



# Definition of a Starshade Optical Demonstration at ISS

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# Argument for an Optical Test

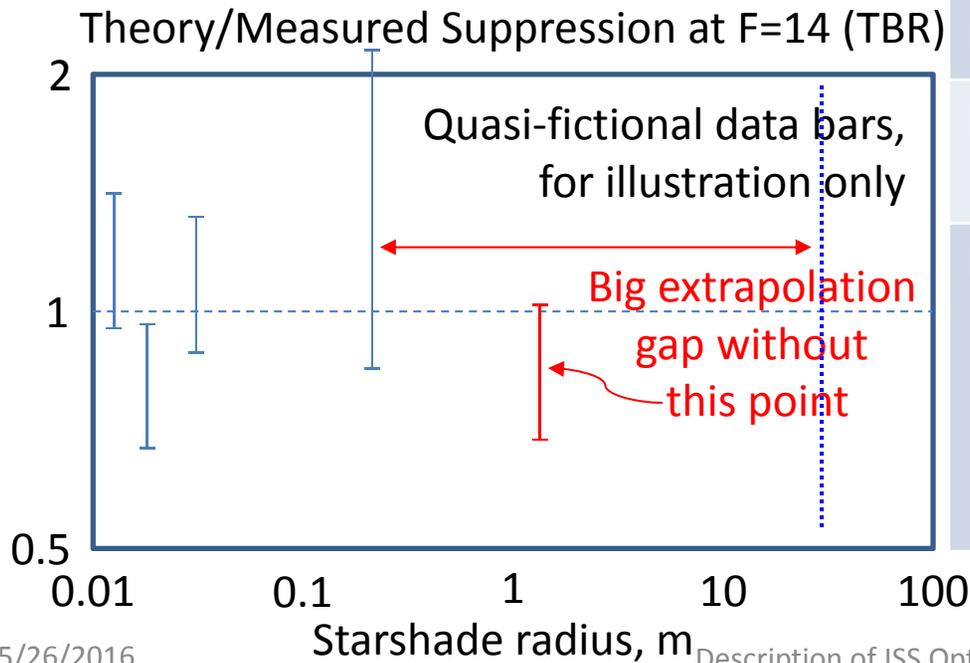
- Level 1 science for a starshade hinges on suppression and stability
- Pre-launch verification of flight starshade's suppression performance on orbit is ONLY by optical modeling
- Optical modeling is rooted in scalar-field Fresnel propagation, possibly enhanced to handle polarization
  - There are a handful of other known corrections to this model, none serious
- **Use of scalar-Fresnel theory is an assumption** which is still untested at the suppression levels we need, especially looking near the petals
  - Laboratory work will continue to shrink this gap
- We also rely on the scalar Fresnel model for *perturbation sensitivities* of the starshade petal shape
  - Rough experimental validation so far
- Suppression, contrast, and sensitivities for all performance budgeting relies on the scalar Fresnel assumption, including starshade-size dependence
  - This is probably correct (or good enough), because known non-Fresnel effects become less important at larger size
  - Are we brave enough to fly a \$B mission without testing for deviations from scalar-Fresnel, at the right Fresnel number and within 10× in size and 2× in suppression?
  - This is an unknown-unknown risk that belongs on our list. Is it serious enough that we should retire it at a lower cost-point first?



# Fill the optical-model validation gap

- Flight demo to validate scalar-Fresnel assumption for starshade optical modeling
- Low-cost, mid-size, high-accuracy

Optical	
Demonstrates	High suppression & accurate modeling
Diameter	1-3m
Formation distance	100-500km
Wavelength range	0.6-2 $\mu\text{m}$ (TBR)
Fresnel number	14 or so
Mounted on	Dragon vehicle or large "cubesat"
Key metrics	<ul style="list-style-type: none"> <li>• Suppression, on-axis and 1<sup>st</sup> min.</li> <li>• Petal shape error sensitivities (optional)</li> </ul>





# Prerequisite Challenges

- Stray light
  - Must always work on night side
  - Need super-bright targets (Jupiter & moons, or GEO satellites?)
  - Short separation → exacerbates stray light from cities & twilight
- Always in a hurry
  - Each experiment completes within 30-40 min
- Generous propulsion  $\Delta V$ 
  - Counteract gravity gradients
  - Maneuver quickly into inertial alignment
- Alignment acquisition and control
  - Probably need to begin setup in sunlight, complete it in twilight
- Safety
  - There's a lot of maneuvering volume that doesn't intersect ISS, but...



# Starshade Demo sizing

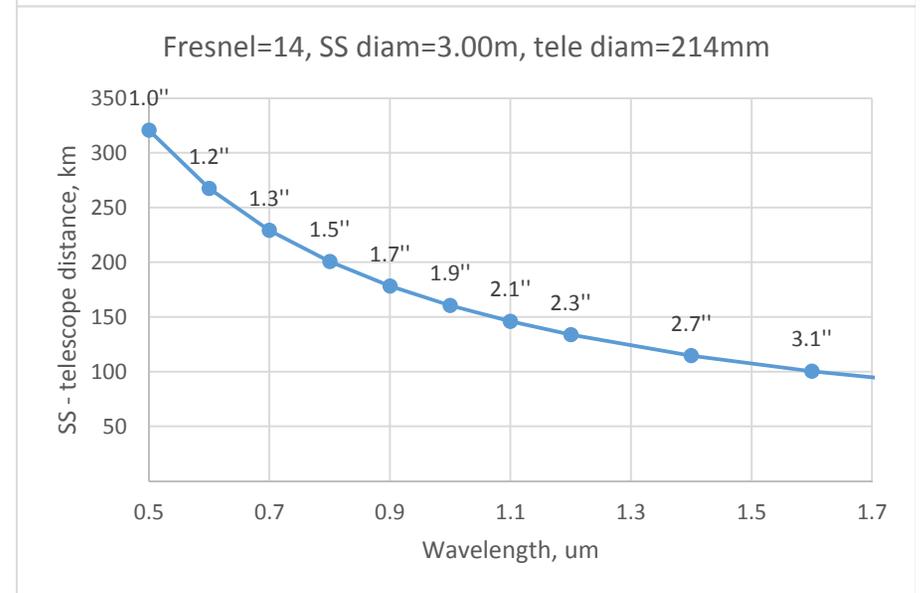
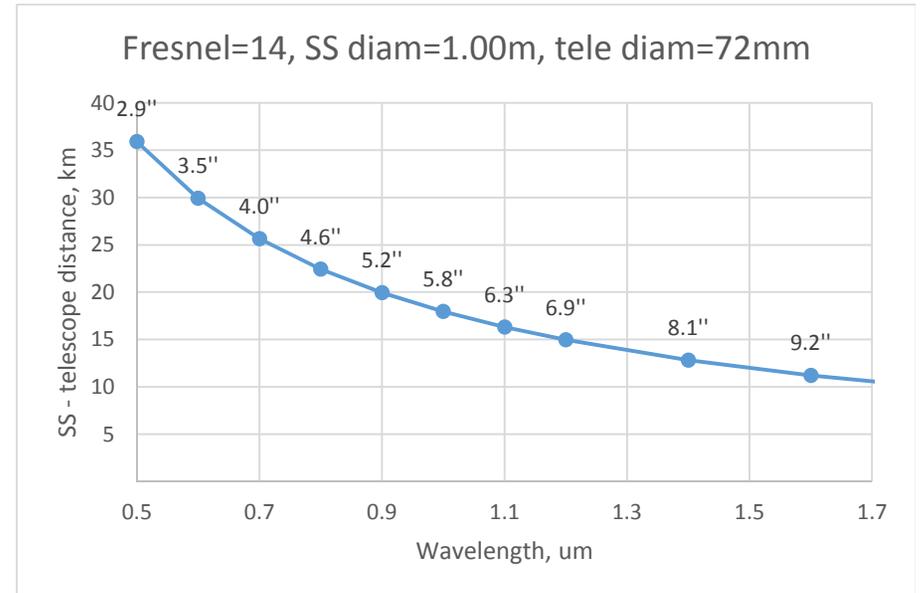
- Require  $F=14$ , comparable to science mission design
- Fix Starshade diameter = 1 or 3m
  - Design choice for tech demo
  - Requires  $IWA \propto \lambda$
- Fix telescope diameter  $D$  so that  $2 \cdot \lambda / D = IWA \rightarrow \text{starshade/tele} = F$

SS diam=1 m  
Tele diam=71mm

$\lambda$	Distance	IWA
0.5 $\mu\text{m}$	35.7 km	2.9"
0.6 $\mu\text{m}$	29.7 km	3.5"
0.7 $\mu\text{m}$	25.5 km	4.0"
0.8 $\mu\text{m}$	22.3 km	4.6"
0.9 $\mu\text{m}$	19.8 km	5.2"
1.0 $\mu\text{m}$	17.8 km	5.8"
1.1 $\mu\text{m}$	16.2 km	6.4"
1.2 $\mu\text{m}$	14.9 km	6.9"
1.4 $\mu\text{m}$	12.7 km	8.1"
1.6 $\mu\text{m}$	11.1 km	9.2"
1.8 $\mu\text{m}$	9.9 km	10.4"

SS diam=3m  
Tele diam=214mm

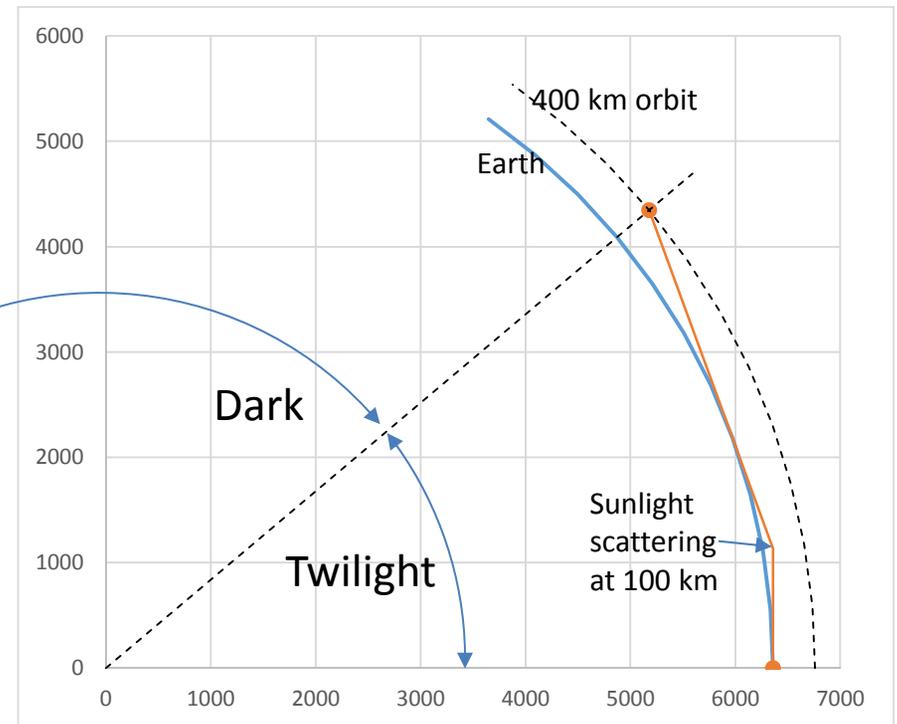
$\lambda$	Distance	IWA
0.5 $\mu\text{m}$	320.9 km	1.0"
0.6 $\mu\text{m}$	267.4 km	1.2"
0.7 $\mu\text{m}$	229.2 km	1.3"
0.8 $\mu\text{m}$	200.6 km	1.5"
0.9 $\mu\text{m}$	178.3 km	1.7"
1.0 $\mu\text{m}$	160.5 km	1.9"
1.1 $\mu\text{m}$	145.9 km	2.1"
1.2 $\mu\text{m}$	133.7 km	2.3"
1.4 $\mu\text{m}$	114.6 km	2.7"
1.6 $\mu\text{m}$	100.3 km	3.1"
1.8 $\mu\text{m}$	89.1 km	3.5"





# Always in a hurry

- ISS orbit is 92 min
- The 46 min in direct sunlight is unusable for observations
  - Stray light overwhelms the diffraction signal
  - Could (must) be used for maneuvering to the next nighttime opportunity
- Subtract 10+ min of twilight at each end of a night run
- Net <26 min of dark time
- All maneuvering and alignment acquisition must be done in direct sun and twilight
- Some orbit designs fight against orbit dynamics and need VERY muscular maneuvering





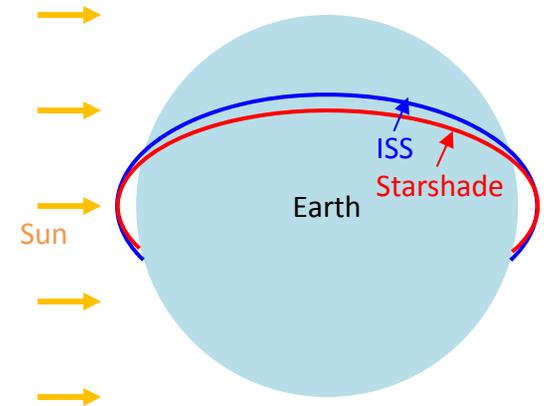
# Orbit Options

- The starshade will fly on halo orbits around the ISS, attempting to use orbital dynamics to advantage
- We can identify 3 options of orbit distinguished by the direction of the line of sight (LOS) to the star relative to the ISS orbit
- We will actually combine these 3 options for each target direction based on observing constraints
  - This discussion points out some comparisons of their virtues



# Orbit option 1: LOS near orbit pole

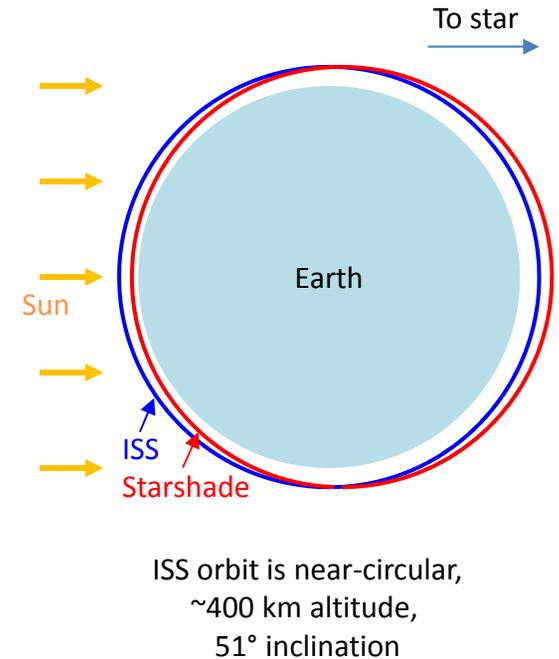
- Starshade orbit tilted vs. ISS plane,
  - 4.5° for ~500 km separation
  - Access to targets near pole of ISS orbital plane
- Starshade-telescope distance  $> \sim 100$  km takes proportionally more maneuvering fuel
  - Naturally repeating oscillation N-S-N-S-...
- Starshade-telescope bearing vector wanders only a little through the orbit
  - Mostly the residual from ISS avoidance maneuvers





## Orbit option 2: LOS near anti-sun

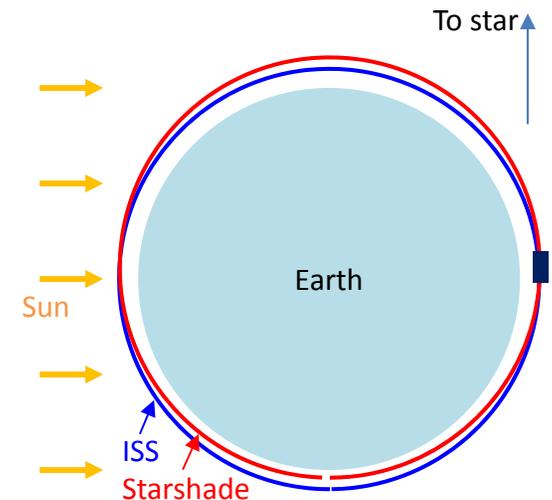
- Starshade orbit in ISS plane, slightly elliptical, offset by  $\sim 100$  km
  - Apogee=500 km on night side, perigee=300 km on day side
  - Access to targets near ISS orbital plane
- Starshade-telescope distance  $> \sim 100$  km takes much greater maneuvering fuel
  - Raise apogee  $> 500$  km, keep perigee  $> 300$  km
  - Aggressively, repeatedly forcing orbital semi-major axis and period
- Starshade-telescope bearing vector wanders throughout orbit, and changing the most during observation (midnight in orbit)
  - Overcoming that to stabilize on target star also requires fuel
- Achieves the longest observing window





## Orbit option 3: LOS earth-trailing/leading

- Starshade orbit in ISS plane, slightly elliptical, offset by  $\sim 100$  km
  - Apogee=500 km on leading side, perigee=300 km on trailing side
  - Access to targets near ISS orbital plane
- Starshade-telescope distance  $>\sim 100$  km takes much greater maneuvering fuel
- Starshade-telescope bearing vector wanders throughout orbit, but most stationary at start of observation (midnight in orbit)
  - Stabilizing it on target star requires somewhat less fuel
- Observing window cut in half: must wait until midnight, when star rises above earth horizon



ISS orbit is near-circular,  
 $\sim 400$  km altitude,  
 $51^\circ$  inclination



# Optical Signal Quality

- Stray light
  - Must always work on night-side, as dark as possible
    - less than 26 min window per orbit
  - Light from cities, flares, and other ground sources, scattering from
    - Near side of starshade (I have some info to estimate this)
    - Starshade propellant

- Target brightness and size
  - Brightest objects in sky are Solar System planets
  - But planets are too big for our starshades
    - Must be much smaller than IWA ~ 1-10 arcsec



- Detected Flux  $< L_{\text{sun}} \cdot \Omega_{\text{SP}} \cdot \alpha_{\text{P}} \cdot \Omega_{\text{EP}} \cdot A_{\text{T}}$ 
  - $L_{\text{sun}}$  = Luminosity of the sun
  - $\Omega_{\text{SP}}$  = Solid angle of sun seen from target planet
  - $\alpha_{\text{P}}$  = Albedo of the target planet
  - $\Omega_{\text{EP}}$  = Solid angle of target planet seen from Earth
  - $A_{\text{T}}$  = Area of the telescope

	Angular radius (as)
Mercury	3.64
Venus	12.05
Mars	8.92
Jupiter	23.40
Saturn	9.71
Uranus	1.93
Neptune	1.17
Pluto	0.04

Seen at best time in orbit

- To use planets as targets, must use smaller starshades and deeper IR



# Optical Signal Limits

- 18 stars or binaries are smaller than 1 arcsec and brighter than Vmag 1
- For the brightest star (Sirius,  $V = -1.09$ ), demonstrating sensitivity to a  $1e-10$  planet at SNR=5 in local+exozodi:

Telescope diameter	Starshade diameter	Integration time	Orbits	Elapsed time
71 mm	1 m	131.4 hr	304	466 hr
214 mm	3 m	1.88 hr	5	7.7 hr

- For Vmag +0.08 (the 6<sup>th</sup> brightest star)

Telescope diameter	Starshade diameter	Integration time	Orbits	Elapsed time
71 mm	1 m	1137 hr	2625	168 days
214 mm	3 m	14.6 hr	34	52 hr



# Propulsion

- Need  $\Delta v \sim 100 - 1000$  m/sec per day of observation
  - See tables below for typical  $\Delta v$  to stop at the pump on ISS and return to a halo orbit around ISS
  - Similar  $\Delta v$  for maneuvering to a different halo orbit for a new target star
  - Some fraction of this to complete and hold alignment on star
- Assume refillable tanks

SS diam=1 m  
Tele diam=71 mm

$\lambda$	Separation	IWA	$\Delta v$
0.5 $\mu\text{m}$	35.7 km	2.9"	40.3 m/s
0.6 $\mu\text{m}$	29.7 km	3.5"	33.6 m/s
0.7 $\mu\text{m}$	25.5 km	4.0"	28.8 m/s
0.8 $\mu\text{m}$	22.3 km	4.6"	25.2 m/s
0.9 $\mu\text{m}$	19.8 km	5.2"	22.4 m/s
1.0 $\mu\text{m}$	17.8 km	5.8"	20.2 m/s
1.1 $\mu\text{m}$	16.2 km	6.4"	18.3 m/s
1.2 $\mu\text{m}$	14.9 km	6.9"	16.8 m/s
1.4 $\mu\text{m}$	12.7 km	8.1"	14.4 m/s
1.6 $\mu\text{m}$	11.1 km	9.2"	12.6 m/s
1.8 $\mu\text{m}$	9.9 km	10.4"	11.2 m/s

SS diam=3 m  
Tele diam=214 mm

$\lambda$	Separation	IWA	$\Delta v$
0.5 $\mu\text{m}$	320.9 km	1.0"	363 m/s
0.6 $\mu\text{m}$	267.4 km	1.2"	302 m/s
0.7 $\mu\text{m}$	229.2 km	1.3"	259 m/s
0.8 $\mu\text{m}$	200.6 km	1.5"	227 m/s
0.9 $\mu\text{m}$	178.3 km	1.7"	202 m/s
1.0 $\mu\text{m}$	160.5 km	1.9"	181 m/s
1.1 $\mu\text{m}$	145.9 km	2.1"	165 m/s
1.2 $\mu\text{m}$	133.7 km	2.3"	151 m/s
1.4 $\mu\text{m}$	114.6 km	2.7"	130 m/s
1.6 $\mu\text{m}$	100.3 km	3.1"	113 m/s
1.8 $\mu\text{m}$	89.1 km	3.5"	101 m/s



# Baseline Concept

Characteristic	Value	Rationale
Telescope diameter	210 mm	Photometry
Starshade diameter	3 m	Premise, Telescope, Fresnel no.
Separation	180-200 km	Fresnel no.
Wavelength	0.8-0.9 $\mu\text{m}$	Fresnel no.
Inner Working Angle	1.5-1.7''	Derived
Suppression sensitivity	$10^{-10}$	Stringent test
Orbit	Halo orbits @ISS	Premise
Operation	Maneuver on day side Observe on night side	Strategy
Propulsion delta-V	1000-1500 m/s/day	Halo orbit speed, Maneuver strategy
Propulsion	Biprop	$I_{sp}$ , refueling

- Hopefully avoid any starshade deployment
- Hopefully avoid IR detectors



# Conclusions

- Haste is a significant challenge
  - Only about 26 min of each orbit is dark enough
- Telescope is small, and integration times are long
  - Subscale test → 1-3 m starshade
  - Want a stringent test of diffraction models,  $\sim 1e-10$  contrast sensitivity
  - Telescope diam  $\sim$  Starshade diam / Fresnel = 71-210 mm
  - Stars are the only viable targets, and there aren't many bright ones
    - Multiple orbits needed in the best case
- Propulsion demand is high
  - $\Delta v \sim 100 - 1000$  m/sec per day of observation
- Use GEO satellite as “synthetic star”?
  - Sunlight, with much smaller propagation distances (larger solid angles)
  - Even more difficult orbit dynamics
  - $42 \text{ m} / 42,164 \text{ km} = 0.2''$  ( $\sim \text{IWA}/10$ )