Stray light lessons learned from the Mars Reconnaissance Orbiter's Optical Navigation Camera

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ABSTRACT

The Optical Navigation Camera (ONC) is a technical demonstration slated to fly on NASA's Mars Reconnaissance Orbiter in 2005. Conventional navigation methods have reduced accuracy in the days immediately preceding Mars orbit insertion. The resulting uncertainty in spacecraft location limits rover landing sites to relatively safe areas, away from interesting features that may harbor clues to past life on the planet. The ONC will provide accurate navigation on approach for future missions by measuring the locations of the satellites of Mars relative to background stars.

Because Mars will be a bright extended object just outside the camera's field of view, stray light control at small angles is essential. The ONC optomechanical design was analyzed by stray light experts and appropriate baffles were implemented. However, stray light testing revealed significantly higher levels of light than expected at the most critical angles. The primary error source proved to be the interface between ground glass surfaces (and the paint that had been applied to them) and the polished surfaces of the lenses. This paper will describe troubleshooting and correction of the problem, as well as other lessons learned that affected stray light performance.

Keywords: stray light, lenses

1. INTRODUCTION

A major goal of NASA's Mars program is to find signs of past life on the red planet. Some ideal landing locations occur at geologically interesting features, such as canyons, where past water activity may have supported life. However, these features pose a risk to landers. Driving to the feature is not viable; the lander placement accuracy of the current rovers on Mars exceeds the distance traveled by them during their entire mission. Higher accuracy in landing location would eliminate the landing risk while leaving the rover at a more reasonable distance from the feature. Traditional spacecraft navigation approaches provide high accuracy during spacecraft cruise, and the spacecraft may be located to very high accuracy once in orbit, but in the days just before Mars orbit insertion, accuracy is not as high as is needed.

An optical navigation camera (ONC) is under development to eliminate this problem. The ONC will use the satellites of Mars (Phobos and Diemos) and background stars to determine the spacecraft location to high accuracy on approach. The ONC is scheduled to fly on Mars Reconnaissance Orbiter in 2005 as a technical demonstration, tracking the spacecraft position on approach without actually being used for navigation. On future missions, the ONC would be an integral part of the navigation system.

A cartoon of the ONC's field of view is shown in Figure 1. The background stars may be much fainter than the satellites, requiring high dynamic range in the camera. At 1 to 2 days prior to orbit insertion, the field of view is comparable in size and very close to Mars (as close as 0.4°, approximately to scale in the figure). Consequently, stray light from Mars is a major concern and must be addressed at every stage of the camera design and implementation.

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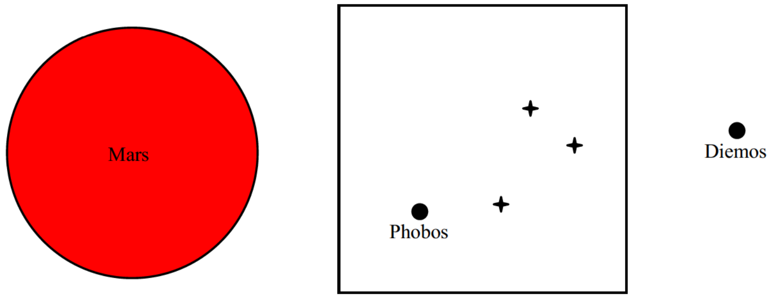


Figure 1. ONC field of view relative to Mars.

2. ONC IMPLEMENTATION APPROACH

The ONC design form was chosen with stray light performance in mind. For example, a preliminary Maksutov design was rejected out of concern for scatter from contamination on the front glass element. The adopted design, shown in Figure 2, is a 500 mm focal length, F/8.3 Ritchey-Chretian. The refractive field corrector is needed because of the large field of view (1.4° square). The filter in front of the CCD blocks wavelengths greater than 650 nm, taking advantage of the red coloration of Mars to block a substantial portion of the light reflected off the planet.

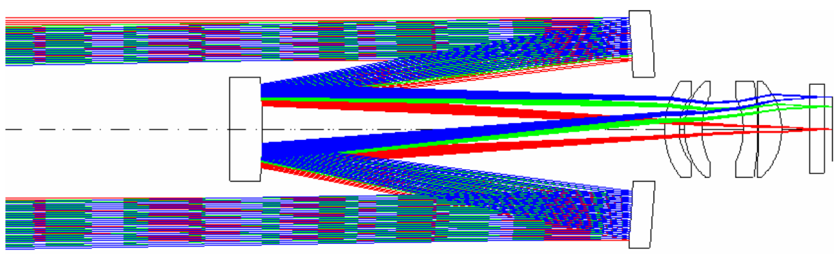


Figure 2. ONC optical design.

Stray light analysis and testing were planned from the start for the ONC, with an emphasis on performance at small angles (1.1° to 3°). Breault Research Organization (BRO) analyzed and suggested changes to the ONC optomechanical and baffle design. The ONC optics and baffles were tested at Utah State University's Space Dynamics Lab (SDL), to validate the analysis and identify any stray light-related problems.

Stray light analysis was performed early in the program, to determine the feasibility of the requirements. BRO derived requirements for surface roughness of 10 Å and contamination Level 300 on the optical surfaces to provide performance acceptable to the ONC principal investigator. These must be budgeted among several surfaces, but the resulting component requirements are not unreasonable.

BRO analyzed and improved the preliminary baffle designs. A cross section of the design is shown in Figure 3. Performance in the form of normalized detector irradiance (NDI) is plotted in Figure 4. The "Original Design" was a simplistic design created by the optical and mechanical engineers as a starting point. "Design 2" incorporates changes suggested by BRO to the baffles and other mechanical surfaces and corresponds to the design that was implemented. "Design 3" contains a subtlety that was missed by the mechanical designer – tapering on the secondary mirror support struts. This minor detail was noticed at a review, after the mechanical parts had been made. This tapering makes a difference only at larger angles, where stray light will be negligible compared to that coming from Mars at smaller angles. As a technology development, the ONC's funding was tight; in the interests of cost and schedule, the parts were not reworked.

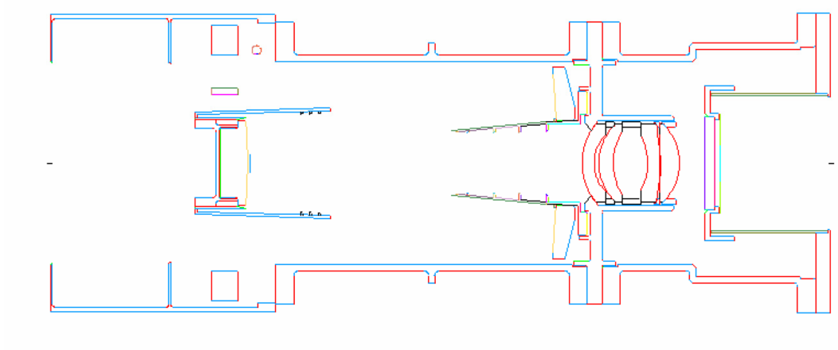


Figure 3. ONC baffle design.

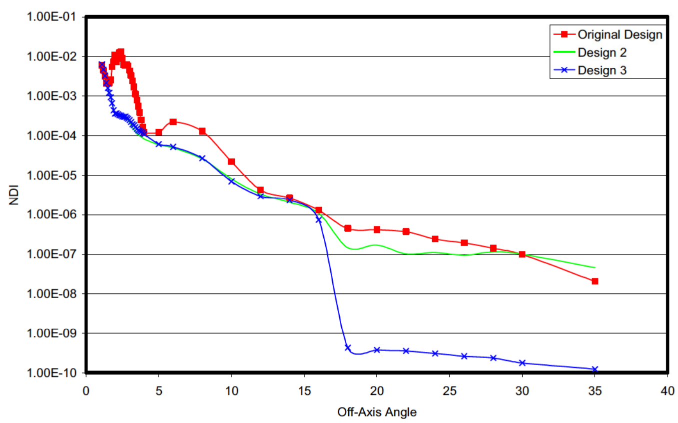


Figure 4. BRO analysis predictions.

3. INITIAL STRAY LIGHT TEST RESULTS

The ONC was taken to the off-axis scatter facility at SDL, which is described in detail by Kemp.[1] This facility has been used to test several spaceborne sensors, including the Galileo Solid State Imaging (SSI) camera, Cassini Narrow Angle Camera (NAC), and the TIMED SABER instrument.[2] Entrance to the room requires passage through an air shower, which removes loose particles from the occupant. The walls, ceiling, and other components of the room are coated with a diffuse black paint to absorb and scatter incident light. The floor is covered with black carpet, whose fibers are resistant to detachment. The instrument under test sits on a motorized rotation stage inside a black specular chamber. HEPA filters are used to maintain a clean room environment (class 100 inside the chamber).

A tungsten-halogen lamp illuminates a large spherical mirror to provide a nominally collimated input beam to the chamber. An improved collimator was installed prior to testing the ONC to reduce scatter at the smaller angles important to this instrument. The beam enters the chamber through a hole and overfills the instrument aperture. Light that misses the instrument goes out another hole and into a beam dump. Light scattered by the instrument is directed away from the instrument aperture by the chamber walls; after several reflections off the walls, the light level is negligible. A photomultiplier tube is placed at the focal plane location on the instrument. The rotation stage and photomultiplier tube are remotely controlled by a PC in another room.

The off-axis response is obtained by incrementally rotating the instrument and recording the signal. The instrument is initially aligned by centering the image of a point source (i.e., pinhole) in a small aperture placed at the center of the ONC focal plane. The on-axis measurement is used to normalize the off-axis measurements, yielding a plot of point source rejection ratio, which is easily converted to NDI for comparison to the analysis.

Initial testing at SDL yielded the results shown in Figure 5. In general, performance was a factor of 10 worse than predicted; at the most critical angles between 1.1° and 3°, stray light was as much as 100 times higher than predicted. Rather than complete the tests, the instrument was returned to JPL for troubleshooting.

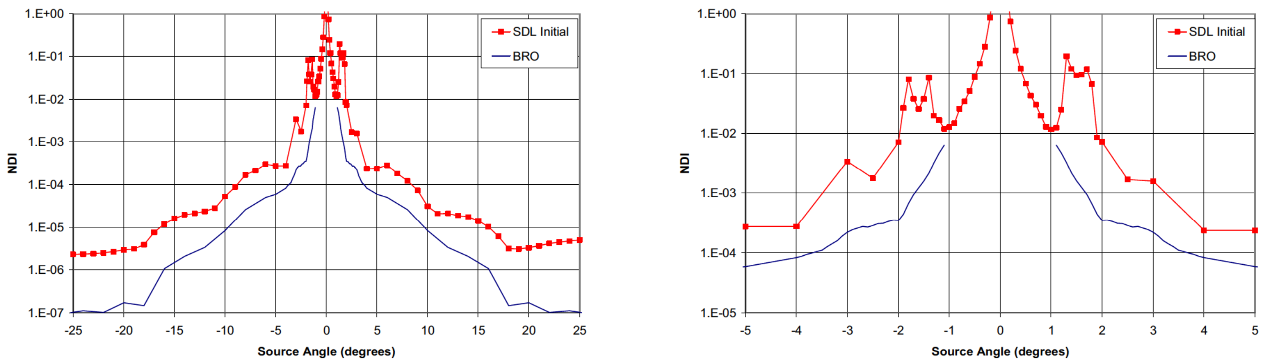


Figure 5. Initial SDL measurements, compared to BRO predictions.

4. INITIAL TROUBLESHOOTING

There are a couple differences between the BRO models and the as-built system. BRO assumed Z306 on all mechanical surfaces, but paint was not used. Rather, Epner laser black[3] was used on all important metal surfaces, the baffles were made from black Delrin, and anodize was used on less critical metal surfaces. The bandwidth used in their analysis, 450-600 nm, was increased to 450-650 nm after their analysis was completed. These may explain some of the general difference in performance, but were unlikely to have caused the spike at small angles. Funding was not available to cover additional analysis to update the models, and some obvious problems in implementation were identified as more likely causes of the measured performance.

A sliver of scattered light was observed at the edge of the aperture. It turns out that the mechanical designer had incorrectly sized the aperture stop, matching the oversized primary mirror clear aperture (60.8 mm) rather than the intended entrance pupil diameter (60.0 mm). As a result of alignment tolerances between the mirror and aperture, part of the ground flat surface outside the mirror's clear aperture was illuminated. In addition to scattering off the ground surface, additional stray light may have leaked by baffle vanes since those were designed to control light from a slightly smaller aperture stop. A smaller aperture was fabricated and bonded behind the original aperture in the ONC.

The stray light test engineer noted that the secondary mirror baffle did not exactly match BRO's design. BRO's baffle had a constant angle relative to the optic axis along the entire length of the baffle, but it proved difficult to fabricate. The mechanical designer modified it, but in doing so made the forward portion of the baffle flat (parallel to the optic axis). This surface could direct grazing incidence light onto the primary mirror. A quick analysis in ASAP[4] showed that this was unlikely to cause the two-humped features in the data at small angles.

During stray light testing, while aligning the ONC to the source, the engineer noticed gaps in the secondary mirror baffle. The baffle had been made from two pieces of black Delrin that were designed to be sealed without undue stress at the ONC's nominal operating temperature; however, at ambient temperature, the gaps allowed light to penetrate directly alongside the secondary mirror. Crescents of light were clearly visible when viewed from the image plane. This probably had a small effect on the on-axis transmission, but scattered light may also have made its way through these gaps at off-axis angles.

The engineer also could see (as viewed from the image plane) the shiny metal screws that held the secondary mirror baffle. The mechanical designer had neglected to specify the type of screws and washers (or lack thereof) needed by the technicians, and the wrong type were installed. These screws were replaced. At the time it was hoped that the multiple angles on these screws was the primary cause of the stray light behavior at small angles, but their contribution may have been minimal.

As a fix for some of these problems, a small cap was made and installed over the forward part of the secondary mirror baffle. This blocked the flat parts of the baffle and covered the gap between the outer and inner baffles, as well as shading the screws. The additional edge, which is slightly smaller than the maximum secondary baffle diameter, will introduce some stray light at larger angles, but this was deemed acceptable given the problems at small angles.

Prior to making any changes, the ONC was set up on a rotation stage in front of a collimator, and several engineers and technicians looked at the off-axis behavior. Several bright features were observed at angles between 1.1° and 1.9°, corresponding to the strong signals measured for those angles at SDL. After making the changes mentioned above, very little change was observed.

5. PAINTED INTERFACE ON LENSES

The primary stray light features observed between 1.1° and 1.9° appeared to be coming from the edges of the field corrector lenses. Figure 6 is a plot of rays traced at different angles. At various angles between 1.2° and 1.8°, the beam is centered on the interface between the flat, ground part and the curved, polished part of the lenses. This observation suggested that the flat-curved interfaces on the lenses could be the problem.

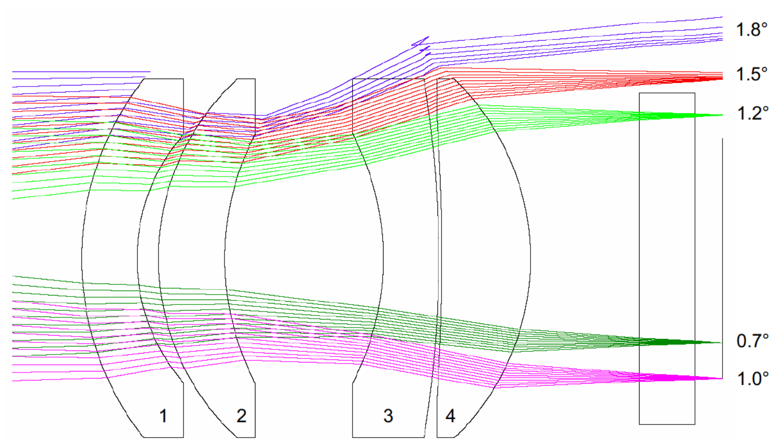
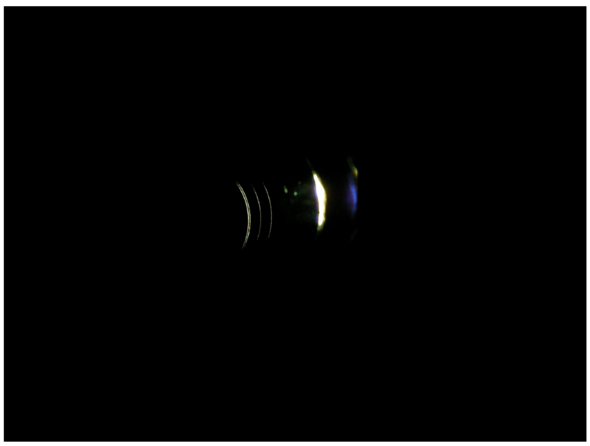


Figure 6. Off-axis rays traced through lenses. 0.7° is the edge and 1.0° the corner of the CCD.

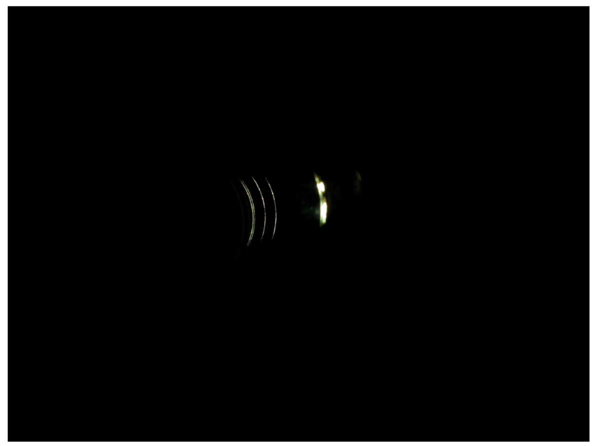
At BRO's direction, black paint had been applied to the flat, ground parts of the lenses to avoid glints that occurred from rays refracted at that surface. The technician who applied the paint was conservative in keeping it away from the "good" polished surfaces of the lenses; consequently this left a small sliver of ground glass unpainted. This area of ground glass, and possibly subsurface damage in the glass that occurred due to grinding of the flats, was not included in the stray light model.

To fix this problem, the lenses were repainted with the paint clearly extending past the interface and onto the polished surfaces. Visual observation was inconclusive; however, closer examination of a series of digital pictures taken of the stray light in both the engineering model (which had not been modified) and the flight model showed a noticeable improvement. Pictures taken at 1.4° are shown in Figure 7 for the original (A) and modified (B) cases. In (B), a shadow from the secondary obscuration is now visible in the bright sliver. At the affected angles, significant amounts of light were still present due to scattering off the edge of the paint. This effect was not considered in the stray light analysis.

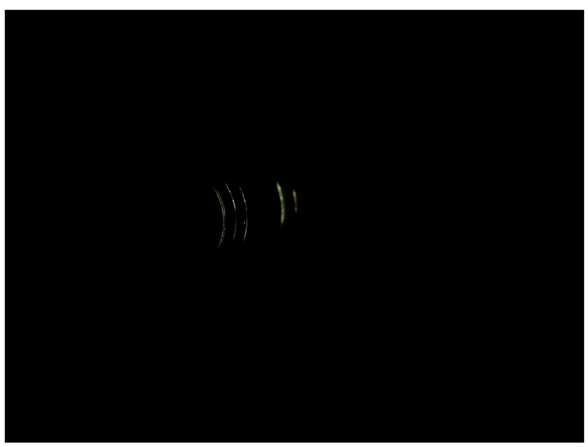
To further reduce the stray light, the concave surfaces of the first and last lenses were painted further, with the paint extended well into the polished surface. The ONC principal investigator had never imposed requirements at the corners of the field and was willing to allow vignetting there, so the paint on the first lens was extended to start vignetting field angles slightly greater than the edge of the CCD. This eliminated the possibility of illuminating the flat-curved interface on lenses two and three. To eliminate minor illumination at some angles of the flat-curved interface on lens 4, the paint on lens 4 was extended far enough to just avoid vignetting at the edge of the CCD. As a result of these interfaces, which previously were illuminated only for angles greater than 1.1°, we expected increased stray light at angles between 0.7° and 1.1°; however, for angles greater than 1.1°, direct illumination would be blocked by the paint on lens #4 and only one flat-curved interface (lens #1) would be illuminated. Digital pictures confirmed a substantial reduction in stray light from the original case, as shown in Figure 7(C). Note that the digital camera had been removed and reinstalled between images (B) and (C), so the alignment is slightly different. As a result, some of the fainter features appear dimmer despite identical exposure settings on the camera, but clearly the brightest feature has been suppressed.



(A)



(B)



(C)

Figure 7. Stray light pictures at 1.4°: (A) unmodified instrument; (B) paint extended just over flat-curved interface on lenses; (C) paint extended on lenses 1 and 4 to vignette corners of field.

The various features seen in these images were compared to a table of critical and illuminated objects at various angles generated by BRO. These objects included the vanes on the primary and secondary baffles and the seat of the lens corrector. The resolution of the table was coarse: 1.1°, 1.6°, 2.1°, 3°. In retrospect, better resolution would have been helpful, but even with these large steps we were able to identify the origin of most of the remaining features based on the angles at which they appeared and disappeared in the images.

One final improvement was made. While the optics were disassembled for repainting of the lenses, the mirrors were recleaned. Despite our efforts to keep the optics clean throughout the assembly process, some obvious contamination had been observed on the mirrors during initial stray light testing. This may have contributed to an overall reduction in measured performance.

6. FINAL TEST RESULTS

The ONC was returned to SDL for additional testing. The results in Figure 8 show the difference between the initial and final tests. Stray light was reduced by a factor of 20 to 100 at the most critical angles (1.1° to 2°). As expected, the stray light level increased slightly between 0.7° and 1.1°. At larger angles, stray light is a factor of 5 to 10 higher than predicted by BRO. Experienced analysts state that with current modeling tools and techniques a factor of 3 uncertainty is reasonable. The larger difference between model and measurement can be attributed to factors that were not included in the analysis: the increased bandwidth; material differences; the edges of the cap that was added to the forward surface of the secondary mirror baffle support; and the wavelength difference between the model and the photomultiplier tube peak response.

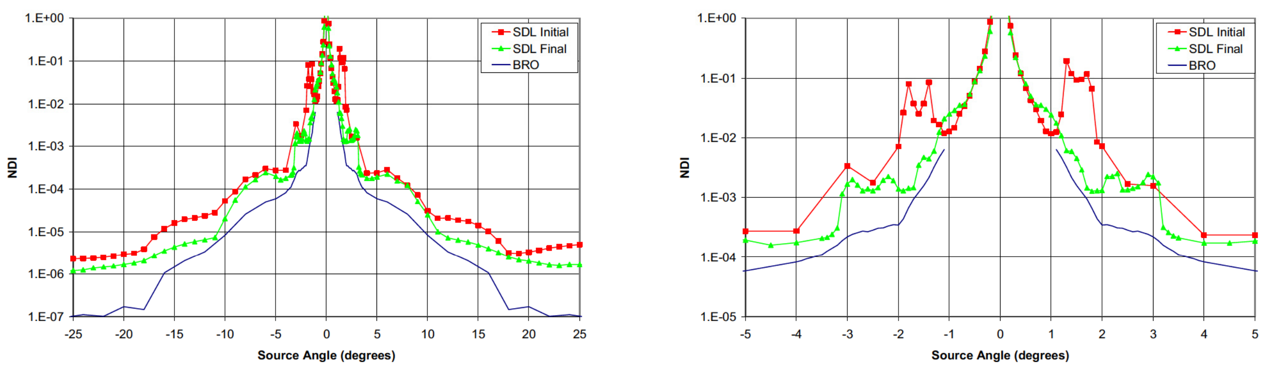


Figure 8. Final SDL measurements, compared to initial measurements and BRO predictions.

7. SUMMARY OF LESSONS LEARNED

The most significant lesson learned was something that was not considered either by the optical designer or stray light analysts: the impact of painted interfaces on glass surfaces. Ground glass or subsurface damage will cause scattering if the paint is not extended far enough over the flat-curved interface; either way, scattering off the edge of the paint also causes stray light. This was probably missed because most optical systems are concerned with stray light in general rather than at specific angles. In addition, scattering is difficult to measure at small angles; testing the ONC at SDL required an upgrade in their collimating mirror to permit measurements down to 1.1°. The initial stray light problem at 1.1 to 1.9° was corrected by vignetting the corners of the field. In the next generation of ONC, and other instruments that have stray light problems at small angles, it would be better to avoid the problem in the optical design by oversizing the lenses to avoid any ground areas that may be directly illuminated. If this is not an option, thin mechanical apertures would be preferable to paint, though these will also introduce some scatter.

Keeping the stray light analysts involved in the project would have eliminated some of the problems that were encountered. The contract with BRO was completed and closed shortly after they delivered their final report. In retrospect, it would have been useful to have the analysts review the baffle detail drawings, where they could have pointed out that the secondary support struts should be tapered and that the secondary baffle design was not equivalent to what they had suggested. The material changes could have been incorporated in their model, preferably using measured BRDF data. The model could have been modified to account for changes in requirements, such as the increased bandwidth. Finally, they could have assisted with reconciling the difference between their predictions and SDL's measurements.

Closer scrutiny of the mechanical design and assembly would have also avoided some problems. It is important for the optical engineer to check critical dimensions, especially the aperture stop, and not assume that the mechanical engineer will do the right thing. Mechanical tolerances on parts may be set to be conservative in one way, such as not undersizing an aperture to avoid reducing the throughput of the instrument, while inadvertently working against a more critical problem, in this case allowing additional stray light to get by the baffles. A technician's idea of being conservative may also be problematic; in our case, he did not extend the paint far enough over the flat-curved interface on the lenses for fear of getting paint onto the "good" part of the lens, which would have been less problematic. Finally, the mechanical designer needs to clearly specify in an assembly procedure and preferably procure the screws that are needed to assemble every part. The majority of fasteners in the ONC are specialized ones for flight hardware – providing the needed reliability for critical mechanical parts – but the secondary mirror baffle had no effect on optical alignment or structural integrity and therefore relatively simple screws were used there, with the technician left to obtain them himself without clear guidance.

Setting up the instrument on a rotation stage in front of a collimator proved immensely useful in observing the character of the stray light, as did photographing the stray light with a digital camera. Had this been done prior to bringing the ONC to SDL for quantitative testing, several problems may have been identified and corrected, such as the undersized aperture and incorrect screws.

The Epner laser black coating used to darken the most critical mechanical surfaces proved difficult to handle. This coating is made by a proprietary process that grows copper dendrites on a metal surface and oxidizes them. Contacting the surface will not cause the coating to come off as is often the case with paint, but the dendrites will be crushed and performance significantly degraded at the contacted location. During assembly of the ONC engineering model, the technician touched the coating with his hands or tools at several locations, and these now-gray areas had to be touched up with paint. For the ONC flight model, the original technician was busy and a different technician was used to perform the same steps, with similar results. Using the same technician for both engineering and flight models would have allowed experience obtained on the first unit to benefit the second. Better fixturing would also have decreased the likelihood of contacting the most critical surfaces.

Contamination was identified early on as critical to the performance of the instrument, but there were shortcomings in our process from the start. Optics can never get better than the cleanliness present when they are removed from a coating chamber. Ideally, the optics are protected from contamination and never cleaned. However, the vendors chosen for the mirrors and lenses had minimal clean room facilities (just flow benches), and instead cleaned the optics prior to delivery. In the case of the lenses, they were allowed to collect a significant amount of dust before their final cleaning. Choosing a vendor who has coating machines in a clean room, and specifying how the optics are to be handled after the optics are coated (or even witnessing it) would eliminate this problem. Technicians who assemble the optics may not appreciate just how contamination-sensitive the instrument is, so clear written procedures are essential.

8. CONCLUSION

The ONC's stray light testing proved valuable, not only in verifying that the instrument can fulfill its intended mission, but also in identifying important lessons to consider for future instruments. These included keeping the stray light analysts involved and the model in agreement with the hardware, better control of contamination, and closer scrutiny of the mechanical design. Some of these lessons are typical of the learning experience that can only come from building hardware. The most significant discovery was an effect that was not considered by the optical designer or experienced stray light analysts: the importance of minimizing and modeling painted interfaces on lenses.

9. ACKNOWLEDGMENTS

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