Starshade Stray Light Assessment presented at Science and Industry Partnership F2F-2

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Introduction

- **We desire ≥ 30 mag planet sensitivity at SNR ≥ 4 to require noise sources ≥ 31.5 mags**
  - 30 mag planet has $1x10^{-10}$ planet contrast relative to a magnitude 5 star
  - Brighter noise sources can be calibrated down to 31.5 mag residuals

- **Here we try to identify all starshade created stray light sources & assesses compliance**
  - Can be considered “foreground” stray light
  - Stuart Shaklan separately presents solar edge scatter
  - Glenn Sellar presents secondary reflections (telescope facing surface with view to sun face surface)
  - Compliance presented for WFIRST Rendezvous but Habex delta’s are also discussed

- **Astronomical background sources are thought to set the noise floor at ~31.5 mags**
  - Can the TSWG confirm this or recommend another limit ?

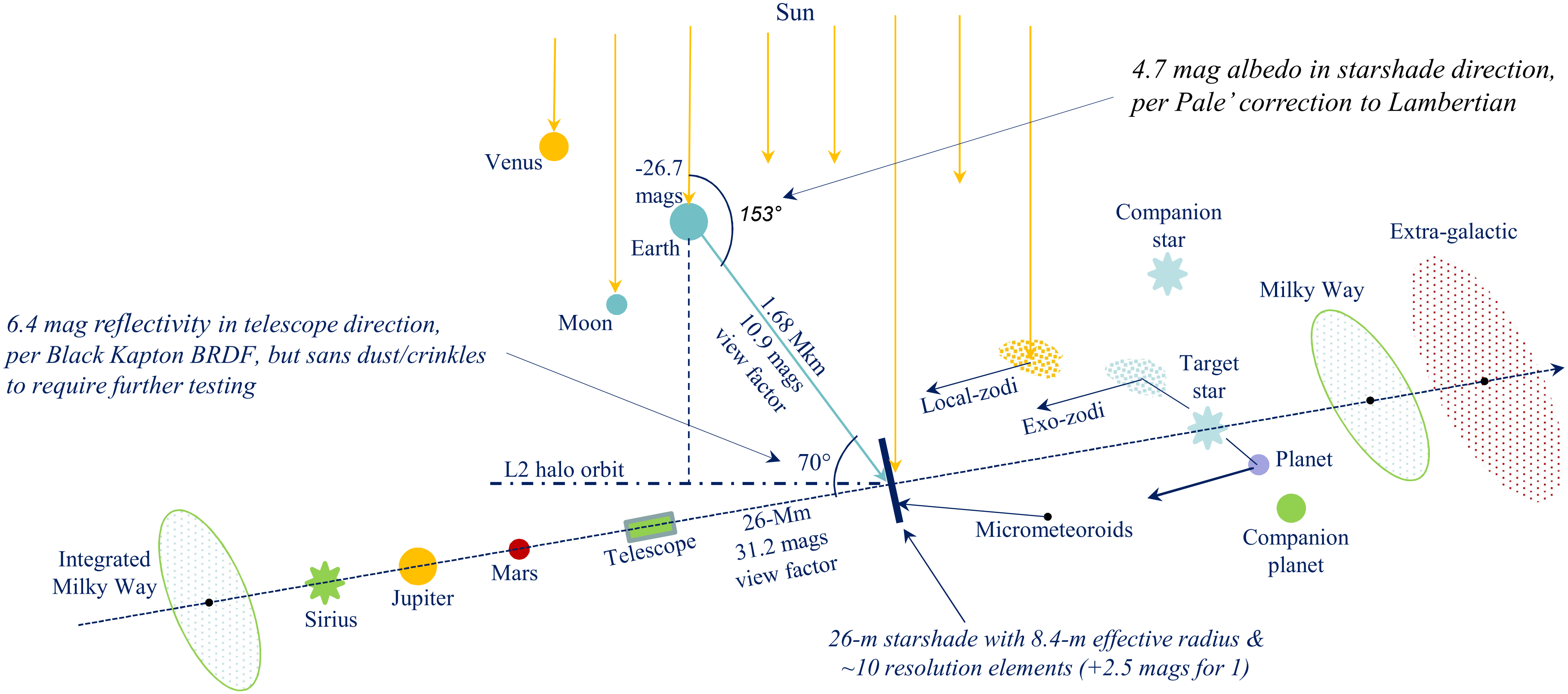
Foreground and Background Stray Light Sources

Starshade reflected bright-bodies
Off-axis **Earth**, Moon and Venus
On-axis Jupiter, Mars and Sirius
On-axis distributed Milky Way
Secondary solar reflections

Starshade solar leakage
Optical edge scatter
Direct material transmission
Optical shield close-out at petal-disk I/F
Transmission thru micrometeoroid holes

Astrophysical Background
Galactic & Extra-galactic
Exo-zodiacal light
Local-zodiacal light
Companion stars & exoplanets

Telescope straylight
Bright bodies direct to telescope
(picture on other side of orbit)



Summary of Results

2 sources detailed here

Bright-body case	Max expected level (mags per telescope res element)	Comments
Off-axis Earth	**29**	Requires calibration to 25% accuracy plus darker starshade &/or target pointing constraints
Off-axis Moon	≥ 31.6	**Gives ≥ 30 mag planet sensitivity without calibration**
Off-axis Venus	34.6	
On-axis Jupiter	32.8	
On-axis Mars	32.8	
On-axis Sirius	34.3	
On-axis integrated Milky Way	32.7	
Sun thru micrometeoroid holes	**37**	Large prelim. margin covers large uncertainty
Material opacity	>> 32	Black Kapton is highly opaque but rapid 2010 measurements are not documented & retest is desired (Princeton testbed)
Sun thru optical shield close-outs	TBD	Will design seals to required level
Optical Edge Scatter	See Shaklan's presentation	
Secondary Reflections	See Sellar's presentation	

Reflected Earth Light

- **Max expected reflected Earth light at the telescope is 29 mags per resolution element**
  - At extreme of orbit and target pointing
  - See table below (all numbers from figure above)

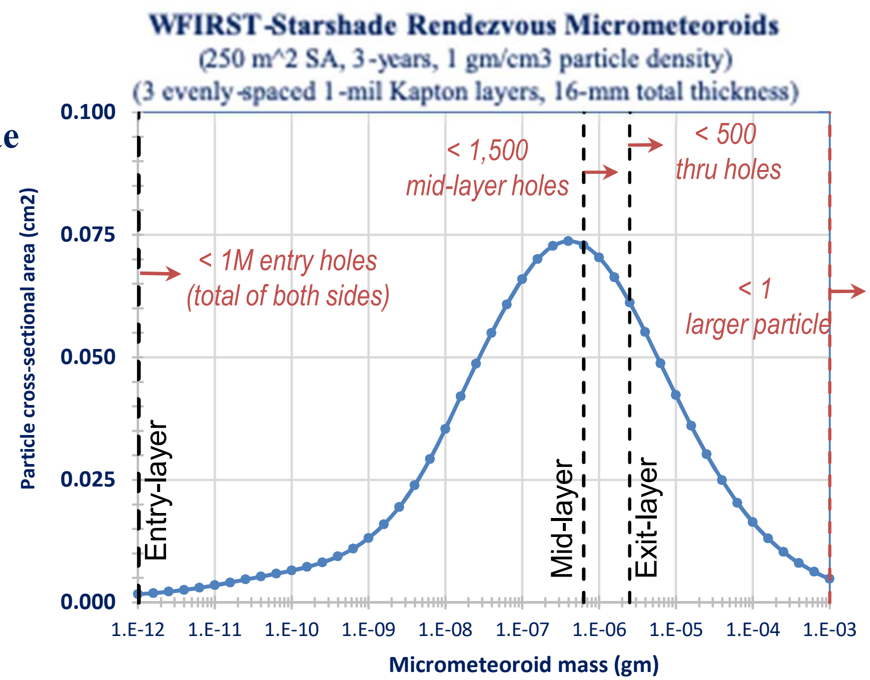
- **Calibration accuracy is probably limited by time varying Earth albedo to ~25%, which yields a planet sensitivity of only 29 mags (see table below) for a SNR of 4**

- **A darker starshade (AR coating) combined with minor pointing restrictions should achieve the 30 mag planet sensitivity goal**

Solar incidence on Earth	-26.7	
Earth albedo at 153 deg	4.7	In direction of starshade
Earth-starshade view factor	10.9	
Starshade reflectivity at 70 deg	6.4	In direction of telescope
1 of ~10 resolution elements	2.5	
Starshade-telescope view factor	31.2	
Earth light at telescope	**29.0**	mags per resolution element

Sun thru micrometeoroid holes

- **Optical shield consists of 3 evenly spaced layers of 1-mil thick Kapton and total thickness of 16-mm**
- **Heaviest particle stopped at each layer per published formulae**
  - NASA Std. PD-EC-1107 for single layer (entry holes)
  - SMAD for 2 spaced layers (3rd layer exit hole calc neglects mid-layer)
  - 50 km/s particle velocity (near max)
  - 2.5 gm/cm^3 particle density (only occurs for smaller particles)
  - Experimental constants for Al shield scaled with density to Kapton (Kapton melts at much higher temps, so should be conservative)
- **Particle flux per Grun model (same as JWST)**
- **Max expected hole area is ~100 ppm in each layer**
  - Particle areas per 1 gm/cm^3 density (only occurs for large aggregates)
  - Integrate area under curve to right for cum area of larger particles and multiply by hole expansion factors relative to particle **diameters**
  - 1.25X entry holes per observed craters
  - 20X mid-layer holes per semi-analogous simulations at much lower velocities (lateral gas cloud expansion is less at higher velocities)
  - 40X exit layer holes (2X spacing but neglects benefit of mid-layer)
- **37 mag per resolution element solar leakage at telescope**
  - 1E-12 (30 mags) porosity based solar transmission (100 ppm)^3
  - See table to right



Solar incidence on starshade	-26.7	
Starshade hole porosity	30	100 ppm^3 = 1E-12
1 of ~10 resolution elements	2.5	
Starshade-telescope view factor	31.2	
Earth light at telescope	**37.0**	mags per resolution element

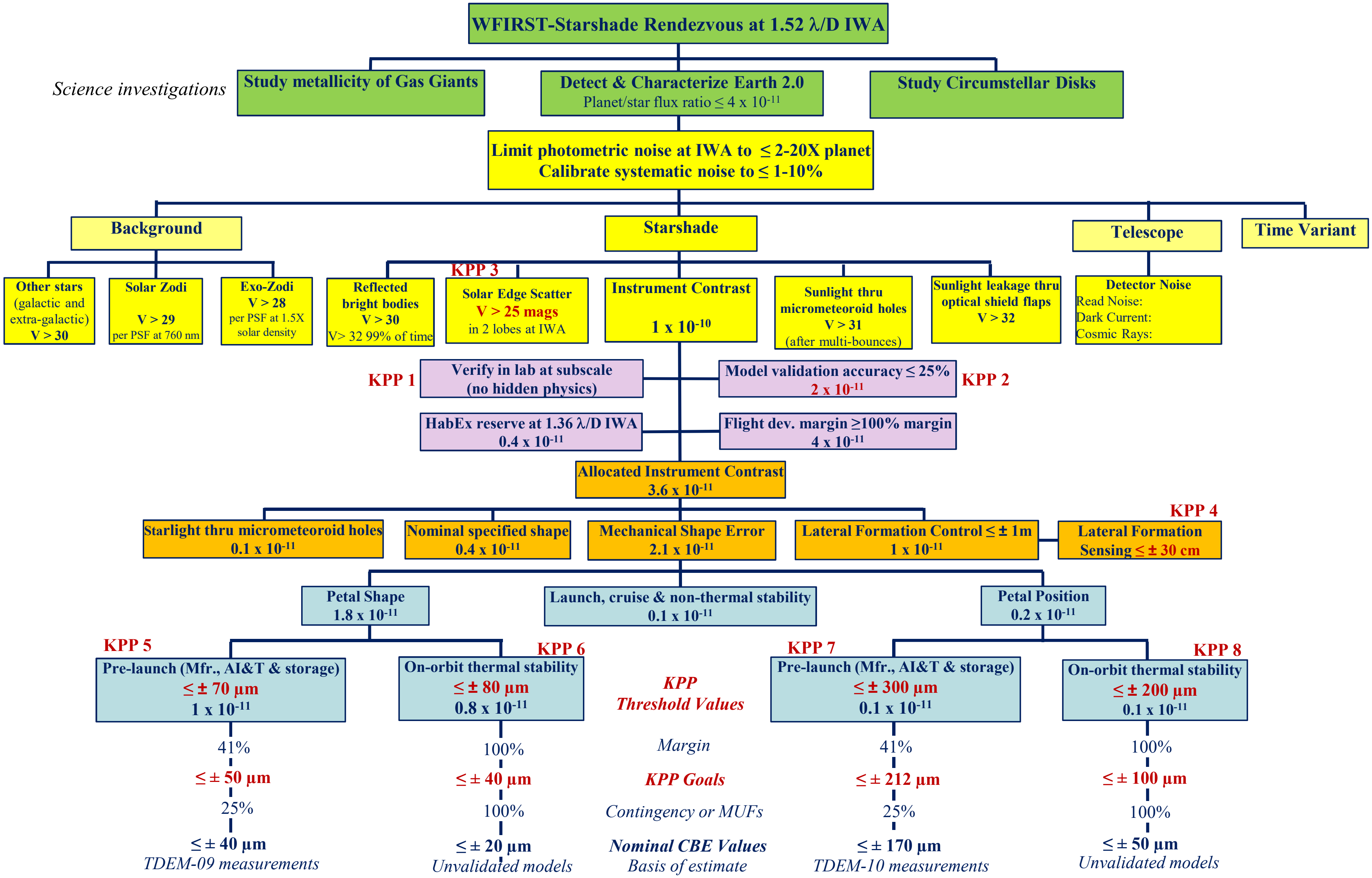
Habex Comparison

- **All reflected bright body levels are ~0.7 mag dimmer for HabEx due to smaller telescope-starshade view factor (radius doubles, but separation distance triples) and fewer resolution elements**

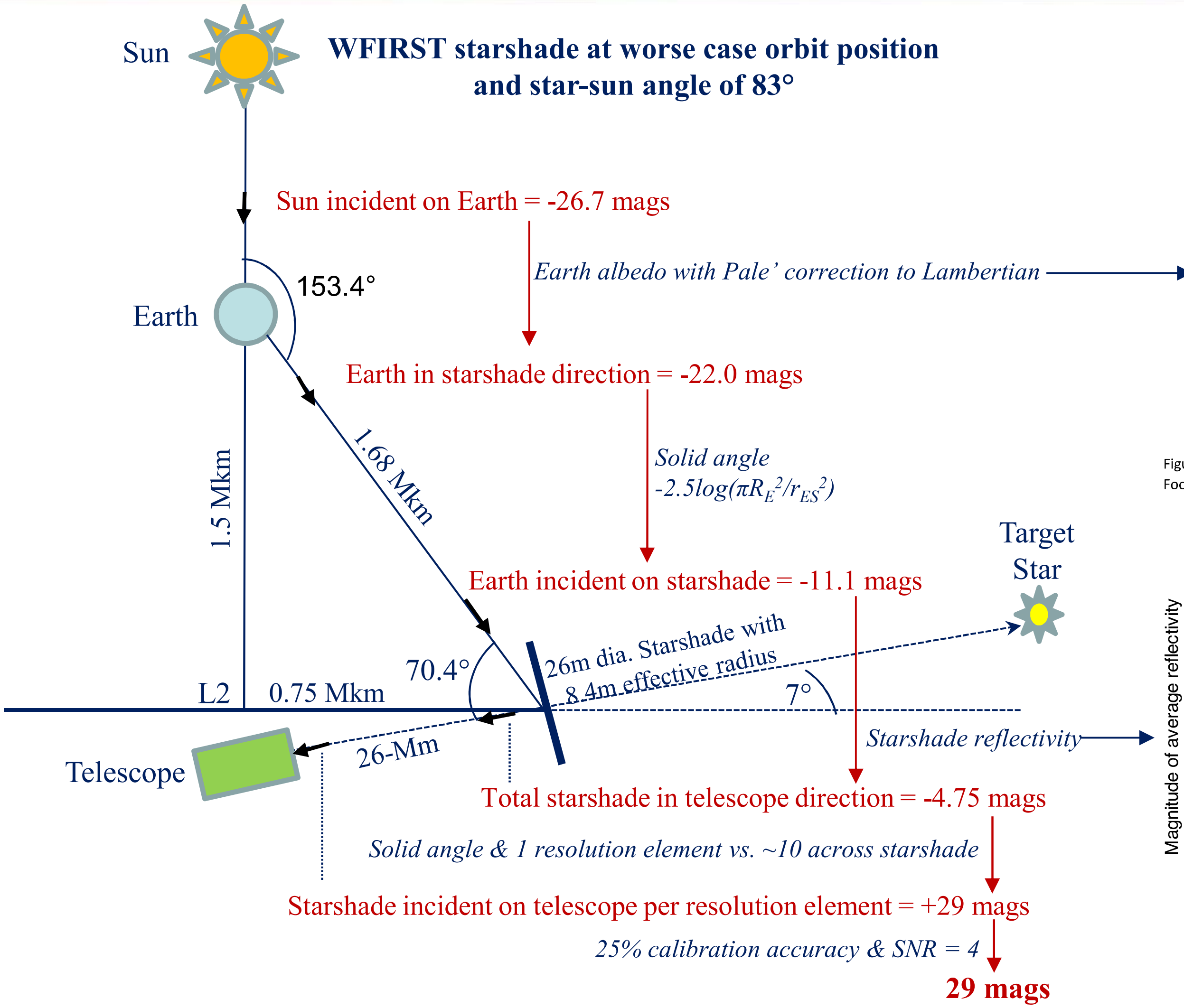
- **Sun thru micrometeoroid holes is ~2 mags brighter due to larger surface area (900 vs. 250 m^2) and longer mission duration (5 vs. 3-years) and fewer resolution elements**
  - Still plenty of margin

Backup Slides

S5 Top Level Error Budget



Reflected Earth Light



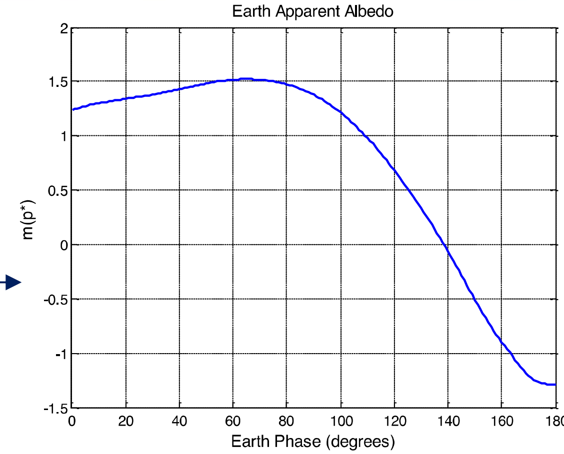
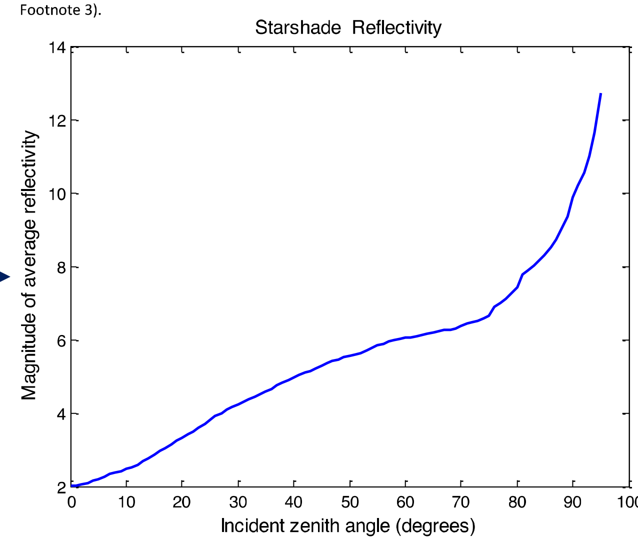


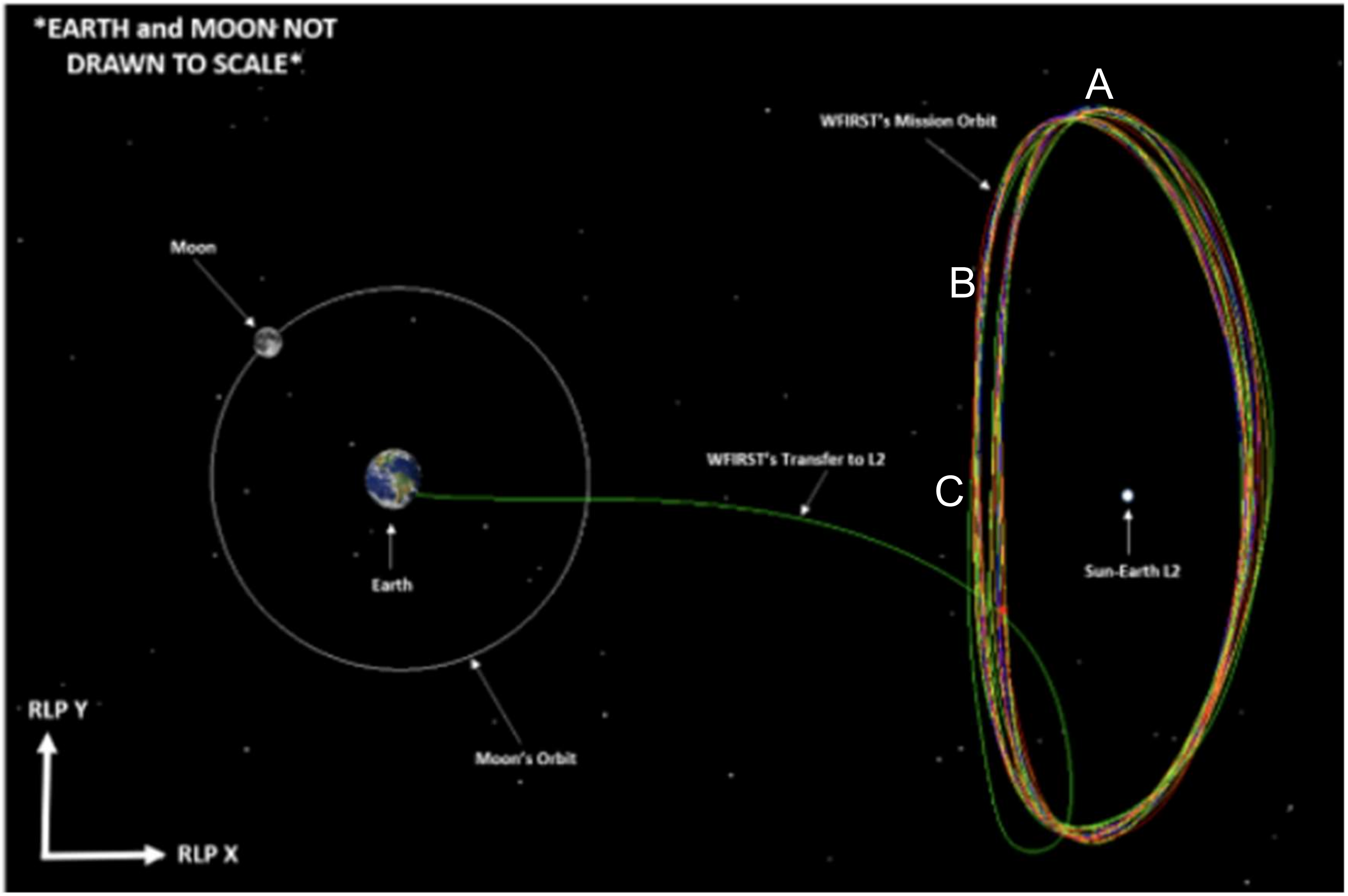
Figure 2: Magnitude of apparent albedo of Earth. Generated using data from Figure 6 of Pallé (see Footnote 3).



Both curves from 2014 Martin Regehr memo

At extreme orbit positions and star-sun angles, Earth-shine exceeds the 30 mag goal and requires a darker starshade and/or restricted pointing

Earth-shine orbit geometry



Reflected Earth Spreadsheet

Orbit position	Orbit Extreme & 83° Sun angle
Distance along Sun-Earth line (Mkm)	1.5
Distance normal to Sun-Earth line (Mkm)	0.75
Starshade angle from Sun-Earth line (deg)	26.6
Earth phase angle (deg)	153.4
Earth phase angle (rad)	2.6779
Lambertian illumination factor	0.0069
Lambertian illumination (mags)	5.40
Pale' adjustment to Lambertian (mags)	-0.7
Earth albedo in starshade direction (mags)	4.70
Solar magnitude at 1AU	-26.7
Earth brightness in starshade direction (mags)	-22.0
Earth radius (m)	6.40E+06
Distance Earth-Starshade (m)	1.68E+09
Solid angle view factor (mags)	10.85
Earth incident on starshade (mags)	-11.15
Star-Sun observing angle (deg)	83.0
Earth incidence angle at starshade (deg)	70.4
Starshade reflectivity at Earth incidence (mags)	6.4
Starshade in direction of telescope (mags)	-4.75
Fraction within 1 resolution element	0.10
Fraction within 1 resolution element (mags)	2.5
Effective SS radius (m)	8.4
Separation distance (m)	2.60E+07
Solid angle view factor (mags)	31.21
Earth mags at telescope per resolution element	**29.0**

Micrometeoroids- Shielding

- **Starshade optical shield provides opacity, limits micrometeoroid holes and limits the solid angle view factor to Sun through through-holes**
- **It consists of 3 evenly spaced 1-mil thick Kapton layers with 16-mm total thickness**
- **Stopped particle mass is computed at near-max particle speed (V) of 50 km/s and 2.5 gm/cm^3 particle density (larger particles are aggregates with lower density)**
- **Particles masses > 1 E-12 gm are expected to enter the shield per:**
  - m = t * (K r^1/6 V^7/8)^-2.84 (NASA Std. PD-EC-1107), where t is layer thickness (cm), K is an experimental factor of 1.1 (scaled with density for Kapton vs. Al test data), r is radius in cm and V is velocity in km/s
- **Particles masses > 6.3 E-7 gm are also expected to pass the mid-layer per:**
  - m=t / C * S'^2 / V (SMAD), where C is an experimental factor of 100 (scaled with density for Kapton vs. Al test data, S' is path distance between layer 1-2 at 45 deg trajectory
- **Particles masses > 2.5 E-6 gm are also expected to exit the shield per:**
  - Same as mid-layer computation but with S' for layer 1-3
  - Mid-layer is conservatively neglected in this computation

Micrometeoroid Spreadsheet

Group	Parameter	Value	Comments
Flux model	Rendezvous starshade surface area (m2)	250	26-m starshade, HabEx area is 900 m2 for 52-m starshade
	Mission duration (years)	3	~160 Ms, Rendezvous prime mission is 2 yrs, HabEx is 5
	$F=c_0\,[\,(c_1 m^{0.306}+c_2)^{-4.38}+c_3(m+c_4 m^2+c_5 m^4)^{-0.36}+c_6(m+c_7 m^2)^{-0.85}]$		Grun model, as used on JWST, gives # larger particles per
	c0	3.16E+07	m2 per year vs. particle mass in grams.
	c1	2200	
	c2	15	Flux diredtion is concentrated in 6 sectors, but effectively
	c3	1.3E-09	isotropic after considering variable starshade pointing.
	c4	1.0E+11	
	c5	1.0E+27	
	c6	1.3E-16	
	c7	1.0E+06	
Particle	Particle density for shield perf., r (gm/cm3)	2.5	Solid silica (<1e-6 gm), applies to entry hole calcs.
	Particle density for particle sizing, r (gm/cm3)	1	Agregates (>1e-6 gm), conservatively applies to all particle sizing
	Particle velocity (km/s)	50	10-70 km/s full range, 20 km/s avg, ~30% flux at 55 km/s
	Particle mass bin size factor	1.58489	gives 5 mass bins per decade
Shield	Construction	Kapton	~1.4 gm/cm3 density, 3 equal & evenly spaced layers
	Thickness, t (mil)	1	
	Thickness, t (cm)	0.00254	
Entry hole area	Experimental factor for Kapton (K)	1.1	Scaled as 1/density with 0.54 for Al
	Smallest particle mass passing outer layer (gm)	1.3E-12	m = t * (K r^1/6 V^7/8)^-2.84 (NASA Std. PD-EC-1107)
	Rounding down to smaller bin size	**1.0E-12**	
	# Larger particles	7.4E+05	From table to right
	Cum larger particle area (cm2)	1.3	From table to right
	Ratio crater to particle diameter	1.25	By observation
	Cum entry hole total area, both sides (cm2)	2.0	Includes both sides of starshade
	Cum entry hole area per side (ppm)	**0.4**	Each side of starshade
Mid-Layer hole area	Separation between shield layers, S (cm)	0.8	3 evenly spaced layers, total thickness of 1.6 cm
	Average path length, S' (cm)	1.128	Avg. 45° off-normal trajectory
	Experimental factor for Kapton, C	100	50 for Al, assume K scales as 1/r (melt temp must be factor)
	Smallest particle mass passing mid-layer (gm)	6.5E-07	m=t / C * S'^2 / V (SMAD), if particle fully vaporized at entry
	Rounding down to nearest bin size (gm)	**6.3E-07**	
	# Larger particles	1342	From table to right
	Cum larger particle area (cm2)	0.51	From table to right
	Ratio Layer 2 hole to particle diameter	20	Penetrating portion of gas cloud expanding over 0.8 cm
	Cum mid-layer hole area (cm2)	204	
	Cum mid-layer hole area, both directions (ppm)	**82**	Allocation is 500 ppm in all 3-layers
Exit hole area	Separation between shield layers, S (cm)	1.6	Neglect benefit of mid-layer
	Average path length, S' (cm)	2.256	45° off-normal trajectory
	Experimental factor for Kapton, C	100	Scaled as 1/density with 50 for Al
	Smallest particle mass exiting outer layer (gm)	2.6E-06	m= t/C * S^2 / V (SMAD), if particle fully vaporized at entry
	Rounding down to nearest bin (gm)	**2.5E-06**	
	# Larger particles	359	From table to right
	Cum larger particle area (cm2)	0.31	Integrate table to right
	Ratio exit hole to particle diameter	40	Penetrating portion of gas cloud expanding over 1.6 cm
	Cum exit hole total area (cm2)	499	Includes both sides of starshade
	Cum exit hole area per side (ppm)	**100**	Allocation is 500 ppm in all 3-layers

Particle mass (gm)	Mean bin mass (gm)	# larger particles	# particles in mass bin	Mean in bin particle dia. (cm)	Mean cross-sectional area (cm2)	Cum in bin particle area (cm2)	Cum larger particle dia. (cm2)	Cum fractional particle area
1.0E-03	8.2E-04	1	0	1.2E-01	1.1E-02	0.00		
6.3E-04	5.1E-04	1	1	9.9E-02	7.8E-03	0.01	0.01	0.005
4.0E-04	3.2E-04	2	1	8.5E-02	5.7E-03	0.01	0.01	0.011
2.5E-04	2.0E-04	3	2	7.3E-02	4.2E-03	0.01	0.02	0.019
1.6E-04	1.3E-04	6	4	6.3E-02	3.1E-03	0.01	0.04	0.029
1.0E-04	8.2E-05	10	7	5.4E-02	2.3E-03	0.02	0.05	0.042
6.3E-05	5.1E-05	17	12	4.6E-02	1.7E-03	0.02	0.07	0.058
4.0E-05	3.2E-05	29	20	4.0E-02	1.2E-03	0.02	0.10	0.077
2.5E-05	2.0E-05	50	33	3.4E-02	9.1E-04	0.03	0.13	0.101
1.6E-05	1.3E-05	83	54	2.9E-02	6.7E-04	0.04	0.17	0.129
1.0E-05	8.2E-06	137	86	2.5E-02	4.9E-04	0.04	0.21	0.162
6.3E-06	5.1E-06	223	135	2.1E-02	3.6E-04	0.05	0.26	0.200
4.0E-06	3.2E-06	359	208	1.8E-02	2.7E-04	0.06	0.31	0.242
2.5E-06	2.0E-06	567	314	1.6E-02	2.0E-04	0.06	0.37	0.290
1.6E-06	1.3E-06	880	462	1.4E-02	1.4E-04	0.07	0.44	0.342
1.0E-06	8.2E-07	1342	667	1.2E-02	1.1E-04	0.07	0.51	0.396
6.3E-07	5.1E-07	2009	939	9.9E-03	7.8E-05	0.07	0.58	0.453
4.0E-07	3.2E-07	2948	1290	8.5E-03	5.7E-05	0.07	0.66	0.510
2.5E-07	2.0E-07	4238	1730	7.3E-03	4.2E-05	0.07	0.73	0.567
1.6E-07	1.3E-07	5968	2266	6.3E-03	3.1E-05	0.07	0.80	0.621
1.0E-07	8.2E-08	8234	2900	5.4E-03	2.3E-05	0.07	0.86	0.673
6.3E-08	5.1E-08	11134	3634	4.6E-03	1.7E-05	0.06	0.93	0.720
4.0E-08	3.2E-08	14768	4465	4.0E-03	1.2E-05	0.05	0.98	0.763
2.5E-08	2.0E-08	19233	5376	3.4E-03	9.1E-06	0.05	1.03	0.801
1.6E-08	1.3E-08	24609	6316	2.9E-03	6.7E-06	0.04	1.07	0.833
1.0E-08	8.2E-09	3.1E+04	7.2E+03	2.5E-03	4.9E-06	0.04	1.11	0.861
6.3E-09	5.1E-09	3.8E+04	8.1E+03	2.1E-03	3.6E-06	0.03	1.14	0.884
4.0E-09	3.2E-09	4.6E+04	9.0E+03	1.8E-03	2.7E-06	0.02	1.16	0.902
2.5E-09	2.0E-09	5.5E+04	1.0E+04	1.6E-03	2.0E-06	0.02	1.18	0.917
1.6E-09	1.3E-09	6.5E+04	1.1E+04	1.4E-03	1.4E-06	0.02	1.19	0.930
1.0E-09	8.2E-10	7.6E+04	1.2E+04	1.2E-03	1.1E-06	0.01	1.21	0.940
6.3E-10	5.1E-10	8.9E+04	1.4E+04	9.9E-04	7.8E-07	0.01	1.22	0.949
4.0E-10	3.2E-10	1.0E+05	1.6E+04	8.5E-04	5.7E-07	0.01	1.23	0.956
2.5E-10	2.0E-10	1.2E+05	1.9E+04	7.3E-04	4.2E-07	0.01	1.24	0.962
1.6E-10	1.3E-10	1.4E+05	2.3E+04	6.3E-04	3.1E-07	0.01	1.24	0.968
1.0E-10	8.2E-11	1.6E+05	2.9E+04	5.4E-04	2.3E-07	0.007	1.250	0.973
6.3E-11	5.1E-11	1.9E+05	3.5E+04	4.6E-04	1.7E-07	0.006	1.256	0.978
4.0E-11	3.2E-11	2.3E+05	4.3E+04	4.0E-04	1.2E-07	0.005	1.262	0.982
2.5E-11	2.0E-11	2.7E+05	5.2E+04	3.4E-04	9.1E-08	0.005	1.266	0.985
1.6E-11	1.3E-11	3.2E+05	6.1E+04	2.9E-04	6.7E-08	0.004	1.270	0.988
1.0E-11	8.2E-12	3.8E+05	7.2E+04	2.5E-04	4.9E-08	0.004	1.274	0.991
6.3E-12	5.1E-12	4.5E+05	8.3E+04	2.1E-04	3.6E-08	0.003	1.277	0.994
4.0E-12	3.2E-12	5.4E+05	9.6E+04	1.8E-04	2.7E-08	0.003	1.279	0.995
2.5E-12	2.0E-12	6.3E+05	1.1E+05	1.6E-04	2.0E-08	0.002	1.282	0.997
1.6E-12	1.3E-12	7.4E+05	1.3E+05	1.4E-04	1.4E-08	0.002	1.283	0.999
1.0E-12	8.2E-13	8.8E+05	1.6E+05	1.2E-04	1.1E-08	0.002	1.285	1.000