Performance of the Star Tracker Lightshades on the Earth Observing Satellite (EOS) Aqua

by
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Abstract

The TRW built EOS Aqua spacecraft uses two Ball Aerospace CT-602 star trackers to provide attitude updates to the 3-axis, zero momentum, controller. Two months prior to the scheduled launch of Aqua, Ball reported an error in the design of the star tracker lightshades. The lightshades, which had been designed specifically for the EOS Common spacecraft, were not expected to meet the stray light rejection requirements of the mission, thus impacting the overall spacecraft pointing performance. What ensued was an effort to characterize the actual performance of the existing shade design, determine what could be done within the physical envelope available, and modify the hardware to meet requirements. Changes were made based on this review activity and Aqua was launched on May 4, 2002. To date the spacecraft is meeting all of its science pointing requirements. Reported here are the lightshade design predictions, test results, and the measured on orbit performance of these shades.

INTRODUCTION

The EOS Aqua spacecraft is the 3rd major EOS Observatory, after Terra and Landsat-7. After successfully launching on May 4th, 2002, Aqua is continuing NASA's Earth Science Enterprise leadership in Earth science investigation. The observatory is comprised of six state-of-the-art instruments flying on a new spacecraft bus: AIRS – Atmospheric Infrared Sounder, AMSU-A1 & A2 – Advanced Microwave Sounding Unit A1 & A2, HSB – Humidity Sounder for Brazil, AMSR-E – Advanced Microwave Scanning Radiometer for EOS, MODIS – Moderate Resolution Imaging Spectroradiometer, and CERES – Clouds and the Earth's Radiant Energy System. Originally scheduled to launch in December 2000, Aqua experienced and overcame numerous technical issues that confronted the Project office. Including these, which all occurred at the last minute: failures of similar flight hardware on other programs – 4th generation transponder failure on X-38, flight hardware "gotchas" – unqualified battery cell crimps, instrument I&T problems – operation, of HSB, with the purge line improperly connected resulting in bearing lubrication issues, launch vehicle concerns – redesign of automatic destruct system (ADS) and fairing air (humidity and temperature) monitoring, plus late hardware deliveries due to paperwork issues, etc... One of the last major problems to strike was the inadequate stray light attenuation in the single-stage lightshade for the Ball CT-602 star trackers.

As late as the Aqua Pre-Ship Review (PSR) on February 5th and 6th, 2002, the Project office was unaware of any issues surrounding the CT-602 single-stage star tracker lightshades. Then, on February 19th, while the launch vehicle Pre-Vehicle On-Stand (Pre-VOS) review was occurring, Aqua Project management was informed by TRW that Ball had told them, that their software, used to model star tracker shades, could be off by 10%. With further investigation the story grew much worse, the problem was such that the 35 degree off boresight requirement could not be met unless off the sun by 70 degrees. If the star trackers were within 60 degrees, the trackers would not function and new shades would not be available for weeks. Aqua was, at the time, scheduled to ship to VAFB on the 25th of February and launch on the 18th of April. The immediate question confronting the Project was – do we ship to Vandenberg Air Force Base (VAFB) in less than 1 week? The "longer term" question was whether the launch date was now in jeopardy.

On February 23rd, the following options were presented to Aqua Project management:

- Implement a two-stage lightshade
- Redesign the single-stage lightshade
- Modify the existing single-stage lightshade
- Implement flight software modifications to overcome the deficiencies

With the Project's driving requirement of not impacting the launch readiness date, a couple of the options were immediately discounted. Implementing a two-stage lightshade was not possible. Aqua barely fit in the Delta II 10-foot composite fairing with the single-stage design, a two-stage design would require significant fairing modifications. Also, redesigning the single-stage lightshade seemed to be an open-ended pursuit that would mean sacrificing the launch date as well. What remained was modifying the existing shade and / or implementing flight software changes as the only possible methods for resolving the stray light attenuation problem and launching on time. An item on the Project's side was the fact that the second EOS Common Spacecraft, Aura, used the same lightshade, so the Project had the luxury of testing and modifying the Aura lightshades without risking the Aqua ones. Having established that there were viable options, the Aqua Project shipped the spacecraft from TRW's Space Park facility to VAFB. The spacecraft arrived early on the morning of the 25th of February – 52 days away from the scheduled launch.

As the star tracker problems continued to be worked, other items marched to the forefront to take its place as the number 1 concern – launch vehicle ADS modifications, new pre-MECO loads from the Delta II series 50 RS-27 main engine, and battery cell crimp integrity. Nonetheless, key people continued to work the star tracker vigorously and by

March 20th the issue was sufficiently understood and under control that it was dropped from the list of 'major issues'...

DISCUSSION

The Problem

The original star tracker specification called for full performance operation when the tracker boresight was as close as 35° to the Sun line. A similar requirement called for operation as close as 25° to the Moon. Ball's original stray light analysis (see "Original Analysis" in Figure 1) predicted that at 45° the Sun would generate approximately 40 counts of background in the CCD image data. This was well within the star tracker system specification limit of 60 counts. That limit was selected to ensure that the less than 5 arcseconds noise equivalent angle (NEA) requirement was met. If the background limit was exceeded, the tracker's "Background High" flag would be set. TRW's flight software was designed to ignore a tracker's position data when this flag was set.

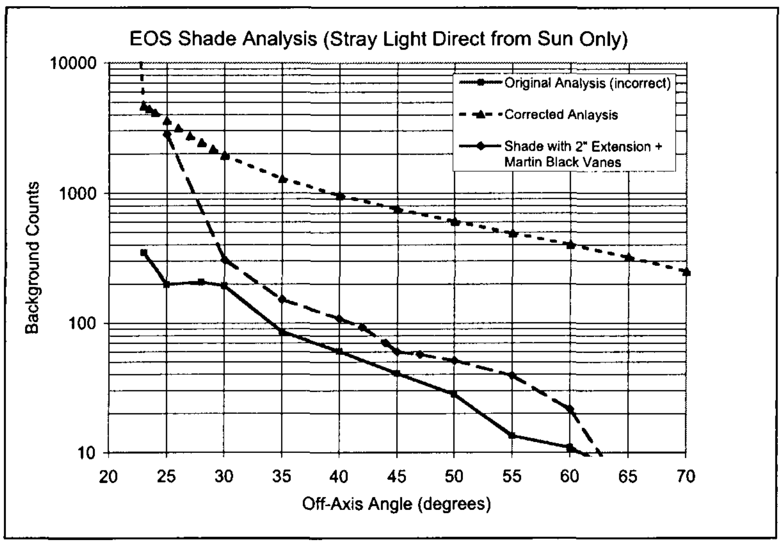

Figure 1: EOS Shade Stray Light Analysis

On February 14th, 2002 Ball notified TRW that there was an error in the design of the Aqua light shades and these performance requirements could not be met. The performance of the original design had been determined using the APART design tool from Breault Research Corporation (BRO). An error was discovered when Ball compared results from the APART tool for models of the same shade executed in the newer ASAP tool (also from BRO). Ball later determined that a function "DELTA" had been applied incorrectly in their APART model. Ball corrected the model for this error. The revised analysis indicated that the light shade would not meet the required Sun performance (see "Current Shade" in Figure 1).

Under normal two tracker operation, a single tracker's data becoming temporarily invalid would not be a problem for Aqua since only one tracker is required for full performance. Aqua's geometry is such that there is no chance that in normal flight the Sun would interfere with both trackers. However, if one tracker should experience a hard failure, this vulnerability could easily become a problem. Although Aqua uses gyro data for position information, periodic updates to the Kalman filter from the tracker are required to compensate for various sources of drift.

The Approach

Given the short time frame to resolve the problem, all parties had to identify where margin existed in the various aspects of the mission so that all options could be considered in the solution trades. The challenge was to find an approach that could be implemented with no impact to the launch vehicle, and as little impact to the spacecraft as possible. Therefore, the trade space included the size of the shade, the tracker performance requirements, the shades vane configuration, the materials used to make the shade, and the star tracker software.

Project mechanical engineers examined the clearances between the STA shade and the launch vehicle fairing. From this study they determined that the shade could increase by at most 2.0 inches in length or 6.0 inches in diameter and maintain sufficient dynamic clearance from the fairing envelope. This restriction eliminated the ideal solution, a true 2-stage design, but it did present the possibility of modifying the design to regain some performance.

TRW and GSFC revisited the orbit and spacecraft configuration studies to determine if there was any flexibility in the encroachment specification. The Aqua spacecraft is in the standard Sun-synchronous polar orbit utilized by Earth resource satellites: 705 km, 98° inclination. The ascending node passes over the equator at approximately 1330 local time. The satellite body frame (SBF see Figure 2) is such that the +Z-axis (yaw) is along the local vertical in the nadir direction. The +X-axis (roll) is in the direction of flight. The +Y-axis (pitch) completes the right hand set and is normal to the side opposite the solar array. The two star trackers (STA) are mounted on the zenith side of the vehicle. The STA's boresight is its +Z-axis. The STA frame is defined as a 1-2-3 rotation (ϕ,θ, then ψ) from the SBF.

$$T_{SBF2STA} = \begin{bmatrix} \cos(\psi) & \sin(\psi) & 0 \\ -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos(\theta & 0 & -\sin(\theta) \\ 0 & 1 & 0 \\ \sin(\theta) & 0 & \cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & \sin(\phi) \\ 0 & -\sin(\phi) & \cos(\phi) \end{bmatrix}$$

Where,

Table 1
SBF to STA Rotations

Axis	STA1	STA2
ϕ	62.763695°	62.763695°
θ	138.358854°	-138.358854°
ψ	-80°	80°

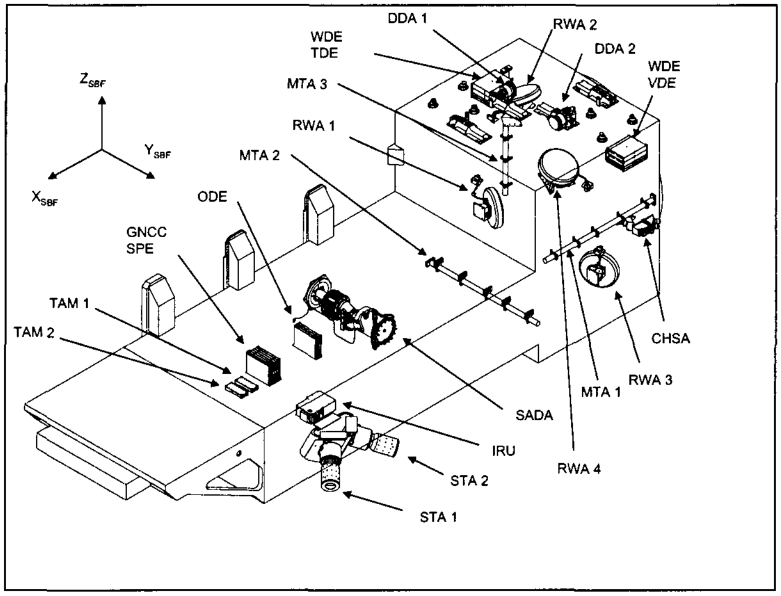

Figure 2: Aqua Attitude Control Component Layout

As a result of this combined orbit and tracker geometry it was expected that there would be regular close approaches of the Sun and Moon. However, GSFC Flight Dynamics predicted that at the minimum beta angle, the Sun would never be closer than 57° to each STA's boresight (see Figure 3). This result suggested that there might be some margin in the original 35° encroachment specification.

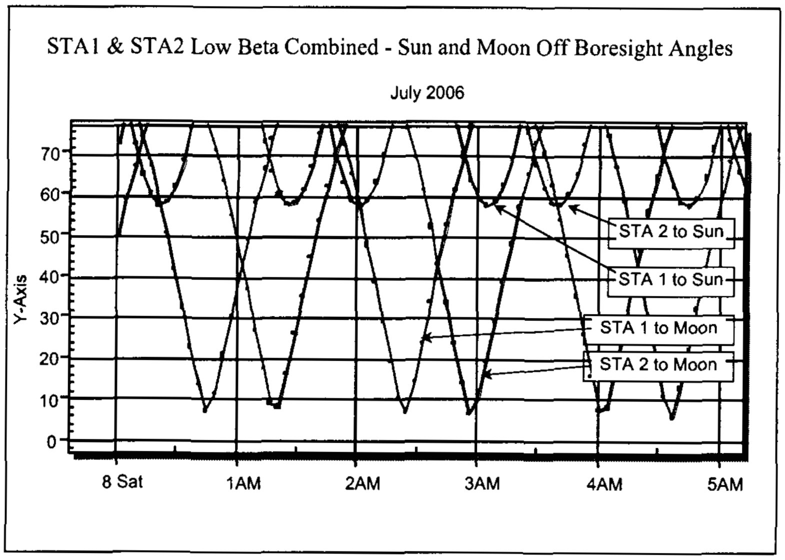

Figure 3: Predicted Sun and Moon Encroachments

To determine whether the encroachment specification could be eased, TRW examined what spacecraft elements might intrude on the star tracker fields of view. Figure 4 shows the impingements. The AMSR-E instrument antenna was responsible for the violation of STA-1's FOV. This large rotating dish (40 RPM) would enter and exit the FOV based on its rotation angle. The AIRS instrument's Earth shield intruded into the STA-2 FOV. Both of the instruments were covered in thermal blankets so they were both potential sources of reflected light. Ball attempted to estimate the contribution these surfaces would make to the overall stray light analysis, the results of which are shown in Figure 5. This Figure shows an approximately 30 count increase in background at 45° relative to the Sun-only intrusion analysis of Figure 1.

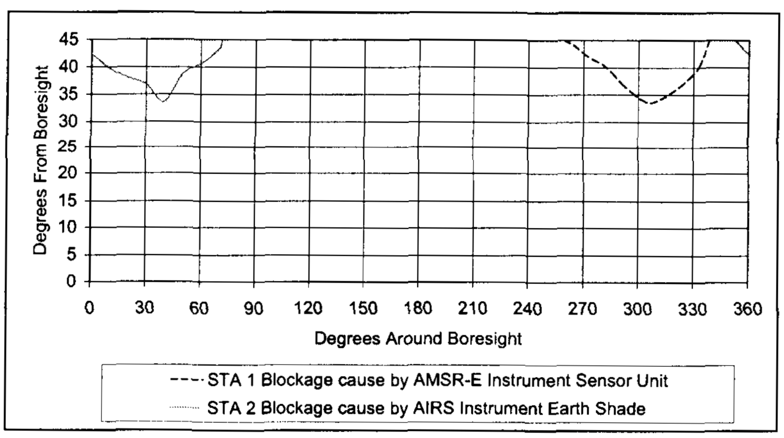

Figure 4: STA 1&2 FOV Blockage by Spacecraft

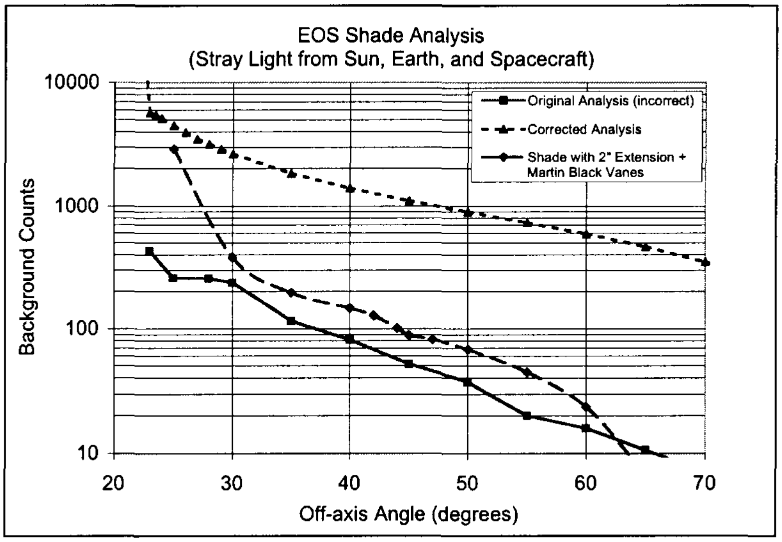

Figure 5: EOS Stray Light Analysis with Secondary Sources

At the spacecraft level, TRW's simulation of Aqua's science pointing mode predicted that the spacecraft would meet all specifications without a star tracker attitude update for at least 23 minutes. After this interval performance would gradually degrade due to gyro drift.

The STA system specification limited background to 60 counts in order to meet, with margin, the specified NEA requirements. Figure 6 shows Ball's estimates as a function of Sun angle and star intensity for a background of 160 counts. TRW had found that the filters in the flight software made them relatively insensitive to NEA. Given the NEA specification was 5 arcseconds for stars as dim as 6.5 M_I it was concluded that a higher background than the original 60 counts could be tolerated.

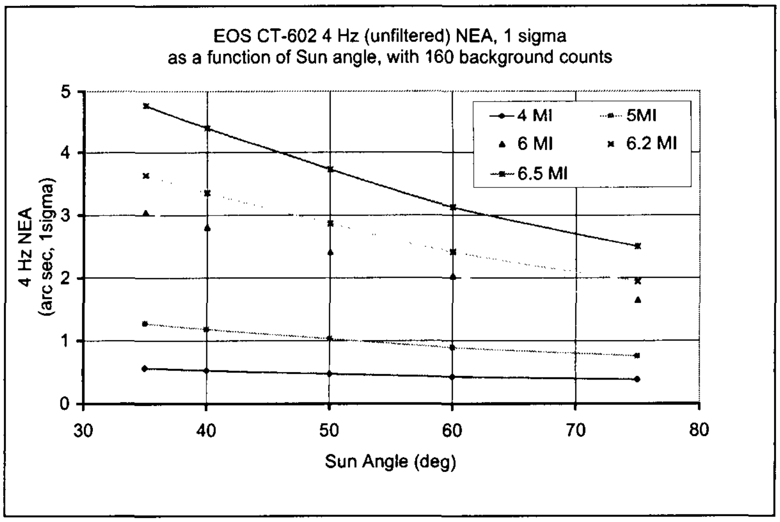

Figure 6: Predicted NEA Performance

The original design had the entire shade interior coated with an optical black paint. This coating was selected for its optical properties and its relatively rugged handling characteristics. Better coatings were available, however, they were notoriously fragile. The original coating was 2% reflective at beginning of life. This led to an end of life performance model of 4% reflective to account for degradation and contamination. Martin Black, however, is less than 1% reflective at beginning of life and was modeled as 2% reflective at end of life.

Finally, the optics was an area to be considered. The optics in the STA provided a significant contribution to the attenuation in Ball's stray light model. The values quoted by Ball ranged from as low as 70x to as high as 300x. Ball's lens cell model at the time indicated about 70x, however, they had test data that indicated better performance.

The Solution

Based on these studies and the available trade space, it was obvious that no single change could provide the solution. In fact, the only possible approach was to make a number of modifications throughout the system. Therefore, a combination of relaxation of specifications, hardware, and software changes were implemented to produce a system that could achieve the revised performance objectives that still met system requirements.

From the FOV studies it was determined that the Sun encroachment specification could be relaxed to 45°. This was done knowing that as a result, more spacecraft structure would be within the FOV of both trackers. However, no direct sun would be closer than 57 degrees. The estimated contribution to background from these secondary sources was expected to be in the range of 30 counts.

Ball recommended that the best use of the available volume was to increase the length of the shade 2.0 inches and add an additional baffle. This modification provided a rudimentary 2nd stage by preventing direct illumination of the original single stage baffles at the new cutoff angle of 45°. The baffles, which had been coated with a black paint, were upgraded to Martin Black. Ball updated the shade model to reflect these changes. The results of for the upgraded design, using the more conservative 70x attenuation for the lens cell, are shown in Figure 7.

Test Data shows ~10X Margin at 45° Sun Angle

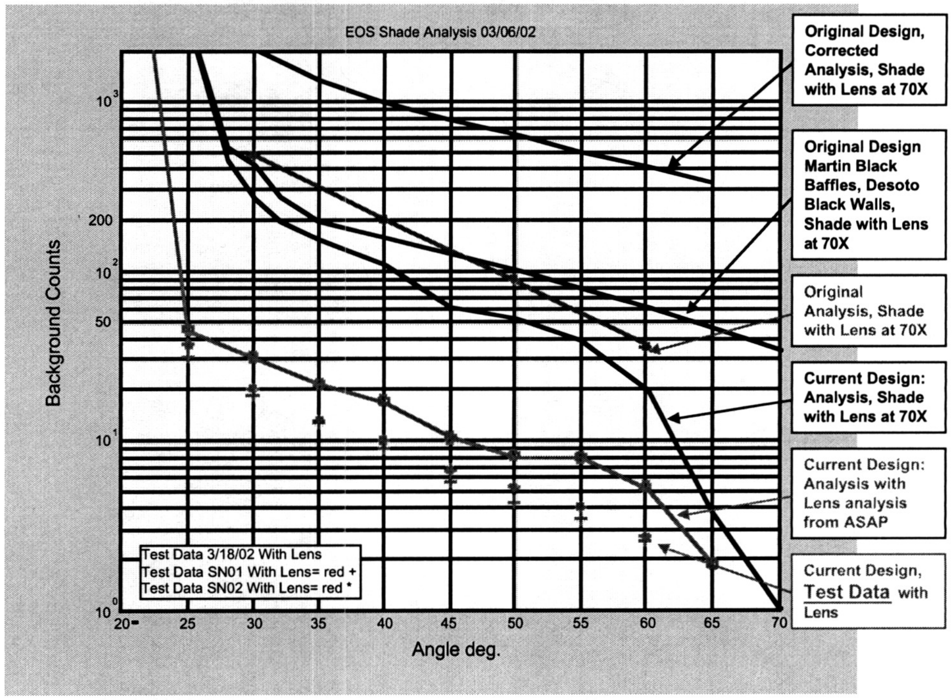

Figure 7: Final Model Performance & Ground Test Results

The tracker had been designed to set a flag in its output data to indicate when the background threshold of 60 counts was exceeded. The latest Ball system analysis indicated that the NEA requirement could be met when the background was as high as 160 counts. To provide the option of increasing the tolerance of background light and thereby providing additional margin on orbit, a software patch was designed that would increase this threshold to 120 counts. This modification also necessitated a change in the trackers charge coupled device (CCD) readout scheme. This change was accomplished via another software patch, which prevented flooding of the CCD's horizontal shift register. These patches were held in reserve for possible implementation after the satellite was on-orbit. The design goal remained to meet the original 60-count limit.

Ground Verification

Ball made several attempts to perform an end-to-end test of the STA. Ideally the test would have included the Sun simulator, the flight shade, and a flight star tracker. The test would have been performed in the flight configuration and the STA would have been exposed to an artificial Sun at various angles off the boresight and the resulting background at the CCD measured. Unfortunately, none of the trials met with success. At the time Ball's facility had a light source that was roughly 3% of Solar intensity. Since then, a new facility has been constructed with a brighter simulated Sun. With this input there was insufficient signal at the detector to register above the dark current noise floor. So a less rigorous method of combining data from separate tests of the individual elements was employed. Results from a shade only test were scaled and combined with the results of a star tracker lens cell test. These results were then combined with the CCD performance to estimate the average background across the detector field of view. The results of this method are shown in Figure 7.

The effects of the software patches were verified via tests at Ball. These tests confirmed that both patches would function as designed. The tests also demonstrated that the procedures to install, activate, and deactivate would function.

On March 21, 2002 Ball personnel hand carried the modified shades to Vandenburg A.F.B for installation, resulting in no impact to the launch schedule.

Flight Results

Shortly after its launch in May, Aqua achieved stable fine point mode. Soon thereafter background data from both trackers were available. Figure 8 and Figure 9 show typical data collected during one orbit on day 142 (May 22, 2002) for STA-1 and STA-2 respectively. The performance of STA-1 reveals the effects of the rotating AMSR-E antenna. In normal operation, STA-1 looks forward through the rotating AMSR antenna toward the Sun as the spacecraft emerges from eclipse. The antenna moves in and out of the shade FOV obstructing the Sun and actually aids shade performance by reducing background. Figure 9 shows what is probably more representative of the true shade behavior. In this case the change in background over time is relatively smooth. Although the background counts for both the entry and exit paths are fairly similar, there is a distinct difference in the behavior prior to the Sun entering the FOV and after it exits. Before the rapid rise the background is about 12 counts. After passage the background falls to about 2 counts. This difference is attributed to the effects of the AIRS Earth shield impingement. Since STA-2 performance is, in general, the worst case, the rest of this discussion will be limited to its performance.

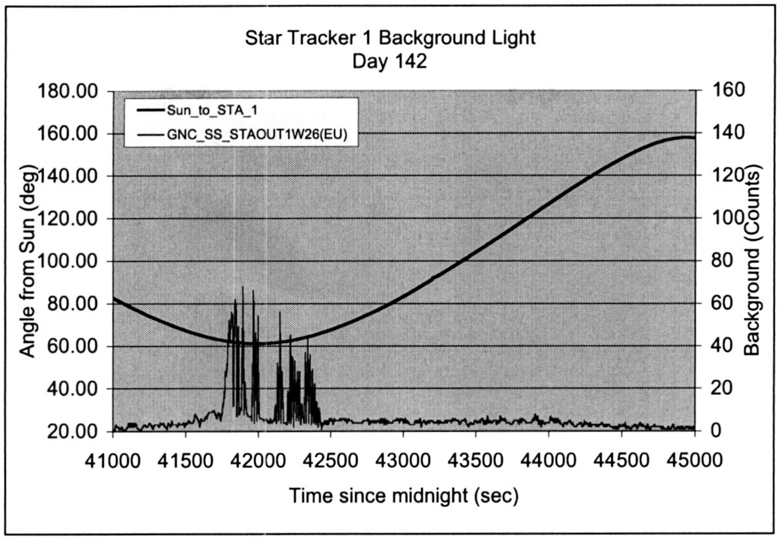

Figure 8: STA-1 Sun Approach Background Telemetry

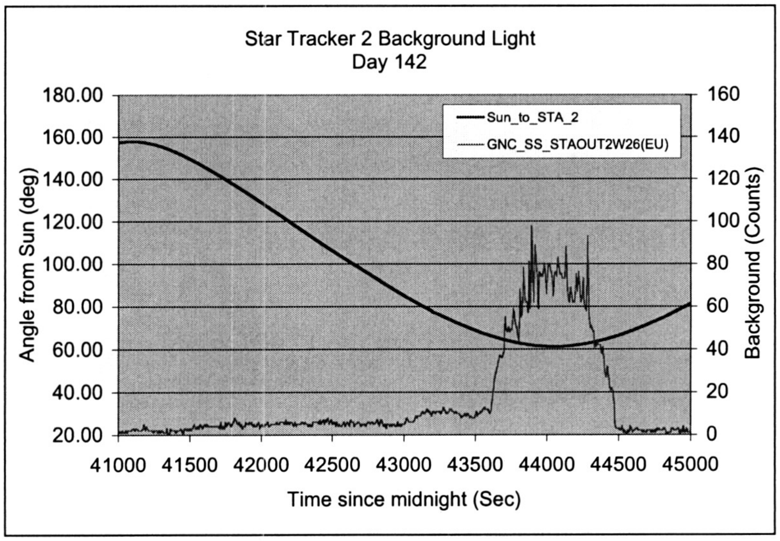

Figure 9: STA-2 Sun Approach Background Telemetry

From Figure 9 it is clear that the shade attenuation performance was not as predicted. In fact the 60-count limit at 45 degrees was being violated when the Sun was 62 degrees from the boresight. This resulted in the trackers data being ignored for roughly 470 seconds. The software patches had not yet been loaded. Both trackers were functional and this violation did not affect spacecraft performance. In fact, even if one tracker had failed the system could have tolerated an outage of this duration. Figure 10 shows the background counts as a function of Sun angle on day 142 and a line representing the pre-launch predictions. This further illustrates that the predicted attenuation, as a function of Sun angle, was off by approximately a factor of 4. Figure 11 shows similar results for day 144 with a slightly lower minimum sun angle.

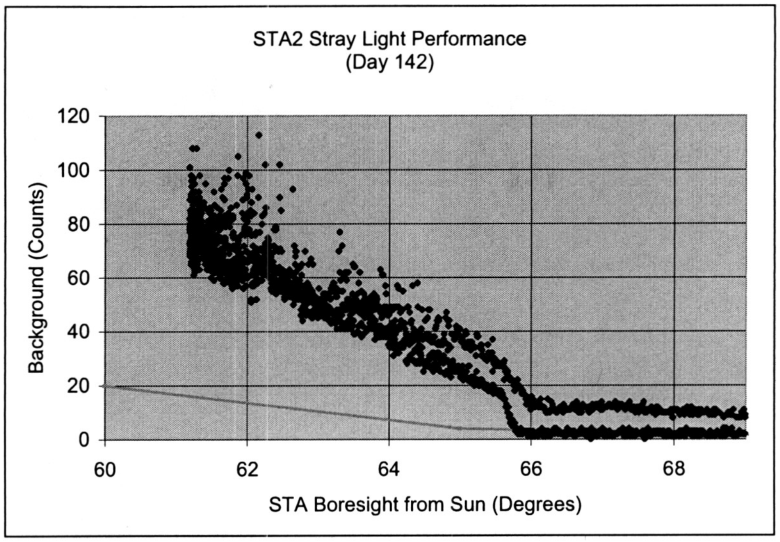

Figure 10: STA-2 Background vs. Sun Angle

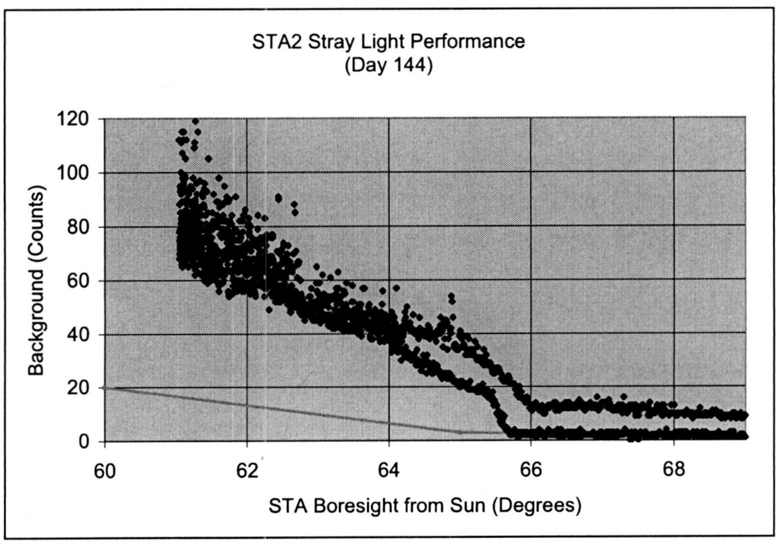

Figure 11: STA-2 Background vs. Sun Angle

On May 24th (day 144) a series of Moon intrusions occurred. In Figure 12, data that includes a lunar crossing is plotted. The outage due to the Moon (background > 60 counts) is approximately 585 seconds. From Figure 13 it can be seen that the shade is meeting its lunar exclusion requirement. In fact performance is met down to 14 degrees from the Moon compared to the required 25 degrees.

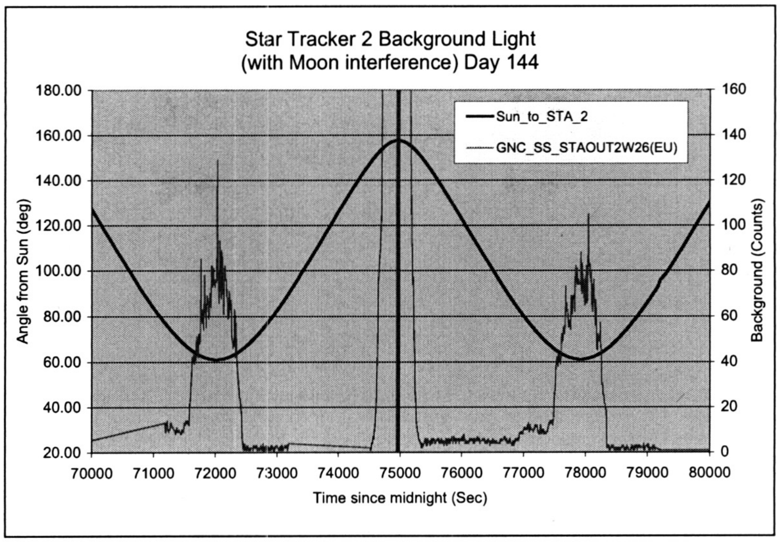

Figure 12: STA-2 Sun and Moon Passage

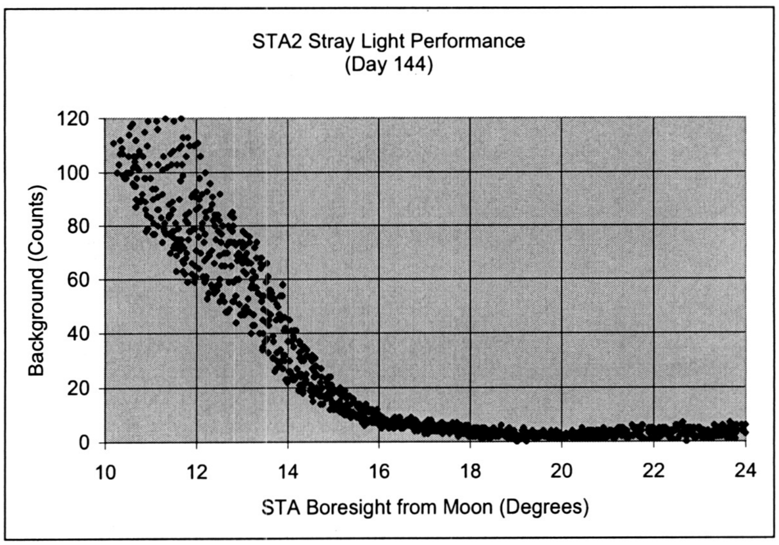

Figure 13: STA-2 Background vs. Moon Angle

On day 216 the software patches were loaded which increased the allowable background to 120 counts in both trackers. The plan was to use the star tracker measurement residuals from the Kalman filter to judge the impact of the patches on performance. Since the residual is the difference between the actual measurement and the predicted measurement it was expected that it would increase if the higher background were negatively impacting the measurements. Each star tracker is capable of tracking up to five stars. For each of these "virtual" trackers there are residuals for both the X and Y measurements. So a total of twenty points were monitored. The residuals are in the telemetry stream and ground processing allows for basic statistics to be calculated for each telemetry point over a window. For Aqua, reference data were collected for a full day (209) and the daily average values for all of the points were averaged. After the patch was applied the residuals were compared to pre-patch values. This was repeated for days 216, 219, and 225. There was no deleterious effect on performance.

Although today Aqua is meeting its pointing requirements, it is still in dispute whether it would meet these requirements in the following scenario: single tracker operational, worst case solar beta angle with consecutive Sun and Moon intrusions. Although this is a rare event it is possible according to analysis. In the worst case, events like this could result in degraded attitude knowledge during the event.

CONCLUSION

Prior to launch, Ball's Aqua lightshade model was reviewed by outside experts, the hardware was tested to the capabilities of the facility, and an apparent margin of between a factor of 2 and a factor of 4 (with software modifications) was identified. To date, data indicate that the shade is underperforming in Sun rejection by approximately a factor of 4. This leaves the shade with little or even slightly negative margin over the mission life.

Ball continues to study this problem for Aqua's sister ship Aura, which has an identical bus. Aura's instrument complement has fewer intrusions into the STA fields of view and is in a slightly better orbit with its ascending node at 1345. What changes, if any, should be made for the Aura shade to improve performance are yet to be determined.

Should Aqua have truly required operation as close as 35 degrees to the Sun, it is doubtful that a single stage shade should ever have been considered as an option. Experience shows that even with the improved tools available today the margin in stray light analysis is best kept in **orders of magnitude**.