Efforts to Mitigate the Effects of Stray Light in the LISA Telescope

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GWADW Scattered Light Workshop

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Outline

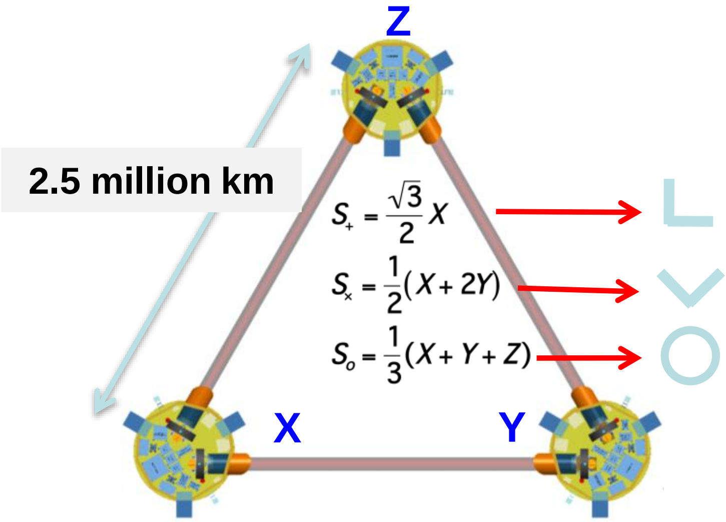
- What is the LISA telescope?
- What is stray light?
- Modeling and mitigating stray light in the LISA telescope

LISA Mission Summary

Mission Design

- Three satellites in an equilateral triangle formation with arm lengths of ~2.5 million km.
- Any two arms of this triangle represent a Michelson-type interferometer.
- Gravitational waves deform space-time and can be detected as a change in the length of the interferometer arms (~ 10 pm/Hz$^{1/2}$).
- Baseline 4 year lifetime + 6 years goal
    - Limited by communications bandwidth

LISA Layout



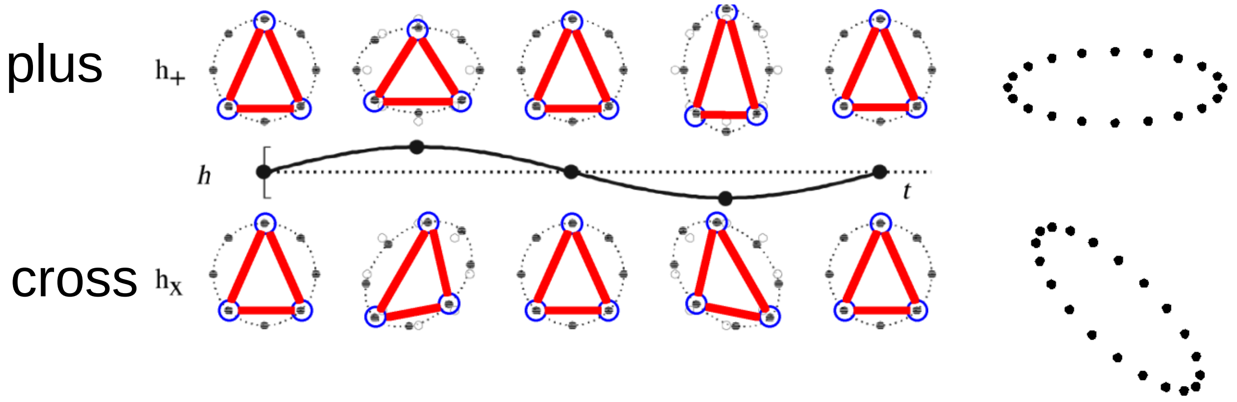
$$S_+ = \frac{\sqrt{3}}{2}X$$

$$S_\times = \frac{1}{2}(X + 2Y)$$

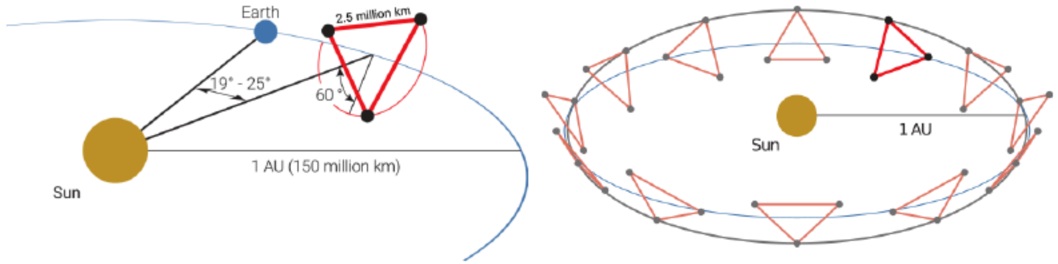
$$S_o = \frac{1}{3}(X + Y + Z)$$

polarization
+ "plus"
X "cross"
"sagnac"

Constellation Response



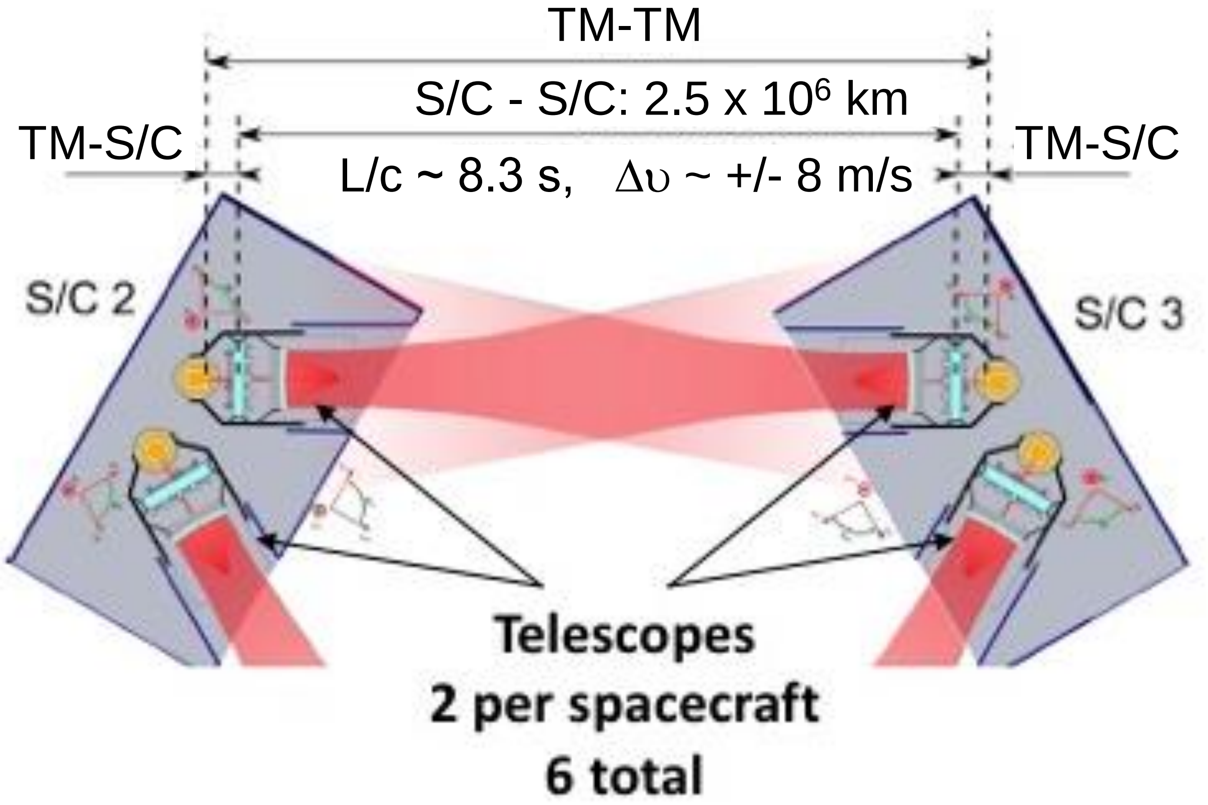
Heliocentric orbit



Constellation Triangle rotates once per year as it orbits

Telescope Functional Description

- Efficiently deliver power on-axis between spacecraft (2.5 million km)
- Simultaneous transmit and receive (TX/RX)
- Afocal beam expander
  - **300 mm dia. large beam**
  - **2.24 mm dia. on bench**
  - **134X magnification**
- **Application is PRECISION LENGTH MEASUREMENT, not image formation**
  - **Keep optical pathlength stable to ~ 1 pm/√Hz over the measurement BW**
  - **Minimize phase noise from coherent transmitter backscattered light**
  - **Minimize tilt to length (TTL) coupling**



LISA Telescope Design

- Constructed from low CTE material (Zerodur) to minimize path length fluctuations due to thermal expansion of telescope components
- Telescope design is a 4 mirror, unobstructed Cassegrain design in order to reduce the amount of backscattered light
- Freeform polynomial M3 mirror minimizes TTL coupling

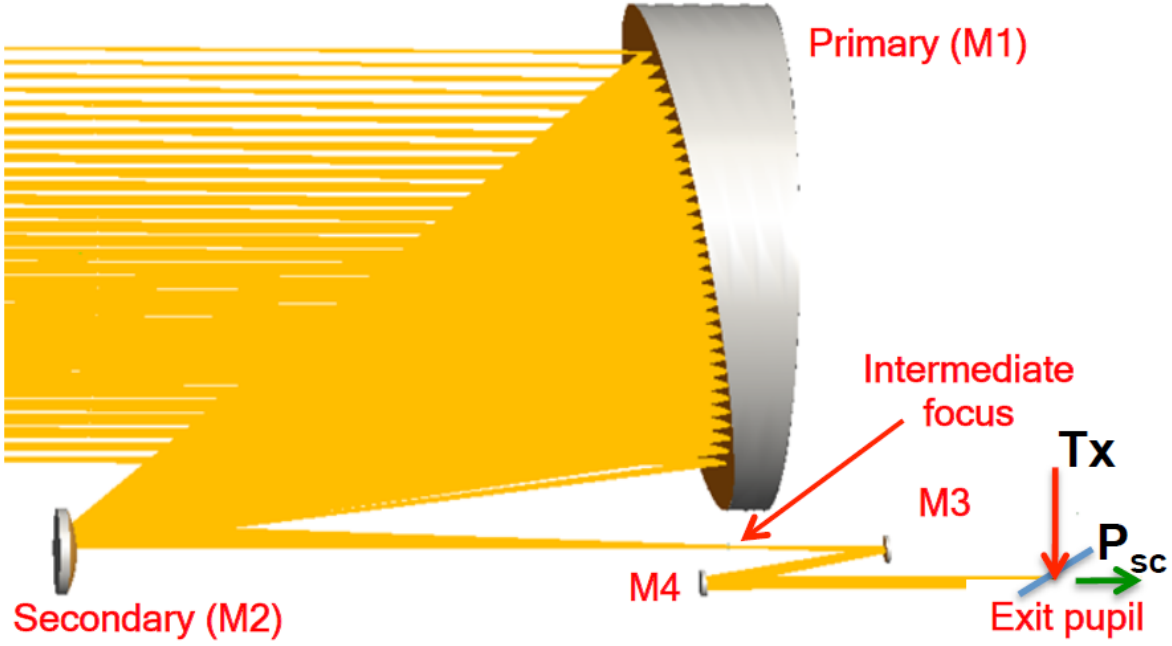


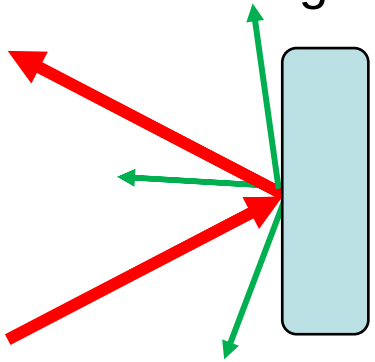
Image credit: Jeff Livas

What is Stray Light?
And why is it bad?

- Stray light is any light in the system that ‘leaks’ out of the main beam
- Stray light causes power loss in the system, creates measurement noise, and introduces cross talk in the telescope

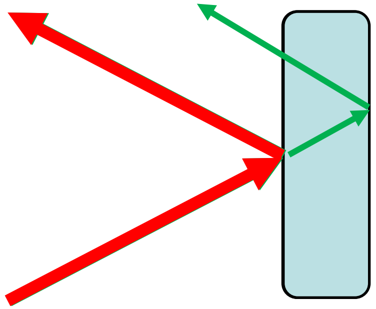
Examples of Stray Light:

Scattered Light



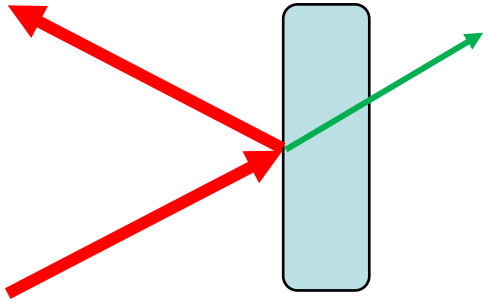
Caused by:
- Surface microroughness
- Particulate contamination
- Uneven films

Ghost Beams



Caused by:
- Less than 100% reflectivity coatings
- Residual reflections

Transmitted Beams



Caused by:
- Less than 100% reflectivity coatings

Stray Light Noise

- Coherent scatter
  - Occurs when the main and stray beams see the same change in phase
  - E.g. backscatter from telescope mirrors.
- Incoherent scatter
  - Occurs then the phase change between main and stray beam is random
  - E.g. scatter from telescope structure

$$\delta L = \sqrt{\frac{P_{ST}}{P_{MB}}}\,\delta x$$

δL = equivalent displacement noise
P_{ST} = power in the stray beam
P_{MB} = power in the main beam
δx = relative displacement of scattering surface

Example:

$$\delta L = 10^{-12}\mathrm{m}$$
$$\frac{P_{ST}}{P_{MB}} = 10^{-6}$$
$$\delta x < 10^{-9}\mathrm{m}$$

Stray Light Noise in the LISA Telescope

$$\delta L = \sqrt{\frac{P_{SC}}{P_{MB}}}\,\delta x$$

$$\delta L = \sqrt{\frac{Stray\ power\ from\ transmit\ beam}{Power\ in\ receive\ beam}}\,\delta x$$

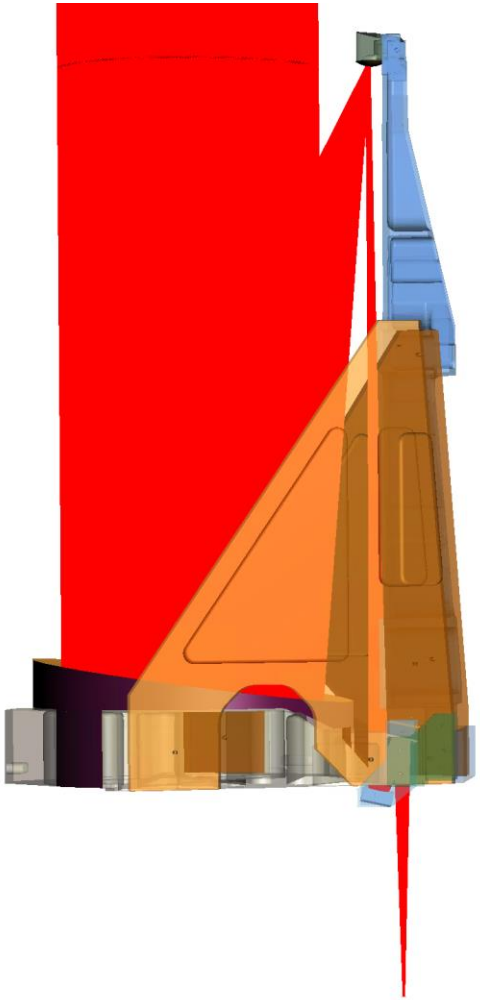
- Relative motion of scattering surface is minimized due to low CTE of Zerodur
- Beam divergence from diffraction leads to an expected Receive/Transmit ratio of $\sim 1.3 \times 10^{-10}$ (between spacecraft)
- Power transfer from Transmit beam to Receive beam via stray light must be less than $\sim 1.3 \times 10^{-12}$ (in the same spacecraft)

$$\frac{P_{ST}}{P_{RB}} = 0.01 \rightarrow \delta x < 3 \times 10^{-10}\mathrm{m}$$

Telescope Stray Light Model in FRED

- Development Team
  - Shannon Sankar – Instrument Scientist (UMD-GSFC)
  - Len Seals – Stray Light Engineer (GSFC)

- Development Highlights
  - Constructed non-sequential optical stray light model based on L3Harris CAD model
  - Compared model's performance to science requirements
  - Used to study backscatter from telescope into entrance pupil
  - Used for initial ghost beam analysis

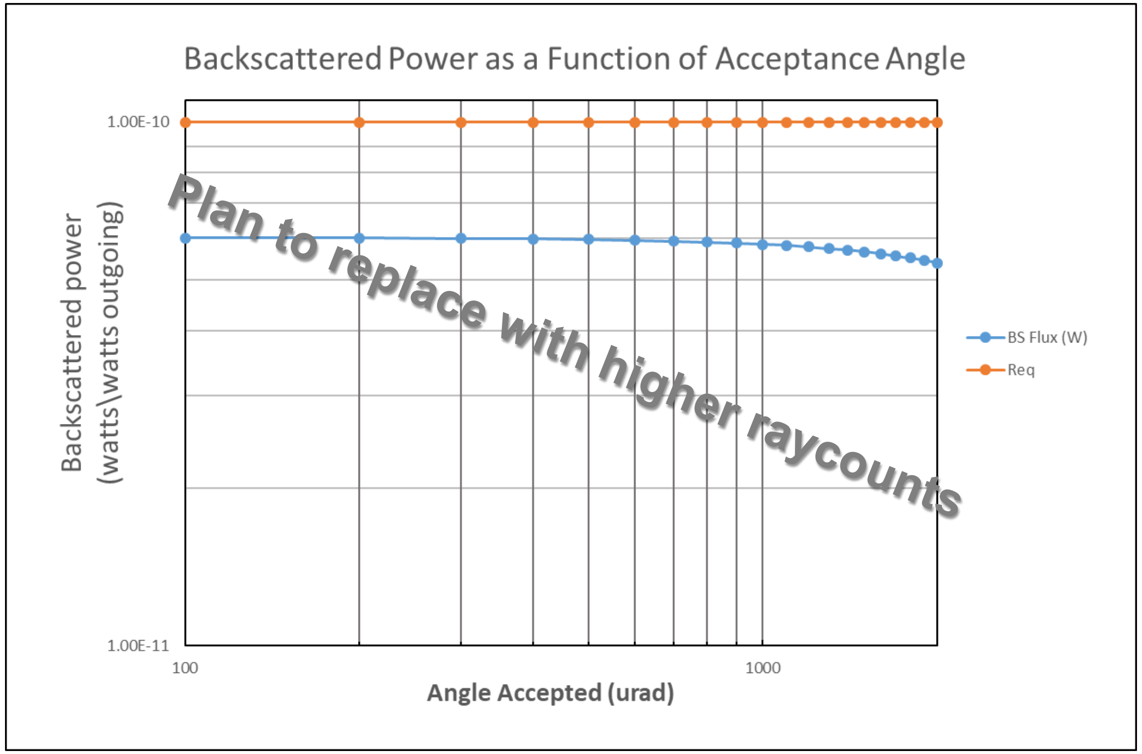


Scatter Irradiance Distribution on the Pupil Plane

Backscattered Power at the small pupil

- Rays representing the transmit beam are traced from the small pupil through the telescope
- Stray light is allowed to propagate though the system
- Light that backscatters to the small pupil is collected on an analysis surface at the small pupil
- Finally, we compare the results of the raytrace calculation to the mission science requirement

Backscattered Power vs Acceptance Angle

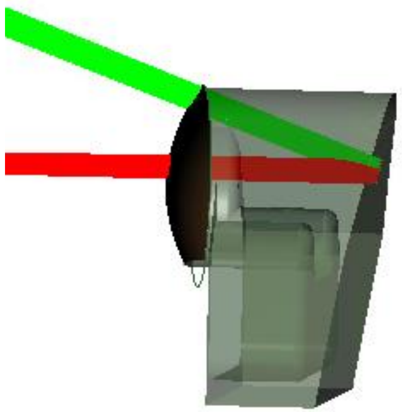


Plan to replace with higher raycounts

Initial Ghost Beam Analysis

- **Ghost beams** result when light incident on a surface is divided into reflected and transmitted components and both continue to propagate
- The unwanted ghost beams in our system are expected to arise from back surface reflections from the planar rear surfaces of our mirrors
- The HR coatings on the mirrors are designed to reflect as much light as possible, thus attenuating the power in the ghost beams
- To prevent ghost beams overlapping the science beam, a wedge angle can be added to the back mirror surface

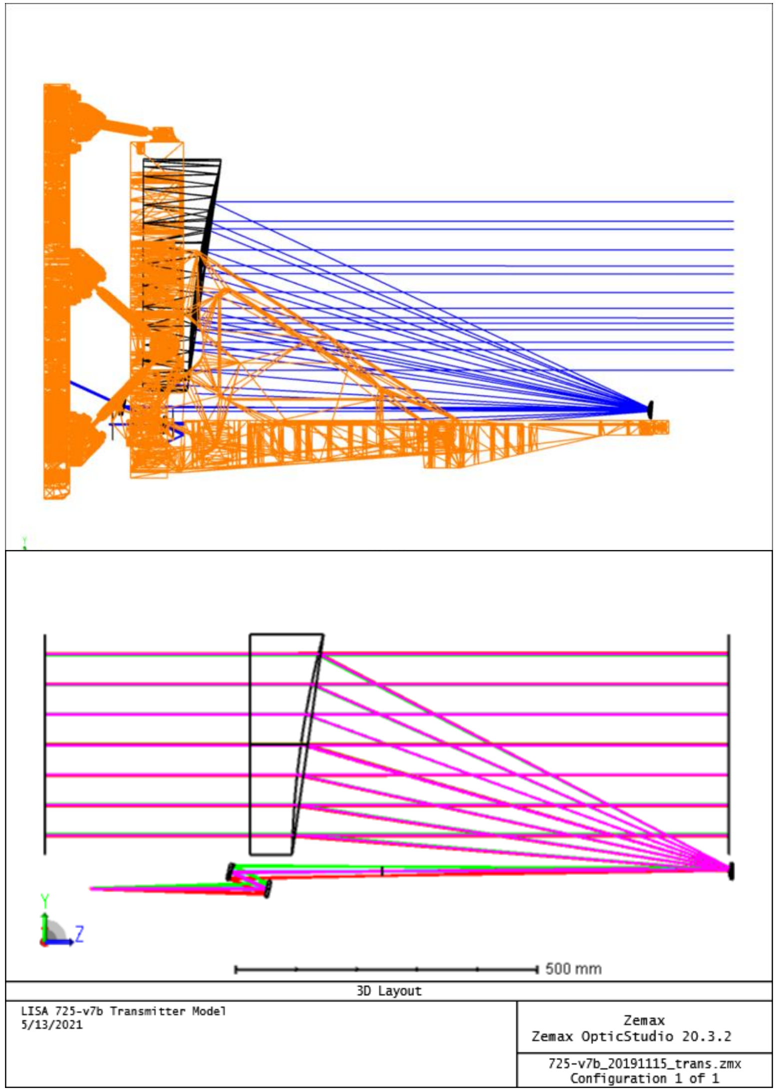
To fully understand the impact of these beams on the system further analysis should be done



Telescope Stray Light Model in Zemax

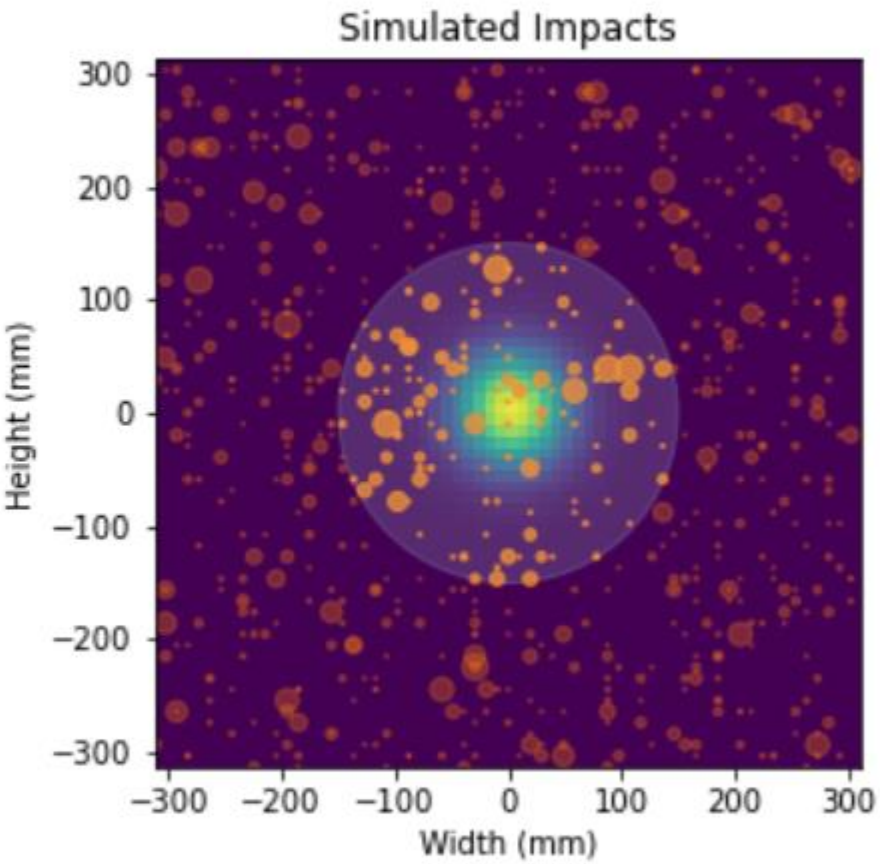
- Development Team
  - – Corey Austin – NPP (GSFC)

- Development Highlights
  - – Constructed non-sequential and sequential optical stray light models based on L3Harris CAD model
  - – Compared model’s performance to science requirements
  - – Used to study propagation of transmitted stray light in the telescope
  - – Used to study power throughput loss in the telescope
    - Sequential model: losses due to micrometeoroids, diffraction
    - Non-sequential model: transmitted stray light losses



Micrometeoroid Analysis

- Monte Carlo simulation to understand the effects of micrometeoroid impacts over the expected mission duration
- Uses Grün micrometeoroid flux model along with several damage crater models to generate a distribution of craters
- Craters are randomly located on the surface of the M1 mirror
- Using data from the Zemax model, compute the power throughput loss from the craters
- Model can also be used to complement work previously done by Len Seals studying backscatter from impact craters



Conclusion

- Special thanks to Len Seals, Shannon Sankar, and Jeff Livas!!
- Thank you for listening!
- Questions?

Extra Charts

LISA Telescope Overview

LISA is a space-based gravitational wave observatory building on the success of LISA Pathfinder and LIGO. Led by ESA, the LISA mission is a collaboration of ESA, NASA, and an international consortium. LISA is planned to consist of three spacecraft that are separated by 2.5 million kilometers in an Earth-trailing orbit . NASA's plan is to develop the precision telescopes that transmit and receive the 1.06 micron coherent laser light. Currently L3Harris is task to deliver one Telescope Engineering Development Unit (EDU).

The following model’s property assignments, analyses methods and results and are intended to be consistent/equivalent with those utilized by L3Harris. The EDU is principally design to assess optical path-length stability… not stray light (SL). However a representative model may serve as an independent cross-check for SL performance prediction and model validation. Additionally it may allow us to investigate back scattered light’s derived daughter requirements such as the effects of contamination, micro meteorite impacts, thermal soaking, etc…

Sources of optical noise

- **Diffraction** is considered a stray light mechanism because it produces a distribution of energy that extends well beyond what would be expected from geometrical considerations; for example, a circular aperture, when illuminated by coherent light, produces an Airy distribution that can cover the area of the detector. Since diffraction irradiance is proportional to the wavelength of light, it is rarely a significant stray light contributor in the UV and visible, but can become very significant in the longwave IR, dominating the effects of optical surface scatter.

- **Ghost images** can result when light incident on a surface is divided into reflected and transmitted components and both continue to propagate; ultimately some portion of the light reaches the image plane. Since ghost images are specular, they can retain coherence and polarization properties of the incident light; it is not uncommon in high-powered laser systems for ghost images to sum coherently to produce high fluence levels capable of shattering an optical element.

- **Diamond-turned surfaces** that are not post-polished typically contain residual periodic grooves left over from the turning process that can act like a diffraction grating. Incident light is diffracted into multiple unintended orders that propagate through the system.

- The **grinding and polishing** processes leave a residual microroughness on an optical surface as well as subsurface damage. A small amount of the light incident on an optical surface is scattered into an angular (typically Lorentzian) distribution centered on specular direction and continues to propagate. At the image plane, the scatter distributions from all of the surfaces add incoherently to create a composite scatter field.

- **Dust**, with its ability to scatter light, is ubiquitous in virtually all environments. The exact distribution of scattered light is a function of the wavelength of light, the complex refractive indices of the particulates and their size population on the surface. While totally unrelated mathematically to surface roughness, particulate scatter distribution is also manifest as a Lorentzian function.

- Recognizing the very wide variation in composition, it is not surprising that **paints and surface treatments** — such as anodization or texturing — can produce very diverse distributions of scattered light. Analysts classify paints and surface treatments into four broad categories: diffuse (matte) finishes, specular (glossy) finishes, hybrid finishes that can vary from diffuse to specular depending upon the angle of incidence of light onto the surface, and “other,” which includes carbon nanotube technology, the “blackest” materials that we know of. Paints and surface treatments can be very effective at controlling stray light but they can also cause unwanted side effects such as outgassing and particulate generation (flaking).

Minimizing Stray Light in Everyday Optical Systems *Rich Pfisterer Photonics Spectra, August 2018.*

Analyzing the Effects of Stray Light

- Stray light can impede the performance of any optical system. With the right tools, optical engineers can predict and compensate for its effects in order meet system requirements.
- Electrical engineers are very familiar with the effects of shot noise, thermal noise, flicker noise and crosstalk and how to recognize and mitigate these effects.
- Most optical engineers, on the other hand, frequently fail to appreciate the effects of optical noise in their systems, leading to non-optimal performance. This can be particularly significant in astronomical observations.
- Knowledge of how stray and reflected scattered light propagates through a system allows for the determination system level optical performance. Software tool such as FRED allows a SL analyst to predict stray light levels, identify sources of stray light and confidently recommend design/implementation changes to an optical instrument.

Stray light metrics

Just as a lens designer might use encircled energy or root-mean-square (rms) wavefront error to characterize the performance of an optical system, stray light analysts use several different metrics for describing the stray light characteristics of an optomechanical system.

Point source transmittance (PST) is the oldest stray light metric dating back to the 1970s and is conceptually very simple: Following from linear system theory, PST is simply the ratio of some measure of energy on the detector to the energy incident into the system, as a function of angle of incidence.

The LISA telescope's telescope coherent back-scattered light is a type of NDI which constitutes a noise coupling path via dimensional instability in the interface to the LISA optical Bench. Shannon Sankar and the LISA Science Study teams have determined noise coupling path metrics for heterodyne detection are the following:

- Fraction of optical **backscattered power**
- **Displacement noise** of the scattering optics (or rather, the pathlength noise experienced by the backscattered light)
- **Signal overlap** of the scattered light with the received field, for a given fixed overlap between received and local fields

The calculation of **backscattered power** is a very intuitive calculation and can be done evaluated by commercial stray light tools such as FRED, TracePro, Light Tools or Zemax. The telescope's stray light is generated primarily by internal stray reflections of the transmit beam. As the telescope's transmit and receive beams share a common path, the amplitude and phase of the beams received by a "far" telescope are also similarly conjoined. This leds to incoherent **backscattered power requirement** of **1E-10W** for the transmit beam.

Baffles design

- Baffles, stops and vanes all work to control the propagation of unwanted light through an optical system. Most optical designers are familiar with field stops to block out-of-field stray light; however these are not always effective in reflective systems where the optical path “folds” onto itself. Lyot stops are stops placed in a conjugate plane to the entrance pupil and are used primarily to block diffraction effects originating from the edge of the pupil.

- Baffles tubes containing vanes are commonly used to shadow an optical system from direct illumination at high off-axis angles and to control the number of scatter events prior to light reaching the optical system. (Since scatter is an inefficient method of energy propagation, sometimes it only takes a few interactions of stray light with vanes along a baffle in order to adequately suppress the stray light.) They are also used in dewars and other detector assemblies to limit illumination of the detector from stray light.

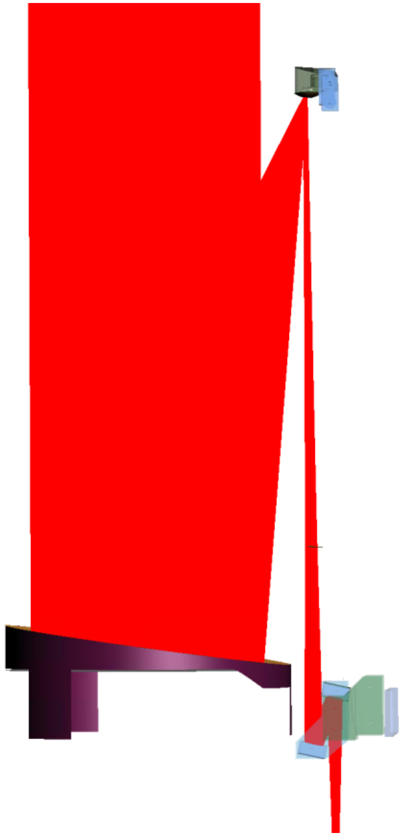
- If the LISA telescope is subjected to external in-band sources of stray light such as those generated by the receive beam field, a field stop should be able to block it. Baffles could also be placed as need to prevent stray reflected light from overlapping the signal

Stray Light Model Overview

FRED Stray Light model

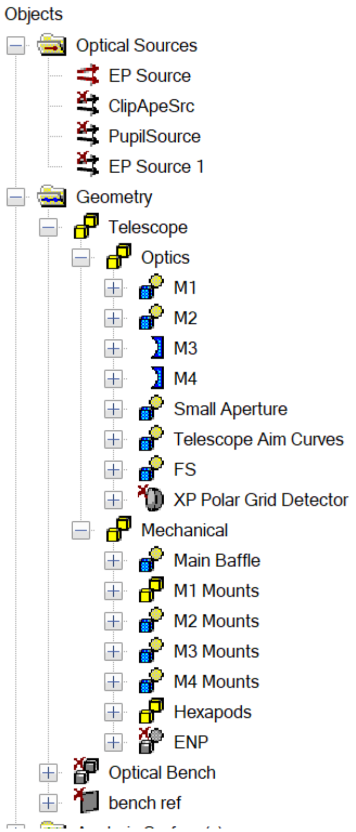
- Geometry layout
- Sources
- Scatter models
- Levels of scatter
- Importance sampling
- Raytrace controls
- Coordinate systems
- Analysis scripts

Telescope Model



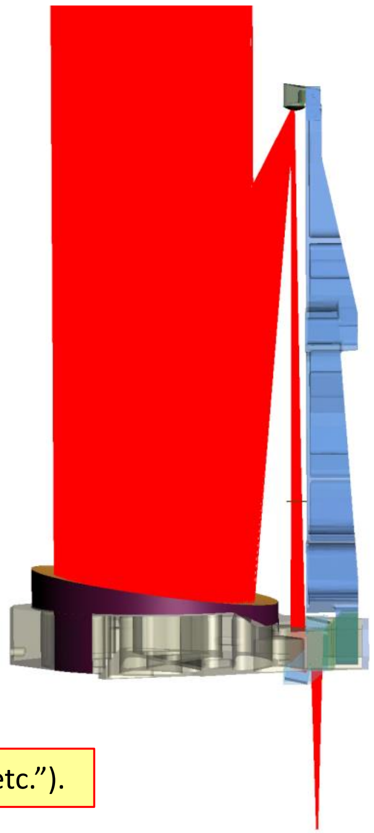
Stray Light Model Overview Cont.

Model Object Tree



Objects
- Optical Sources
  - EP Source
  - ClipApeSrc
  - PupilSource
  - EP Source 1
- Geometry
  - Telescope
    - Optics
      - M1
      - M2
      - M3
      - M4
      - Small Aperture
      - Telescope Aim Curves
      - FS
      - XP Polar Grid Detector
    - Mechanical
      - Main Baffle
      - M1 Mounts
      - M2 Mounts
      - M3 Mounts
      - M4 Mounts
      - Hexapods
      - ENP
  - Optical Bench
  - bench ref

FRED Model



Sources

Geometry

Several objects were left “turned off” (Sky, Plane representing the exit pupils, etc.”).

Some surface such as the “XP polar grid” are used for cross-checking analysis routines

Scatter Function and Important Direction Assignments

Scatter Functions and Importance Sampling

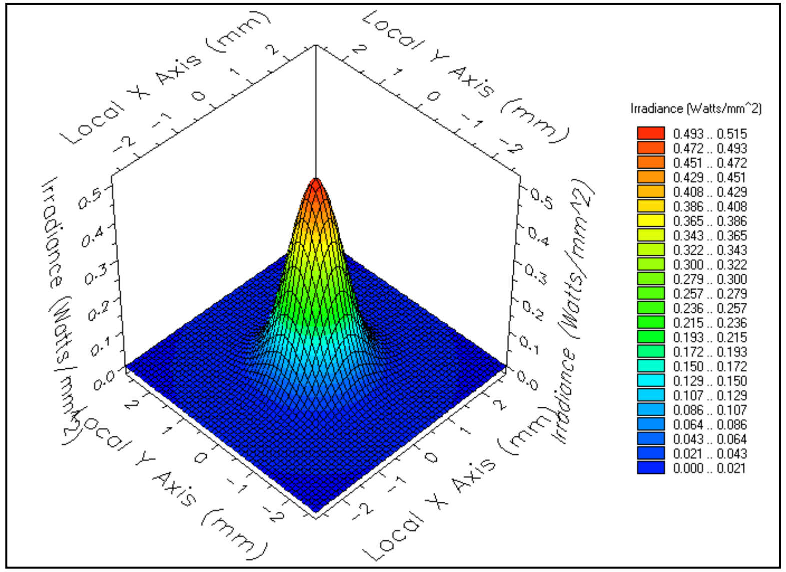
- FRED models optical surface roughness as smooth scatters (Harvey-Shack Scattering functions)
- Particulate Contamination is modeled by MIL-1246C (MIE Scattering functions)
- Most systems are well-characterized for stray light when only one level of scatter is considered; since the absolute power levels typically drops by 2-3 orders of magnitude for each additional scatter level, it frequently makes no sense to calculate higher levels of scatter
- To improve the efficiency, we use “importance sampling” to “steer” the scattered rays towards the object(s) of interest (usually into the entrance aperture of an instrument or, within an instrument, to the detector)

Contamination and Scatter assignments

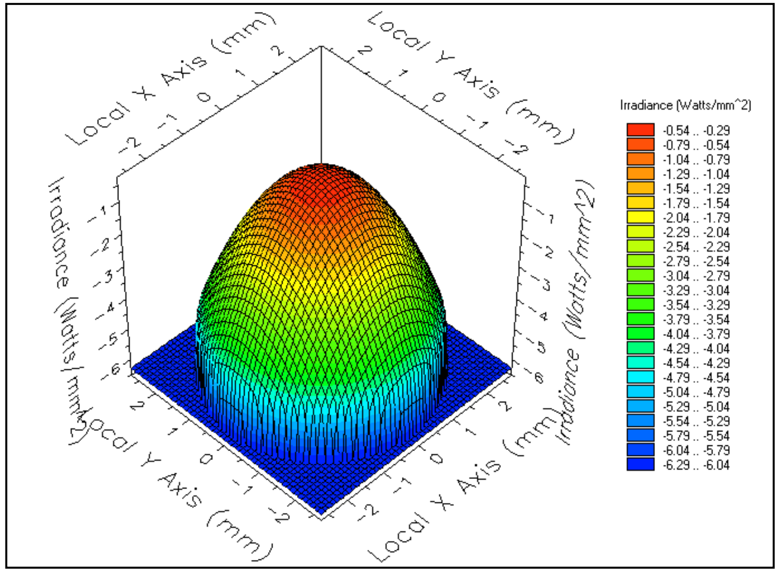
- Z307 has been applied to most mechanical surfaces
- Mirror Surface Roughness varies from 5A on the smaller surfaces to 15A for the larger conics
- Expected particulate contamination various from 200 to 570CL and its effected need to be characterized, bounded and possibly controlled.

Source Model

Source irradiance



Log_{10}(Source irradiance)



Note the steep beam edge indicating truncation

- Wavelength = 1.064 microns
- $1/e^2$ semidiameter = 1.12 mm
- Beam semidiameter = 2.5 mm (fills exit pupil)
- TEM_{00} mode
- Total power = 1W
- Source located at the small pupil

Scatter assignments expected for L3Harris EDU

- Primary mirror M1
  - 15Å rms surface roughness
  - MIL-STD-1246D CL 300 particulate contamination
- Secondary mirror M2
  - 15Å rms surface roughness
  - MIL-STD-1246D CL 200 particulate contamination
- Tertiary mirror M3
  - 5Å rms surface roughness
  - MIL-STD-1246D CL 200 particulate contamination
- Quaternary mirror M4
  - 5Å rms surface roughness
  - MIL-STD-1246D CL 200 particulate contamination

L3Harris will provide analyses, measured PSD and optical performance data to verify the properties of various optical components

Optical Coating assignments expected for L3Harris EDU

- Primary mirror M1 and Secondary M2
  - Font Surface: AR coating (99% Reflecting)
  - Rear Surface:
    - Black Paint or Ground Glass scatter model (4% Reflecting)
    - Wedged: Yes
  - Mirror Edges: Black Paint or Ground Glass (4% Scatter Only)

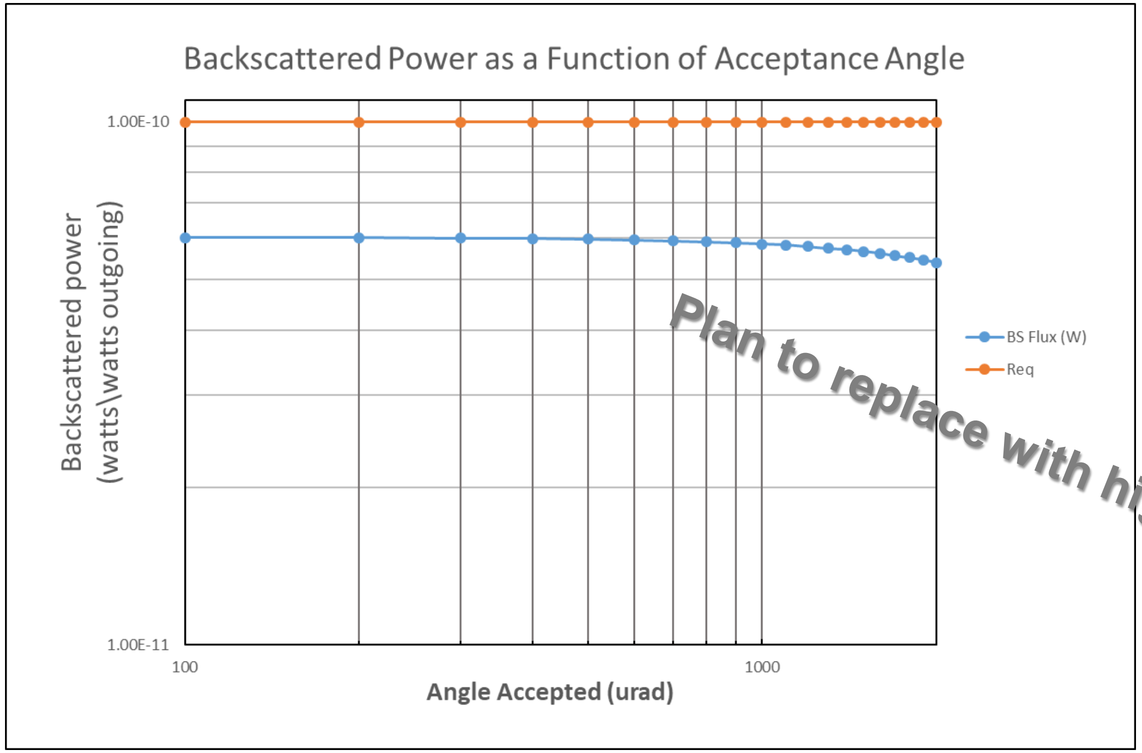
- Tertiary mirror M3 and Quaternary Mirror M4
  - Font Surface: AR coating (99% Reflecting)
  - Rear Surface:
    - Black Paint or Ground Glass scatter model (4% Reflecting)
    - Wedged: No
  - Mirror Edges: Black Paint or Ground Glass (4% Scatter Only)

Optical surface with wedged surfaces are commonly used to steer ghost beams away the primary raypath

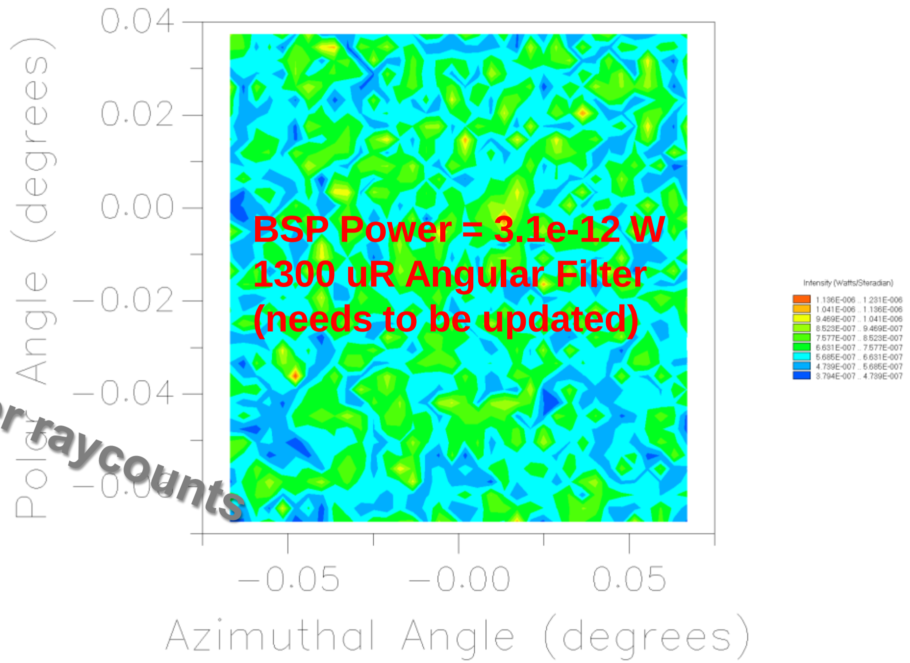
Scatter Irradiance Distribution on the Pupil Plane (cont.)

Backscattered power ~ 5.8e-12W at 1300uR

Polar Grid Intensity BS Flux = 3.1e-12 W



Plan to replace with higher raycounts



BSP Power = 3.1e-12 W
1300 uR Angular Filter
(needs to be updated)

Stray Light Report

- The Stray Light Path Analysis allows the raytrace raypath data associated with each scatter to be identified and analyzed

- The Stray Light Report is a utility that allows raytrace path data to be quickly sorted and presented in a compact format based on the following path characteristics:
  - The last entity along the path sequence (the Stray Light Report refers to this as the "Receiver")
  - The number of scattering events along the path sequence OR the number of specular splitting events along the path sequence

- The Stray Light Report displays only a subset of information for each path ending on the designated receiver and is intended to compactly communicate where the critical scattering or ghosting surface interactions along each path occurred.

Scatter Irradiance Raypath Analysis

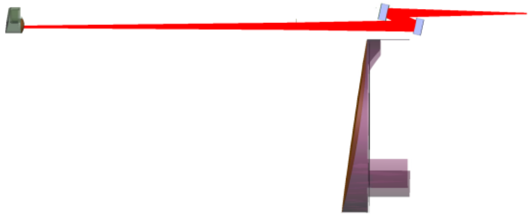
These pictures are really hard to follow

1st Scatter Surface	Backscattered Power	Percent (%)
M2	4.80E-10	94.50%
M4	2.60E-11	5.10%
M3	1.90E-12	0.40%
M4	3.40E-13	0.10%

The basic path report reflects all the power collected at the small pupil.
This data is not filtered by acceptance angle, as such it can't be compared directly to the requirement.

Properly scaled and analyzed a SL report can rank the top contributors. The report can also be used to determine optical transfer functions (view factors) . These values can be used to access the efficacy of vanes and baffles as well as their placement and properties. Thermal effects as well as surface damage due to localized features such as micro meteoroid impacts can also be analyzed by this method.

M2 Backscattered Raypath



M4 Backscattered Raypath

M3 Backscattered Raypath