WHITE PAPER

SPACE-QUALIFIED ENHANCED GOLD OPTICAL COATING FOR 1550 NM: ENVIRONMENTAL STABILITY AND PERFORMANCE

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ABSTRACT

The rapid growth of Low Earth Orbit (LEO) satellite constellations necessitates optical coatings that deliver high performance at 1550 nm while withstanding harsh environmental conditions without performance loss. Traditional enhanced gold coatings, while valued for their high infrared reflectivity, often degrade under thermal cycling, vacuum exposure, and high-humidity conditions. This work presents a newly developed enhanced gold coating, building on decades of experience, that meets stringent space-qualification requirements while maintaining stability across all tested environments. The coating design incorporates novel process modifications and material interfaces that preserve both optical and mechanical properties under stress. Comprehensive testing, including thermal cycling in vacuum, humidity exposure, and extended durability evaluations—demonstrates that the enhanced gold surface maintains its reflectance and shows no measurable degradation, even after repeated environmental cycling. Although optimized for deposition on aluminum substrates, the coating has demonstrated equally strong adhesion and environmental resilience on glass substrates, extending its applicability to a broad range of optical assemblies. At the 1550 nm communication band, the coating achieves high reflectance with little change in reflectance relative to conventional gold films. This new design represents a significant advance in space-qualified coatings, offering a robust solution for optical terminals and beam-steering elements in LEO satellite communication systems.

INTRODUCTION

The rapid expansion of Low Earth Orbit (LEO) satellite constellations has fundamentally transformed global telecommunications, shifting the focus toward high-speed, long-distance optical inter-satellite links (OISLs). These systems predominantly operate at the 1550 nm wavelength, a standard in fiber-optic communications that offers high data rates and compatibility with established terrestrial technologies. (Wang, et al., 2020) However, the effectiveness of these optical terminals is strictly governed by the performance and longevity of their optical coatings, which must maintain exceptional reflectivity while surviving one of the most unforgiving environments known. (Wernham, 2011)

Spaceborne optical components face a unique combination of degradation mechanisms. In LEO, coatings are subjected to extreme thermal cycling—often ranging from - -50°C to +80°C — as satellites transition between solar illumination and Earth's shadow. This constant expansion and contraction can lead to delamination, cracking, and increased surface roughness. Furthermore, the vacuum environment causes outgassing and moisture release, which, in traditional porous coatings, induces spectral shifts and mechanical stress.

Gold (Au) remains the industry standard for infrared applications due to its inherently high reflectivity and chemical stability. However, "enhanced" gold coatings—which use dielectric overlayers to boost reflectance and provide protection—frequently suffer from poor adhesion and environmental instability when applied to common spaceflight substrates like aluminum. Under the stress of thermal cycling and high-humidity pre-launch storage, these interfaces often degrade, resulting in significant loss of optical performance.

This paper introduces a newly developed, space-qualified enhanced gold coating designed specifically for the 1550 nm band. By implementing novel process modifications and engineered material interfaces, we have addressed the historical trade-off between peak optical performance and mechanical durability. This work details the design architecture of the coating and presents comprehensive results from rigorous qualification testing—including vacuum thermal cycling and extended humidity exposure. Furthermore, we demonstrate the versatility of this design by evaluating its performance and adhesion on both aluminum and glass substrates, offering a robust, universal solution for the next generation of LEO beam-steering and communication assemblies.

EXPERIMENTAL

COATING DEPOSITION

The gold coatings presented here were prepared using an ion-assisted e-beam evaporation system equipped with 6-pocket e-gun, thermal heaters, and planetary rotation. During the process, the components were secured by their edges in an aluminum holder (coating tool).

Coating samples were made of high-purity RSA aluminum that has an exceptionally low surface roughness after diamond turning. (Gubbels, Vnrooy, Bosch, & Senden, 2008). This material was used in this study since the initial surface roughness will not mask surface roughness contribution from the coating. Flats (3" in diameter, 0.5" thick) of the RSA aluminum were fabricated on a diamond turning lath (Moore 450UPL) using a single point diamond tool with optimal cutting parameters with the aim to achieve a surface roughness and flatness less than 4.4nm and 0.304 waves @632.8nm respectively.

The coating process began by loading the parts into the aluminum tool and placing them into the vacuum chamber. Once the pressure reached less than 10-5 Torr, deposition commenced. An ion gun was first utilized with argon for 10 minutes to pre-clean the substrates and remove trace contaminants to improve adhesion. Following pre-cleaning, the ion gun was deactivated and the e-gun activated with a shutter over the deposition path; this allowed the adhesion layer material to heat up while preventing deposition onto the substrate. Once the heating was completed, the shutter was removed from the deposition path, allowing material to be deposited on the substrate.

Once the target thickness was achieved, the shutter was closed and the e-gun deactivated. The next material was then heated with the shutter in place. Once heated to evaporation temperature, the shutter was removed and deposition continued until completed. After the gold layer was deposited, the ion gun was used and remained on for every subsequent layer to help densify and fully oxidize the enhancement layers.

All layers, including the gold, were deposited via e-beam evaporation. The top enhancement layers were evaporated as pure oxides, with the ion-assist primarily used for densification and oxidation.

COATING CHARACTERIZATION AND TESTING

Reflectance measurements were taken using a Perkin Elmer 1050+ spectrometer equipped with a TAMS accessory that allows measurements at any angle of incidence between the desired 5 and 45°.

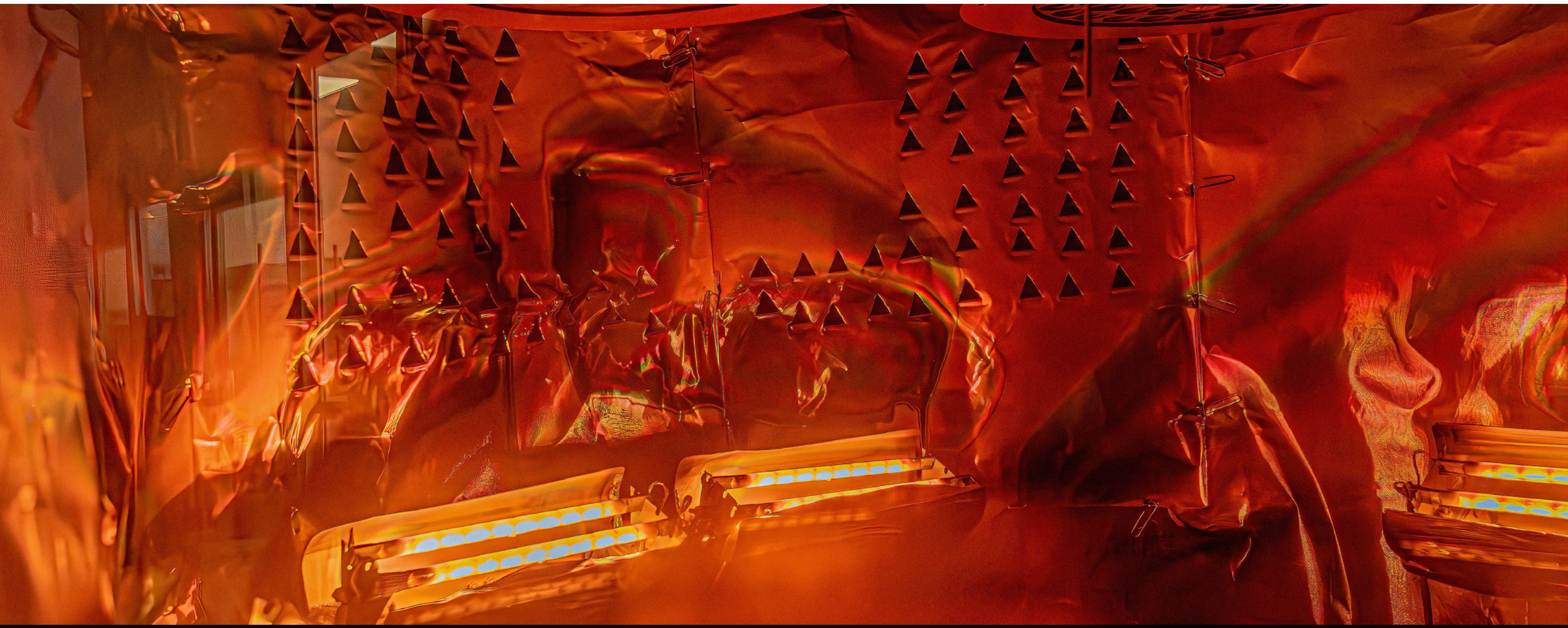
Temperature and humidity testing was carried out in an Espec environmental testing chamber following the standard MIL-C-48497A paragraph 4.5.4.1 and 4.5.3.2 testing conditions respectively. Vacuum heating cycles were performed in a coating chamber equipped with internal heaters. Moderate abrasion and adhesion tests were performed in accordance with MIL-C-48497A paragraphs 4.5.3.3 and 4.5.3.1.

Additionally, solubility and cleanability were evaluated per MIL-C-48497A paragraph 4.5.4.2.

In addition to standard MIL-C-48497A testing, samples underwent an environmental testing sequence designed to mimic an optic's operational lifetime. This sequence included:

1. Three thermal cycles between -40°C and 80°C (1-hour soak at each extreme) and 2°C/minute rate of change between temperature extremes.
2. Immersion in a 95% relative humidity environment for 72 hours.
3. Three vacuum cycles between room temperature and 80°C.

Flatness measurements were taken on a Zygo phase-shift interferometer equipped with a λ/20 transmission reference flat. The Zygo instrument was configured in a horizontal position with the parts secured in a three-jaw chuck to facilitate measurement alignment.



RESULTS

Samples (159 pieces) of the rapidly solidified aluminum (RSA) 6061-T6 purchased from RSP Technologies were diamond turned into optically flat pieces. The effects of the coating process and resulting surface stress were evaluated for changes in surface flatness (surface stress), surface roughness (spatter and defects), and subsequent resilience to environmental conditions.

SURFACE ROUGHNESS

One typically achieves very low surface roughness using this RSA 6061-T6 aluminum (between 1nm and 3nm) attributed to its homogenous and fine microstructure (approx. 1um). (Horst, de Haan, Gubbels, & Senden, 2012) (Choi, et al., 2023). As such, this was the material chosen in this study as standard 6061 having a higher surface roughness (5-8nm) (Wang, Xia, Wang, Yin, & Sun, 2020) may hide changes in surface roughness induced by the coating.

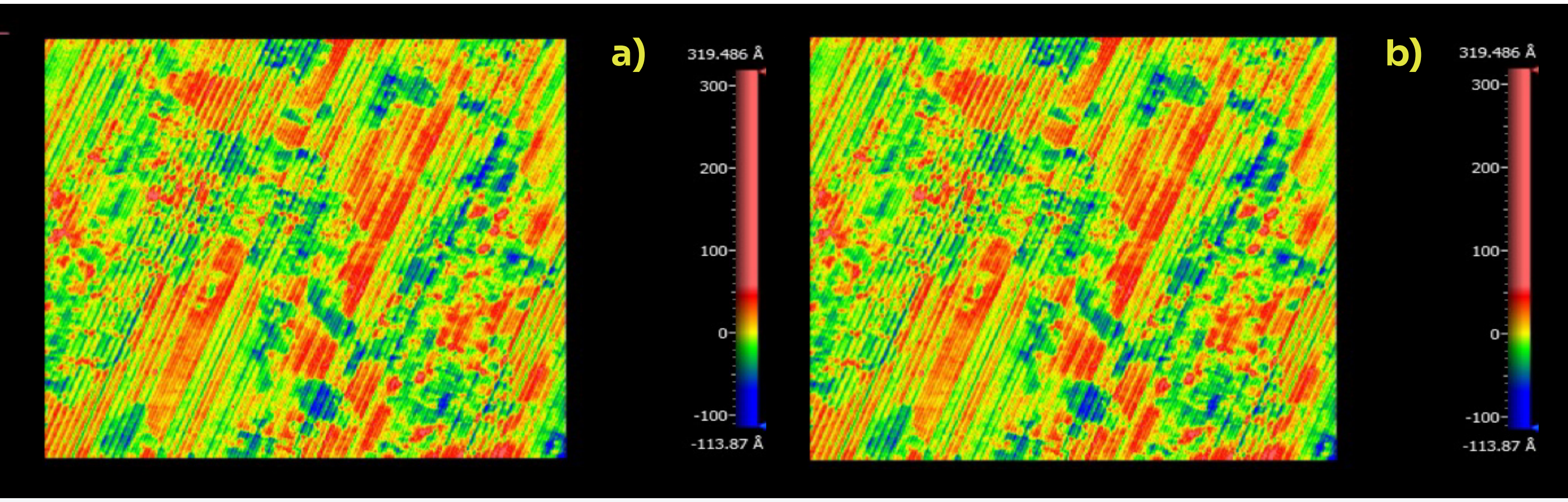


Figure 1 - Surface roughness of samples before coating (a) and samples after enhanced gold coating (b). The surface roughness in a) is Rq=2.498nm, Ra=1.95nm and b) Rq=2.52nm and Ra=2.02nm.

Comparing a total of 159 pieces before and after coating shows the true picture of the statistics change of the roughness. The result of the F-test acts as a “green light” for a comparison between the means of the roughness 29nm and 28nm (Figure 2). Because the F-test showed no significant difference in variances, a pooled variance t-test, was used and is generally a more powerful and reliable than versions used for unequal variances.

SURFACE ROUGHNESS, CONT.

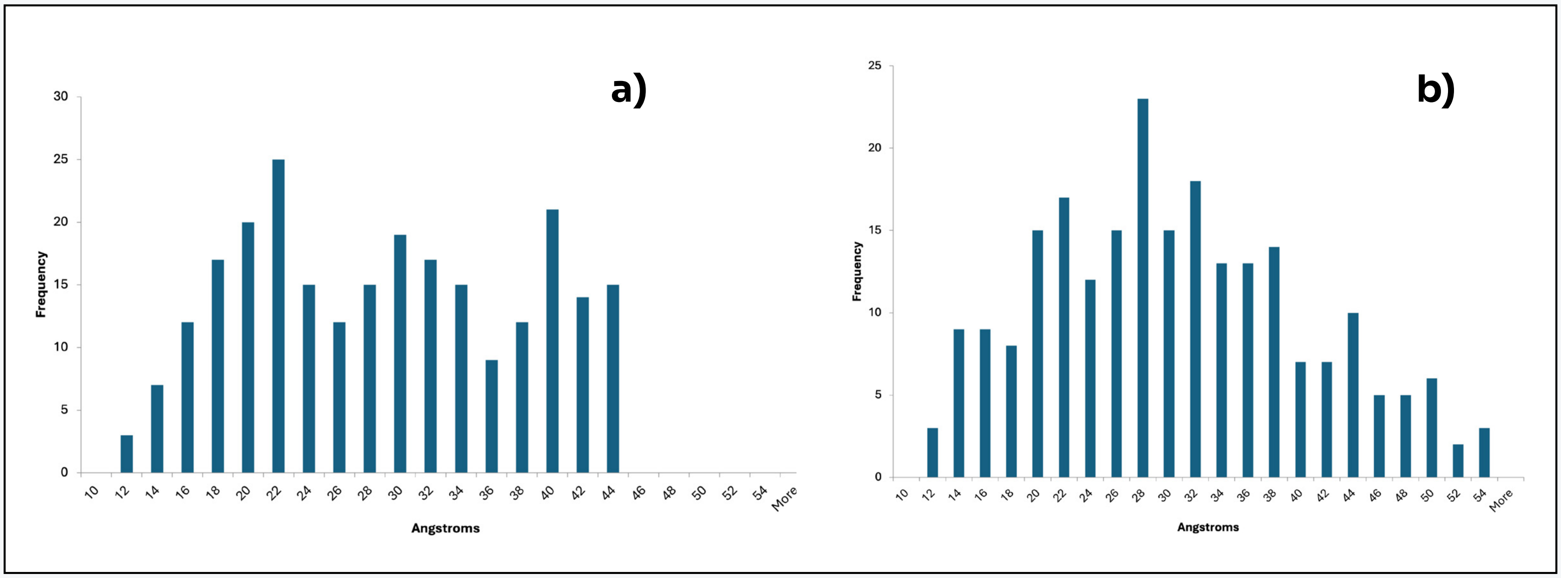


Figure 2 - Surface Roughness of RSA samples before (a) after (b) coating. The average surface roughness before and after coating is 2.8nm and 2.96nm with a variance of 10.03 and 8.497 respectively. T-test of the surface roughness indicates that there is no significant difference in the average surface roughness before and after coating.

The t-test was used to determine if the differences between the means (29vs28) is a real effect or just "noise" relative to the 100.3 and 84.97 variance. Since the variances are quite high compared to the noise of the small mean differences, the "noise" is relatively large.

The t-statistic was calculated at 1.84 falling below the t-critical of 1.94 and therefore it is concluded that the difference in the means are not statistically significant to conclude that they are different. Moreover, the calculated P-value of 0.065 indicates that there is only a 6.5% chance that this difference occurred due to random sampling variation rather than a real underlying cause. Because this is slightly above the typical 0.05 threshold, the result is often described as "marginally significant" or a "trend." It suggests that while there might be a slight difference between the groups, the current data doesn't provide enough evidence to prove it definitively.

SURFACE FLATNESS

When a thin film is deposited onto a substrate, internal stresses—either tensile or compressive—can significantly alter the substrate's global surface flatness. This phenomenon occurs because the film and substrate act as a coupled system attempting to reach mechanical equilibrium. If the film is under tensile stress, it tries to contract, pulling the edges of the substrate inward and causing it to bow into a concave (cup-like) shape. Conversely, a film under compressive stress tries to expand against the substrate, forcing it to bow into a convex (dome-like) profile. This macroscopic distortion is often quantified using the Stoney equation, which relates the change in the substrate's radius of curvature to the film's thickness and intrinsic stress.

In high-precision applications like diamond-turned optics even moderate thin-film stress can degrade flatness beyond acceptable tolerances. For example, depositing a reflective or protective coating on a 6061-T6 aluminum mirror can introduce "fringe" errors that distort the reflected wavefront. The thinner or more flexible the substrate, the more pronounced these effects become.

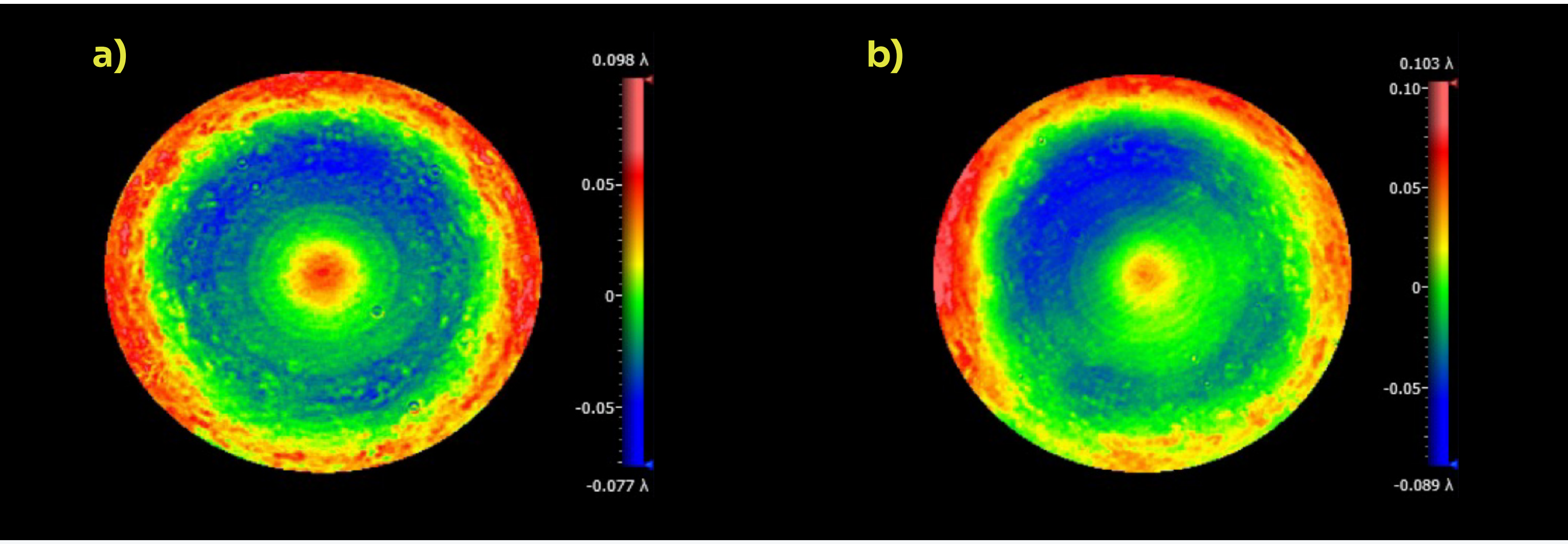


Figure 3 - Flatness of RSA aluminum before coating (a) and after gold coating (b). The flatness measured before coating is 0.174 waves and 0.192 waves at 632.8nm respectively.

Further analysis of the 159 samples of the same optics analyzed for surface roughness was also analyzed for surface flatness to provide a true picture of the changes. Similar to the above analysis, a pooled variance t-test, was used and is generally more powerful and reliable than versions used for unequal variances.

SURFACE FLATNESS, CONT.

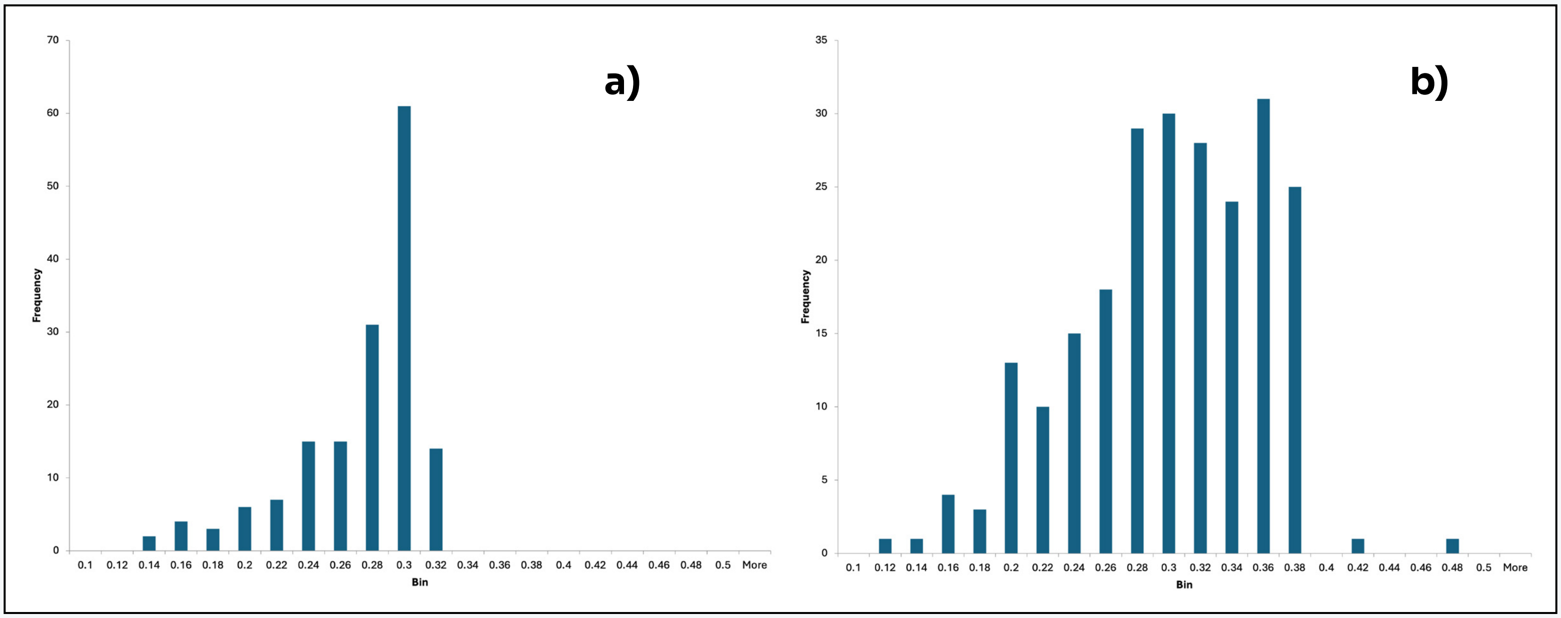


Figure 4 - Surface roughness histogram of 158 samples of aluminum uncoated (a) and coated (b) parts. The average shows a slight difference between the uncoated and coated surfaces. The uncoated parts show an average of 0.26 waves whereas the coated version shows an average of 0.29 waves @632.8nm.

To evaluate the mechanical impact of the enhanced gold coating on the substrate figure, surface flatness was measured for a large sample set both before and after the deposition process. The mean flatness prior to coating was 0.264 waves, while the post-coating mean was 0.292 waves. A two-sample t-test was conducted to determine if the observed increase in the flatness value—representing a slight reduction in surface figure quality—was statistically significant.

The statistical analysis yielded a t-stat of 5.53, which significantly exceeds the t-critical value of 1.97 for a 95% confidence interval. The resulting p-value of 5.96x10-8 confirms that the change in surface flatness is highly statistically significant and not a result of random measurement variation. While this increase in the flatness value indicates that the coating process resulted in changes in the flatness to the optic, it is important to note that the post-coating average of 0.292 waves remains comfortably within the design specification of <0.304 waves (the end user specifications). This demonstrates that while the deposition process does alter the surface figure, the engineered interfaces effectively manage stress to keep the optic within functional tolerances.

OPTICAL PERFORMANCE

Finally, and most importantly, the coating was evaluated for optical performance over a small band centered at a wavelength of 1550nm. As noted above, the 1550 nm wavelength is the gold standard for space-based laser communications primarily due to its alignment with the C-band of fiber optic technology (1530-1565) and L-band (1565-1625nm), which allows space systems to leverage highly mature, high-speed terrestrial hardware. In the context of satellite-to-ground links, 1550 nm falls within a critical atmospheric window where absorption from water vapor and carbon dioxide is minimal, ensuring high transmission efficiency. Even when considering a single wavelength, the communications between satellites may shift due to doppler shift, linewidth and instrument stability (LIu, Zhao, Zhao, & Li, 2017). As such, these optics were analyzed between a full 1400 to 1600nm spectrum.

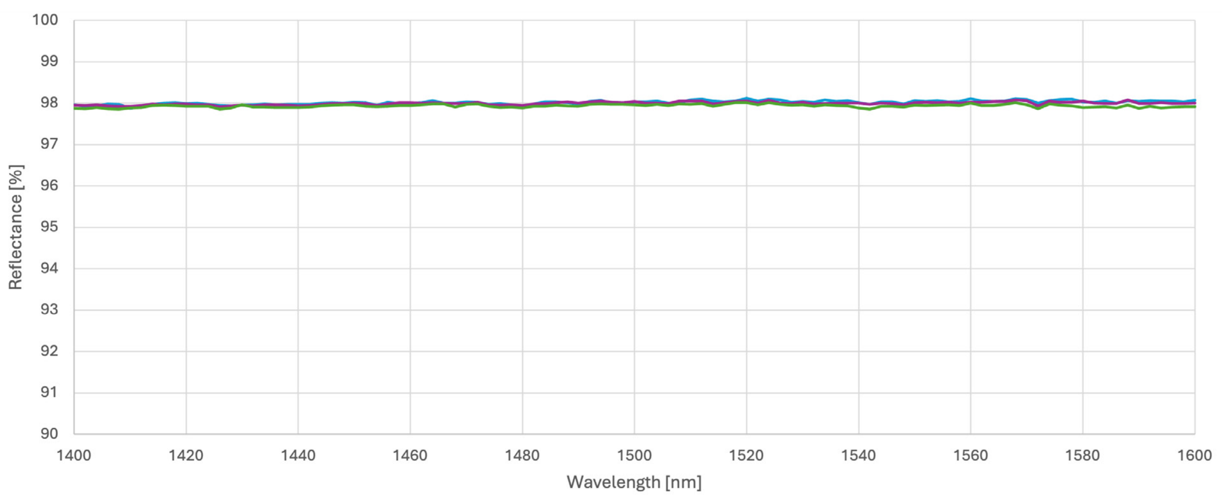


Figure 5 – Typical Optical spectra of gold coating deposited on an aluminum substrate taken at 14, 21 and 28 angle of incidence (AOI).

As seen in the spectrum illustrated in Figure 5, the, the aluminum mirror featuring an enhanced gold coating demonstrates superior optical efficiency and angular stability compared to traditional unprotected gold surfaces. While standard gold typically yields a reflectance of approximately 97% in the short-wave infrared, this enhanced coating achieves a consistent reflectance of 98%. Critically, this performance remains remarkably stable across a broad range of incidence, showing no significant degradation as the Angle of Incidence (AOI) shifts from 14° to 28°. Beyond these optical gains, the enhanced surface provides a level of physical durability and environmental resistance than unprotected gold, which is notoriously soft and susceptible to handling damage, making it a more robust solution for high-precision optical systems.

OPTICAL PERFORMANCE, CONT.

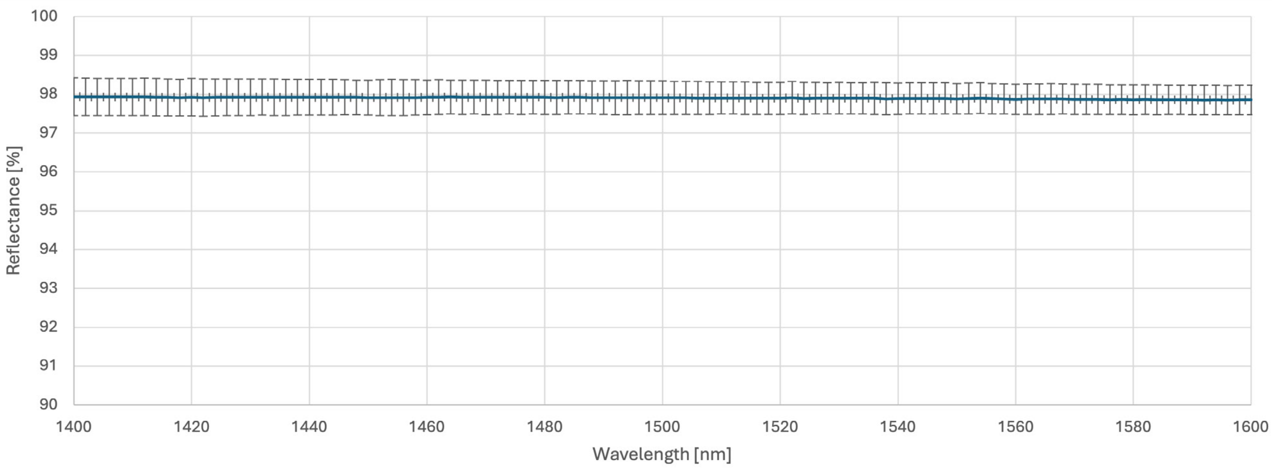


Figure 6 – Optical spectra and calculated standard deviation at each data point from 20 coating runs spread over a year. The total overall spectral change is within ±0.5% from nominal, an exceptional attribute to indicate the repeatability of this coating and therefore little no changes from batch to batch.

The manufacturing process for this enhanced gold coating demonstrates exceptional batch-to-batch repeatability, maintaining a reflectance deviation of only 0.5% (Figure 6). This level of precision is typically reserved for pure gold surfaces, yet it has been successfully realized here within a more complex, multi-layer enhanced stack. Achieving such tight tolerancing is particularly noteworthy given the use of e-beam evaporation; while evaporation systems are traditionally more susceptible to the drifting and lower repeatability often associated with sputtering processes, our refined deposition controls mitigate these inherent variabilities. The result is a highly reliable production cycle that ensures consistent optical performance across multiple coating runs, providing the high-fidelity uniformity required for mission-critical aerospace and communication hardware.

ENVIRONMENTAL TESTING

Environmental testing was conducted in compliance to the process noted in the environmental procedure noted earlier. The data presented here is the typical response of the coating as this procedure has been repeated numerous times.

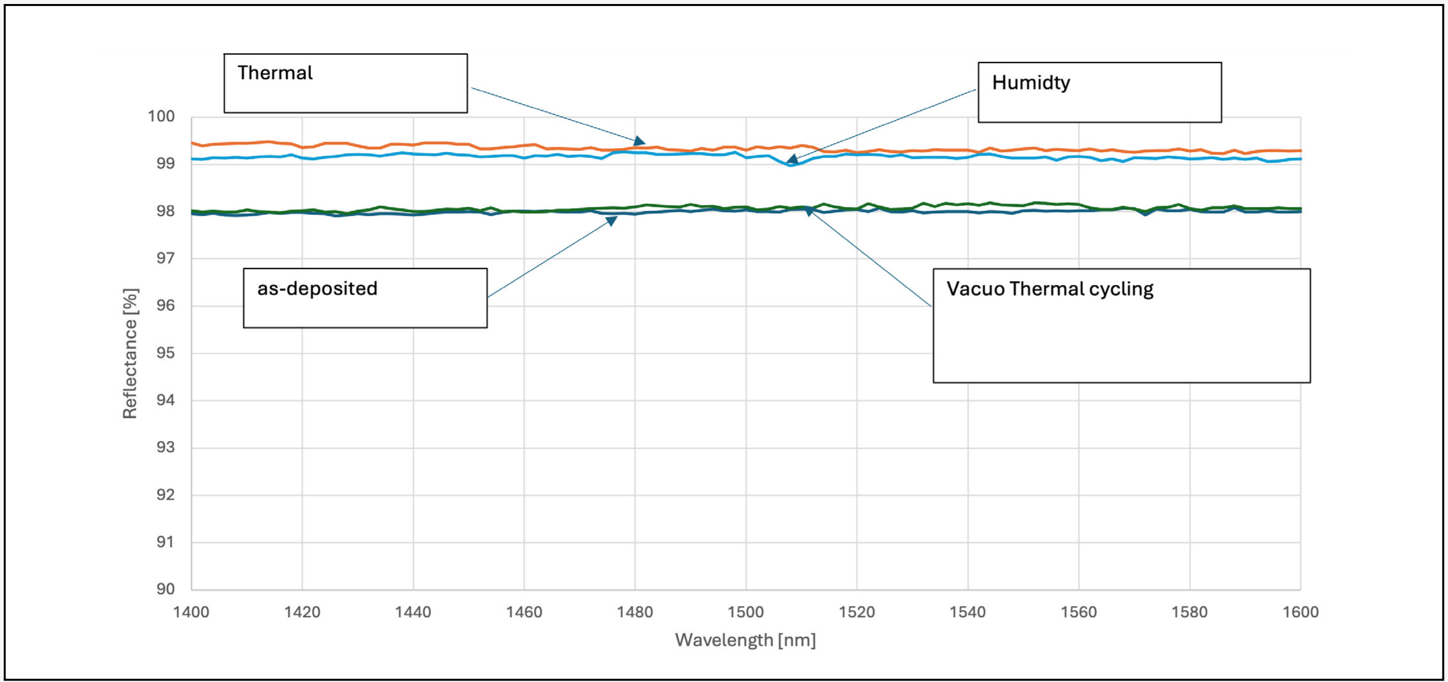


Figure 7 - Spectral performance after environmental testing. Measurements were taken at 21°AOI on the same sample after gold coating, after thermal cycling, humidity exposure, and then vacuo thermal cycling.

The environmental stability of the enhanced gold coating was evaluated at a 21° Angle of Incidence (AOI), revealing a unique and robust response to varied stress conditions. Initial thermal cycling resulted in no observable degradation; rather, the mirror exhibited a slight enhancement in performance, with reflectance increasing to 99%. This elevated efficiency was maintained through subsequent humidity immersion testing, demonstrating the coating's resilience against moisture-induced losses. Interestingly, this gain in reflectance persisted until the sample underwent thermal cycling within a vacuum environment, at which point the optical performance reverted to its original as-deposited state of 98%. This reversible behavior suggests that the minor spectral shifts are likely tied to surface adsorption effects or subtle, non-permanent structural changes in the enhancement layers that are neutralized under vacuum-thermal conditions. The source and neutralizing effects are still under investigation, and more research is required.

CONCLUSION

The evaluation of an enhanced gold coatings on rapidly solidified aluminum (RSA) 6061-T6 substrates reveals a highly stable and repeatable process suitable for high-precision optical applications. This study concludes the following:

- **Surface Roughness Integrity:** The coating process does not significantly degrade the ultra-smooth surface finish of the RSA aluminum. Statistical analysis ($p = 0.065$) confirmed that changes in roughness were not statistically significant, preserving the 1nm–3nm quality required for high-performance optics.
- **Managed Surface Stress:** While the deposition process introduces a statistically significant change in surface flatness ($p < 0.001$) due to thin-film stress, the effect is physically minimal. The post-coating average of 0.292 waves remains within the strict end-user specification of <0.304 waves, proving that the substrate-coating interface effectively manages mechanical distortion.
- **Superior Optical Performance:** The enhanced gold coating outperformed standard gold with a consistent 98% reflectance at the critical 1550nm wavelength. This efficiency remains stable across varied angles of incidence (14° to 28°), making it ideal for the dynamic requirements of space-based laser communications.
- **Process Reliability:** Long-term data across 20 coating runs over one year showed a spectral variation of only ±0.5%. This high level of repeatability ensures consistent manufacturing outcomes for large-scale or long-term optical projects.

Overall, the combination of RSA 6061-T6 and enhanced gold coating provides a robust, high-reflectance solution that maintains critical mechanical tolerances and surface quality under industrial coating conditions.

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