Starshade Stray Light Status Report
to
Science and Industry Partnership Group

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Overview

- Primary stray light updates reported here are to account for the:
  - Systematic component of noise (post-calibration residual uncertainty)
  - Latest edge scatter measurements with ”Zecoated” coupons
  - Reflected light from center of the Milky Way
  - Levels at 1AU solar equivalent angle rather than IWA
  - Attenuated solar leakage with a labyrinth seal at deployable disk optical shield interface to truss

- Secondary solar reflections are under study via ray trace analysis of system CAD model
  - Telescope facing surfaces with view factors to sun facing surfaces, with or without deformed shape

- Noise budgets compile stray light & astrophysical background noises to yield planet sensitivity
  - Total stray light brightness is less than the local zodiacal light

- Planet sensitivity is translated to HZ search completeness and cumulative HZ search space
  - Sun-like FGK stars with completeness cutoff at ≥ 20%
  - Consider variable band, exozodi level and exozodi calibration accuracy

- First, stray light sources and their geometry are reviewed
**Stray Light and Background Sources and Geometries**

**Starshade stray light**
- Starlight leakage, Solar glint (edge scatter)
- Solar leakage: opacity, mm holes, OS closeout
- Reflected bright-bodies: Earth, Venus, Jupiter, Milky Way
- Secondary solar reflections, fluorescence,
  Thruster exhaust solar scatter, micrometeoroid flashes

**Astrophysical Background**
- Milky Way stars
- Other galaxies
- Exozodi & local zodi light
- Companion stars & exoplanets

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**Diagram Notes**
- Milky Way Center (assume all reflected light is at peak brightness)
- L2 halo orbit
- 26-m starshade (mostly 3-layers of Kapton)
- 3-layer optical shield
- Leaked sunlight to telescope after multiple bounces & Lambertian dispersion
- Leaked starlight to telescope dispersed by diffraction only
• Systematic noise stems from the imperfect calibration of any noise source with spatial structure to present photon source uncertainty
  – Adds in quadrature with the photon count uncertainty from photometric noise
  – Formulation below is consistent with CGI error budgets (B. Nemati, 2016)

• SNR is the ratio of planet counts \((KC_p)\) to the RSS of photometric counts \(\sqrt{KC_n}\) and systematic noise counts \(KC_n\delta\), or:
  – \(SNR = \frac{KC_p}{\sqrt{KC_n + \delta^2K^2C_n^2}}\)
  – where: \(K\) is star counts, \(C_p\) is planet contrast, \(C_n\) is noise contras and \(\delta\) is calibration accuracy

• Solving for planet contrast \((C_p)\) gives:
  – \(C_p = SNR \left(\frac{C_n}{K} + \delta^2C_n^2\right)^{1/2}\)
  – Note the systematic term is independent of integration time

• Exozodi calibration accuracy \((\delta_Z)\) is critical and highly uncertain
  – Planet extraction simulations to inform exozodi calibration capability are critically needed
  – A \(\delta_Z\) goal of 5% is evaluated here, but also show results for 3.33% and 0%
Optical Edge Coating

- Solar glint is greatly reduced by “ZeCoated” edges
- A JPL optical model is validated and used to choose coating application angle, LoS vs. uniform, etc.
- JATIS paper submitted for review by Dylan McKeithen, Stuart Shaklan, David Sheikh, et al
- Future optimizations include finer coating thickness resolution & weighted sun angles
- Prototype plans include performance verification after thermal cycles and stow cycles

![Graphs showing fractional scatter vs. coating angle](image)

*Fig 6: Comparison between the SAS experimental data and Lumerical results for coatings (a) 450:800-3, and (b) 450:1000-1 showing good agreement for coatings applied at three different angles.*

*Fig 7: Plot of the average in-band scatter as a function of coating angle. Note the minimum around $\alpha = 60^\circ$, and a maximum near $\alpha = 150^\circ$.*

### Table 7: Estimated Glint Lobe Magnitude for the SRM 425-552 nm Band

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>IWA Phot. 95% conf.</th>
<th>Improvement Ratio</th>
<th>$\Delta$Mag</th>
<th>Final Mag</th>
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</thead>
<tbody>
<tr>
<td>53</td>
<td>27.3</td>
<td>9.2</td>
<td>2.4</td>
<td>29.7</td>
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<tr>
<td>63</td>
<td>27.5</td>
<td>16.7</td>
<td>3.1</td>
<td>30.6</td>
</tr>
<tr>
<td>73</td>
<td>27.3</td>
<td>26.8</td>
<td>3.6</td>
<td>30.9</td>
</tr>
<tr>
<td>83</td>
<td>26.7</td>
<td>20.5</td>
<td>3.3</td>
<td>30.0</td>
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</table>

### Table 8: Estimated Glint Lobe Magnitude for the SRM 615-800 nm Band

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>IWA Phot. 95% conf.</th>
<th>Improvement Ratio</th>
<th>$\Delta$Mag</th>
<th>Final Mag</th>
</tr>
</thead>
<tbody>
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<td>53</td>
<td>25.2</td>
<td>14.3</td>
<td>2.9</td>
<td>28.1</td>
</tr>
<tr>
<td>63</td>
<td>25.4</td>
<td>33.3</td>
<td>3.8</td>
<td>29.2</td>
</tr>
<tr>
<td>73</td>
<td>25.2</td>
<td>61.0</td>
<td>4.5</td>
<td>29.7</td>
</tr>
<tr>
<td>83</td>
<td>24.6</td>
<td>85.3</td>
<td>4.8</td>
<td>29.4</td>
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</table>
Reflected Milky Way Light

• Center of Milky Way is the brightest body for reflected light, when seasonally behind the telescope
  – Peak brightness is 20.57 mags/arc-sec²
  – ~5% starshade hemispherical reflectance (+3.25 mags)
  – +1 mag fill factor – petals instead of disk
  – Conservatively assume that all reflected light comes from the brightest part of the Milky Way
  – Yields 31.3 mags per resolution element at IWA

• Combine with Earth at grazing angles for total of 28.2 + θ_{mas}/40 mags (Green-Band)
  – 30.8 mags per resolution element at IWA

• Additional light reflected by Jupiter and Venus is possible, but rare and operationally avoidable

• All other bodies are much dimmer
Translation to 1AU solar equivalent angle

- Off-axis fall-off for star leakage & solar glint is simulated and curve fit over angles of interest
Deployable disk optical shield (OS) requires a hinged interface at each truss node, with a mechanical clearance (gap) that can leak Sunlight.

A labyrinth seal design (by Manan Aria) expected to transmit $\leq 10^{-13}$ (vs. $10^{-12}$ predict for mm holes) is to be verified with straylight tool.
Optical Shield Closeout - 2 of 2

Sun enters gap between longeron and node plate

Inner disk optical shield

A final bounce is required at OS – Black Kapton

On-axis to telescope

Longeron cover “flap”

Truss Node

Petal
Secondary Solar Reflections

- **Photon Engineering (Scott Ellis) is conducting a rigorous analysis of starshade stray light**
  - Ray tracing tools applied to starshade system CAD model
  - Computationally challenged by extremely low light level sensitivity
  - Further challenged by limited fidelity CAD model with non-flight like features (iterative CAD fixes)

- **Emphasis is on secondary solar reflections for both nominal shape and twisted/out-of-plane petals**
  - Telescope facing surfaces with a view factor to Sun facing surfaces
  - Machined CFRP side-wall of optical edge substrate to disk optical shield is an example
  - BRDF measurement of this atypical material is underway

- **Expect all secondary reflections will be much dimmer than solar glint, after mitigations**
  - ZeCoat provided dark coating on Kapton is now under test as one mitigation

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*Side-wall of optical edge substrate (machined CFRP, 1.125 mm thick)*

*Inner disk optical shield (conical, Black Kapton)*

*Telescope*
Noise Budget Approach & Assumptions

- Focus on top 3 stray light terms, plus a conservative allocation for other sources
- Focus on top 3 astrophysical background sources
- Include systematic noise
- All noise terms combine in quadrature (same as CGI methodology)
- Detector QE is per WFIRST ipac website and includes a variable factor for QE degradation (0.5X does not change planet sensitivity)
- SNR is set to 4 for broadband detections
- Consider both Green and Blue Bands
- Exozodi CBE is 3X Local zodi density (6X brightness) and we also explore 2X density
- Exozodi calibration accuracy best guess is 3-5% and we also consider 0% residuals for the case with smooth symmetric exozodi
## Rendezvous Green-Band Noise Budget

### Exoplanet Exploration Program

<table>
<thead>
<tr>
<th>Mission</th>
<th>SNR (broadband detection)</th>
<th>Exo-zodi density</th>
<th>Band</th>
<th>Bandpass</th>
<th>Point sources</th>
<th>Extended sources</th>
<th>QE degrade factor</th>
<th>IWA (mas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rendezvous</td>
<td>4</td>
<td>3</td>
<td>Green</td>
<td>615-800</td>
<td>4.20E+14</td>
<td>1.40E+15</td>
<td>1</td>
<td>103</td>
</tr>
</tbody>
</table>

\[ I = BOL, \ 0.5 \text{ ~EOL} \]

<table>
<thead>
<tr>
<th>Star</th>
<th>L</th>
<th>d (parsecs)</th>
<th>1AU Angle (°, mas)</th>
<th>Vmag</th>
<th>Point sources</th>
<th>Extended sources</th>
<th>Planck Function</th>
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</thead>
<tbody>
<tr>
<td>Tau Ceti</td>
<td>0.52</td>
<td>3.65</td>
<td>198</td>
<td>3.49</td>
<td>1.66E+13</td>
<td>5.52E+13</td>
<td>0.202</td>
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</tbody>
</table>

### Noise Source

<table>
<thead>
<tr>
<th>Noise Source</th>
<th>Angle dependence</th>
<th>mags at 1AU</th>
<th>Noise Contrast</th>
<th>Background Counts ((BC = C_n \ K))</th>
<th>Photometric counts (\sqrt{BC})</th>
<th>Cal Accuracy ((\delta))</th>
<th>Systematic counts (\delta BC)</th>
<th>RSS Total noise counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starlight leakage (1E-10 at IWA)</td>
<td>(\Delta m = 21.7 + q/36)</td>
<td>30.7</td>
<td>1.33E-11</td>
<td>220.7</td>
<td>14.9</td>
<td>10%</td>
<td>22.1</td>
<td>26.6</td>
</tr>
<tr>
<td>Solar Glint (coated edges, 73° Sun)</td>
<td>(m = 27.1 + q/40)</td>
<td>32.0</td>
<td>3.81E-12</td>
<td>63.0</td>
<td>7.9</td>
<td>10%</td>
<td>6.3</td>
<td>10.1</td>
</tr>
<tr>
<td>Reflected Milky Way &amp; Earth</td>
<td>(m = 28.2 + q/40)</td>
<td>33.1</td>
<td>1.38E-12</td>
<td>76.2</td>
<td>8.7</td>
<td>25%</td>
<td>19.1</td>
<td>21.0</td>
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<tr>
<td>Other stray light counts (1 per hour)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>24.0</td>
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<tr>
<td>Total straylight (RSS)</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td>19</td>
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<tr>
<td>Local Zodi (22.7 mags/arc-sec2)</td>
<td>28.81</td>
<td>7.45E-11</td>
<td>4110</td>
<td>64</td>
<td>1%</td>
<td>41</td>
<td>76</td>
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<tr>
<td>Exo/Local Zodi brightness ratio</td>
<td>6</td>
<td>26.86</td>
<td>4.47E-10</td>
<td>24661</td>
<td>157</td>
<td>5%</td>
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<td>Planet shot noise (iterative solver)</td>
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<td>Astrophysical background (RSS)</td>
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<td>184</td>
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<tr>
<td>Stray light &amp; background (RSS)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>185</td>
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</tbody>
</table>

| Min detectable planet counts | 4992 |
| Planet contrast sensitivity | 3.0E-10 |
| Dimmest detectable planet (mags)* | 27.3 |

* A constant for all target stars, dominated by exo-zodi

** micrometeoroid flashes, solar leakage thru micrometeoroid holes, fluorescence, thrust plume solar scatter, etc.
# Exoplanet Exploration Program

## Rendezvous Blue-Band Noise Budget

### Reference star counts (days=1, L=1, d=1 pc)

<table>
<thead>
<tr>
<th>Mission</th>
<th>SNR (broadband detection)</th>
<th>Exo-zodi density</th>
<th>Band</th>
<th>Bandpass</th>
<th>Point sources</th>
<th>Extended sources</th>
<th>QE degrade factor</th>
<th>IWA (mas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rendezvous</td>
<td>4</td>
<td>3</td>
<td>Blue</td>
<td>460-600</td>
<td>5.50E+14</td>
<td>1.80E+15</td>
<td>1</td>
<td>77</td>
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</tbody>
</table>

### Star counts (K) after 1 day

<table>
<thead>
<tr>
<th>Star</th>
<th>L (parsecs)</th>
<th>d (parsec)</th>
<th>1AU Angle ($\theta$, mas)</th>
<th>Vmag</th>
<th>Point sources</th>
<th>Extended sources</th>
<th>Average Planck Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tau Ceti</td>
<td>0.52</td>
<td>3.65</td>
<td>198</td>
<td>3.49</td>
<td>1.86E+13</td>
<td>6.08E+13</td>
<td>0.173</td>
</tr>
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### Noise Sources

<table>
<thead>
<tr>
<th>Noise Source</th>
<th>Angle dependence</th>
<th>mags at 1AU</th>
<th>Noise Contrast</th>
<th>Background Counts (BC = C + K)</th>
<th>Photometric counts = \sqrt{BC}</th>
<th>Cal Accuracy ($\delta$)</th>
<th>Systematic counts = $BC$</th>
<th>RSS Total noise counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starlight leakage (1E-10 at IWA)</td>
<td>$\Delta m = 22.5 + \theta/36$</td>
<td>31.5</td>
<td>6.38E-12</td>
<td>118.5</td>
<td>10.9</td>
<td>10%</td>
<td>11.8</td>
<td>16.1</td>
</tr>
<tr>
<td>Solar Glint (coated edges, 73° Sun)</td>
<td>$m = 28.8 + \theta/37$</td>
<td>34.1</td>
<td>5.50E-13</td>
<td>10.2</td>
<td>3.2</td>
<td>10%</td>
<td>1.0</td>
<td>3.4</td>
</tr>
<tr>
<td>Reflected Milky Way &amp; Earth</td>
<td>$m = 28.0 + \theta/37$</td>
<td>33.3</td>
<td>1.15E-12</td>
<td>69.8</td>
<td>8.4</td>
<td>25%</td>
<td>17.5</td>
<td>19.3</td>
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<tr>
<td>Other stray light counts (1 per hour)</td>
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<td>24.0</td>
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<tr>
<td>Total stray light (RSS)</td>
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<td></td>
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<td>14</td>
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<tr>
<td>Local Zodi (22.7 mags/arc-sec2)</td>
<td></td>
<td>29.41</td>
<td>4.29E-11</td>
<td>2604</td>
<td>51</td>
<td>1%</td>
<td>26</td>
<td>57</td>
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<tr>
<td>Exo/Local Zodi brightness ratio</td>
<td>6</td>
<td>27.46</td>
<td>2.57E-10</td>
<td>15626</td>
<td>125</td>
<td>5%</td>
<td>781</td>
<td>791</td>
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<tr>
<td>Planet shot noise (iterative solver)</td>
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<td>56</td>
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<td>56</td>
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<tr>
<td>Astrophysical background (RSS)</td>
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<td></td>
<td>146</td>
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<td></td>
<td>782</td>
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<tr>
<td>Total noise (stray light &amp; astrophysical)</td>
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<td></td>
<td></td>
<td>147</td>
<td></td>
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<td>147</td>
</tr>
</tbody>
</table>

### Planet detection limits

- Min detectable planet counts = Total noise * SNR
- Planet contrast sensitivity = min planet / star point source counts
- Dimmest detectable planet (mags)*

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* A constant for all target stars, dominated by exo-zodi

** micrometeoroid flashes, fluorescence, thrust plume solar scatter, etc.

(vs. 27.3 for Green-Band)

(Blue-Band can detect 1.7X dimmer planets)
Exozodi dominated planet sensitivity

Green-Band Planet Contrast Sensitivity

Blue-Band Planet Contrast Sensitivity

Planet sensitivity scales with residual Exo-Zodi uncertainty & also \( \lambda^2 \) and the Planck Function
Residual Exozodi uncertainty (systematic noise) decimates Rendezvous performance

Combinations of bandpass, planet size & residual exozodi level restore some performance
Evolved systems are expected to have highly uniform (not lumpy) exozodis. This would allow subtraction of exozodi based on image symmetry. Here we assume perfect exozodi calibration.
Conclusions

• The good news is that starshade stray light is well under control
  – Barely detectable at 1AU solar equivalent distances for nearby stars
  – Verification efforts are ongoing and not all sources are quantified

• The bad news is that planet sensitivity is not so good for CBE of 3X mean exozodi density
  – And for reasonable calibration accuracy (3-5%)
  – We critically need to inform the actual calibration capability, via planet extraction simulations

• Evolved systems may have very uniform exozodi that can be very well calibrated
  – Resolution is sufficient to subtract symmetric exozodi

• Performance improves with the Blue-Band and larger rocky planets (1.4X Earth mean)