COATING GEMINI'S MIRRORS WITH PROTECTED SILVER

Maxime Boccas

On May 31, 2004 the Gemini South telescope became the first large telescope system to be fully coated with high-reflectivity and low-emissivity protected silver films. This is an important milestone because the mirror-coating technology for astronomy had not evolved since the 1930s, when John Strong (California Institute of Technology) perfected the aluminum evaporation technique and applied it to telescope mirrors.

Although the glass industry commonly uses protected silver coatings for low-emissivity windows in order to control heat transfer (which helps with air-conditioning costs), it does not have experience with durability of large front-surface films. Their coatings are typically encapsulated between two sealed windows, with substrates on surfaces smaller than 24 square meters (6 × 4-meter flat-pane glass in roller coaters). Therefore coating the 50-square-meter Gemini primary with silver is truly a landmark for the entire industry. The Gemini Observatory has been working toward this technological development since the inception of the project. In this report, we will review the completion of this engineering development that has been recently presented to the community (SPIE in June 2004 and the 5th ICCG* in July 2004).

Coatings Used for Large Astronomical Telescopes

The aluminum evaporation technique for astronomical mirrors has been the standard coating solution for more than 70 years. Only in the 1990s did large 8–meter class telescope projects like the Gemini Observatory and the European Southern Observatory's Very Large Telescope move to the magnetron sputtering process.

Why Silver – A Scientific Perspective

By Tom Geballe

The Gemini telescopes were designed to optimize performance at infrared wavelengths. One goal is to minimize infrared radiation from the telescope itself, which can cause the telescope to glow and make it more difficult to detect faint and distant objects in the cosmos. For example, the supports required to hold Gemini's secondary mirror are very thin as viewed from below, so that they block very little of the incoming radiation from a targeted astronomical object. More importantly, the amount of infrared radiation they emit into the telescope is minimized.

The telescope mirrors themselves are another source of background radiation. Although they look virtually spotless, dust particles, water droplets and other contaminants cause them to radiate more than pristine mirrors would. Thus the Gemini optics are cleaned frequently, and strict usage rules help protect the telescope from windblown dust, precipitation, and high humidity. In addition, the mirror coatings are a source of radiation, even when they are clean. Aluminum has long been the coating of choice because its reflectance is high (about 97% in the optical). It is relatively easy to apply, fairly resilient, and its infrared emissivity (how much heat it actually emits compared to the total amount a surface can theoretically emit) is only 3%. When coated with aluminum, Gemini's primary and secondary mirrors have a combined emissivity of about 6%. This seems like a low value, but at many infrared wavelengths where the atmosphere is highly transparent, the mirrors are the dominant source of extraneous and unwanted radiation.

Silver has an infrared reflectance of ~ 99% and an emissivity of only about one percent per mirror and in principle is a much better choice for an infrared-optimized telescope like Gemini. However, silver is much more difficult to apply and unless overcoated with a protective layer, is much more susceptible to damage from the environment. After lengthy and detailed tests, Gemini's engineers developed the techniques (described in the accompanying technical article) to coat the huge primary mirror and secondary mirror of each telescope with both silver and protective layers to assure a reasonable lifetime between re-coatings.

The scientific impact of this effort has already been felt. The effective increase in sensitivity at some near/mid-infrared wavelengths is equivalent to increasing our mirror's surface area by 13% when compared to an identical aluminum-coated mirror. This gives Gemini a significant advantage when exploring everything from the faint infrared glow of brown dwarf stars orbiting bright companions to distant galaxies exhibiting key spectral features that have been shifted into the infrared.

Silver coatings have the highest reflectivity for wavelengths beyond 400 nanometers (nm), and some attempts at producing, durable, silver-based films for astronomy (using physical vapor deposition) were made in the 1980s. Since the emission from warm objects (mirrors, baffles, or whatever is in the light beam path) produces noise in the signals from celestial targets, low emissivity is a key factor that increases telescope sensitivity for near-infrared observations and optimizes them especially for mid-infrared (see box above). 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 microns (µm), the reflectivity of freshly evaporated films is respectively 99.5% and 98.7% for silver (Ag) and aluminum (Al). If we assume that $\varepsilon = 1-R$, we find that Ag has an emissivity only 0.38 times that of Al. This is equivalent to saying that the signal-to-noise ratio (S/N) of the telescope only, not counting the sky

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** ICCG: International Conference on Coatings on Glass (held every two years in Germany)*

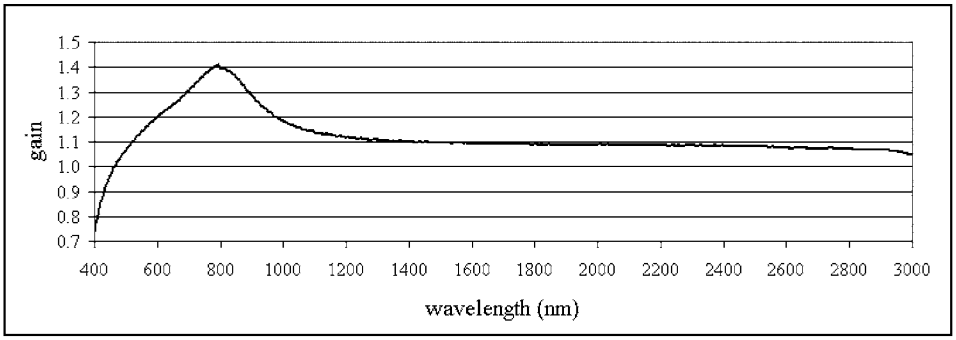

Figure 1: *Reflectivity gain offered by our four-layer protected Ag over Al for a 3-mirror telescope*

and the scientific instrument attached to the telescope, is 1.6 times higher, since sensitivity is proportional to $1/\sqrt{\varepsilon}$. Figure 1 shows the gain for a three-mirror telescope (three reflections) obtained by using four-layer protected-silver coatings compared to bare aluminum (real data measured on our sputtered films). The net gain starts at a wavelength of 470 nm and continues to the infrared. Compared to aluminum, there is a noticeable gain around 800 nm, where, for example, it could benefit wavefront sensing in an adaptive optics system.

Gemini contracted an initial study in 1992 that reviewed tarnishing mechanisms and identified multi-layer recipes and sputtering as the most appropriate techniques to deposit durable silver films on large optics. A 1998 progress report summarized the results of the feasibility study and demonstration phase. More recently, progress has been reported on durable silver-based coatings but no large astronomical mirror had yet been coated with protected silver. Gemini can now report on the performance of the protected silver coatings applied on the 8-meter primary (M1), the 1-meter secondary (M2) and the 0.5-meter tertiary (M3 also called science fold) mirrors of our southern telescope between April and June 2004.

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 should be: 88% over 0.3 – 0.7 µm, and 84% over 0.7 – 1.1 µm (based on an aluminum coating, which exhibits an absorption dip at 830 nm). Reflectivity goals are: 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 infrared configuration will have maximum telescope emissivity (with scattering and diffraction) of 4%, with a goal of 2% immediately after coating or recoating optics, and with 0.5% maximum degradation during operations at any single wavelength beyond 2.2 µm. The later requirement is very stringent and will determine our strategies for coating maintenance. We acquired a handheld 2.2-µm reflectometer to monitor this requirement in situ.

Feasibility and Demonstration Study for Low-emissivity and Durable Coatings

The final report of this study 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. made hafnium oxide (HfO_x) protected films using a microwave energy-supported plasma. Both experiments consistently reached the same reflectivity of $R_{10\mu m} = 99.1\%$ in production but the SiN_x protection proved to be slightly superior for durability in a 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.

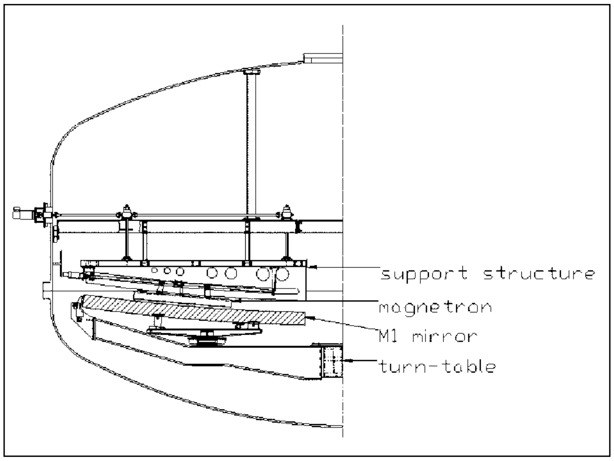

Figure 2: *Cross-section of the vacuum chamber.*

Obtaining accurate reflectivity measurements to reach the goal of $R_{10\mu m} = 99.2\%$ was a very important phase of the study. ODA and its subcontractors used similar and/or directly comparable spectrophotometers for the ultraviolet (UV)-visual-near-infrared (NIR) range, absolute instruments like the Hitachi 4001 and Cary 5E, and relative devices like the PE 983G for the mid-infrared (MIR) range. The measurements were compared to National Institutes of Standards and Technology (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 environmental testing of the samples to assess their durability was the last critical phase of the study. Four different tests were performed: weathering (cycling through high temperature and humidity, 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. 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 was done).

In conclusion, the feasibility study contracted to external coatings experts had demonstrated that a relatively simple recipe, which protects silver from tarnishing, could be applied successfully on giant mirrors in an observatory facility and have acceptable durability for a semi-outdoor environment (open dome at night). It brought the dreams of most infrared astronomers one step closer to reality.

Some Technological Aspects

The vacuum vessel for the process is a 150 meter^3 stainless steel chamber (Figure 2), formed by two parabolic-like shells with an overall size approximately nine meters in diameter and six meters high. Sputtering magnetrons are mounted on several radial support structures attached to the upper vessel while the mirror rests (face-up) on a whiffle tree which rotates underneath.

High-vacuum pumping is accomplished by two large cryopumps. Rough pumping (to 5×10^{-3} Torr) is done typically in 80 minutes and the vessel reaches low pressure (10^{-6} Torr) after another six hours.

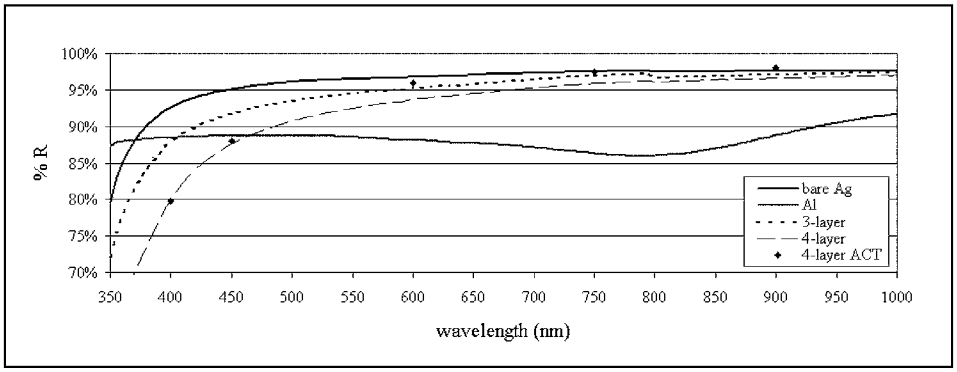

Fig. 3. Comparison of Al, bare Ag and protected Ag in the visible

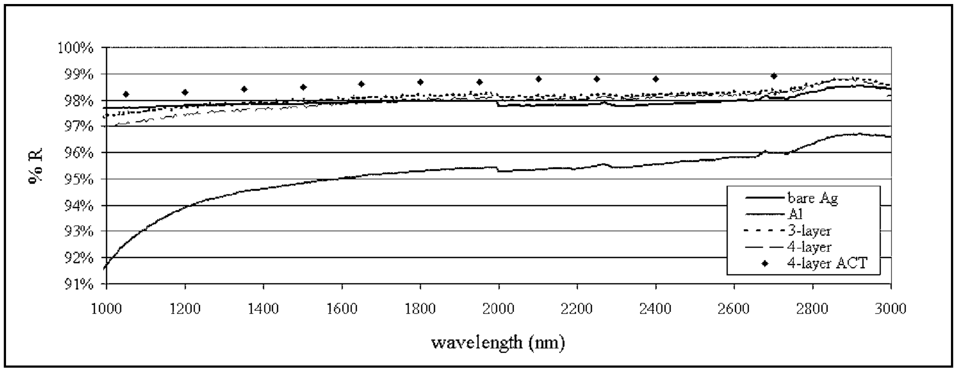

Fig. 4. Comparison of Al, bare Ag and protected Ag in the NIR

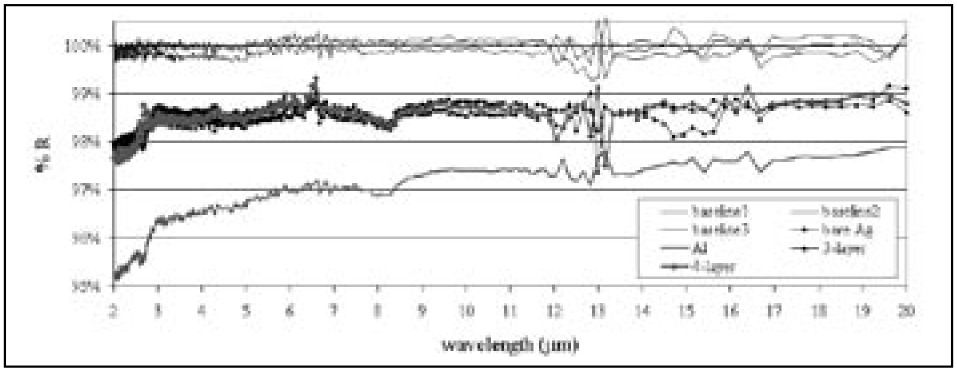

Fig. 5. Comparison of Al, bare Ag and protected Ag in the MIR

We acquired planar DC magnetrons from various vendors (Gencoa Ltd., Teer Coatings Ltd. and Angstrom Sciences Inc.) They are used to deposit the thin film by ionizing a gas and producing a plasma in the vessel. The result is an intense bombardment of ions (argon or nitrogen) onto a very pure plate called the target. It is sustained and intensified by a field created by magnets behind the target (hence the name "magnetron"), which knocks off atoms from the target and, by transfer of kinematic energy in the collision, eject them into the chamber. They hit and adhere to the mirror substrate located at close proximity (target-glass distance is typically 110 millimeters). We now have a family of three magnetrons at each site capable of depositing the materials used in our multi-layer recipe.

The power requirement was originally set to operate aluminum targets at 40 kilowatts in order to obtain the required thickness (typically 800 Ångstroms (Å)), in a reasonable amount of time. The power is such that the target surface would heat up to several hundred of degrees if it was not cooled directly on its back face.

The effective target length is 1.15 meters and width varies between 0.15 and 0.25 meter. Because the radius of glass to be covered on M1 is 3.5 meters (due to the central hole), the coating is done in 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. It 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 1Å) 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 to define the precise areas to be coated on the substrate. At the joints between rings and where the shutter operates, we have localized thickness defects that we estimate to be about 25% of total thickness over areas 15 millimeters wide. Both shutter and mask are also internally cooled with water to prevent thermal deformation.

Our four-layer process requires about seven hours (five hours total magnetron run time) to apply our standard recipe (65Å $NiCrN_x$ / 1100Å Ag / 6Å $NiCrN_x$ / 85Å SiN_x).

Reflectivity and Emissivity Results

Figures 3, 4 and 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 infrared wavelength range (1.5 – 20 µm) but causes increased absorption toward bluer wavelengths (3% at 500 nm and 8% at 400 nm). This absorption is constant for thicknesses between 50 Å – 100Å but increases by another 5% for a thickness of 230Å. We also plotted data obtained by ACT (the main contractor in 1995). The overlap region (2 – 3 µm) between the two main measuring instruments (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 micro-structure, and we think that an optimal combination of parameters (throw distance, power, base vacuum, etc.) should lead to improved performance.

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, thicknesses of 5 Å, 10 Å and 15 Å cause respective reflectivity losses of 2.7%, 8.3% and 11.9% compared to bare Ag (97.8%). The thickness repeatability of this layer of +/-1 Å makes the precise control of blue reflectivity difficult, and we typically see $R_{470\mu m}$ vary between 90 and 93%.

For emissivity measurements, we used reference mirrors coated at NOAO in 1992 and measured between 1992 and 1995 with their emissometer. At 3.8 µm, the measured emissivity of fresh films is: 2.6% for Al (but up to 7% after six months in operation in the telescope), 0.6% for Ag, 1.2 % for the four-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 four-layer Ag coatings on both primary and secondary mirrors, we achieved $\varepsilon_{telescope}$= 2.6% at 3.8 µm.

Emissivity measurements are also taken directly through observation with near-infrared and mid-infrared instruments on the telescope at night. With clean aluminum coatings on both M1 and M2, we had measured 3.5% telescope emissivity at 9 µm. With all mirrors silver-coated, T-ReCS measured a new record of 1.7% in June 2004. We have thus lowered the telescope contribution to a level comparable or below the other two limiting factors: the instrument (about 1-2% entrance window emissivity) and the sky (typically 1-2% for a clear very dry night). The 30% gain in overall emissivity compared to aluminum should translate into a 13% sensitivity increase, a value that might not revolutionize infrared astronomy, but that is a boost in efficiency for science. This is significant when the systems are down to a level where every couple percentage points of improvement is a real engineering challenge.

Durability: 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 centimeters and are 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 dust only. This experiment indicates a 10% visible reflectivity loss in seven 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.

Typically a tarnish film forms on freshly deposited silver when exposed to our atmosphere in the presence of moisture, and 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, but kept in a box in an office for up to 20 months), do not undergo any cosmetic deterioration. Bare Ag samples under the same conditions show a minor visible R loss of 1.1% and the protected Ag samples 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 observed photocorrosion (since the sample took a yellowish tint). We also noted that airborne particulates (dust) are clearly what transport the contaminants onto the thin film since downward-looking samples and upward-looking samples washed regularly corroded much more slowly than upward-looking samples with no cleaning.

By comparing the aging rates 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 a thicker $NiCrN_x$ layer (4%/year with 6 Å and 0.5%/year with 15 Å) and that SiN_x only is less efficient if the intermediate $NiCrN_x$ is not present. This confirms other studies showing the importance of a thin, non-continuous monolayer of $NiCrN_x$ to enhance the protection of the top SiN_x layer.

The three-layer Ag coating was applied on the downward-looking M2 in the Gemini South telescope in October 2003, but did not prove to be durable enough. Some event, probably contamination from the exhaust of our auxiliary generator, in addition to exposure of dome lights, triggered a rapid degradation, with an average R loss of 0.23%/day! M2 was recoated in April 2004 with the definitive four-layer recipe during a record engineering exercise that caused only one night of down time in science operation.

After 14 months of exposure in the dome, the four-layer samples exhibit no reflectivity loss (after a wash to remove dust) and cosmetics are still perfect. One of these samples that was openly exposed outdoors and suffered a variety of extreme natural weathering conditions (dust, rain, snow, birds landing on it, etc.) did not show any cosmetic or chemical degradation, but had minor reflectivity loss due to dust embedded in the film. After exposure in our generator exhaust plume, which is the worst possible environment for a coating we found that the four-layer sample lost 0.7% in the visible whereas the three-layer test had lost 44%. Finally, samples were tested in environmental chambers under accelerated-aging conditions: both three- and four-layer samples passed high RH/T cycling tests; the three-layer sample lost 1.5% in the salt fog exposure whereas the four-layer was intact; H_2S fog destroyed the three-layer coating after only 10 ppm/hour exposure ($R_{0.5\mu m}$ down to 15%) but the four-layer coating resisted until 500 ppm/hour ($R_{0.5\mu m}$ still at 88.3%).

Coating Preparation and Maintenance

It is well known that particles on the substrate prior to coating form pinholes that are the main conduits for water to diffuse contaminants into the film. This problem becomes difficult to deal with for such giant optics unless the coating area has a dedicated clean room. The amount of particles is quantified with a dust monitor and a simple analysis of pinholes in the film seen by looking at it with light under 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 dramatically reduced the amount and size of pinholes and at Gemini South we were left with an average of five pinholes of about 10 µm/inch^2 and five pinholes < 5 µm/inch^2. In the past we have seen pinholes as large as 1 mm and up to 10 pinholes between 0.1 and 0.5 mm/inch^2. This improved HEPA-filtered system is now being installed at the Gemini North coating plant with an even higher degree of perfection.

In order to fulfill the demanding emissivity requirements for mirror operation, we have implemented an in-situ wash process of both M1 and M2 in the telescope (see image on inside front cover). The technique is standard contact-wash with natural sponges and soap, followed by a de-ionized water rinse and drying. We have retrofitted the telescope with all the hardware needed to assure a quick and safe washing process, that can be accomplished within a single day without interrupting science operations. We anticipate washing M1 approximately every four to six months, or when necessary in case of a sudden major contamination, and still maintain our emissivity within 0.5% of the fresh coating performance.

Most large telescopes with aluminum coatings are recoated every one to two years (or more) when the reflectivity drops by 10% or more depending on the environment. Although we don't yet know the final lifetime of our protected silver coatings in operation, we anticipate recoating every two years but will work to maintain ultra-low emissivity <u>all</u> the time. This is an improvement almost as important as being able to coat with silver (or any other material), and will clearly keep Gemini optimized for infrared observations in the long term, rather than briefly after each new coating. This maintenance concept is clearly an issue for future giant segmented telescopes, where recoating will be a time-consuming task, and should drive engineering requirements in the design.

Summary

This is the first time mirrors of a large astronomical telescope have been coated with protected silver. Because of the encouraging durability results from our four-layer samples, and the fact that they are subjected to a more extreme environmental exposure than our 8-meter primary mirror, we have strong indications that the Ag coating recipe should maintain its reflectivity and emissivity performance for up to two years with appropriate maintenance. Due to the size of this 8-meter "sample," only real-life experience will tell us exactly what the durability will be like for a large telescope mirror.

Since the Gemini North mirror was first coated with aluminum in 1999, the Gemini engineering team, as an interdisciplinary group with expertise in mechanics, electronics, and software, is now concluding a several-year-long coating development program in November 2004. As this newsletter went to press, we were within a week of fully coating the Gemini North primary mirror with protected silver in the same manner as its southern twin.

Other observatories have already expressed interest in having their mirrors coated in our facility, and the glass industry is watching the results of this unique durability experiment of a high-reflectivity front surface-silvered mirror. Several companies have supported our work, in particular Soleras, ODA, Angstrom Sciences, Gencoa and Advanced Energy and deserve our acknowledgments.