Application Note 1

Stray Light Analysis in Imaging Systems Using Non-Sequential Ray Tracing

Software referenced: TracePro

Introduction

Stray light is one of the primary to degraded performance in optical imaging systems. Even when an optical system has been optimized for aberrations and imaging performance, unwanted light can enter the detector through indirect optical paths. These paths often involve reflections from mechanical structures, scattering from imperfect surfaces, or multiple reflections between optical elements. The result is reduced contrast, elevated background signal levels, and in severe cases ghost images that obscure useful information.

In modern optical instruments such as machine vision cameras, medical imaging devices, aerospace sensors, and scientific telescopes, stray light control is a critical part of system design. These systems frequently operate in environments where bright sources exist outside the nominal field of view. If these sources interact with internal surfaces, light may propagate through unexpected paths and ultimately reach the detector.

Traditional sequential optical design methods are well suited for evaluating imaging performance, aberrations, and focal properties. However, they assume that rays interact with optical surfaces in a predefined order. Stray light does not follow such orderly paths. A ray may scatter from a mechanical surface, reflect from several optical components, and then arrive at the detector after multiple interactions.

For this reason, stray light analysis requires a non-sequential ray tracing approach. In non-sequential simulation, rays propagate freely throughout the system and interact with any surface they encounter. This modeling approach allows engineers to evaluate how optical and mechanical components interact under realistic conditions.

This application note describes a practical work contributors flow for performing stray light analysis using Monte Carlo ray tracing and illustrates how engineers can identify and mitigate problematic light paths early in the design process.

Understanding the Sources of Stray Light

Stray light in an optical system can originate from several physical mechanisms. Although the exact contribution of each mechanism varies by application, most stray light problems arise from a combination of scattering, reflections, and mechanical interactions.

Surface scatter is one of the most common contributors. Even highly polished optical surfaces possess microscopic roughness that causes light to scatter in multiple directions. While the scattered energy from a single interaction may be small, the cumulative effect of multiple scatter events can become significant. Mechanical components are often much worse in this regard. Structural surfaces such as lens mounts, housings, and baffles may reflect or scatter substantial amounts of light if they are not properly treated.

Ghost reflections are another major source of unwanted illumination. These occur when light reflects between two or more optical surfaces before reaching the detector. In lens systems with many elements, ghost paths may form between curved surfaces, filters, or detector windows. Even surfaces with anti-reflection coatings can produce measurable ghost reflections when bright sources are present.

Diffraction and edge scattering also contribute to stray light. Apertures, mechanical edges, and partially obstructed surfaces can redirect light in ways that are not accounted for in simple imaging models. In compact optical instruments where space constraints limit the use of large baffles, these effects can become particularly important.

Finally, internal reflections from mechanical structures can propagate through complex paths before reaching the detector. A ray may reflect from the inside of the housing, scatter from a mount, and then reflect again from an optical element. Without a non-sequential model, such interactions are extremely difficult to identify. Understanding these mechanisms is the first step toward constructing a meaningful stray light simulation.

Why Non-Sequential Ray Tracing Is Required

Sequential optical modeling assumes that rays encounter surfaces in a predetermined sequence. This assumption simplifies calculations and works well when modeling well-behaved imaging systems. However, stray light paths rarely follow the intended optical path.

In a non-sequential simulation environment, rays are allowed to propagate freely throughout the optical system. Whenever a ray encounters a surface, the simulation evaluates the physical interaction at that location. The ray may reflect, refract, scatter, or be absorbed depending on the defined material and surface properties.

Because there is no predetermined order of surface interactions, rays may bounce between multiple surfaces or pass through unexpected regions of the system. This flexibility allows engineers to model complex interactions between optical components and mechanical structures.

Monte Carlo ray tracing is commonly used in this context. Rather than tracing a small number of deterministic rays, the simulation launches large numbers of rays sampled from statistical distributions. These distributions represent the angular and spatial properties of the light source. By tracing many rays, the simulation produces statistically meaningful predictions of irradiance distribution within the system.

This method is particularly effective for identifying low-probability stray light paths that may still produce measurable detector signals.

Building the Optical System Model

A successful stray light analysis begins with an accurate representation of the optical system geometry. Both optical components and mechanical structures must be included in the simulation model. While optical surfaces are obvious contributors to stray light behavior, mechanical surfaces often become the dominant sources of scattered light.

The optical portion of the model typically includes lenses, mirrors, filters, windows, and detectors. These elements may be imported from lens design software or constructed directly within the simulation environment. Maintaining accurate curvature, spacing, and material properties is essential for realistic results.

Mechanical geometry is frequently imported from CAD models. Lens mounts, housings, baffles, and structural supports should be included whenever possible. Engineers sometimes underestimate the influence of these structures, yet they frequently introduce the largest stray light contributions.

Once the geometry is imported, each surface must be assigned realistic optical properties. Reflectivity, transmission, and scattering characteristics should reflect the materials used in the physical design. Mechanical surfaces often receive diffuse scattering models, while optical surfaces use measured or theoretical scatter functions.

At this stage, the engineer also defines coatings and material properties. Anti-reflection coatings, metallic reflectors, and absorbing surfaces must be modeled accurately in order to predict ghost reflections and scattered light behavior.

Defining the Light Source and Detector

After constructing the optical model, the next step is to define the light sources entering the system. The source definition should represent the real operating environment as closely as possible. In some cases the source may be a simple point emitter, while in others it may represent extended illumination or environmental background light.

For imaging systems exposed to outdoor environments, engineers often simulate off-axis sources such as the sun or bright reflections from nearby objects. These sources may lie far outside the nominal field of view but still produce stray light contributions through indirect interactions.

The detector must also be defined carefully. The detector plane typically represents the imaging sensor or focal surface where stray light effects are measured. Parameters such as spatial resolution, physical size, and spectral response may be included depending on the desired level of analysis. During the simulation, the detector records the irradiance produced by traced rays. This irradiance distribution forms the basis of the stray light analysis.

Running the Monte Carlo Simulation

With geometry, materials, sources, and detectors defined, the system is ready for ray tracing. Monte Carlo ray tracing launches a large number of rays through the optical system. Each ray is assigned an initial direction and position based on the source definition.

As rays propagate through the system, the simulation evaluates their interactions with surfaces. A ray may reflect from a surface, refract into another medium, scatter in multiple directions, or be absorbed. These interactions follow the physical models assigned to each surface.

Because rays may interact with many surfaces before reaching the detector, the simulation keeps track of each ray path. Engineers can later inspect these paths to determine how stray light propagates through the system.

The number of rays used in the simulation determines the statistical accuracy of the results. Early exploratory simulations may use relatively small ray counts to identify obvious stray paths. Final verification runs often use much larger ray sets to ensure accurate predictions of detector irradiance.

Low probability paths, such as stray light paths, may be under-sampled using traditional Monte Carlo methods. Importance Sampling is a valuable tool that can be used to improve the sampling in low probability paths.

Interpreting Simulation Results

Once ray tracing is complete, several analysis methods can be used to identify stray light sources. Detector irradiance maps provide a direct visualization of how light is distributed across the sensor surface. These maps often reveal patterns that indicate stray light contributions. Uniform background illumination, localized hot spots, or faint ghost images may appear depending on the nature of the stray light.

Ray path visualization tools allow engineers to examine the trajectories of rays that reach the detector. By tracing these paths backward, it becomes possible to identify the surfaces responsible for unwanted light contributions. This capability is especially useful when stray light originates from complex multi-reflection paths.

Ghost path analysis can further isolate reflections between optical surfaces. By examining these interactions, engineers can determine whether ghost images originate from lens elements, filters, or detector windows. These analytical tools transform raw ray tracing results into actionable engineering insights.

Mitigating Stray Light in Optical Systems

Once stray light sources have been identified, engineers can evaluate design modifications to mitigate the problem. Mechanical baffles are among the most effective solutions. By strategically placing absorbing structures along the optical path, engineers can prevent unwanted rays from reaching the detector.

Surface treatments are another common mitigation strategy. Mechanical surfaces may be coated with low-reflectance materials or textured finishes to reduce scattered light. These coatings significantly reduce the amount of light that reflects back into the optical system.

Optical coatings can also play an important role. High quality anti-reflection coatings reduce ghost reflections between optical elements and help maintain image contrast.

In some cases, adjusting the position or size of apertures can eliminate certain stray paths without introducing additional components. Simulation allows engineers to evaluate these modifications quickly and determine their effectiveness before committing to hardware changes.

Benefits of Early Stray Light Simulation

Performing stray light analysis during the early stages of optical design provides substantial advantages. Engineers can identify problematic light paths before mechanical components are finalized, reducing the likelihood of expensive redesigns later in development.

Simulation also enables rapid iteration. Multiple design modifications can be evaluated quickly, allowing engineers to explore different mitigation strategies and determine the most effective solution.

Perhaps most importantly, early stray light analysis improves overall system performance. By minimizing background illumination and ghost reflections, engineers can achieve higher contrast, improved signal detection, and more reliable optical measurements.

Conclusion

Stray light is a critical factor in the performance of modern optical imaging systems. Reflections, scattering, and mechanical interactions can introduce unwanted illumination that degrades detector performance and reduces image quality.

Non-sequential Monte Carlo ray tracing provides a powerful method for identifying these effects and evaluating mitigation strategies. By accurately modeling both optical and mechanical components, engineers can visualize stray light paths, quantify detector irradiance, and optimize system performance before physical prototypes are built.

Through careful simulation and analysis, optical designers can reduce development risk, accelerate system optimization, and deliver high-performance optical instruments capable of operating reliably in demanding environments.