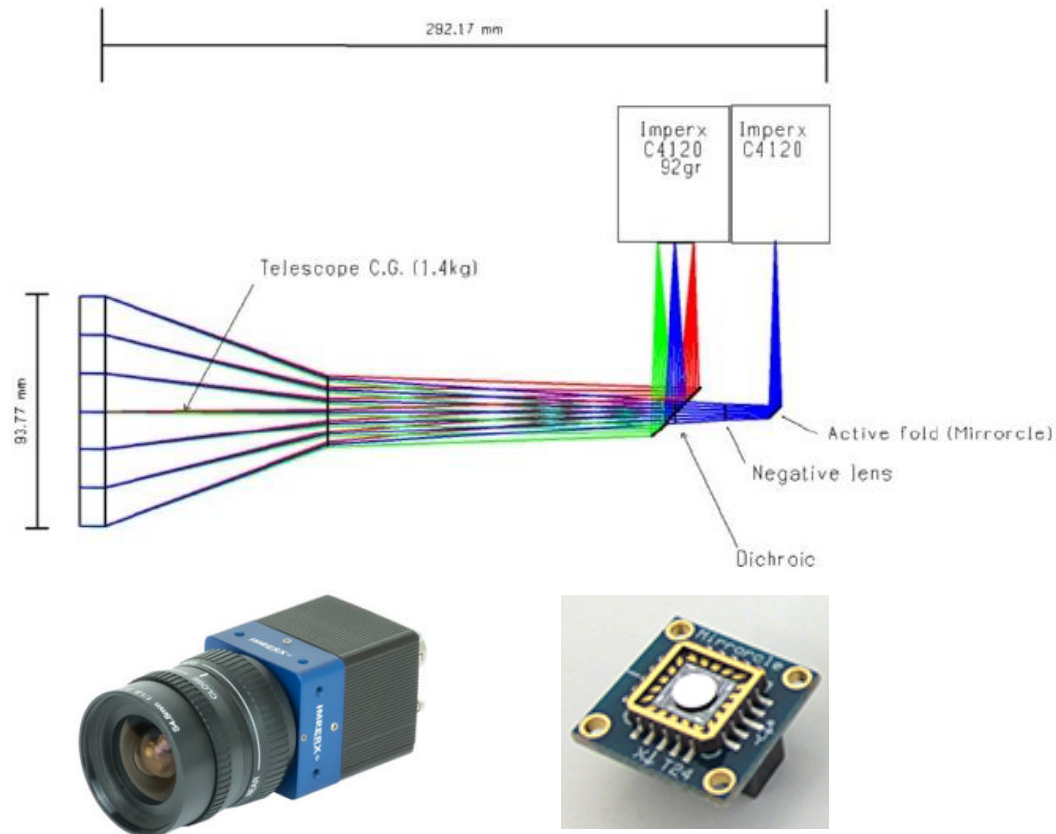


# Technology Readiness Level

- Most subsystems have TRL >7
- Subsystems with TRL 5-6
  - Starshade hub and motor with 16 deployable petals (Tendeg)
  - Telescope assembly with tip/tilt mirror and TEC (Planet)
  - Two (2x) Software Defined Radios with S-band module and antennas (Cesium)
  - Autonomous formation-flying software for precision navigation and control (Stanford)
  - Propulsion system with 11x 5N HPGP thrusters (ECAPS), LMP-1035 green propellant
- It is believed that all subsystems can be matured to TRL 6 within 2 years
  - Ground and qualification testing (starshade, communication)
  - Flight demonstrations (propulsion, GNC software)



# Payloads: Telescope from Planet Lab



Telescope	Parameter	Unit
Aperture	9.2	[cm]
Effective f/#	9	[-]
Focal length	70	[cm]
Weight	1400	[gr]
HFoV	1.484	[deg]
Camera	Parameter	Unit
Px size	3.45	[um]
Px count	4112	[px]
Mass	91.8	[gr]
FoV	1.2	[deg]

# Flight System: Launch Vehicle

