Silver Coating on Large Telescope Mirrors Tutorial

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Introduction

Applying a reflective coating to large astronomical telescopes is a costly procedure and time consuming. There are a variety of systems that need to perform to specification so that the reflective coating can be applied evenly, without defects, and with good cohesion. The vacuum chamber and sputtering devices need to work properly, and mirror surface needs to be free from contaminants.

In general, the primary mirrors of large telescopes are coated with a thin film of aluminum. The Gemini Observatory was designed specifically to perform with a mirror that is coated in silver. From a research perspective there are many advantages to the use of silver on the primary, secondary, and tertiary mirrors. There are also many difficulties associated with a silver coating that are not present in aluminum coatings.

This tutorial presents a basic overview of coating procedures, from stripping the mirror of an old coating to sputtering of a new coating. The tutorial also presents provides a brief description of quality control tests that are performed on the finished mirror. Finally, data that has been gathered concerning the durability of the coatings is presented.

Mirror Coating Systems

The vacuum vessels at both Gemini North and Gemini South are 150 m^3 stainless steel chambers that are formed by two parabolic-like shells. These shells are approximately 9 meters in diameter and 6 meters high. The vacuum chamber can attain a vacuum of around 10^{-6} Torr, with remained gases composed primarily of Nitrogen and Oxygen. Sputtering magnetrons are mounted on radial support structures that are attached to the upper vessel, with the mirror resting on a whiffle tree that rotates underneath.

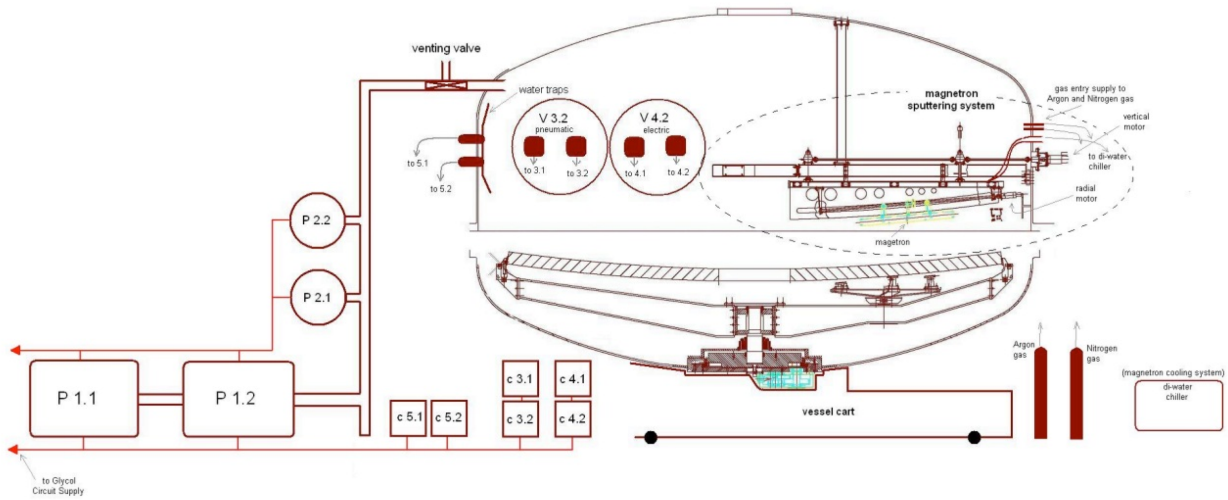

Figure 1: Vacuum chamber, sputtering magnetrons, and vacuum systems

The magnetron system consists of the cooled cathode (target) which is sputtered, and a counter electrode as an anode. When a voltage is applied, an acceleration field is formed between the cathode and the anode. The back of the target is comprised of a system of permanent Neodymium magnets that lengthen the effective ionization by deflecting electrons. The lines of the magnetic field in the active area form an arc which is shaped to exit through the target and re-enter on the other side of the pole. The field forms a closed tunnel loop in which electrons are held back. This electron trap creates a high specific ionization, and thus a high plasma density. The ions in the plasma are accelerated towards the cathode surface, where their impulse is transferred to the target surface, and the target particles are knocked out of the target lattice bond. The target materials used for the Gemini coating are 99.999% pure Silver, Nickel Chromium, and Silicon Nitrate, which are bonded to a copper backing plate with indium.

The sputtering magnetrons that are used at Gemini are 1.6m long and 0.3m wide. The magnetrons each have a mask that is used to change the size of the sputtered area. In addition there is an aperture with a wedge shape to ensure a uniform coating. Since the mirror is rotated radially, there needs to be compensation between the inner and outer velocities of the sputtered area.

The rotation device that is used to rotate the primary mirror during the sputtering process is a wiffle tree assembly with a motor drive. The wiffle tree acts a structural support for the primary mirror when it is lowered into the vessel. Since the Gemini primary mirror is made from ULE-581, with a thickness of 20 cm and a weight of 22,200 kg, it cannot support itself. The wiffle tree assures that the mirror is fully supported.

Figure 2: Primary mirror wiffle tree supports

Mirror Stripping Processes and Procedures

The mirror stripping process begins after the mirror is lowered from the observation floor onto the wash cart that is located on the ground floor. First, the top of the mirror undergoes a wash with neutral soap and water. A series of acid solutions are then applied to the coating to strip away the various coating layers. The required chemicals for this procedure are potassium hydroxide, hydrochloric acid, cupric sulfate pentahydrate, nitric acid, and ceric ammonium nitrate. It is necessary to use several acid solutions because of the strong bond that Nickel Chromium exhibits. Due to the danger of handling these acids, it is important that people involved in the process are dressed in full chemical hazmat suits, with appropriate gloves and breathing apparatuses. After the acids have finished dissolving away the old coating and contaminants, the mirror needs to be washed again and rinsed thoroughly with deionized water. The mirror is then checked for any residual coating, and if any is found an additional acid wash is performed. Once the pH of the deionized water reaches 7, the mirror can be assumed to be clean. It is very important at this stage in the mirror stripping process that the mirror is kept wet. If water is allowed to dry on the surface of the mirror, it causes visible water spots. Once the rinsing procedure is complete, air knives are used to herd the remaining water droplets off of the mirror surface before they can evaporate. After the mirror has been completely stripped and dried, it is checked for any water spots or residual coating. Any residual coating that is not stripped off will interfere with the coating adhesion, and will decrease the performance of the mirror.

During the coating procedure, particles and contaminants on the glass surface will result in a decrease in coating performance and the presence of pinholes that act as an entry point for contaminants. To minimize particle contaminants a HEPA filtered air system maintains a positive air pressure inside the vessel. Additionally CO_2 snow is showered across the mirror as it enters the vacuum chamber.

It is very important to have at least twice as much acid on hand as is actually necessary, in case there is a problem with the mirror coating and it needs to be stripped again.

Mirror Coating Process

The mirror coating process begins after the mirror has been moved into the vacuum chamber, and a pressure of 10^{-6} Torr is reached. At the Gemini Observatory, a 4-layer silver coating is used for several reasons. Unlike aluminum, silver has difficulty adhering to glass. In order keep the silver from flaking off, a thin layer of Nickel Chromium is sputtered onto the glass surface, and acts as a bonding agent. The other issue that is encountered is the degradation of the silver surface due to tarnish. Tarnish on silver is caused by hydrogen sulfide gas, and will cause a rapid deterioration of mirror performance, especially in the 400-500nm wavelength range. To protect the silver from tarnish, a thin layer of silica is sputtered onto the silver surface, with nickel chromium acting as a bonding agent once again. Additionally, the NiCr layer between the silver and silicon adds an impedance response to the coatings, making it strongly capacitive, and further slowing degradation compared to a simply SiNx topcoat.

The sputtering of the mirror requires the use of excitation gases. These gases are pumped into the chamber, and essentially knock off the atoms on the magnetron target. For silver, pure argon is used, while for nickel chromium and silica, pure nitrogen is used.

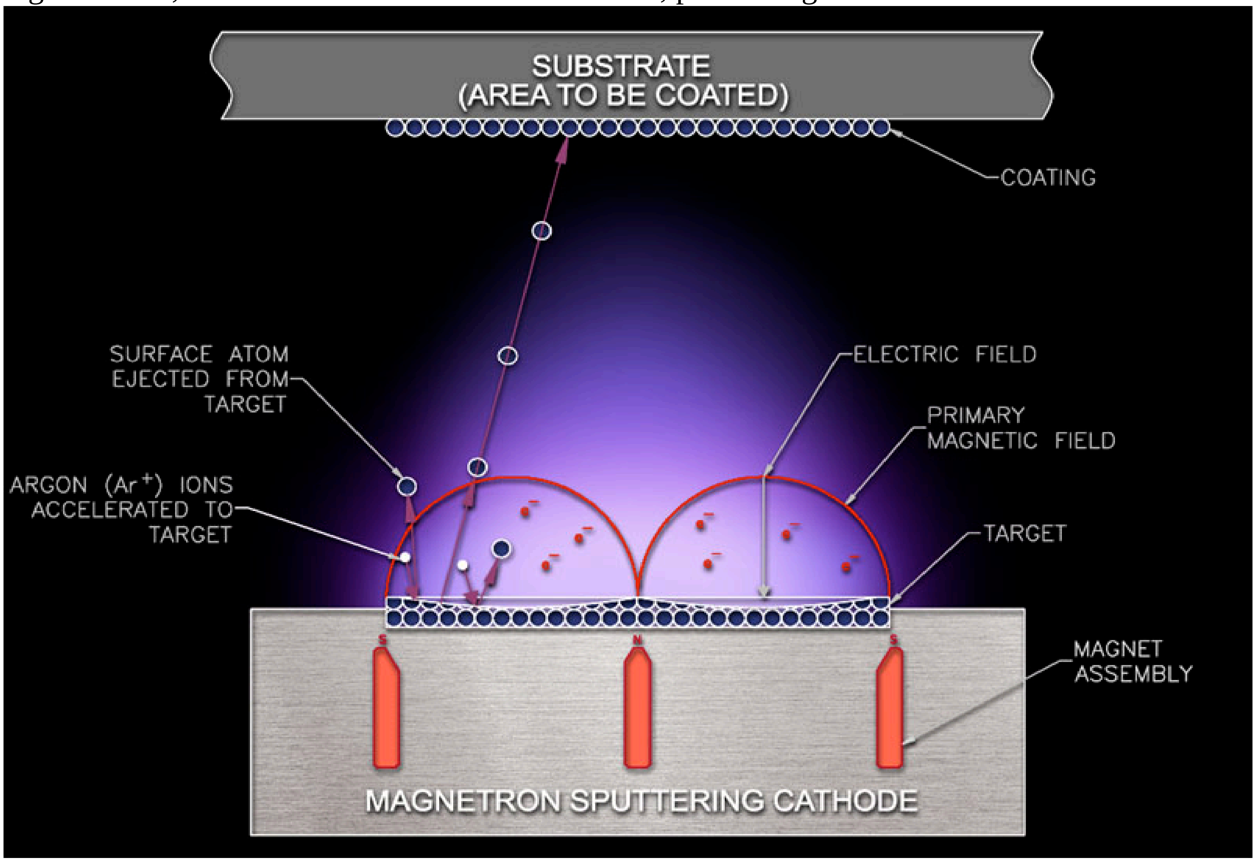

Figure 3: How sputtering works

The sputtering process itself takes approximately 8 hours. Since the magnetron lengths are about 1/3 the radius of the primary mirror, 3 successive rings of material need to be sputtered onto the mirror. A specific rotation speed is calculated for each ring so that uniform thickness can be maintained and the thickness of each layer is controlled through the mirror's rotational speed. Through trial and error at Gemini, the final 4-layer recipe was determined as 65 Å NiCrNx, 1100 Å Ag, 6 Å NiCrNx, and 85 Å of SiNx. A coating thickness uniformity of ±5% is required, and is measured with quartz crystal sensors that have a repeatability of 1 Å. Due to the magnetron size, there is a variation in localized thickness of about 25% over an area of 15 mm at the ring joints.

Quality Control

After the mirror coating process has finished, the mirror must be inspected. The first quality of the mirror that is judged is its reflectivity. A handheld reflectometer is used to measure the reflectance of the mirror at 470nm, 530nm, 650 nm, 880nm, and 2200nm. The goal for coating reflectivity is 92% over 0.3-0.7µm, and 98% over 0.7-2.2µm. Next, a pinhole test is performed on the mirror. This is done by shining a flashlight through the bottom of the mirror and counting the number of pinholes that are observed. Generally, an average of 5 pinholes with 10µm size and 5 pinholes under 5µm per square inch is considered acceptable. This test is not done across the entire mirror, just a select spots. The final test that is performed on the mirror is the coating adhesion test. This should not be performed on the mirror itself, but instead on a glass blank that is coated along with the mirror. For this test a square of Crystal Clear Scotch tape is placed on the mirror (sticky side down) and pressed down upon gently to even out the contact area. The tape is then removed in one quick fluid motion. The amount of coating that comes off with the tape is an indication of coating success. If the coating comes off from areas adjacent to where the tape is placed, then the coating process needs to be redone.

Coating Performance

In many areas a silver coating will outperform a tradition aluminum coating, especially in the infrared. At Gemini, the protected silver coatings have proven to perform well for long durations. The protected silver coating also allows for the mirror to be washed in-situ once to twice a year, returning the reflectivity to almost new.

There are losses in reflectivity with the 4-layer protected silver coating that is used, but the coating still performs better the Aluminum at wavelength larger than 400nm. The SiNx layer is transparent in IR wavelengths (1.5-20µm) but causes increased absorption towards bluer wavelengths (3% at 500nm and 8% at 400nm). An additional absorption is caused by the NiCr layer, with 2.7% absorption at 5Å thickness.

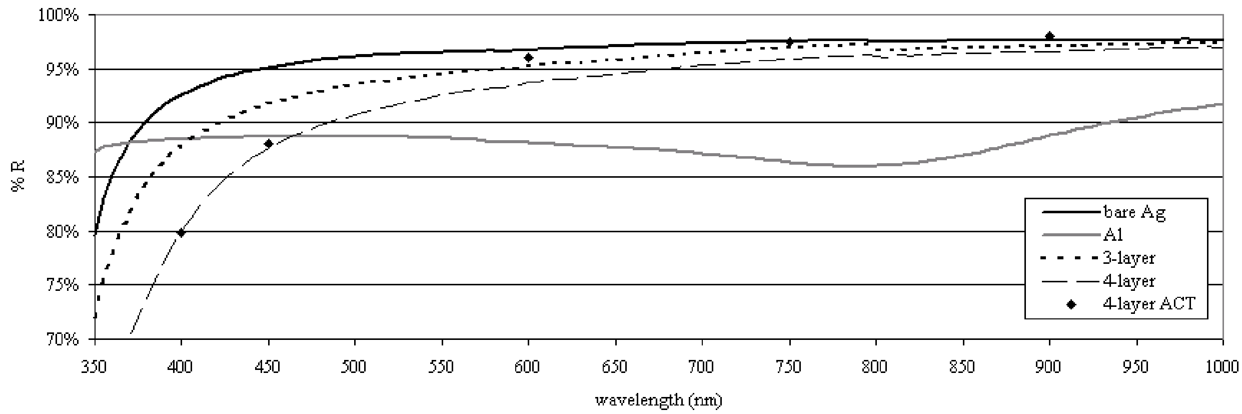

Figure 4:Visible wavelength comparison of bare Al, bare Ag, Ag coating without silicon layer, 4-layer coating

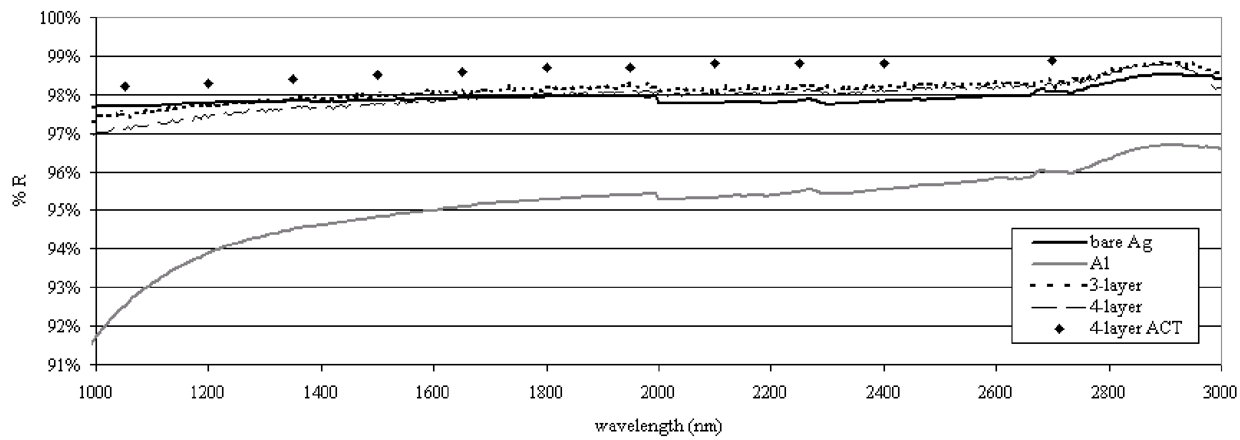

Figure 5: Comparison of same coating in the Near-Infrared

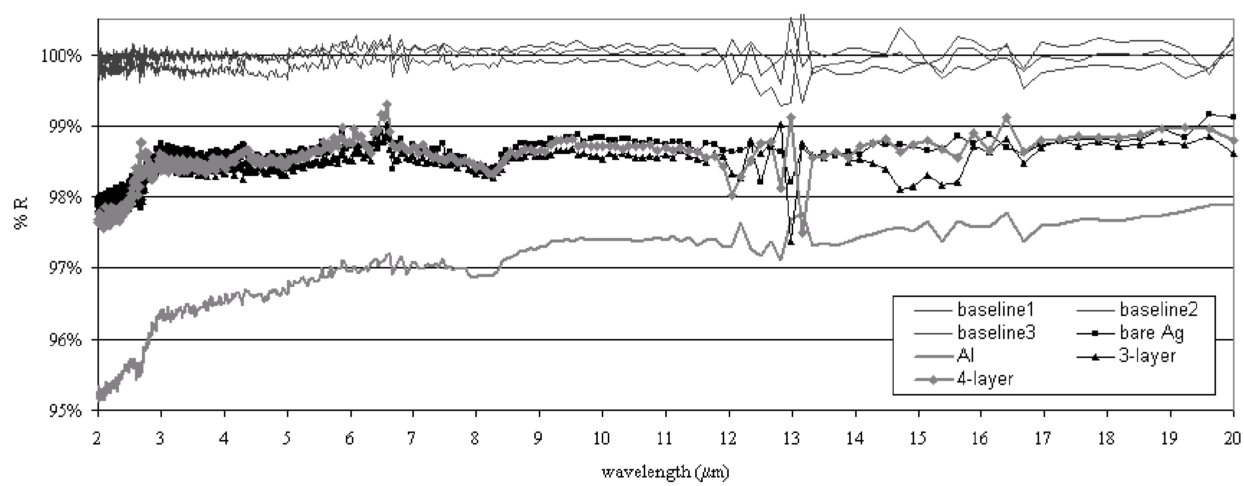

Figure 6: Comparison of coating in the Mid-Infrared

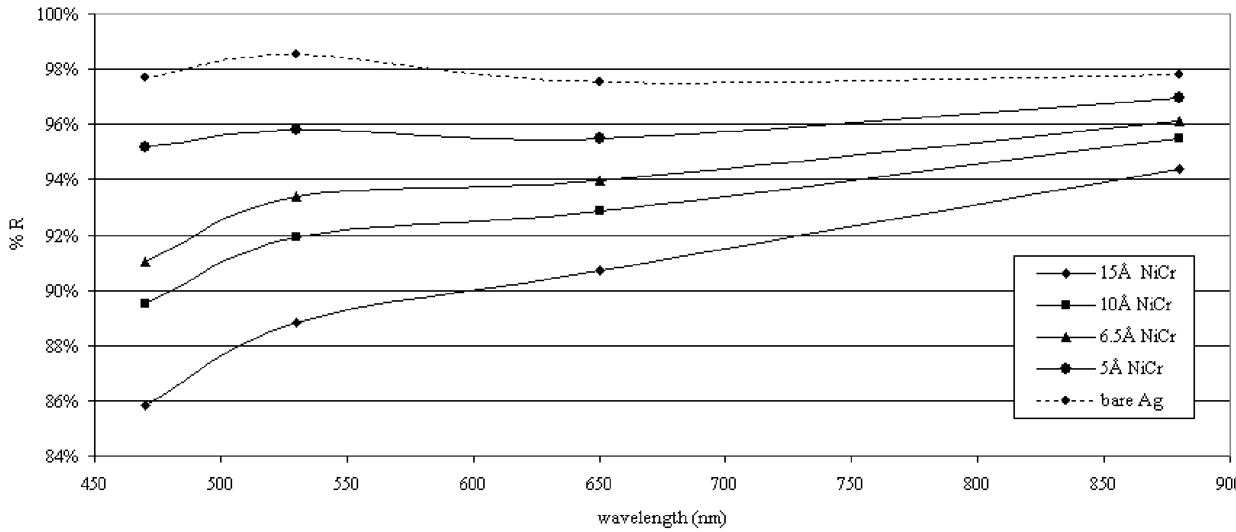

Figure 7: Absorption from NiCr layer on top of the Ag layer

It may seem as though the coating performs better without the NiCr layer between the silver and silica layers. Without the NiCr layer though, the coating degrades much more quickly. When the silver coating was being developed, tests were conducted to characterize the reflectivity loss from the various coatings.

Coating	**Monthly loss rate at 470nm at GS** (dust loss excluded)	**Sample age** days	**Monthly loss rate at 470nm at GN** (dust loss excluded)	**Sample age** days
Bare Ag	3.98 %	566	1.47%	566
SiN_x-protected Ag	2.28 %	315	-	-
3-layer Ag	0.28%	411	0.47%	263
4-layer Ag	0 %	263	0 %	263

Figure 8: Reflectivity loss for different coatings at Gemini North and Gemini South

The In-situ wash is one method that is used to return the mirror reflectivity to almost new. The downside is that the washing process causes a quicker degradation of the protecting layer, thus necessitating more frequent recoating. This is more of a problem at Gemini South in Chile, since there is more dust contamination than at Gemini North. The following graphs show the reflectivity measurements since the last recoating of each primary mirror.

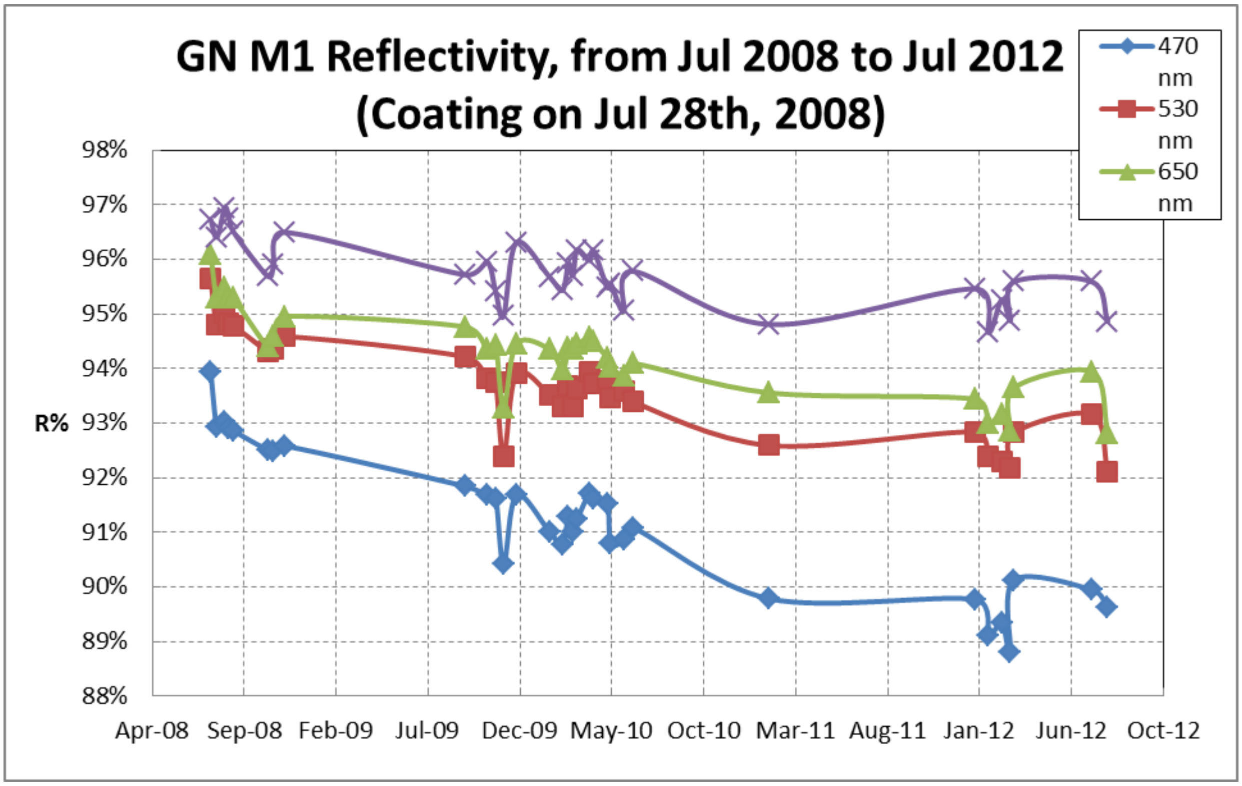

Figure 9: Gemini North Reflectivity measurements at 4 wavelenghts since last recoating in 2008

Figure 10: Gemini South Primary Mirror since last recoating in August of 2011

It can be seen from these graphs that the Gemini North primary mirror has only lost about 3 percent of its reflectance in all the measured wavelengths over three years. The Gemini South mirror, which is exposed to a much harsher environment, lost a little more than 4 percent of its reflectivity across all measured wavelengths over one year. After an in-situ wash at Gemini South in August the reflectivity to values were almost identical to a freshly coated mirror.

Degradation on the secondary mirror is also seen at both locations, but has been observed at about 0.25% per year or less. Since the secondary mirror is hanging upside down, it does not accumulate the same quantity of contaminants, and the coating lasts longer.

Currently the Gemini North primary mirror is scheduled for a recoating in January, due to adhesion problems beginning to show up which will not allow for an in-situ wash.

Further Discussion

Silver mirror coatings are good for observing wavelength from the visible spectrum into the infrared. Unfortunately, silver also shows high absorption towards the UV which is compounded by absorption from the protective layers. In this area of the spectrum, aluminum outperforms silver. In order to gain some information in the past 400nm, the Gemini Observatory is now in the process of developing a hybrid silver-aluminum coating.

Hopefully from this brief tutorial on the mirror coating process at Gemini North, you have an idea of what is involved with coating an 8 meter monolith mirror. Here is a timelapse movie that shows all the processes involved in coating the Gemini primary mirror: http://www.youtube.com/watch?v=bFiI680NShU.

References

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