Definition of a Starshade Optical Demonstration at ISS

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Argument for an Optical Test

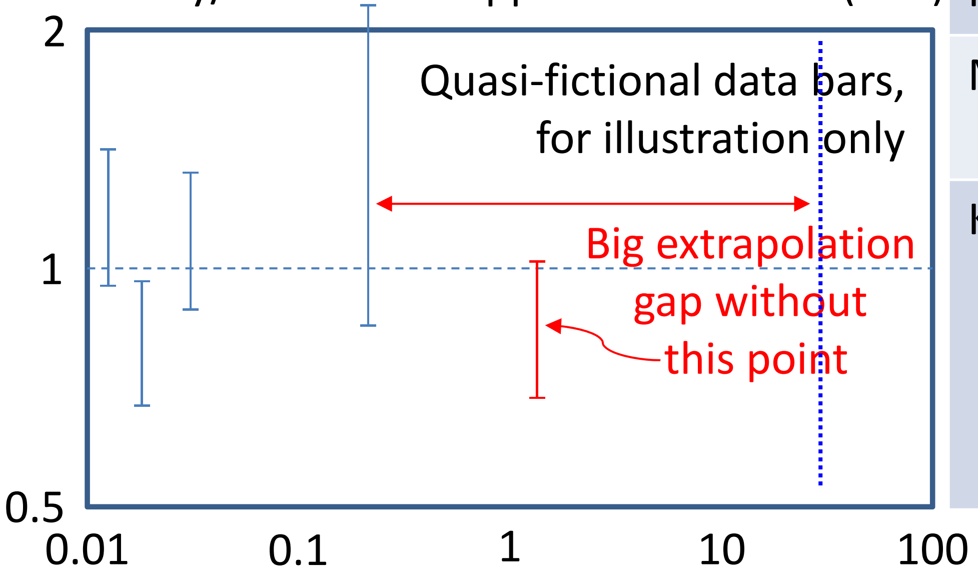
- Level 1 science for a starshade hinges on suppression and stability
- Pre-launch verification of flight starshade's suppression performance on orbit is ONLY by optical modeling
- Optical modeling is rooted in scalar-field Fresnel propagation, possibly enhanced to handle polarization
  - There are a 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 µm (TBR)
Fresnel number	14 or so
Mounted on	Dragon vehicle or large “cubesat”
Key metrics	• Suppression, on-axis and 1st min. • Petal shape error sensitivities (optional)

Theory/Measured Suppression at F=14 (TBR)



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 ΔV
  - 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

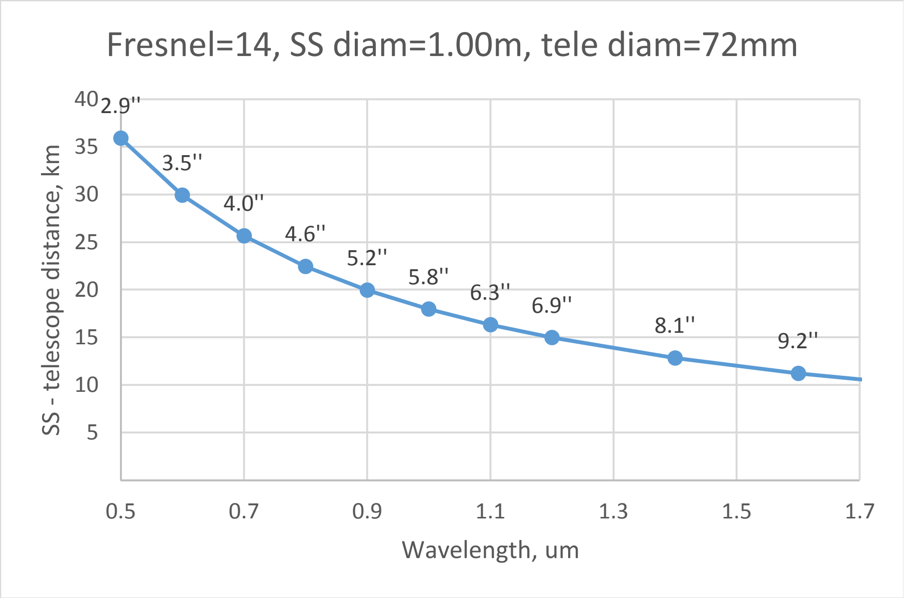
- Require F=14, comparable to science mission design
- Fix Starshade diameter = 1 or 3m
  - Design choice for tech demo
  - Requires IWA ∝ λ
- Fix telescope diameter D so that 2·λ/D = IWA → starshade/tele = F

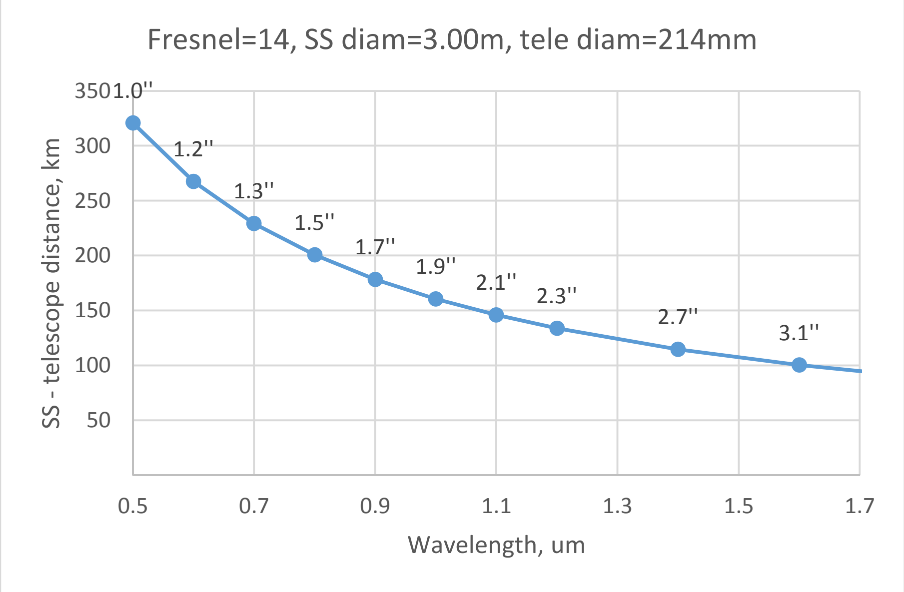
SS diam=1 m
Tele diam=71mm

λ	Distance	IWA
0.5 μm	35.7 km	2.9"
0.6 μm	29.7 km	3.5"
0.7 μm	25.5 km	4.0"
0.8 μm	22.3 km	4.6"
0.9 μm	19.8 km	5.2"
1.0 μm	17.8 km	5.8"
1.1 μm	16.2 km	6.4"
1.2 μm	14.9 km	6.9"
1.4 μm	12.7 km	8.1"
1.6 μm	11.1 km	9.2"
1.8 μm	9.9 km	10.4"

SS diam=3m
Tele diam=214mm

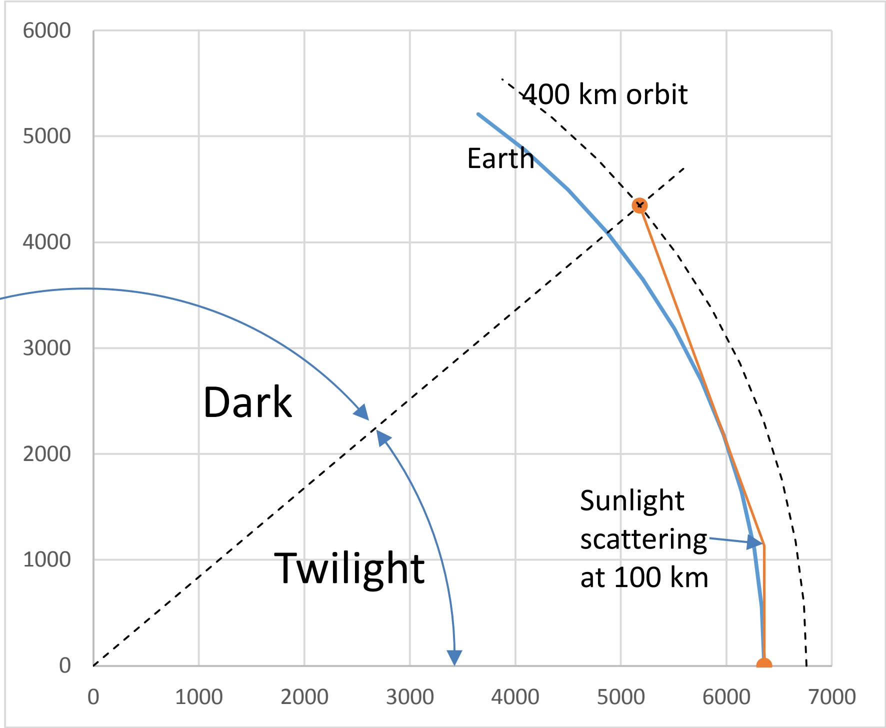
λ	Distance	IWA
0.5 μm	320.9 km	1.0"
0.6 μm	267.4 km	1.2"
0.7 μm	229.2 km	1.3"
0.8 μm	200.6 km	1.5"
0.9 μm	178.3 km	1.7"
1.0 μm	160.5 km	1.9"
1.1 μm	145.9 km	2.1"
1.2 μm	133.7 km	2.3"
1.4 μm	114.6 km	2.7"
1.6 μm	100.3 km	3.1"
1.8 μm	89.1 km	3.5"





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 <u>each end</u> 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

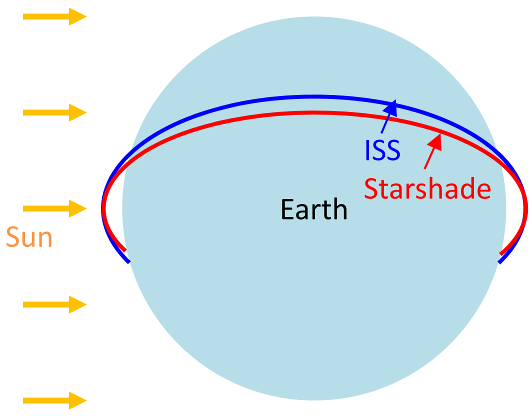


Orbit Options

- 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

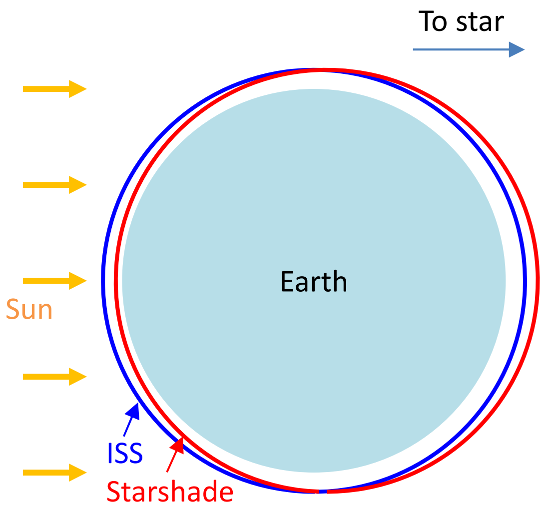
Orbit option 1: LOS near orbit pole

- Starshade orbit tilted vs. ISS plane,
  - 4.5° for ~500 km separation
  - Access to targets near pole of ISS orbital plane
- Starshade-telescope distance >~ 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

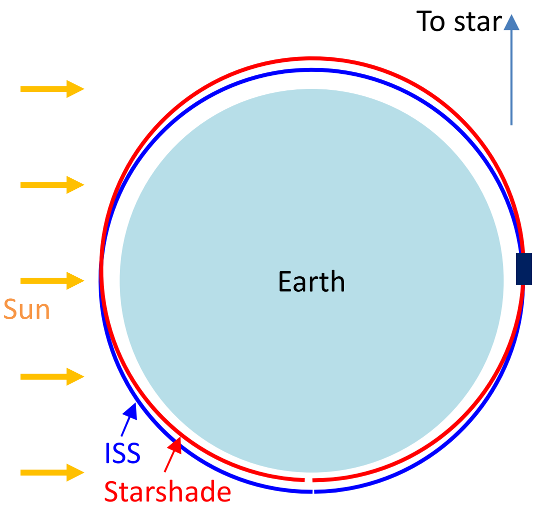
- Starshade orbit in ISS plane, slightly elliptical, offset by ~100 km
  - Apogee=500 km on night side, perigee=300 km on day side
  - Access to targets near ISS orbital plane
- Starshade-telescope distance >~ 100 km takes much greater maneuvering fuel
  - Raise apogee > 500 km, keep perigee > 300 km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



ISS orbit is near-circular,
~400 km altitude,
51° inclination

JPL Orbit option 3: LOS earth-trailing/leading

- Starshade orbit in ISS plane, slightly elliptical, offset by ~100 km
  - Apogee=500 km on leading side, perigee=300 km on trailing side
  - Access to targets near ISS orbital plane
- Starshade-telescope distance >~ 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,
~400 km altitude,
51° 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

	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

- Detected Flux $< L_{sun} \cdot \Omega_{SP} \cdot \alpha_P \cdot \Omega_{EP} \cdot A_T$
  - L_{sun} = Luminosity of the sun
  - Ω_{SP} = Solid angle of sun seen from target planet
  - α_P = Albedo of the target planet
  - Ω_{EP} = Solid angle of target planet seen from Earth
  - A_T = Area of the telescope
- 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 6th 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 Δv ~ 100 – 1000 m/sec per day of observation
  - See tables below for typical Δv to stop at the pump on ISS and return to a halo orbit around ISS
  - Similar Δv 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

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

SS diam=3 m
Tele diam=214 mm

λ	Separation	IWA	Δv
0.5 µm	320.9 km	1.0"	363 m/s
0.6 µm	267.4 km	1.2"	302 m/s
0.7 µm	229.2 km	1.3"	259 m/s
0.8 µm	200.6 km	1.5"	227 m/s
0.9 µm	178.3 km	1.7"	202 m/s
1.0 µm	160.5 km	1.9"	181 m/s
1.1 µm	145.9 km	2.1"	165 m/s
1.2 µm	133.7 km	2.3"	151 m/s
1.4 µm	114.6 km	2.7"	130 m/s
1.6 µm	100.3 km	3.1"	113 m/s
1.8 µm	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 µm	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, ~1e-10 contrast sensitivity
  - Telescope diam ~= 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
  - Δv ~ 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 m / 42,164 km = 0.2" (~ IWA/10)