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The Gemini Observatory protected silver coating: ten years in operation

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ABSTRACT

Since 2004 the Gemini telescopes have used a protected 4-layer silver coating on their 8-meter diameter primary mirror and other smaller optics. Protected silver was chosen for the twin telescopes due to its high reflectivity and low emissivity properties. For over 10 years the protected 4-layer silver coating at Gemini exceeded the science requirements for reflectivity of 88% between 0.4-0.7 µm and 84% between 0.7-1.1 µm. Initial durability requirements that the coating should last at least two years have been also been surpassed. All mirrors have met the durability requirement, with most outlasting it significantly. Provided is a ten year retrospective on the progress in the use and maintenance of 4-layer silver coatings on large astronomical optics.

Keywords: Protected silver coating, High reflectivity, Low emissivity, Durability,

1. Introduction

Since 2004 the Gemini telescopes have used a protected 4-layer silver coating on the primary (M1), secondary (M2), and tertiary (SF) mirrors, as well as the GeMS optical path mirrors. A protected silver coating was chosen for the twin telescopes due to the high reflectivity and low emissivity properties of silver. For over 10 years the protected 4-layer silver coating at Gemini has met the science requirements for reflectivity of 88% between 0.4-0.7 µm and 84% between 0.7-1.1 µm[1]. Initial requirement also stipulated that the coating should last at least two years[2]. All the mirrors have far outlasted this two year requirement, with the exception of the Gemini North secondary mirror which only exceeds this requirement by one year.

All mirror recoatings, including mirrors for peripheral wavefront sensors, apply a recipe of 65 Å of nickel chromium (NiCr), 1100 Å of silver (Ag), 6 Å of NiCr, and 85 Å of silicon nitride (Si_3N_4). The first layer of NiCr is sputtered with nitrogen as process gas, and acts as an adhesive layer between the glass substrate and the silver layer. The silver layer is sputtered onto the NiCr base layer with argon process gas to a thickness of 1100 Å. Next the interlayer of NiCr is sputtered on top of the silver in a low power setting to apply only a whisper of material, 6 Å thick. Finally, the Si_3N_4 layer is applied by sputtering a boron doped silicon target with nitrogen process gas. According to Chu et al., a Si_3N_4 overcoat on Ag without a NiCr interlayer acts as a "leaky capacitor" and is prone to corrosion. With the NiCr interlayer the impedance response of the coating becomes strongly capacitive, and corrosion is slowed. It is believed that the NiCr interlayer provides nucleation sites that facilitate the growth of a dense and protective Si_3N_4 layer[3].

Dust and other particulate matter accumulate on the mirrors over time, and cause losses in reflectivity, as well as increases in infrared emissivity. The accumulated material must be removed regularly to meet the reflectivity and emissivity standards. Every week M1 and M2 are cleaned with CO_2 snow to remove dust and small debris. Liquid CO_2 is used to create very pure snow crystals which impact and dislodge particulates on the substrate surface. The CO_2 snow sublimates and allows the particulates to glide off of the mirror surface on gas sled[4].

The mirrors also undergo in-situ washes with mild soap and de-ionized water to restore their reflectivity when necessary[5]. An in-situ wash is scheduled on an as need basis for the primary mirror at Gemini North, and yearly at Gemini South. All other mirrors are washed on an as needed basis. The in-situ wash of the primary mirrors has prolonged the usable life of the coating, regularly restoring reflectivity and reducing emissivity.

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The previous coating dates for the Gemini North mirrors were:

	M1	M2	SF	Periscope
1st Coating	November 26, 2004	November 28, 2004	November 28, 2004	November 28, 2004
2nd Coating	July 28, 2008	October 10, 2008	July 7, 2009	June 18, 2013
3rd Coating	September 23, 2013	January 7, 2012	July 25, 2010	

Table 1: Dates of GN 4-layer coatings

For Gemini South, the coating dates for their mirrors were:

	M1	M2	SF	AO	Periscope
1st Coating	May 31, 2004	March 16, 2004	March 17, 2004	October 9, 2010	March 16, 2004
2nd Coating	October 8, 2010				
3rd Coating	October 24, 2015				

Table 2: Dates of GS 4-layer silver coatings

2. Reflectivity

2.1 Measuring Devices

In order to monitor the status of the mirror coatings, reflectivity data is gathered on the primary and secondary mirrors at both sites at regular intervals with IRIS scatter-reflectometers. The IRIS scatter-reflectometers measure the reflectivity in-situ at 470nm, 530nm, 650nm, and 880nm. At Gemini North, a new Surface Optics 410-Solar handheld reflectometer was recently purchased as an upgrade to the IRIS. The 410-Solar measures seven wavelength bands from 335-2500 nm for diffuse, specular, and total reflectance. At Gemini South, an A1 Pixel CT7 scatter-reflectometer was recently repaired and will be used in conjunction with the IRIS. The CT7 measures seven discrete wavelengths from 365-970 nm. Figure 1 shows the discrepancy in measurement between the different handheld reflectometers compared to the results from a Cary5000.

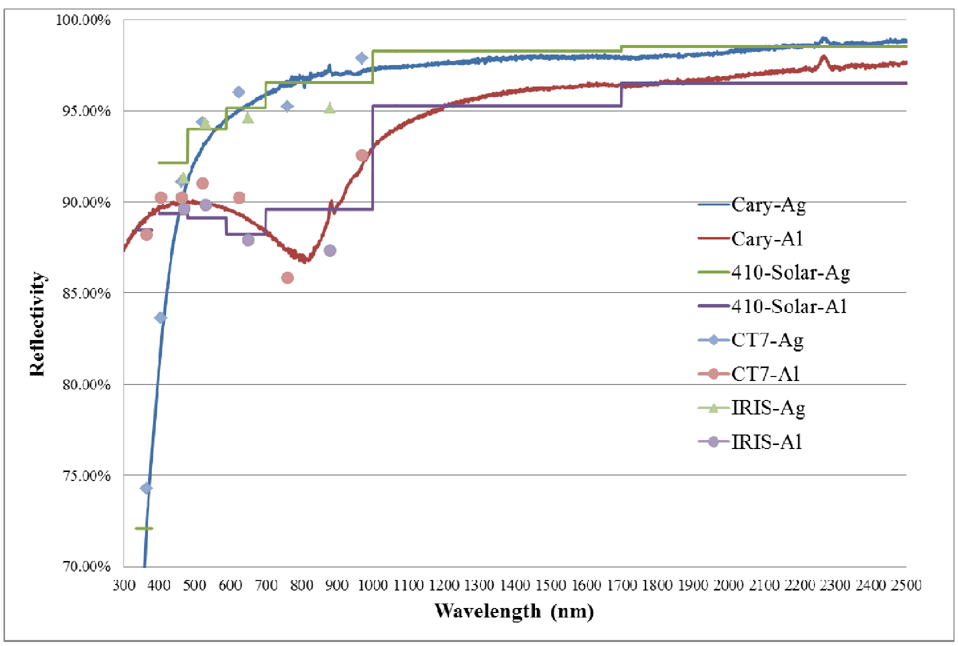

Figure 1: Comparison of the different reflectivity measuring devices at Gemini. Devices each measured the same samples of silver or aluminum.

2.2 M1 and M2 Reflectivity

The Gemini Observatory has strict requirements for the operational reflectivity of the mirrors in the science path. The original requirements and goals for reflectivity were:

Wavelength	0.3-0.4µm	0.4-.0.7µm	0.7-1.1µm
Requirement	88%	88%	84%
Goal	92%	98%	98%

Table 3: Reflectivity Requirements and Goal for the Gemini Observatory[6]

The requirements for 88% reflectivity from 0.3-0.4µm proved impossible with current coating techniques. The other requirements have been easily met at both sites.

The Gemini South M1 was recently recoated in October of 2015, after 5 years in operation. During these 5 years, the coating was able to endure in-situ washes on at least a yearly basis. In some years dust accumulation on the mirror was so rapid that in-situ washes were needed every 6 months. Despite this rough treatment, the reflectivity of the mirror was restored to nominal after each in-situ wash. The mirror was only recoated in 2015 so that the skill set necessary to perform the coating could be maintained.

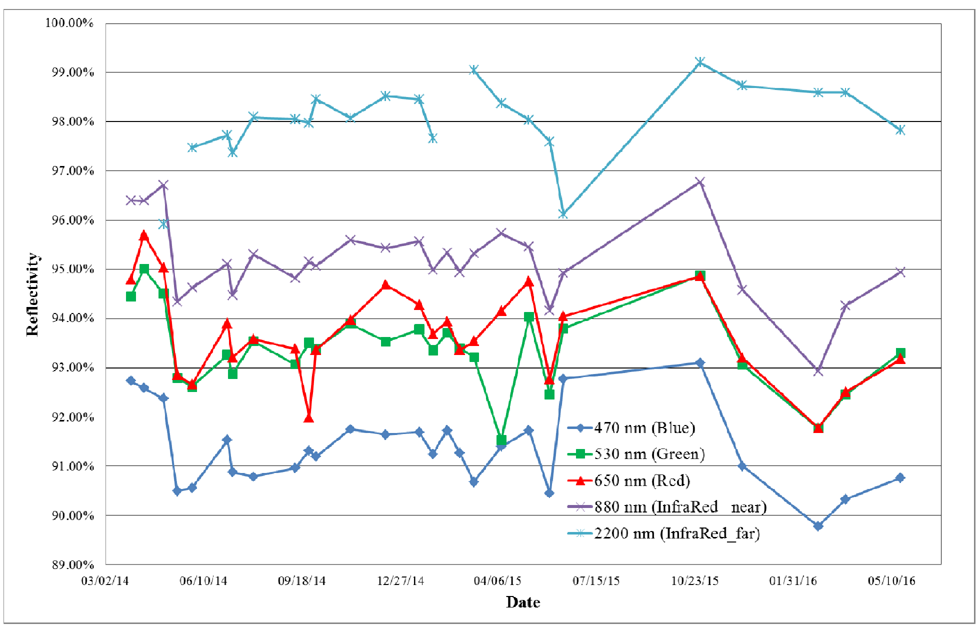

Figure 2: GS M1 Reflectivity Data from March 2014 to May 2016. Recoating was October 2015.

The Gemini South M2, which was last recoated in 2004, has shown almost no signs of degradation thanks to the protected silver coating, and two washes. After 12 years in operation the secondary mirror reflectivity has degraded by approximately 3% at 470 nm and ~1% at 2200nm. It can be seen in figure 3 that it was possible to recover the losses in reflectivity after each in-situ wash. It is probable that current losses in reflectivity will be regained after the next in-situ wash. A recoating of M2 will not be necessary until it begins to tarnish badly, or until reflectivity cannot be restored after an in-situ wash.

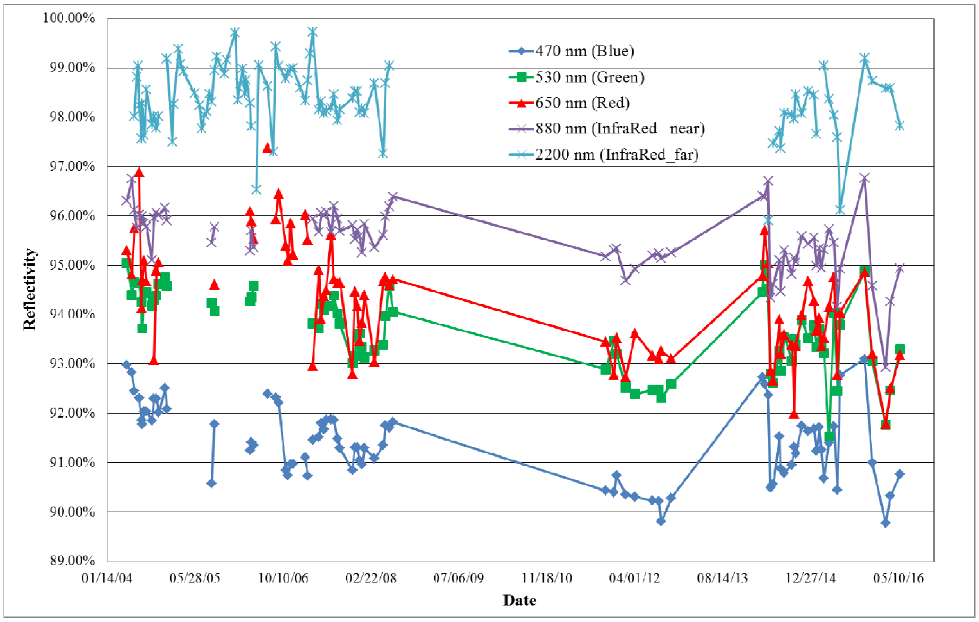

Figure 3: GS M2 Reflectivity from January 2004 to May 2016.

At Gemini North, the primary mirror was recoated in September 2013, and the reflectivity has not yet degraded enough to warrant an in-situ wash. The reflectivity does show almost a 3% loss at 470nm, with less variation at longer wavelengths. There is a variation in reflectivity measurements of approximately 2%, so the losses may be less than 3% over 2 years. This variation is due in part to issues that arose during the most recent M1 coating. Excessive arcing on the silica magnetron required a momentarily stop of the coating process. When restarting the process, additional silica was applied at one location. Witness samples also showed that there was a small difference in the thickness of the silica layer along the length of the magnetron resulting in additional reflectivity inconsistencies. Because of these errors, the coating reflectivity can show slight variations depending on where it is measured.

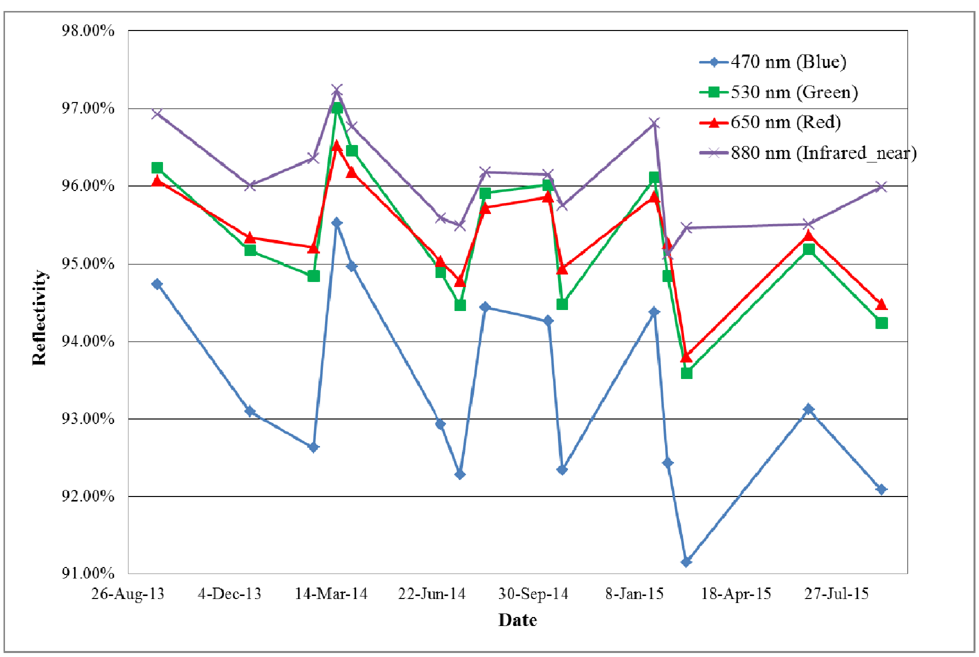

Figure 4: GN M1 Reflectivity data from September 2013 to September 2015.

The Gemini North secondary mirror, which was recoated in September 2015, is the only mirror that has shown significant cosmetic deterioration in less than 5 years. Although the reflectivity remained above the science requirement, the mirror began to show signs of tarnish over large areas. At this time it is not currently known what is causing advanced degradation of this mirror when compared to the other mirrors. The degradation could be caused by an abnormally thin protective silica layer. It could also be degrading due to exposure to H_2S that accumulates in greater concentrations at the top of the dome from vehicles and volcanic vog. During the most recent coating, a thicker Si_3N_4 top layer was applied to the M2 with the expectation that it would slow or halt the degradation. There is a trade-off in reflectivity with a thicker silica layer, but it only present at the shorter wavelengths. Using the newly acquired 410-Solar reflectometer, the difference in reflectivity after recoating M2 can be seen in figure 5.

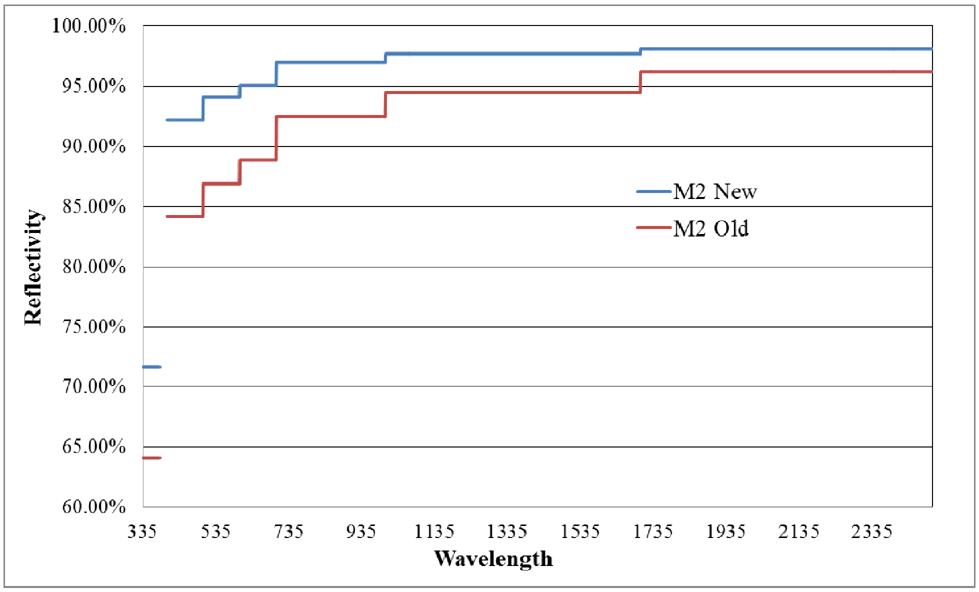

Figure 5: GN M2 Reflectivity before and after recoating in September 2015, measured with Surface Optics 410-Solar.

2.2 Witness Samples

During the coating process witness samples are also produced so that reflectivity measurements can be taken with a Cary5000 spectrophotometer. Test samples were produced at Gemini North with the same coating recipe directly after coating the M1. Samples were produced at the center each of the three rings, and one set was produced from the inner to outer diameter of one ring.

Analysis of these samples with the Cary5000 spectrophotometer showed a difference between the two sample batches. The first batch, which was produced at the center of coating ring, showed no difference in reflectivity properties from 200nm to 2500nm. The four samples that were equally placed from the inner diameter to the outer diameter of the ring did show variations in reflectivity between 200nm and 800nm, with much smaller variations between 800nm and 2500nm.

The difference in reflectivity between the four samples can be attributed to differences in the thickness of the top Si_3N_4 layer. This shows that the silica magnetron is not applying a coating of uniform thickness across the length of the magnetron. This can also help to explain the discrepancy in coating quality of the Gemini North secondary mirror.

Since the M2 diameter is 1.022 meters and the magnetron length is 1.15 meters, the secondary mirror is coated in a single pass under each magnetron for each respective layer. Due to the hyperbolic convex surface which is being coated the center of the mirror is closer to the magnetron than the outer diameter. This causes a differential in the surface thickness that is applied by the magnetron. In addition, there is a slight differential in surface thickness that is being produced along the length of the magnetron as well. This leads to an irregular difference in the silica surface thickness across the secondary mirror. There is some uncertainty in using the reflectivity measurements to determine the thickness of the protective Si_3N_4 layer. Ellipsometer measurements must be used instead to accurately measure the Si_3N_4 layer.

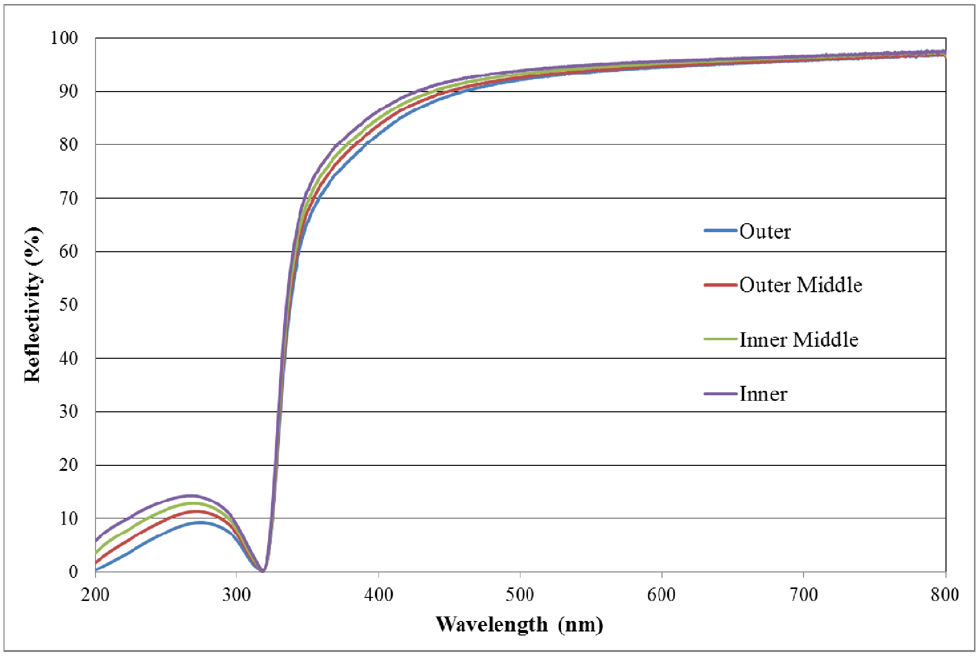

Figure 6: Reflectivity of Gemini North tests samples from 2013 M1 recoating spaced equally along the 1.15 meter magnetron length.

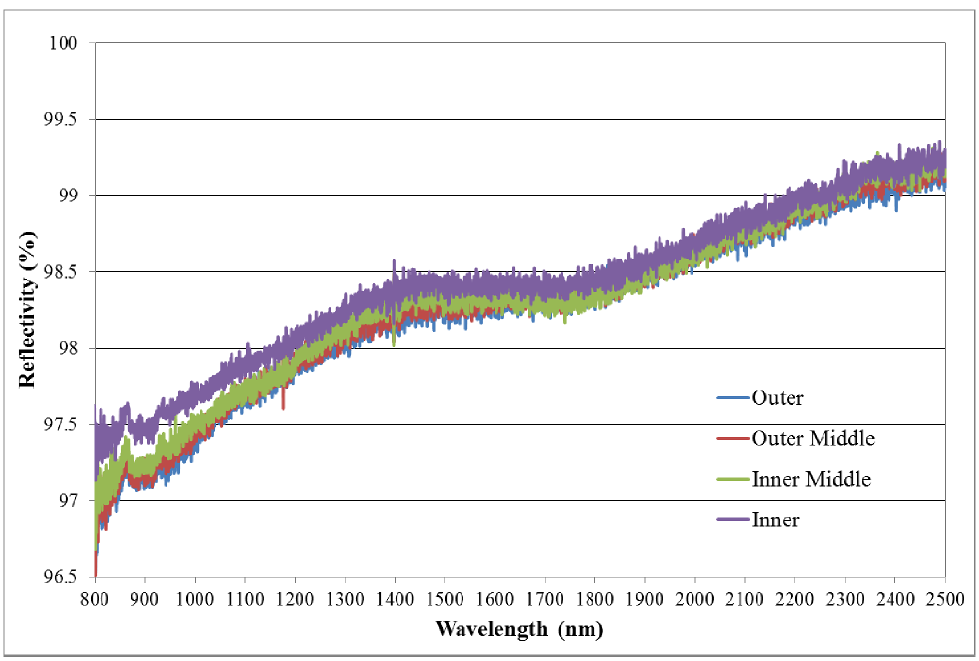

Figure 7: Gemini North test samples from 2013 M1 recoating. Reflectivity measured from 800 nm to 2500 nm.

Recently J.A. Woollam Co. provided some ellipsometer measurements of the Si_3N_4 layer from samples that were produced during the Gemini North M2 and Gemini South M1 recoatings in 2015. Samples produced alongside M2 during the Gemini North M2 recoating had Si_3N_4 thicknesses of 9.52 nm and 8.35 nm, corresponding to the areas of M2 that were closest and furthest from the magnetron. The thicker sample was located approximately 40 mm closer to the magnetron. Measurements showed that two samples produced just prior to the Gemini South M1 recoating had Si_3N_4 thicknesses of 7.88 nm and 5.10 nm. The NiCr interlayer was omitted from the latter sample, which could account for the thickness difference. Measurements of 121 points on the former samples showed a top to bottom thickness variation of ±0.65 nm along its 100 mm length, as seen in figure 8. The measurements by J.A. Woollam Co. demonstrate the difficulty in maintaining a uniform layer across the length of the magnetron due to the curvature of the mirrors.

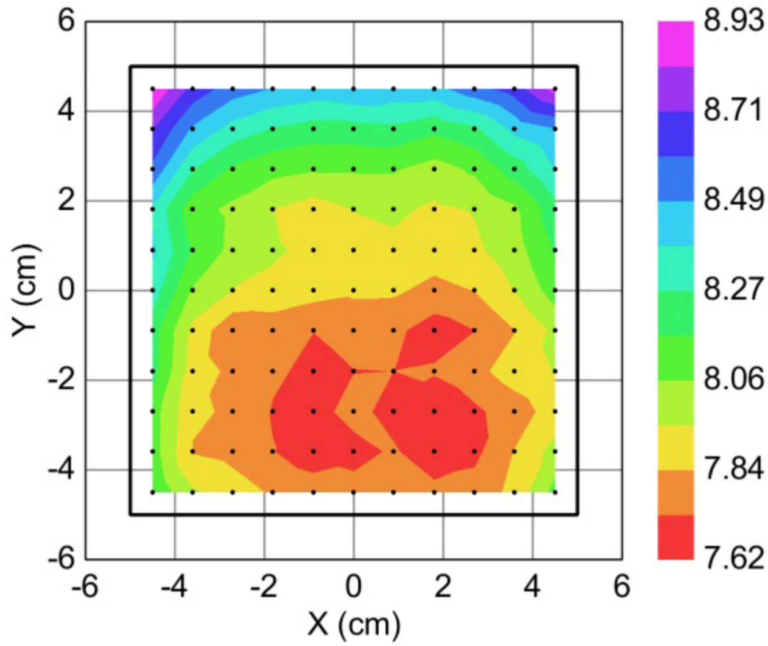

Figure 8: Measured thickness of the Si3N4 protective layer on a sample produced at Gemini South in preparation for coating M1. Thicknesses are in nm.

3. Emissivity

3.1 Emissivity measured with NIRI

Currently, the only way to measure emissivity at Gemini North is to use the Near InfraRed Imager and spectrometer (NIRI). NIRI is used to take on-sky pupil images, which measure the combined emissivity of M1 and M2, the M2 central hole, and the M2 support structure spider veins. The image is then compared to images of the instrument cover which is assumed to be a black body at ambient temperature[2]. After the recent recoating of M1 at Gemini North, the emissivity measured by NIRI was 5.34±0.14% at 3.78 μm, and 4.77±0.16% at 4.0 μm. These emissivity measurements also include the NIRI emissivity, which cannot be measured separately. Previous measurements from the Gemini South instrument T-ReCS measured their instrument emissivity at about 3%, mostly from the warm instrument window[2]. The emissivity contribution from NIRI is estimated at a maximum of 2%, since it is known to perform better than T-ReCS. Under this assumption then, the combined emissivity of M1, M2, the M2 spiders, and the periscope mirrors is 3.34±0.14% at 3.78 μm and 2.77±0.16% at 4.0 μm. This agrees well with the emissivity measurements of the tertiary mirror, which was measured at around 0.80% at 3.78 μm and 0.93% at 4.0 μm. Prior to recoating M2 at Gemini North, a handheld emissometer was borrowed form Surface Optics. This device showed an emissivity for M1 of 1.16% and 4.3% for M2. Emissivity measurements from the same time, just before the M2 recoating, showed a telescope emissivity of 7.09±0.15% at 3.8 μm and 6.54±0.17% at 4.0 μm. This would suggest that recoating M2 caused an ~2% decrease in emissivity at 3.8 μm and 4.0 μm.

The emissivity measurements and pupil images taken by NIRI are important for helping to determine the appropriate time for performing and in-situ wash or recoating a mirror. Emissivity measurements in the past have shown an increase of 0.95% at 3.8 µm and 0.84% at 4.0 µm in a little over 12 months at Gemini North. It is unknown how much of the increased emissivity is contributed from M1, M2, or the periscope mirrors. The previous increases in emissivity may be attributable primarily to M2 and its degradation. As seen in figures 9 and 10, the emissivity in the pupil image decreased more substantially after the M2 recoating than after the M1 recoating.

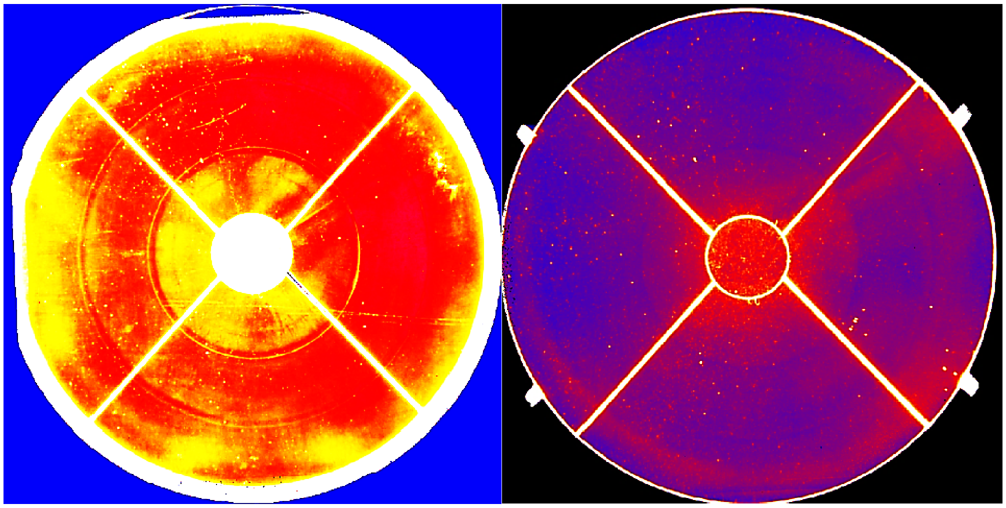

Figure 9: Emissivity at GN measured by NIRI before M1 recoating and periscope replacement (left) and after M1 recoating and periscope replacement (right)

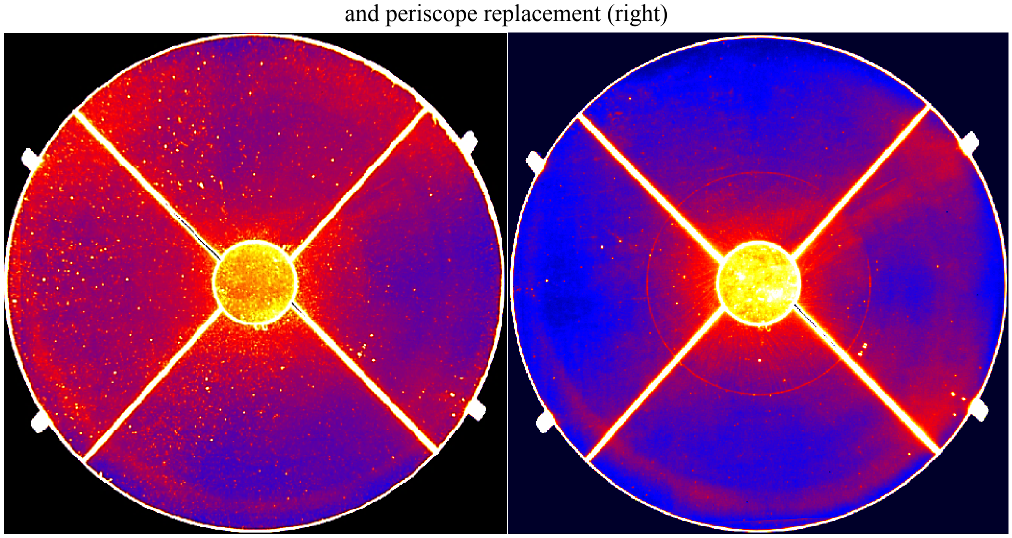

Figure 10: GN telescope emissivity as taken with NIRI before and after M2 recoating.

4. Coating Durability and Maintenance

4.1 Tarnish on the main mirrors

Surface contamination of dust or cleaning agents during the coating process allows for the formation of macroscopic pinholes, which are the main vectors for coating degradation[7]. Tarnish on any of the Gemini silver mirrors is almost exclusively limited to the Gemini North M2 at this time. Since coating the Gemini South M2 12 years ago, the surface has remained free of tarnish and lost reflectivity has been restored after both in-situ washes that it has undergone. The Gemini North and South primary mirrors have shown minimal tarnish as a result of minor contamination during the coating process. The tarnish on the primary mirrors manifests as small ~1 mm diameter areas at random locations on the surface. The Gemini North M2 showed tarnish around the inner and outer edges, which increased incrementally from one side of the mirror to the other.

One potential cause of the rapid degradation of the Gemini North M2 may be the SO2 and H2S emissions from the nearby Kilauea volcano. These emissions are mostly contained below the inversion layer, around 3,000 m; though sometimes appear to reach the summit at around 4,205 m. Recent tests that exposed witness samples to outside air at sea level in Hilo showed degradation after three months that was consistent with degradation seen after two years on the summit. Degradation on the samples was most prominent around large pinholes and along the edges which had not been cleaned thoroughly. Unfortunately, at this time there are no devices at the summit that are capable of measuring the concentrations of volcanic emissions.

4.2 Coating Maintenance

In order to maintain high reflectivity and low emissivity the primary mirrors undergo weekly CO_2 snow cleaning and the secondary mirrors undergo bimonthly CO_2 snow cleaning. The primary mirror is also inspected periodically for water spots. Any water spots on the primary mirror are immediately cleaned using deionized water and Kimwipes. This periodic cleaning of water spots has reduced the need for in-situ washes at Gemini North.

When the mirrors become sufficiently contaminated, washes are performed to remove contaminants. In-situ washes consist of a standard contact-wash with mops covered in chamois fabric and neutral soap. This is followed by a rinse with deionized water and drying with portable air knives[5]. The reflectivity gains after a wash are dependent on the cleanliness of the mirror prior to the wash. The in-situ wash of M1 has been shown to raise the reflectivity by as much as 6.2% at 470 nm, 5.4% at 530 nm, 5.8% at 650 nm, 4.8% at 880 nm, and 2.7% at 2200 nm[2]. Typically, the largest gains in reflectivity are produced at the shorter wavelengths. The resultant gains in reflectivity from the most recent Gemini South M2 wash are documented in table 4.

Wavelength	**470 nm**	**530 nm**	**650 nm**	**880 nm**
M2 (before washing)	89.46 %	91.60 %	93.11 %	94.21 %
M2 (after washing)	92.17 %	94.09 %	95.09 %	95.92 %
Difference	**2.71 %**	**2.49 %**	**1.98 %**	**1.70 %**

Table 4: Gemini South M2 reflectivity gains from in-situ wash in 2013

In-situ washes at Gemini South are scheduled at one year intervals due to the large amounts of dust in the desert and its ability to adhere to the mirror. Gemini North in-situ washes take place on intervals of one year or more, as the volcanic dust does not seem to adhere very well to the mirror surface.

5. Conclusion

Since 2004, the 4-layer protected silver coating that is used at the Gemini observatory has surpassed expectations in terms of performance and durability. Even the M2 at Gemini North, which has required more frequent recoatings, has outlasted the initial requirements. Future improvements will allow coatings which can meet the science requirements for upwards of 10 years before recoating is necessary.

Upgrades to the coating chamber, coating process, and stripping process are being explored in order to achieve better reflectivity, emissivity, and durability for all of the silver coated optics. There are plans to minimize water spots under the coating by making improvements to the air-knife that is used during the M1 drying process. Process gas lines are being upgraded from plastic to stainless steel to reduce the possibility of contamination during sputtering. Sputtering sensors will be attached to the magnetron below the sputtering target in order to measure deposition rate during the M1 coating. Testing is also underway to determine if the magnetron to substrate distance can be increased without negatively affecting coating quality. These incremental improvements to the coating process will help the Gemini Observatory achieve a more durable and higher quality reflective silver coating.

References

[1] Boccas, M., Vucina, T., Araya, C., Vera, E., Ah Hee, C., “Protected-Silver Coatings for the 8-m Gemini Telescope Mirrors,” Thin Solid Films, 502, 275-280 (2006).

[2] Vucina, T., Boccas, M., Araya, C., Ah Hee, C., “Gemini’s Protected Silver Coatings: first two years in operation,” Proc. SPIE 6273 (2006).

[3] Chu, C., Fuqua, P. D., Barrie, J. D., "Corrosion characterization of durable silver coatings by electrochemical impedance spectroscopy and accelerated environmental testing," Applied Optics, 45, 1583-1593 (2006).

[4] Kimura, W.D., Kim, G.H., Balick, B., “Comparison of Laser and CO_2 Snow for Cleaning Large Astronomical Mirrors,” Astronomical Society of the Pacific, 107, 888-895 (1995).

[5] Vucina, T., Boccas, M., Araya, C., Ah Hee, C., Cavedoni, C., “Gemini primary mirror in situ wash,” Proc. SPIE, 7012, (2008).

[6] Boccas, M., Vucina, T., Araya, C., Vera, E., Ah Hee, C., “Coating the 8-m Gemini telescope with protected silver,” Proc. SPIE, 5494, 239-253 (2004).

[7] Hass, G., Heany, J. B., Herzig, H., Osantowski, J. F., Triolo, J. J., “Reflectance and durability of Ag mirrors coated with thin layers of Al2O3 plus reactively deposited silicon oxide,” Applied Optics, 14, 2639-2644 (1975).