Reducing stray light in Opto-Mechanical Systems

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Abstract

Almost every optical imaging system suffers from stray light or unwanted light. In an optical imaging system, stray light is caused by light from a bright source shining into the front of the system and reaching the image as unwanted light. Stray light also occurs in non-imaging systems. Stray light is commonly manifested in two ways: ghost images and scattered light. This paper investigates stray light problems and demonstrates how to reduce stray light in two typical opto-mechanical systems.

Several Causes of Stray Light

Stray light in imaging systems can come from a variety of sources. They are listed in the following sections in the normal order of severity, although this order depends on the particular design of the optical system.

- "Straight shots" mainly in reflective systems
- Ghosting in refractive optics and windows
- Single scattered light due to non-optimal baffle design or a highly reflective detector
- Multiple scatter stray light due to non-optimal baffle design

Straight shots can occur in a Cassegrain-type system when the central obstruction is too large and/or the telescope tube is too short. Light from outside the field of view can enter the telescope, travel past the secondary mirror, through the hole in the primary mirror, and strike the focal plane directly as stray light. This type of stray light can be a disaster if sunlight is allowed to enter the telescope.

Ghost images are so called because they are out-of-focus or ghostly-looking images of bright sources of light. Ghost images are caused by reflections from lens surfaces. To cause a ghost, light must reflect an even number of times from lens surfaces. There are two-reflection ghosts, four-reflection ghosts, etc. Optical systems consisting of only first-surface mirrors (a Cassegrain telescope, for example) do not suffer from ghost images. The sun causes ghost images in a photograph if it is in or near the field of view being photographed. Automobile headlights and streetlights cause stray light in a nighttime photograph. If the bright source is small, each ghost takes on the shape of the aperture stop of the optical system.

Single scatter stray light occurs when a stray light source such as the sun directly illuminates the optics in the system. Some portion of the light will scatter in a direction that causes it to reach the focal plane. We say that it scatters into the field of view. Once light has scattered into the field of view, it becomes stray light, and there is no way to eliminate it without also causing vignetting. Thus a basic goal of baffle design is to keep light from shining on the optics.

Multiple scatter stray light occurs when stray light sources indirectly illuminate the optics. These paths cause stray light indirectly, by first scattering from the baffle surfaces and then illuminating the optics. Stray light from this source will always be smaller than direct scatter, but it may still be large enough to be of concern.

Eliminating Stray Light

Stray light can never be totally eliminated. However, it can often be reduced to a level at which it is tolerable. Stray light can be called by another term: optical noise. Just as electrical or acoustical noise can be reduced, optical noise can also be reduced by proper design of the opto-mechanical system. In this paper we will show examples of how to reduce straight shots and ghosting.

Eliminating Straight-Shots

Normally, rays come into a telescope within the field of view and are imaged to the detector as shown in Figure 1.

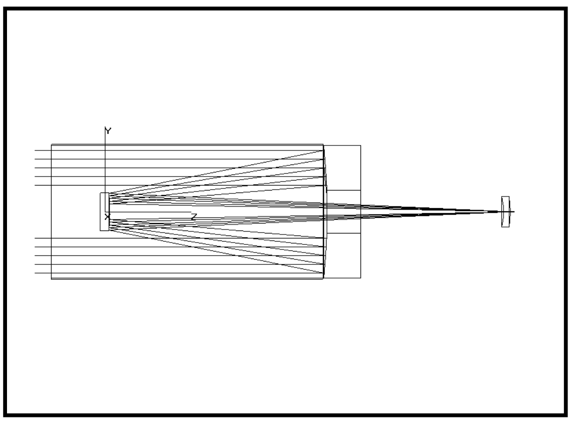

Figure 1 - Ray Traced Cassegrain Telescope

But what happens when an out-of-field source enters the picture? Figure 2 shows an out-of-field source sending a straight shot to the detector without being imaged via the primary and secondary mirrors.

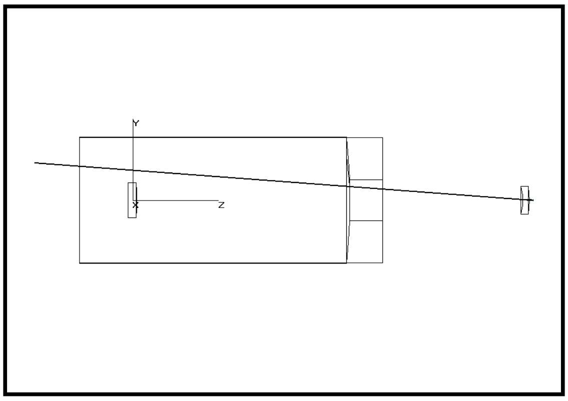

Figure 2 - Straight shot depicted

The only way to stop straight shots is by adding baffles to the telescope. For this case, to create the correct baffles the user needs to trace three ray bundles, first a bundle of rays on axis that fill the primary, secondary and reach the detector, see Figure 3. Then trace a second ray bundle back from the detector to the secondary, see Figure 4.

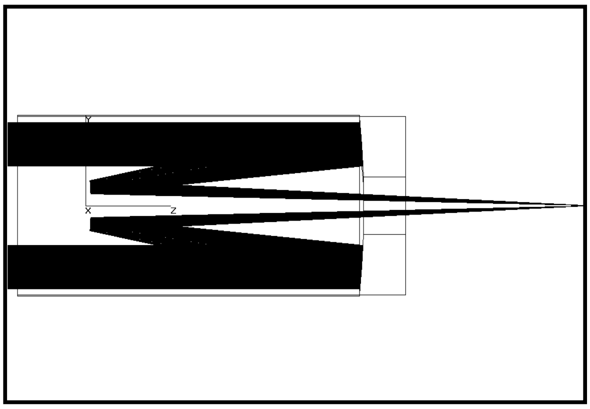

Figure 3 - Bundle traced to the detector

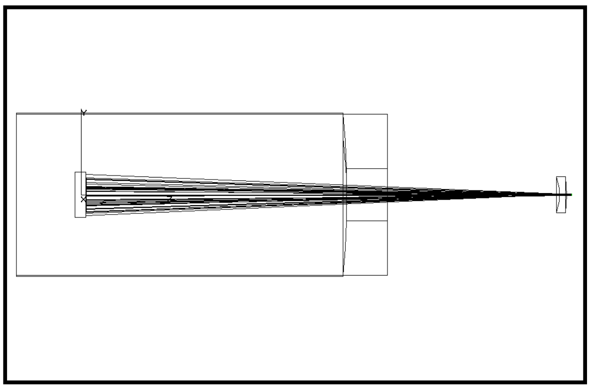

Figure 4 - Bundle traced back from detector

Finally, we must also take into account the FOV of the system. Figure 5 shows a grid of rays angled downwards at .025 degrees, the edge of the FOV. The outside FOV rays are the most critical bundle; these rays limit the size of your baffles the most. It is now a simple matter to create a primary and secondary baffle that do not impinge on any of these ray bundles.

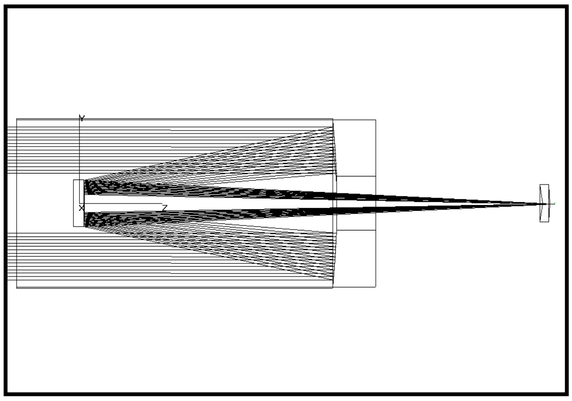

Figure 5 - System with FOV rays traced

First, we create a secondary baffle that will slightly vignette the off-axis ray bundle. The standard way to create this baffle is to start at the outside of the secondary mirror and extrude the tube outwards until it hits the last ray in the outside FOV ray bundle, see Figure 6.

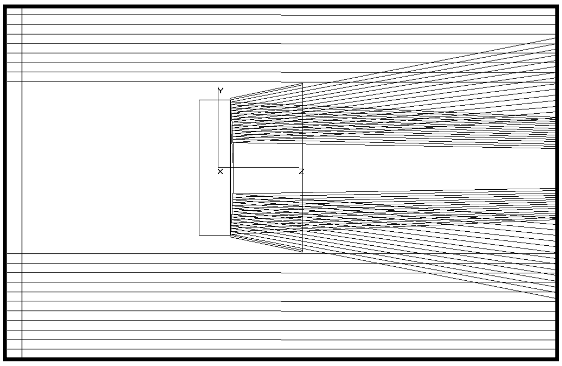

Figure 6 - Secondary Baffle

Next, create the primary baffle by extruding a tube from the inner ring of the primary that will fit within the outside FOV ray bundle and checking whether any of these rays impinge on the on-axis or detector-traced rays.

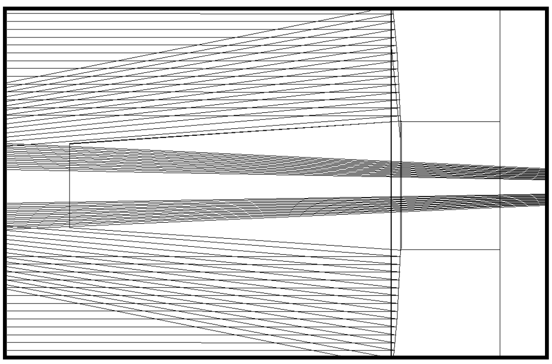

Figure 7 - Primary baffle correctly sized.

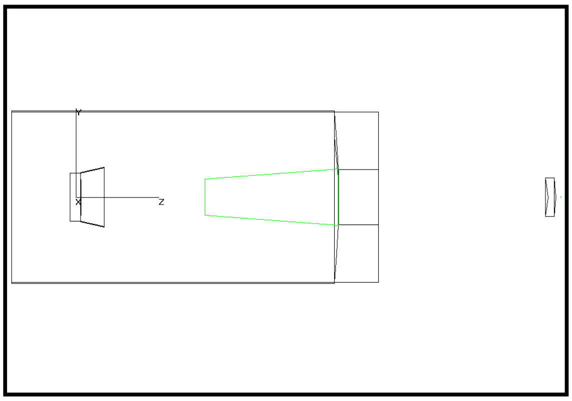

Figure 8 - Final Primary and Secondary Baffle

With the correct primary and secondary baffle inserted, possibilities of a straight shot into this Cassegrain system are eliminated.

Eliminating ghosting in refractive optics and windows

A good example of ghosting is the standard Cooke triplet shown in Figure 9. Ghosting occurs due to Fresnel losses at the intersection of each ray with each uncoated lens surface. Normally, this Fresnel loss is between 4 and 5 percent of the total energy intersecting each surface depending on the angle of incidence with the surface and the index of refraction. Figure 9 shows 5 collimated rays traced through the Cooke triplet system with perfectly transmitting surfaces.

In Figure 9, the starting 5 rays are shown as 5 horizontal lines propagating down the Z axis from left to right through each of the 3 lenses, finally stopping at the observation plane on the far right of the figure.

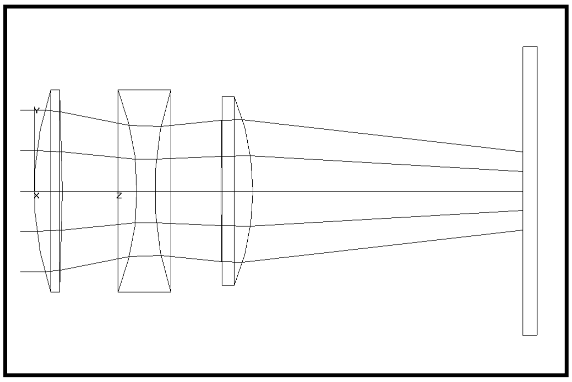

Figure 9 - Cooke Triple with 5 collimated rays traced

Figure 10 shows the same system with 5 collimated rays traced through the same Cooke triplet, but using normal uncoated lenses that you would buy off the shelf. The non-horizontal rays represent the Fresnel-reflected portion of the rays created at the intersection of each lens surface.

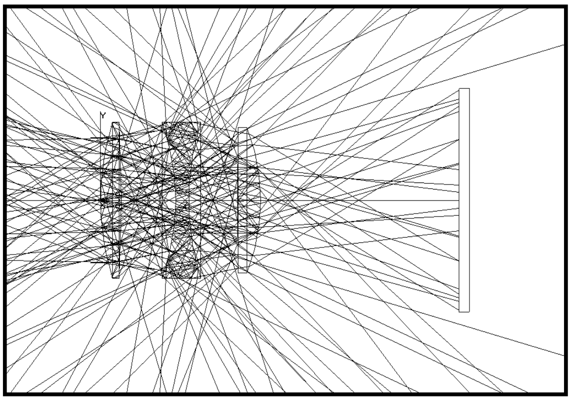

Figure 10 - Rays traced through triplet with no coatings

Figure 11 shows an irradiance map of all 40 rays that reach the detector, in which 5 specular rays and 35 ghost rays reach the detector. Figure 11 shows a cross section of the flux at the left and bottom of the irradiance map. Each of the five specular rays is shown as large spikes that contribute 1.8E+7 W/m^2 of irradiance in the left cross section. Each of the 35 ghost rays contributes approximately 4E+4 W/m^2 of irradiance. There is a 3 order of magnitude drop in irradiance comparing specular and ghost rays.

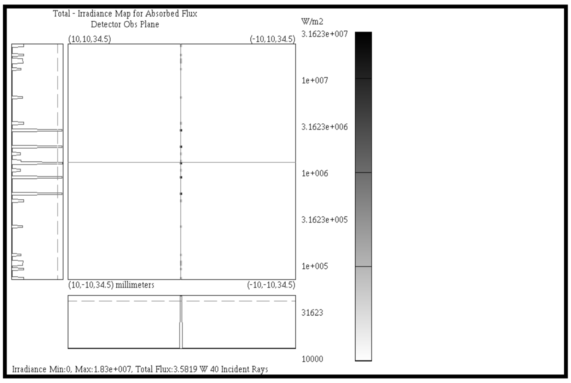

Figure 11 - Irradiance map of ghost and specular rays

For all ghost analyses all rays were stopped when they dropped below a flux threshold of .01% of the starting ray value at any surface intersection. This reduces the infinite number of rays that could be generated due to Fresnel reflections.

Normally an anti-reflection coating is applied to each lens surface to get rid of this type of ghost problem. Figure 12 shows the same system after coating each lens with a .25% reflecting and 99.75% transmission coating with the same 5 rays traced. There are no rays reaching the detector that have a flux greater than .01% of the starting power.

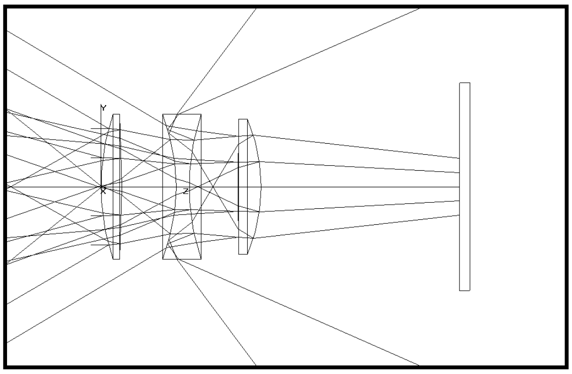

Figure 12 - Cooke Triple with AR coating

Thus in many cases it is an easy task to eliminate ghost reflections using AR coatings, but the cost of the coatings will certainly increase the cost of the system.

Eliminating Single Scatter Paths

Returning to the Cassegrain system, we can eliminate one of the single-scatter paths. The most obvious single-scatter paths are ones that allow the detector to receive scattered light directly. If we trace backward from the detector we can see all of the single-scatter possibilities. The first two objects the detector sees are the inside of the primary and the inside of the primary baffle. It is important to stop a one-bounce scatter from an out-of-field source to these objects. Figure 13 shows this single-scatter path.

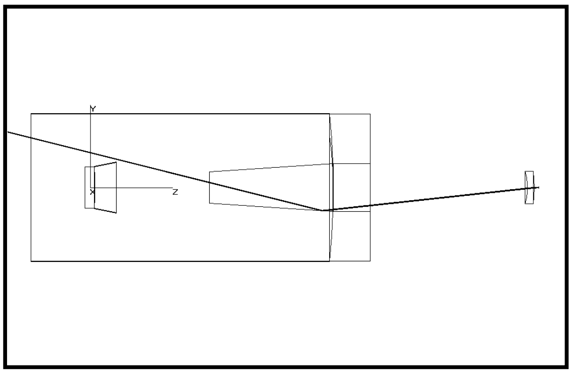

Figure 13 – Single-scatter path shown

To eliminate this path we need to create a set of conical vanes that block the detector from seeing the area illuminated by the off-axis source. This area is from the beginning of the baffle to the vertex of the primary as we can see from Figure 13. The detector sees the entire inside of the primary and inside of the primary baffle. It is now important to create a vane that blocks coincident areas seen by the detector and illuminated by the source that does not impinge on the imaging rayset.

We must create baffles that block the detector from seeing the inside of the conical baffle that is illuminated by possible off-axis sources. For this system we will need to create two baffles for this task.

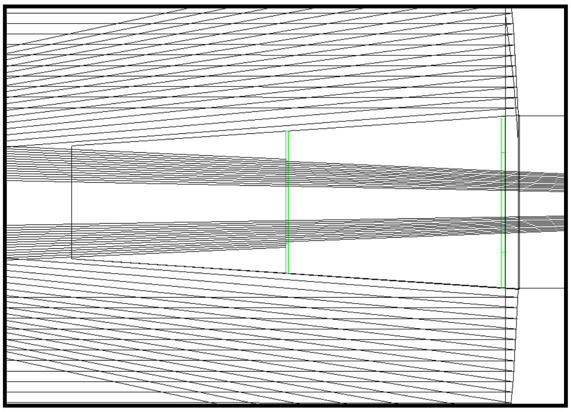

Figure 14 - Baffles that impinge on ray bundle

It is also necessary to make sure that these baffles do not impinge on the ray bundle within the FOV. As can be seen in Figure 14 an incorrect baffle size will cause vignetting of your incoming ray bundle.

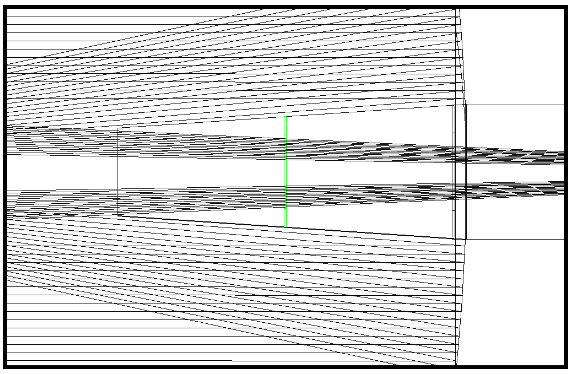

Figure 15 - Correct Baffle size

Eliminating Multiple Scatter Paths

The same procedure can be used for creating baffle vanes for the main baffle, breaking the baffle up into two sections, illuminated zones and those seen by the detector directly or through mirror reflections. In this manner, radiation cannot be transmitted through multiple scatters directly to any object seen by the detector.