GEMINI
8-M Telescopes Project

TN-I-G0023

Stray Radiation Issues in Astronomical Systems with Adaptive Optics

Stephen M. Pompea
Instrumentation Group

Abstract. The prevention and removal of stray radiation in adaptive optics systems is critical. The range of potential issues is large; they must be addressed early in the system design of the astronomical telescope / adaptive optics / instrument system. After potential problems are identified, a systems level analysis using stray light analysis software can identify the most important problems and assess the magnitude of the effect on system performance.[i]

Key Words: adaptive optics, instrumentation, stray light, black surfaces, baffles, contamination, scattering, bidirectional reflectance distribution function, points source normalized irradiance transmittance.

Outline

1. Introduction: What is Stray Light?

In this paper I will give a brief introduction to stray light issues in astronomical systems with adaptive optics. I will discuss the problem from a qualitative point of view as there are very few quantitative studies of stray light in such systems or stray light models that have been produced. Fortunately (or unfortunately, depending on your perspective) many of the first-order stray light problems that affect astronomical telescopes must be well controlled in order for the adaptive optics system to work effectively. Therefor, much of this paper will be a review of some general stray light problems that are very important but not peculiar to adaptive optics systems.

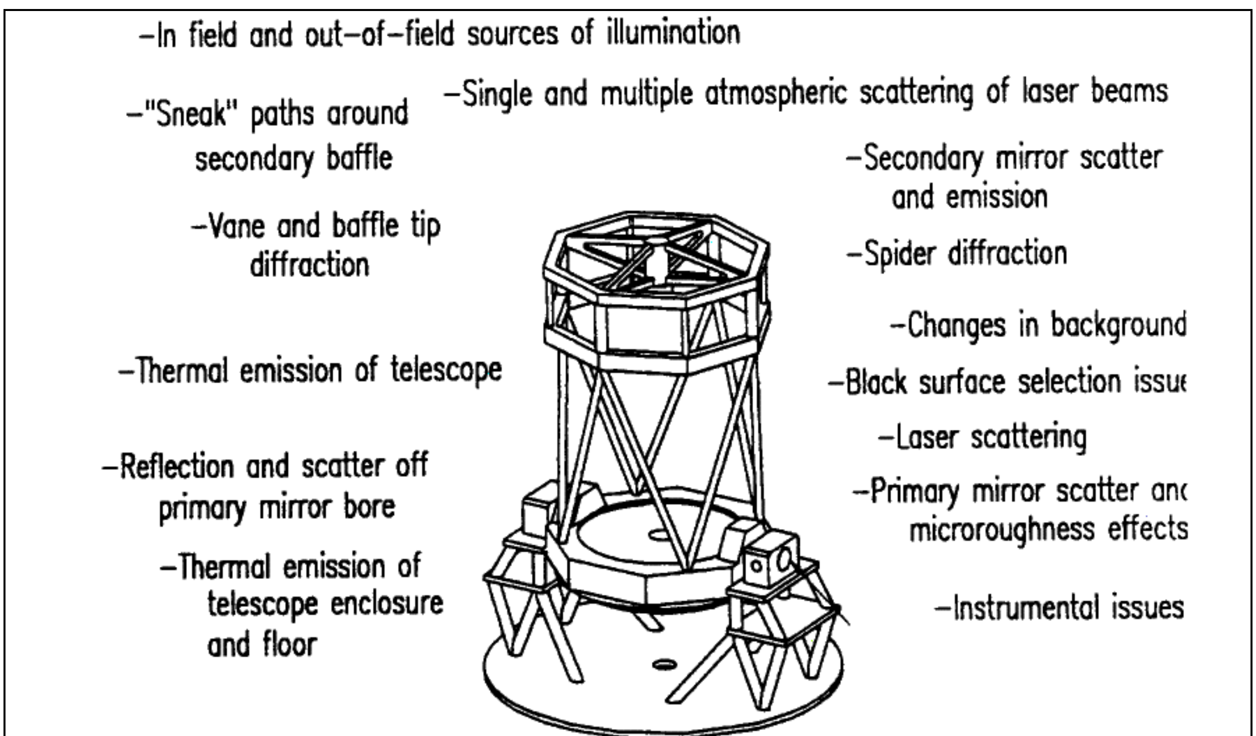
In my lecture, I had three items that I used to symbolize the key concepts of stray light. My flashlight, tinted swim goggles, and hat are indicative of the approaches we use in the field of stray light analysis. The flashlight represent our approach to understanding how radiation propagates in an optical system. We shine rays figuratively and literally through the system to understand the paths unwanted off-axis radiation or thermal radiation can take. The tinted swim goggles represent filtering, the spectrally selective removal of radiation. We shall see that this is extremely important in adaptive optics systems. And my hat represents the most fundamental approach to stray light removal, the blocking of out-of-field radiation which can create dynamic range problems. This glare can scatter through the system, reducing the contrast. In the extreme case, glints are produced by this off-axis radiation.

What is stray light? I like to define it in a very general way, as any radiation that reduces the performance of an optical system. One way of thinking about optical design is that there are two types of electromagnetic radiation or photons propagating through the system - the 'wanted' part and the 'unwanted' part. The wanted radiation comes from the objects of interest and are imaged on the detector. In general, they are controlled by the 'idealized' optical system, which contains the optical elements that you can describe in an optical design code. The ensemble of elements defined in the design code is a simplified and highly idealized subset of the finished optical system. Many mechanical and structural components are missing.

There is also ’unwanted’ radiation which is propagated and generated by the actual optical system. This can include radiation from an unwanted source (say a source outside of the field-of-view) or radiation from thermally emissive objects inside or outside of the optical system. It may also include radiation that is diffracted, scattered due to microroughness and contamination of optical surfaces, or scattered from inhomogeneities in transmissive elements.

You will notice that I often use the word "system". It is a very important concept for stray light. A system is the whole arrangement of things that have been placed together to perform a ftmction. Although the primary fimction of an optical system is to collect, direct, and focus light, there will be many other components that have important functions from a stray light point of view even if they have no role in forming an image. For example, motors that move filter wheels emit radiation that can reach the detector. In the case of adaptive optics, it is the telescope / adaptive optics / instrument system that is important, and which must be made to work. Actually, the *system* is even more complex. Included in this system are the various telescope and atmospheric components that the AO system must work with. Since all of these aspects must work together to give the desired performance, we must consider stray light factors in each part of the system. Considering the’optical system’ alone would yield a very narrow perspective.

Let me illustrate the concept of system performance and wanted and unwanted radiation with a simple example - the overhead projector. We know what the desired optical performance is,



Characteristic Stray Light Issues of Cassegrain Telescope Systems

what the designer must be trying to accomplish with a few lenses and a bulb. The optical system by itself has certain ghosts and diffraction effects from the fresnel lens, which must also be minimized to get good system performance. The overall system performance must also include the screen, the background room illumination, and the person doing the viewing. A good lens design is only a promising invitation to good system performance, particularly is system operation is ignored, or downplayed. For example, these projectors always project up in directing light to the screen, but the distortion from pointing up is rather severe and is not compensated for in the design (perhaps it is too difficult or expensive). I attended a talk where the speaker put up a viewgraph with a circle and an ellipse to represent two galaxies of different inclinations. Unfortunately, as viewed by the audience, the circle on his viewgraph became an ellipse and the ellipse had became a circle, because of the distortions introduced by the projector. Fortunately, the human brain is very good at making compensations; otherwise everybody would be crowded into the very few center seats of a movie theater, where the screen and picture do not appear to be trapezoids!

I bring up the issue of optical distortion being ignored, because the actual use is not considered, to point out how the real use of a system differs from the way it might be described in a computer model. This point is pertinent to astronomical systems as they are often used in ways that are not intended by the original design. We know as well of astronomical instruments where the design revolved around a particular function that was difficult to engineer, and then when the instrument reached the telescope, that function was never used. In a stray light analysis we often find things outside the system that were not anticipated, but which have potentially damaging effects. But no matter how good the lens design, the system performance will be poor if other stray light issues (such as room illumination) are not taken into account.

2. Some Common Stray Light Problems in Astronomical Systems

Let me describe some conunon stray light problems in astronomical systems before I turn to issues specific to AO systems. As I just discussed, the overall 'system' can include the atmosphere, the floor, Moon, telescope structure, the enclosure 'baffle', nuts, bolts, and screws in an instrument, edges, dust, and warm motors, to name a few items. The telescope structure and baffling act as a giant non-imaging system, collecting rays that hit it from all directions, and redirecting some of the rays to the image plane as well as generating thermal radiation that may also get to the image plane. Some of the different issues in astronomical systems involve:

- Excess noise in thermal infrared systems. This is often solved by blocking the detector's view of warm objects, removing these objects, or decreasing the emissivity of surfaces through deaning or use of low emissivity materials.
- Background radiation due to out-of-field sources such as moonlight. The telescope enclosure, baffles, and filters are often used to reduce the direct effect of moonlight. Scattered light (such as moonlight) from the sky is much more difficult to reduce as it fills the field and is broad spectrum.
- Ghost images, from lenses or filters. Filters near the focal plane often play an important role in creating ghosts and often are tilted to limit this effect.
- Dfffraction-related effects, from spiders or apertures.

- Overfilling of optical elements by the beam.
- Reentrant spectra in spectrographs.
- Focal plane straylight structure.
- Coronagraphic mask design
- Contamination by dust and hydrocarbons

3. Why Must We Tackle These Problems?

How important are these factors that degrade performance? Must they be found and eliminated? The answer depends on the performance levels desired. Just as adaptive optics is most valuable when the optical aberrations of the telescope/instrument system are small, design and analysis for stray light control is most important when higher performance and more quantitatively useful data are desired. A broad range of observational desires using AO will require conscious stray light control:

- Detection of faint sources in the sky / instrument background noise
- Reduction of confusion in crowded fields
- Reduction of diffraction effects at certain distances from a target object
- Better background subtraction
- More accurate photometry

4. Adaptive Optics Stray Light Issues

The adaptive optics instrument has a number of performance threatening stray light issues. Many of these issues arise from the presence of a laser system at the telescope. Others arise from the juxtaposition of a bright laser beacon in a field of view where a very faint star is being observed. Still others simply come from the higher performance expectations of AO systems and the hard scientific problems that they are being built to address. The relationship between adaptive optics systems and focal plane instrumentation is a complicated one and is well addressed by Ridgway (1994).

The presence of laser beacons adds several new stray light issues. The current approach is that the bright laser beacon (say of $m_v = 10$) is projected to be coincident with a very faint science object and must be removed. A very good filter will be needed and improvements in filter technology may be necessary. The Rayleigh scatter pattern probably needs to be removed or blocked. The polarization properties of the Rayleigh scatter may be useful in removing it. The secondary mirror can be used to block the Raleigh scatter, particularly if the mirror is reasonably large. The role of multiple scattering in the atmosphere has not been examined in detail and may prove important.

The presence of the bright in-field source furnished by the laser beacon may accentuate problems of near-angle scatter from mirrors, and bulk and surface scatter through transmissive elements, though filtering again should be useful. If the telescope system is used to project the laser beam, several new problems may be introduced. The laser beacon may induce fluorescent effects on mirrors and on mirror contaminants. This may not be so easily filtered out as the wavelengths involved are much less predictable. As an obvious example, any residual traces of mirror cleaning detergent with fluorescent 'whiteners' in it could cause a problem. Black paints can also exhibit fluorescent effects under laser illumination. Laser beacons may also create ghosting effects and blooming effects in detectors. A bright source in the field can also lead to a pronounced structure in the focal plane due to scattered light.

Since there are often several to many telescopes clustered at the best sites, it is important to consider what the effect of having laser beacons from several telescopes operating simultaneously will have on the performance of each system. Each system must be relatively impervious to stray light sources in a variety of directions, unless some coordinated observing program could be agreed upon. Another issue for laser launch systems is the scattering of light out of the beam by atmospheric aerosols and dome dust. Because of its close proximity to the detector, this source of source of stray light may need to be modeled. It may be particularly important in bringing the beam to the region behind the secondary where a laser launch telescope may be located.

Wavefront sensors have their own unique stray light problems. For infrared AO work, wavefront sensors have a first-order requirement to work in moonlight. Yet there may be no baffling against off-axis sources on an infrared telescope. Internal baffling in the wavefront sensor will be needed to achieve the performance desired in moonlight.

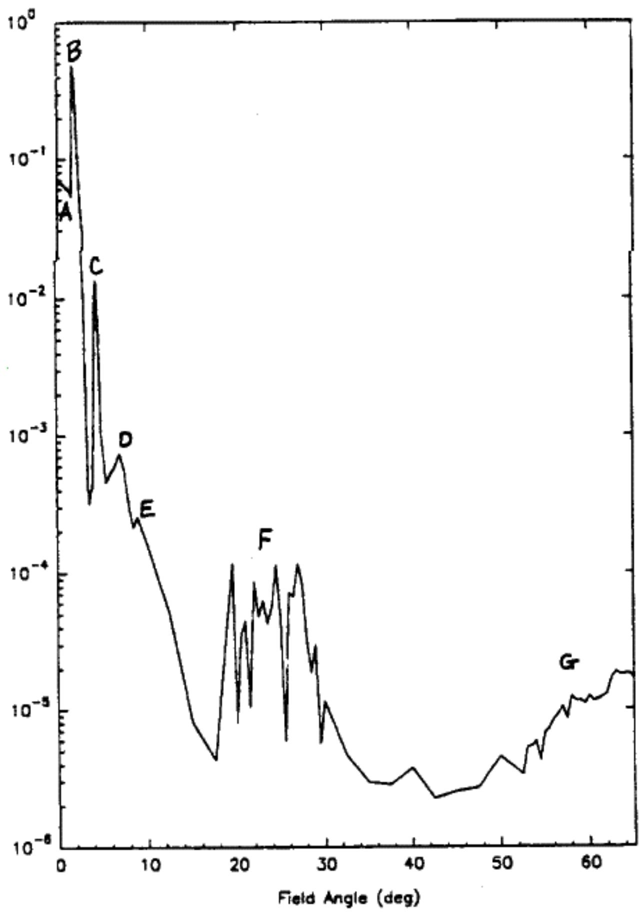
Coronagraphs are designed to suppress wings of the PSF at the points of interest. These instruments requires low scatter optics, control of spider and aperture diffraction effects, and specially fabricated masks. A stray light analysis can aid in the specification of optical elements and in system performance definition, as well as in the design of apodized masks. Another stray light issue involves the use of cold masks (Lyot stops) in infrared instruments. With the movement of a deformable mirror, will the background be variable? One of the key areas of current interest is very near angle scatter from mirrors. The scatter pattern at several tens of arcseconds and beyond is much better understood than the scatter characteristics of telescope systems at several arcseconds away from a bright object, where planets might be seen. Contamination and cleaning issues in optical systems have traditionally been part of the stray light field and are addressed in stray light analyses. A key issue is the long term degradation of optical surfaces which have very frequent cleaning. The concerns I have raised about AO systems is not an exhaustive list. It is a starting point for identifying and modeling problems that may be important.

5. Approaching Stray Light Problems

I would like to discuss first a few conceptual approaches for identifying stray light concerns in new systems where there is not much operational experience and in mature systems that are being used at higher performance levels. My discussion applies to the design of an AO system as well as how one can improve an already built system. First, in our approach to these problems, we must shift our thinking process. Our final output at the focal plane with an AO system is not the type of image we are used to seeing in a CCD or IR detector frame. In the case of laser beacons, we see a sodium star on top of a pattern of Rayleigh scatter, and we see a variable PSF across the frame. We must keep this new image in mind as we try to obtain the best possible performance.

Second, as we try to understand potential stray light effects, we should start from the inside out. Start at the detector and ask what the detector sees and how radiation can get to the detector. Putting ourselves conceptually at the detector or putting our eye at the focal plane is a valuable approach. Rather than mentally trace rays through the system and see how rays can scatter to the detector, it is more useful to look at which objects are seen from the detector and ask what processes can add power to these surfaces. In the case of a cassegrain telescope, this approach highlights the role of the inner surface of the inner conical baffle and of the inner mirror bore surface in transferring power to the focal plane. These surfaces are seen because of their close proximity to the detector. These surfaces are most important because they are struck at grazing incidence by scattered rays from various objects, which makes their reflectivity high.

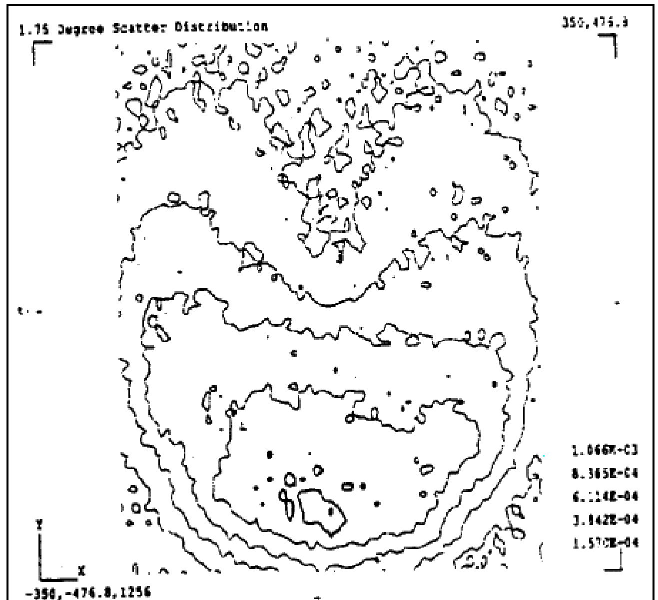
A third requirement is that we be creative in thinking of potential problems. We must think of the problems in the most general terms, since the system we build may be used for different purposes in a few years. For example, ff we plan on filtering out a sodium laser beacon, we may pick a filtering approach and feel very confident with this approach. If we reframe the problem in terms of multiple beacons of the same color, or several beacons of different colors, another completely different approach may be required. If we are to retain flexibility in our instrument design we must attempt to anticipate the future problems that may arise.



Point Source Normalized Irradiance Transmittance

Most importantly, stray light problems must be treated seriously in the initial instrument design, in the analysis and evaluation of this design, and in the testing phase of an AO instnunent. Too many problems are "saved" for the testing phase. Unfortunately, the use of testing to find stray light problems is becoming increasingly difficult as the system performance keeps improving. In any case, testing after the instrument is built is not the time to try fix problems that show up. If fundamental problems are present, then fundamental changes have to be made in the instrument.

A careful effort at eliminating common stray light problems in the optical design is the first step. When the optical and opto-mechanical design of the AO instrument have been completed, the instrument should have a proper stray light analysis. Just as the optical design is analyzed using spot diagrams, the design must be analyzed to see if the "optical design for contrast" is acceptable.



Scattered Light Patterns Across a Focal Plane

The design must be analyzed from this point of view; the performance degradation due to stray light issues are often serious and sometimes catastrophic. Small errors in instrument design can be serious and have monumental budget and schedule implications. A recent example of this is the warm surface in the Infrared Space Observatory that can radiate to a LHe cooled area. A simple stray light problem such as this, which would have been easy to solve in the design phase often become apparent after construction and has potential to disrupt the schedule.

The Hubble mirror problem is another example of a small oversight with extensive ramifications. The fundamental problem that caused the manufacturing of a spherically aberrated mirror was a stray light problem. A black cap on a polished spacer rod had a chip in the paint that reflected a laser interferometer beam. The beam was supposed to travel further by going through a hole in the cap and reflecting off of the rod. This stray light signal was interpreted as the correct measurement, which led to the wrongly constructed null corrector and eventually to a mirror with the wrong prescription. (Of course the consequences of this mistake should have been caught, but that is another story.)

The tremendous attention to optical design and maximization of image quality and the relatively little analysis attention often paid to potentially more serious stray light issues is what I call "stray light myopia". Every time you think of Hubble's myopia think of stray light myopia. A problem doesn't have to be elegant, elaborate, or subtle to destroy the performance of your system. It may be simple and easily caught. But it may be caught too late if the analysis stage is bypassed. So I emphasize again:

The contrast performance or overall performance of the imaging and non-imaging components must be treated as Mousey as the optical designfor image quality.

6. The Role of a Stray Light Analysis

When a stray light analysis is done on a system, the first thing that is done is to create a model and to verify the optical design. This part of the analysis provides an independent look at the design and is often very beneficial to piece of mind. The intent of the stray light analysis is to include all of the system aspects that are needed. The experience of the analyst is critical to ensure that a representative model is constructed, and that it can be run in a finite amount of computer time.

Stray light analyses have been done on a variety of space telescopes and instruments, including IRAS, HST, SIRTF, ISO, and DIRBE. For ground-based astronomical telescopes a general analysis was done for the Sloan Digital Sky Survey Telescope (Pompea et al. 1993), and an emissivity analysis was done for Gemini telescopes (Dinger 1993). The performance of ground-based instruments and telescopes has now become as demanding as space-based systems, and the analysis is just as necessary. This form of analysis is also done on a wide variety of non-astronomical optical systems, including remote sensing systems, laboratory spectrometers and physics experiments such as for laser interferometric detection of gravitational waves.

Three major (and a variety of minor) software packages are available for stray light analysis. The major ones include GUERAP, APART, and ASAP. For a review of these programs and other stray light software see Breault (1990). Of the three programs, ASAP (Advanced Systems Analysis Package) is probably the most flexible and user-friendly. All of the codes are used to trace rays to verify the optical design, create important objects in the system (the level of detail needed is an important topic unto itseff.), and send large numbers of rays through the system from a variety of angles. Since only one ray in only 10^{13} may be incident at the focal plane, intelligent sampling must be used to adequately represent the stray light paths. Reflected, transmitted and scattered rays can be trace forwards and backwards through the system. The analysis gives the critical paths to the detector, so that these can be removed to the extent possible. Ideally, after each system modification, the analysis code is rerun.

What does the output look like? One important end product of such an analysis is a PSNIT (Point Source Normalized Irradiance Transmittance) curve. The PSNIT is the ratio of the irradiance at the detector to the irradiance at the entrance aperture at a plane normal to the off-axis radiation. The PSNIT plot is as valuable to the stray light designer as the spot diagram or encircled energy curve is to the optical designer. The general trend of the PSNIT curve is that it falls off with increasing off-axis angle. Any departure from this general trend (e.g. the labeled regions) represents a stray light paths where possible improvements to the optical system can be made (Pompea et al. 1993). A second important result is a map of the stray light noise at the focal plane, for various off-axis source angles. The scatter function structure at the focal plane is an estimate of the background which may confuse the data. Broad structures can generally be removed, while glints may prove troublesome.

7. The Importance of Surface Studies

The PSNIT curve is only as good as the model of the system. For the stray light model to be successful, the properties of the surfaces in the system must be well represented. Thus the scatter properties of mirrors and black surfaces must be known. For high performance systems, it is important to model the surfaces as they are are, with dust or other contaminants on them. The usual way to describe a surface is through its Bidirectional Reflectance (or Scatter) Distribution

Function, called the BRDF (or BSDF). The BRDF is a function that describes the scatter at a particular wavelength for a given input angle and scatter angle. Available measurements are often at 0.6328 microns, though a much larger set of measurements are just becoming available with automated scatterometers using multiple lasers. The BRDF is, in theory, an instrument invariant function, since the measurement is normalized by the detector solid angle. The measurements are still somewhat expensive to make, and an international database of such measurements has been proposed so that measurements are not repeated unnecessarily (McCall et al. 1993b). While very black surfaces cannot compensate for poor layout of a system, in a well thought out system they can make a tremendous difference (Bergener et al. 1984; Pompea et al. 1989).

There is a great deal of effort underway to study contamination issues in astronomical systems, and to characterize these surfaces with an effective emissivity and BRDF. I am in the process of characterizing particle sizes and numbers for some surfaces exposed inside the IRTF mirror cell. These experiments should give a good measure of the scattering we might expect for exposed surfaces on Mauna Kea. I am also very excited by the jet spray, laser, and other cleaning techniques which we have been investigating for some time to clean mirrors in space satellite optical systems.

The selection of surfaces, such as black baffle surfaces, is a whole area into itself (see, for example, Pompea & McCall 1993; McCall et al. 1993a; and Pompea & Breault 1994). When system expectations are high, the selection of surfaces becomes more complicated. Since this issue is already addressed in some detail in other papers, I will not discuss it here. The creation of accurate surface models for real surfaces that will appear in AO systems will be a continuing important challenge.

8. Summary

My talk can be summarized in a few points: Stray light is a problem of all optical systems. Serious stray light problems are not confined to infrared telescopes or instruments. As the performance of astronomical systems improve, the stray tight problems assemble. That is, as other problems get solved, the stray light problems rise in importance, and often limit the overall system performance. Surface selection and contamination issues are becoming more complex for such systems, and more data is needed in this area in order to support the software modeling efforts.

The stray radiation issues must be addressed early and considered at each stage of the AO/Instrument/Telescope system development. Most importantly, these problems must be treated seriously and resources must be allowed to address them in detail. The modeling of the system performance using stray light analysis software is essential to a diagnosis. And there must be an early diagnosis for a favorable prognosis. Otherwise, stray light myopia may prove fatal to the health of the optical system.

9. Acknowledgments

Special thanks to Gary Peterson and Bill Weller for comments on previous drafts.

10. References

1. Anderson, S., S.M. Pompea, and D.F. Shepard, "Performance of a Fully Automated Scatterometer for BRDF and BTDF Measurements at Visible and Infrared Wavelengths," *Proceedings of the SPIE: Stray Light and Contamination in Optical Systems*, 967 (1989) 159.

2. Bergener, D. W., S.M. Pompea, D.F. Shepard, and R.P. Breault, "Stray Light Rejection Performance of SIRTF: A Comparison", *Proceedings of the SPIE: Stray Radiation IV*., 511 (1984) 64.

3. Breault, R.P., "Stray Light Technology: Overview of the 1980 Decade (And a Peek into the Future)", *Proceedings of the SPIE: Stray Radiation in Optical Systems*, 1331 (1990) 2.

4. Dinger, A., "Thermal Emissivity Analysis of a Gemini 8-Meter Telescope Design", *Proceedings of the SPIE: Stray Light IV*, 1753 (1993) 183.

5. McCall, S.H.C.P., S.M. Pompea, R.P. Breault, and N.L. Regens, "Reviews of Black Surfaces", *Proceedings of the SPIE: Stray Light IV*, 1753 (1993a) 158.

6. McCall, S.H.C.P., R.L. Sinclair, S.M. Pompea, and R.P. Breault, "Spectrally Selective Surfaces for Ground and Space-Based Instrumentation: Support for a Resource Base", *Proceedings of the SPIE: Space Astronomical Telescopes and Instruments II*, 1945 (1993b).

7. Pompea, S.M., D.F. Shepard, and S. Anderson, "BRDF Measurements at 6328 Angstroms and 10.6 Micrometers of Optical Black Surfaces for Space Telescopes", *Proceedings of the SPIE: Stray Light and Contamination in Optical Systems*, 967, (1989) 236.

8. Pompea, S.M., J.E. MentzeR, and W.E. Siegmund, "A Stray Light Analysis of the Sloan Digital Sky Survey Telescope", Proceedings of the SPIE: Stray Light IV, 1753 (1993) 172.

9. Pompea, S.M., and S.H.C.P. McCall, "Outline of Selection Processes for Black Baffle Surfaces in Optical Systems", *Proceedings of the SPIE: Stray Light IV*, 1753 (1993) 192.

10. Pompea, S.M. and R.P. Breault, [Invited chapter] "Optical Black Surfaces", in Handbook of Q12tics. 2nd edition, Optical Society of America, expected publication date, 1994.

11. Ridgway, ST., "Me Impact of Adaptive Optics on Focal Plane Instrumentation", this volume.

[i] In Adaptive Optics for Astronomy, edited by D. Alloin and J.-M. Mariotti, Kluwer Academic Publishers, 1994.