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Thin Solid Films 502 (2006) 275 – 280

thin solid films

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Protected-silver coatings for the 8-m Gemini telescope mirrors

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Available online 2 September 2005

Abstract

The twin 8-m diameter Gemini telescopes were designed to use silver-based coatings on the mirrors in order to provide very high reflectivity and ultra-low emissivity for optimal infrared performance. A feasibility study provided both techniques and recipes to apply these thin films, and showed that a reflectivity of 99.1% at 10 μm was achievable. We have now produced bare and protected silver sputtered films in our coating plants and conducted environmental testing, both accelerated and in real-life conditions, to assess the durability in an observatory environment. We have also already applied, for the first time ever, protected-silver coatings on the main optical elements of a large telescope. We report here the performance of the films, the challenges to coat a 50 m^2 primary mirror (M1) and our plans for coating maintenance.

Keywords: Sputtering; Silver; Mirror; High reflectance; Low emittance; Durability

1. Introduction

1.1. Coatings used for large astronomical telescopes

The aluminum evaporation technique has been the standard coating solution [1] for large astronomical mirrors since it was perfected by Strong in the 1930s. Only in the 1990s did large 8 m-class telescope projects like the Gemini Observatory and the European southern observatory's very large telescope decide to move to magnetron sputtering. Gemini is the first large ground-based observatory that was designed to use multi-layer protected silver films for the mirror coatings.

Silver is the metal having the highest reflectivity for wavelength beyond 400 nm, and some attempts [2] of producing, by physical vapor deposition, durable silver-based films for astronomy started in the 1980s. For near- and especially mid-infrared optimization, low emissivity is a key factor to increase telescope sensitivity since the emission from warm objects (mirrors, baffles, or whatever is in the path of the light beam) represents noise in the signal recorded from celestial objects. Besides obvious telescope design considerations (optical stop position, obstructions, etc.), low emissivity (ε) is obtained by the use of high reflectivity (R) coatings. At 10 μm, reflectivity [3] of freshly evaporated films is respectively 99.5% and 98.7% for Ag and Al, so if we assume that $\varepsilon = 1 - R$, we find that Ag has an emissivity 0.38 times that of Al. This is equivalent to say that the signal-to-noise ratio (S/N) of the telescope only, not accounting the sky and the scientific instrument attached to the telescope, is 2.6 times higher. Fig. 1 shows the gain for a 3-mirror telescope (three reflections) obtained as the ratio of the reflectivity of 4-layer protected-silver and bare aluminum (real data measured on our sputtered films). The net gain starts at a wavelength of 470 nm and continues to the IR.

In 1992, Gemini contracted an initial study [4] that reviewed tarnishing mechanisms and identified multi-layer recipes and sputtering as the most appropriate techniques to deposit durable silver films on large optics. In 1998, a progress report [5] summarized the results of the feasibility study and demonstration phase. More recently, progress has been reported on durable silver-based coatings [6] but no large astronomical mirror had yet been coated with

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doi:10.1016/j.tsf.2005.07.295

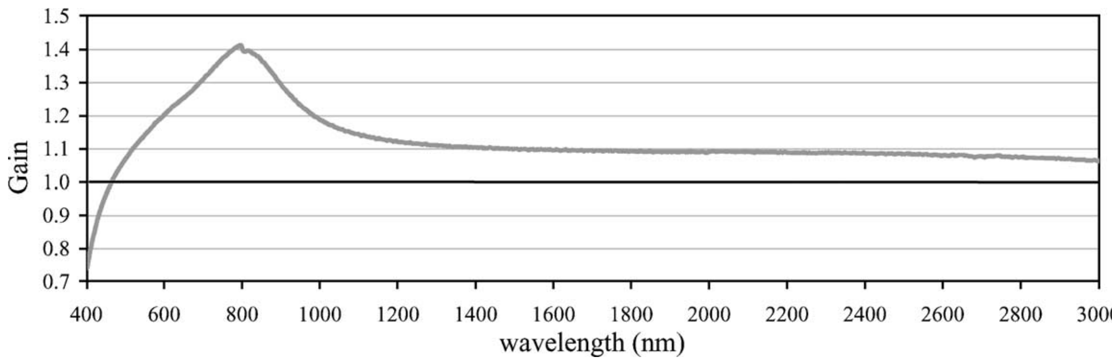

Fig. 1. Gain offered by our 4-layer protected Ag over Al for a 3-mirror telescope.

protected silver. In this paper, we report on the performance of the protected silver coatings applied on the 8 m-primary (M1), the 1 m-secondary (M2) and the 0.5 m-tertiary (M3) mirrors of our southern telescope in March and May 2004 for the first time.

1.2. Science requirements for coatings

The Gemini Observatory science requirement details the performance expected for coatings both in terms of reflectivity and emissivity. The requirement for visible reflectivity of freshly coated surfaces shall be: 88% over 0.3–0.7 μm, and 84% over 0.7–1.1 μm (requirement is based on an aluminum coating, which exhibits an absorption dip at 830 nm). The goal for reflectivity is: 92% over 0.3–0.7 μm, and 98% over 0.7–1.1 μm. This can only be achieved with silver-based films.

The fully optimized IR configuration will have a telescope emissivity, including scattering and diffraction, of 4% with a goal of 2% immediately after coating or recoating optics, with 0.5% maximum degradation anytime during operation, at any single wavelength beyond 2.2 μm. The later requirement is very stringent and will determine our strategies for coating maintenance. We are acquiring a handheld 2.2 μm reflectometer to monitor this requirement in situ. There is no official requirement for durability although it is clear that it must be as long as possible to minimize downtime for science and the risk associated with the handling of an 8-m diameter meniscus mirror.

1.3. Feasibility and demonstration study for low-emissivity and durable coatings

The final report of this study [7] from Optical Data Associates (ODA) was delivered in 1995. ODA selected two subcontractors for the demonstration phase: Airco Coating Technologies (ACT) produced silicon nitride (SiN_x) protected films whereas Deposition Sciences Inc. (DSI) made hafnium oxide (HfO_x) protected films using a microwave energy supported plasma. Both experiments consistently reached the same reflectivity $R_{10\ \mu m}=99.1\%$ in production but the SiN_x protection proved to be slightly superior for durability in tarnishing environment. Because the SiN_x film deposition was also made under classical sputtering, it is the path that Gemini selected for specifying the coating plant hardware.

A very important phase of the study was obtaining accurate reflectivity measurements in order to reach the goal of $R_{10\ \mu m}=99.2\%$. ODA and its subcontractors used similar and/or directly comparable spectrophotometers: for the UV–Vis–NIR range, absolute instruments like the Hitachi 4001 and Cary 5E; and relative devices like the PE 983G for the MIR range where the measurements were compared to NIST standards (Al and Au) analyzed with the Cary and with a 10.6 μm absolute reflectometer (using a CO_2 laser source) built by Helios Inc. The accuracy obtained at 10 μm was ±0.01%. Other consistent measurements were also performed at National Optical Astronomy Observatory (NOAO) with an emissometer working at $\lambda=4$ μm.

The last critical phase of the study was the environmental testing of the samples to assess their durability. Four different tests were performed: weathering (cycle through high temperature and humidity T/RH, salt fog), delamination (scotch tape pull), abrasion and tarnishing (exposure to hydrogen sulfide fog). However, no real-life exposure tests were conducted at an observatory. The final optimal coating recipe was a stack with the following four layers (substrate to air): 5 nm of $NiCrN_x$ (adhesor), 200 nm of Ag (reflector), 0.8 nm of $NiCrN_x$ (adhesor) and finally 15 nm of SiN_x overcoat. To avoid the absorption caused by the SiN_x layer at wavelength <500 nm, an alternative 'minimal' design, the three-layer design, omitted the top layer and proved to have promising durability (passed adhesion, T/RH and salt fog tests but was scratched under abrasion testing; no H_2S test done).

2. Description of hardware

2.1. Vacuum system

The vacuum vessel is a 150 m^3 stainless-steel chamber (Fig. 2), formed by two parabolic-like shells with an overall size approximately 9 m in diameter and 6 m high. Sputtering

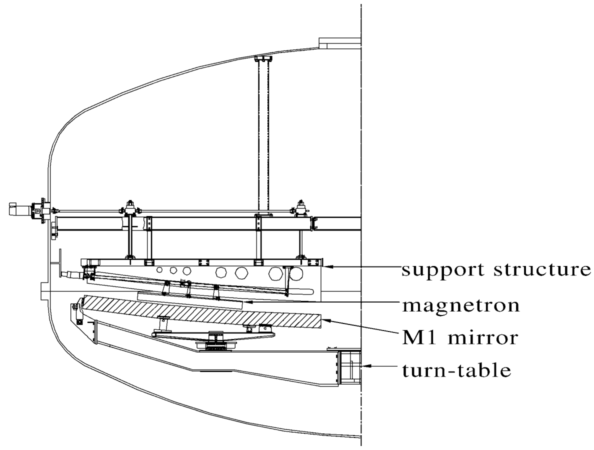

Fig. 2. Cross-section of the vacuum chamber.

magnetrons are mounted on several radial support structures attached to the upper vessel while the mirror resting on a whiffle tree rotates underneath facing up.

The high-vacuum pumping is accomplished by two Leybold RPK 30,000 cryopumps, each equipped with one single-stage cold head and two dual-stage cold heads. The cryopumps are located behind large 40″ VAT gate valves on a side wall of the upper vessel. The magnetron nearest to the cryopumps, and thus with an expected slightly better vacuum, is usually operated with the reflective material target to optimize film purity. Two additional single-stage cold heads are used as water traps. Rough pumping (to 5×10^{-3} Torr) is done typically in 80 min the vessel reaches low 10^{-6} Torr after another 6 h. The cold environment of the mountain top has caused several operational and maintenance difficulties for the vacuum equipment. Because of air leaks, our vacuum is typically dominated by nitrogen (1.3×10^{-6} Torr) and oxygen (3.2×10^{-7} Torr) in reduced pumping mode for sputtering.

2.2. Deposition system

We successively acquired planar DC magnetrons from various vendors (Gencoa Ltd., Teer Coatings Ltd. and Angstrom Sciences Inc.) and we have now at each site a family of three magnetrons. The first Al coating was made in 1999 at Gemini North (GN). The magnetrons have balanced magnetic fields and are of the direct-cooling type with an effective target length of 1.15 m and width varying between 0.15 and 0.25 m. The power requirement was originally set to operate aluminum targets at 40 kW in order to obtain the required thickness, typically 800 Å, in a reasonable amount of time (target to glass distance is typically 110 mm). The power module consists of a stack of three Advanced Energy 20 kW Pinnacle supplies in master/slave configuration. Because the radius of glass to cover on M1 is 3.5 m, the coating is done as three concentric rings by moving the magnetron radially after each revolution. A specific rotation speed is calculated for each ring in order to maintain uniform film thickness. In addition, a thickness uniformity mask, consisting of two stepper motor driven blades, acts as a variable pie-shaped aperture. The aperture is placed below the deposition target in order to compensate for the radial variation in linear speed of the magnetron above the substrate. The proper combinations of speed and mask aperture for each ring are calculated geometrically and confirmed experimentally. The thickness uniformity requirement is ±5% (that is ±1 nm for a substrate polished to a surface figure of 20 nm RMS). Our measurements with quartz crystal sensors (repeatability of 1 Å) located at various locations along the target length and radius to be coated indicate that we meet this requirement. An open/close pneumatic shutter is activated between the target and the mask in order to define precisely the coated areas on the substrate. At the joints between rings and where the shutter operates, we have localized thickness defects that we estimate to about 25% of total thickness over areas of 15 mm in width. Both shutter and mask are also internally cooled with water to prevent thermal deformation.

For deposition of the SiN_x dielectric layer (boron-doped silicon target), we acquired an Advanced Energy Starburst 20 kHz pulser which we use in continuous pulsing mode. We normally use pulsing mode for Ag and 'Active-Arc' mode for the NiCr target (80%/20%). Our 4-layer process requires about 7 h (5 h total magnetron run time). When applying our standard recipe of four layers (65 Å $NiCrN_x$/1100 Å Ag/6 Å $NiCrN_x$/85 Å SiN_x), the pressure varies between 1.3 and 3.5 m Torr, power varies from 1 to 7 kW and rotation speed varies from 1 to 7 rph for the outer ring.

3. Reflectivity and emissivity data

3.1. Measurement devices

We have been using a combination of the following instruments:

- Iris 908RS scattero-reflectometer: this is a handheld unit made by DMO. It measures the reflectivity at 470, 530, 650 and 880 nm, and the BRDF at three angles at 670 nm. The reflectometer has its own calibration gauge which is a stable absolute reference that allows precise determination of loss rate for example.
- Cary 500 spectrophotometer in VW absolute mode (0.3–3 μm), and PE983G spectrophotometer (2–56 μm). The PE983G sample compartment is not purged so the data show atmospheric absorption features (no attempt to smooth them out in our figures). ODA uses a NPL standard to calibrate the PE983G with the Cary 5E.
- Emissivity Measuring Unit (EMU) at 3.8 μm: an in-house built emissometer similar to NOAO's, allowing us to compare with the results of the demonstration phase.

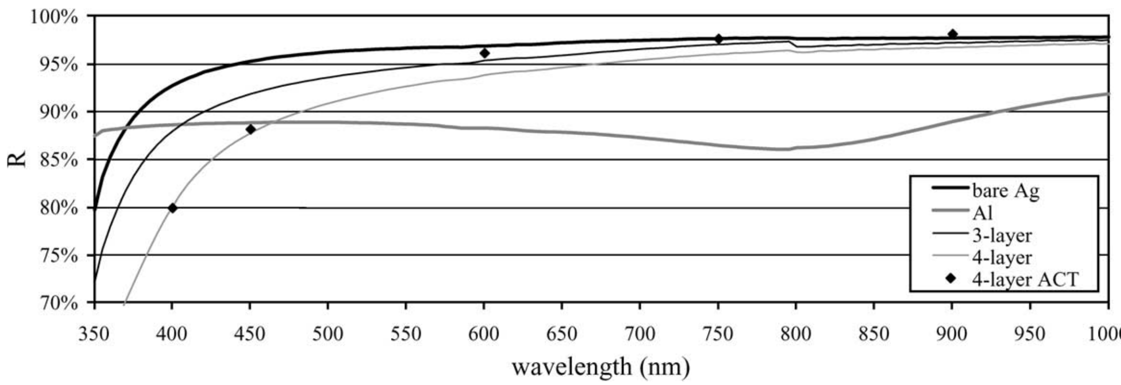

Fig. 3. Comparison of Al, bare Ag and protected Ag in the visible (data with Cary 5 at ODA).

3.2. Reflectivity results

Figs. 3–5 show data between 0.3 and 20 μm comparing samples coated with Al, bare Ag and protected Ag. The SiN_x layer is transparent over the IR wavelength range (1.5 to 20 μm) but causes increased absorption toward bluer wavelengths (3% at 500 nm and 8% at 400 nm). This absorption is constant for thickness from 50 to 100 Å but increases by another 5% for a thickness of 230 Å. For reference, we plotted data obtained by ACT. The overlap region (2–3 μm) between Cary and PE983G verifies the absolute calibration.

We found that the $R_{10\ \mu m}$ values obtained are inferior to the ones mentioned previously for fresh evaporation (−0.7% and −1.3% respectively for Ag and Al), and also to the ones obtained in the demonstration phase (−0.4% for protected Ag). This is likely due to film purity and microstructure, and we think that an optimal combination of parameters (throw distance, power, base vacuum, etc.) should lead to improved performance in the future.

Originally, the third layer ($NiCrN_x$) was designed as an adhesor between Ag and SiN_x. It clearly needs to be as thin as possible to limit the absorption in the visible: at 470 nm, thickness of 5, 10 and 15 Å cause, respectively, a reflectivity loss of 2.7%, 8.3% and 11.9% compared to bare Ag (97.8%). The thickness repeatability of this layer of ±1 Å makes difficult the precise control of blue reflectivity and we typically see $R_{470\ nm}$ vary between 90% and 93%. In the reflectivity optimization of the Ag layer, we have not seen any clear trend with base vacuum quality (monitored with a RGA) or throw distance but rather with power levels (variations of 0.8% in the visible over 2–10 kW). Pulsing the power did not produce any improvement in the reflectivity.

3.3. Emissivity results

We use reference mirrors coated at NOAO in 1992 and measured between 1992 and 1995 with their emissometer. At 3.8 μm, we have measured the emissivity of fresh films to be: 2.6% for Al (but varying up to a level of 7% after 6 months in operation in the telescope), 0.6% for Ag, 1.2% for the 4-layer protected Ag. We also measured an emissivity increase of up to 0.25%/month for the up-looking samples (no cleaning). Overall, with the current 4-layer Ag coatings on both primary and secondary mirrors, we achieved $\varepsilon_{telescope} = 2.6\%$.

Emissivity measurements are also taken directly through observation with NIR and MIR instruments on the telescope at night. With clean aluminum coatings on both M1 and M2,

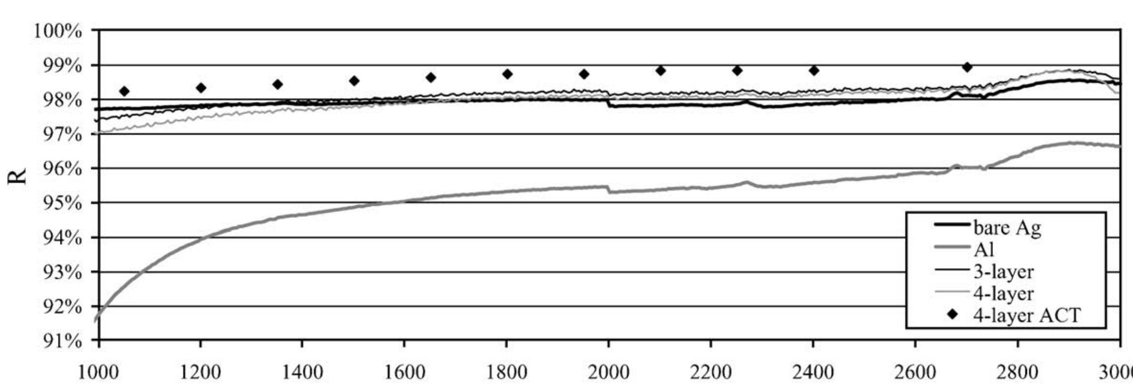

Fig. 4. Comparison of Al, bare Ag and protected Ag in the NIR (data with Cary 5 at ODA).

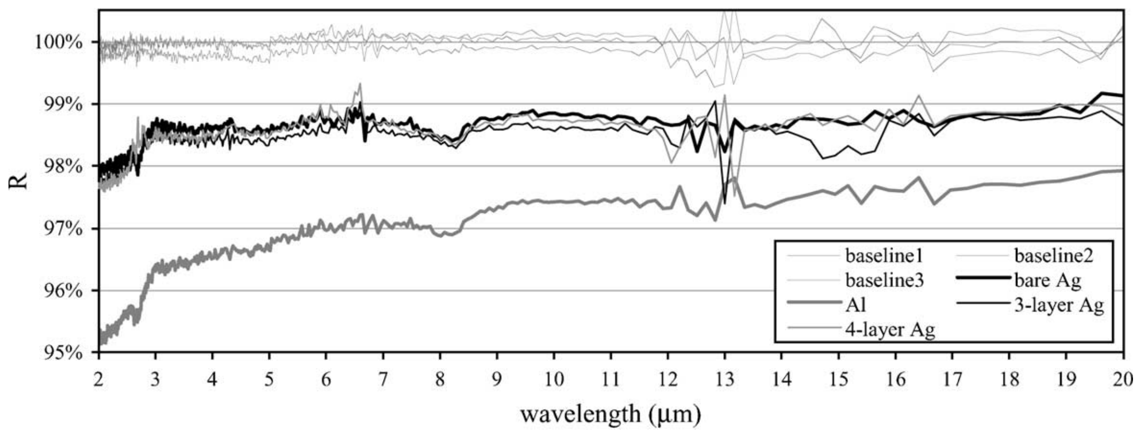

Fig. 5. Comparison of Al, bare Ag and protected Ag in the MIR (data with PE983 at ODA).

we have measured 3.5% telescope emissivity at 10 μm. After all mirrors are silver-coated, the limitation will be the instrument (about 1%–2% entrance window emissivity) and the sky (typically 1%–2% for a clear dry night).

4. Durability

4.1. Reflectivity loss and tarnishing

In parallel with the coating development, we have been conducting an intensive durability campaign with tens of samples exposed in different places around the telescopes at both sites. Most of the samples are 30×30 cm^2 float glasses, and coated in pairs: one is immediately exposed in the dome and the other is kept in a box (no special sealing) inside the building. Samples are located near M1, under a small roof that prevents particulates from falling straight down onto the sample, but allows air to flow across it. This partial exposure setup attempts to simulate the real exposure of M1: fully covered during the day and fully exposed during the night. We used an Al witness sample, exposed the same way as the family of Ag-based samples, to determine the reflectivity loss due to the dust only. Between 470 to 880 nm, this experiment indicates a uniform 10% reflectivity loss in 7 months (1.4%/month), which is significantly worse than the 0.35%/month that we see on the Gemini South M1. Therefore our exposure setup provides a harsher environment than that seen by telescope mirrors in routine use.

It is well known [8] that a tarnish film forms on freshly deposited silver when exposed to atmosphere in the presence of moisture, and that sulfides are by far the most damaging environmental constituent for Ag coatings. Our first important observation is that the Ag coating samples, protected or not, kept in a box, in an office, for up to 20 months, do not undergo any cosmetic deterioration (bare Ag samples show a minor and constant R loss of 1.1% between 470 and 880 nm and that seem to occur in the first 20 days, and the protected Ag ones exhibit no loss at all). With another bare Ag sample, kept in the same office but out of the box, and facing down to avoid dust accumulation, we evidenced photocorrosion [9] since the sample took a yellowish tint. We also observed that airborne particulates (dust) are clearly what transport the contaminants onto the thin-film since downward-looking samples and upward-looking samples washed regularly have corroded much slower than upward-looking samples with no cleaning.

By comparing aging rate of Ag samples with different layers of protection (SiN_x alone, $NiCrN_x$ alone and $NiCrN_x$ covered by SiN_x), we also conclude that reflectivity loss decreases with thicker $NiCrN_x$ layer (4.5%/year with 6 Å and 0.5%/year with 15 Å at 650 nm) and that SiN_x only is less efficient if the intermediate $NiCrN_x$ is not present. This confirms other studies [10] showing the importance of even a thin, non-continuous, monolayer of $NiCrN_x$ to enhance the protection of the top SiN_x layer. The 3-layer Ag coating was tested on the downward-looking M2 in the telescope but did not prove to be durable enough since some event, probably a contamination from the exhaust of our auxiliary generator, triggered a rapid degradation during which the R loss averaged 0.23%/day between 470 and 650 nm (and only 0.08%/day at 880 nm)! Reflectivity variation was usually assessed over the range 470–880 nm (with the Iris) and in some cases over 0.3–3 μm (with the Cary): it is fairly achromatic for the 4-layer coatings, whereas 3-layer and unprotected silver exhibit increasing loss toward bluer wavelength.

After 260 days of exposure in the dome, the 4-layer samples exhibit no reflectivity loss at all and cosmetics are still perfect. One of these samples that was openly exposed outdoor and suffered a variety of extreme natural weathering conditions (dust, rain, snow, etc.) did not show any cosmetics degradation but minor reflectivity loss due to dust embedded in the film. After exposure in our generator exhaust plume, we found that the 4-layer sample would lose 0.7% at 500 nm, whereas the 3-layer had lost 44% (and the loss clearly increases toward bluer wavelength). Finally, samples were tested in environmental chambers under accelerated-aging conditions: both 3- and 4-layer samples passed high RH/T cycling tests; between 0.3 and 3 μm, the 3-layer sample lost a constant 1.5% reflectivity in the salt fog exposure whereas the 4-layer was intact; H_2S fog destroyed the 3-layer coating after only 10 ppm-h exposure ($R_{0.5\ \mu m}$ down to 15%) but the 4-layer coating resisted until 500 ppm-h ($R_{0.5\ \mu m}$ still at 88.3%).

4.2. Coating preparation and maintenance

It is well known that particles on the substrate prior to coating form pinholes that are the main entries for water to diffuse the contaminants into the film. This problem becomes difficult to deal with for such large optics unless the area is a dedicated clean room. The amount of particles is quantified with a dust monitor and a simple analysis of pinholes in the film by looking in transmission with light shining through the backside of the glass. We recently implemented both a HEPA-filtered air system from the top port of our vessel, maintaining positive pressure inside, and a CO_2-snow 'shower' across the mirror as it enters the vessel. This has already reduced dramatically the amount and size of pinholes: we are left with an average of 5 pinholes about 10 μm-size and 5 pinholes <5 μm-size per inch^2 (whereas we used to have pinholes as large as 1 mm and up to 10 pinholes between 0.1 and 0.5 mm per inch^2).

In order to fulfill the demanding emissivity requirement in operation, we have implemented an in situ wash process of both M1 and M2 in the telescope. The technique is standard contact-wash with natural sponges and soap followed by de-ionized water rinsing and drying. We have retrofitted the telescope with all the hardware needed to make a quick and safe in situ process. We anticipate washing M1 approximately every 4 to 6 months, or in the case of a sudden major contamination.

5. Conclusion

For the first time, mirrors of a large astronomical telescope have been coated with protected silver. Because of the encouraging durability results from our 4-layer samples (the longest exposure is 10 months) and the fact that they are subjected to a more extreme environmental exposure than our 8-m primary mirror, we have strong indications that the Ag coating recipe should maintain its reflectivity and emissivity performance for more than a year with appropriate maintenance. Because of the size of this 8-m 'sample', only real-life experience will tell us exactly what the durability is like for a large telescope mirror.

Acknowledgements

Over the last three years of this coating development program, many people have supported our work. Internally, we want to thank the mechanics and electronics groups at both sites. Several external contractors have also contributed: M. Plaisted (Soleras); M. Jacobson (ODA); M. Bernick, R. Belan and J. Hrebik (Angstrom Sciences); G. Bobnar (VAT); D. Monaghan, N. Monaghan and V. Bellido-Gonzalez (Gencoa); D. Pelleymounter and various other staff (Advanced Energy).

The Gemini Observatory is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science Foundation (NSF) on behalf of the Gemini partnership: the NSF (United States), the Particle Physics and Astronomy Research Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil) and CONICET (Argentina).

References

[1] R. Wilson, Reflecting Telescope Optics II, Springer-Verlag, Berlin, 1999, p. 423, (chapter 6).
[2] D.Y. Song, R.W. Sprague, H.A. Macleod, M.R. Jacobson, Appl. Opt. 24 (8) (1985) 1164.
[3] J.M. Bennett, E.J. Ashley, Appl. Opt. 4 (2) (1965) 221.
[4] M.R. Jacobson, Investigation and Demonstration of the Feasibility of Low-Emissivity Durable Coatings: Literature Search, Gemini contract, Optical Data Associates, Tucson, 1992.
[5] M.R. Jacobson, R. Kneale, K. Raybould, F.C. Gillett, R. Laird, R.P. Shimshock, D.C. Booth, Development of Silver Coating Options for the Gemini 8-m Telescopes Project, Proceedings of SPIE, vol. 3352, 1998, p. 477.
[6] N. Thomas, J. Wolfe, UV-Shifted Durable Silver Coating for Astronomical Mirrors, Proceedings of SPIE, vol. 4003, 2000, p. 312.
[7] M.R. Jacobson, S.E. Jacobson, Investigation and Demonstration of the Feasibility of Low-Emissivity Durable Coatings: VI Quarterly Report and Final Report, Gemini contract, Optical Data Associates, Tucson, 1995.
[8] D.K. Burge, H.E. Bennett, E.J. Ashley, Appl. Opt. 12 (1) (1973) 42.
[9] T.E. Graedel, J. Electrochem. Soc. 139 (7) (1992) 1963.
[10] P.D. Fuqua, J.D. Barrie, Proceedings of Properties and Processing of Vapor-Deposited Coatings, Mater. Res. Soc. Proc., vol. 555, 1998, p. 85.