



CHARA TECHNICAL REPORT

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Optical Coatings for CHARA Reflective Optics

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ABSTRACT: High efficiency coatings offer significant advantages for CHARA, but all options come with a substantial price and compromises. Many available commercial options are poorly documented or have identifiable shortcomings. The logistics of coating Array optics, and especially of recoating, are formidable. This report recommends developing the capability to do the coatings in-house. This development will be relatively expensive as well.

1. INTRODUCTION

It is possible to build an optical interferometer with about 20 optical surfaces in the optical train, provided this goal is maintained paramount in developing the concept¹. However, this results in a number of compromises that most interferometry groups have found unacceptable. Recent interferometric array projects entail more typically about 40 optical surfaces, plus or minus depending on such details as whether windows are used for the beam transport path.

The CHARA Array has 37 optical surfaces between the star and the infrared detector, 24 of them reflective. As a result, the ultimate limiting sensitivity of the CHARA Array will vary significantly with the reflectivity of its mirrors. High efficiency optical coatings are thus an important consideration. This report reviews the options for high reflectivity coatings, summarizes the results of a survey of available coating products which may be of interest for CHARA mirrors, reports on some vendors, and makes a number of recommendations for coating tests.

2. OVERVIEW OF REFLECTIVE COATING OPTIONS

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¹ The premiere examples are the original I2T and GI2t interferometers at the Observatoire de la Cote d'Azur.

The CHARA Array requires reflective coatings with high efficiency over the spectral range 0.5 to 2.4 μm . Among current product types, metallic coatings are the only options that appear to offer high efficiency, broad spectral range, and availability.

Aluminum is the old stand-by for astronomers, used almost universally for telescope primaries, with good but not outstanding reflectivity from the blue to the infrared (except for a significant dip near 0.7 μm). Aluminum can be easily applied, cleaned, and removed, to optics of all sizes.

Gold is very attractive owing to its high red reflectivity and inherent non-reactivity. Gold does not bond well directly to most optical materials, but a metallic interface layer and special coating techniques solve this problem very nicely. However, gold has a low reflectivity at the 0.5 μm end of the CHARA pass-band, and must be ruled out for that reason (expect possibly on the IR side of the dichroic beamsplitter).

Silver is nearly as reflective as gold in the infrared, and has excellent performance down to 0.5 μm as well. The most serious drawback to silver is its reactivity, especially to airborne sulfur. Many coating shops have developed techniques for over-coating silver to protect it from damage. The over-coatings are not failsafe. Damage still commonly occurs through pinholes in the coatings, through the edges of the coatings, leakage from the substrates, and possibly other less obvious phenomena.

Both gold and silver coatings, in the multilayer configurations of interest here, are rather specialized and much more expensive than aluminum. They require special coating facilities which few observatories possess, hence they normally require commercial vendors. The costs may be high. Coatings may not be available for large optics, especially telescope primary mirrors. The elapsed time, and the risk of damage or loss to components when shipped to a vendor, must be considered.

3. ESTIMATES OF PERFORMANCE FOR ALUMINUM

As of this writing, all CHARA optics are bare aluminum, mostly coated by Mt. Wilson scientists in the Mt. Wilson 100" coating chamber. No reflectivity measurements are available at this time and there is no monitoring of the reflectivity. The performance of the current coatings can be estimated from aluminum characteristics computed from optical constants, and measured at other telescopes.

Figure1 shows the expected single surface reflectivity of fresh aluminum as available in handbooks or computed from the optical constants. The reflectivity of fresh aluminum, as deposited in observatory coating facilities, has been confirmed to fall close to the theoretical performance.

Reflectivity of Aluminum

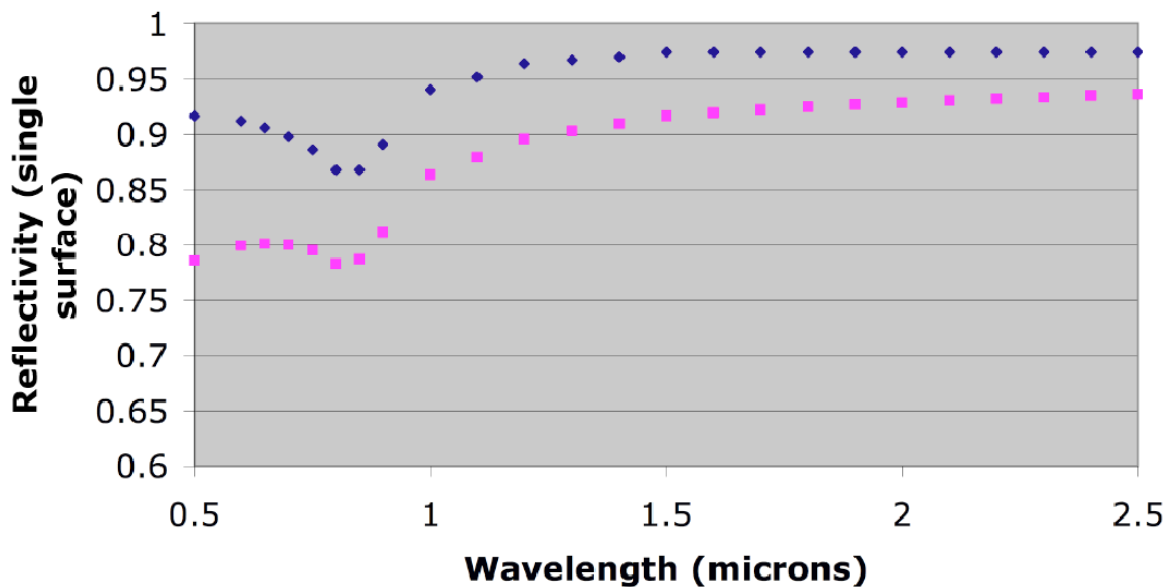


Figure 1. The theoretical single surface reflectivity of fresh, bare aluminum and the estimated reflectivity of old aluminum.

Estimating the actual reflectivity is more problematic, since no useful measurements are available at CHARA. Experience at Kitt Peak National Observatory (Chuck Gessner, private communication) has been accessed for actual telescope primary reflectivity before cleaning, in order to obtain a reference point in the blue. In the infrared, measurements from UKIRT of near-IR emissivity indicate that the 3.8 micron reflectivity may be down from the fresh value of order 0.98 to of order 0.96. Somewhat arbitrarily, these measurements were used to define an excess absorption varying as λ^a where a was found to be -0.8. This provides the second estimate of reflectivity in Figure 1.

Since modern mirror cleaning techniques restore aluminum mirrors to near the fresh aluminum reflectivity, it appears likely that the well-protected CHARA optics (in the laboratory and in the vacuum tubes) are performing at close to the fresh aluminum level, while the telescope optics are probably no worse than the lower performance shown in Figure 1.

4. CHARA ARRAY THROUGHPUT

From a spreadsheet of the CHARA optics, the throughput has been calculated. This calculation has not been done with utmost care - transmissive efficiencies are only estimated, since the objective of this study is the possible gain with reflective coatings..

The calculation was done twice. In the first case, the fresh aluminum values were adopted throughout. In the second case, the "dirty" aluminum values were used for all mirrors which are in the telescope and the fresh aluminum values for the coatings in the laboratory. The resulting net throughput estimates are shown in Figure 2.

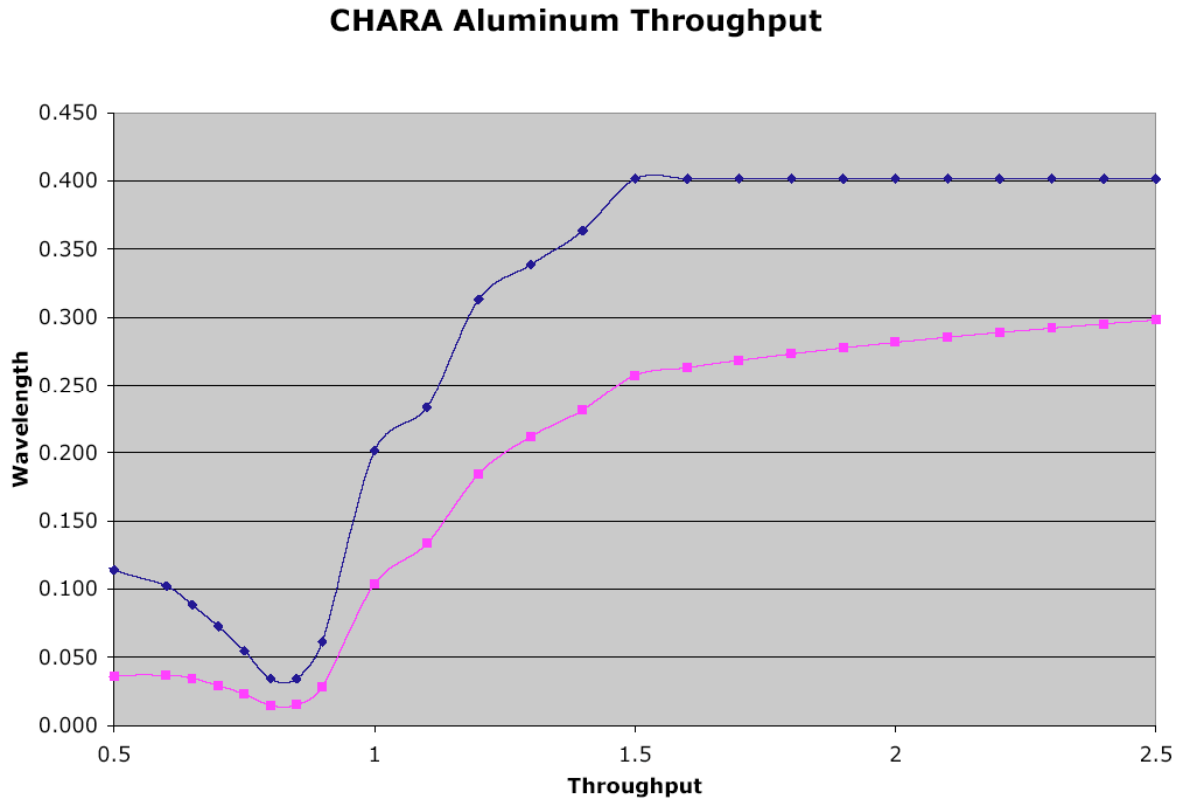


Figure 2. Estimated throughput for the CHARA optics based on all fresh aluminum values (upper curve) and on fresh aluminum values for surfaces in a protected environment and aged/dirty aluminum values for telescope and other exposed optics (lower curve).

Note that the visible-red and infrared fluxes are separated on a dichroic. The infrared beam then has additional aluminum reflections that do not occur on the visible-red side. In the spreadsheet calculation, the appropriate components were designated - this results in a discontinuity in the efficiency at 1 micron.

The assumed reflectivity of telescope optics is probably on the low side, since some of these optics are better protected than a telescope primary mirror. The assumption of fresh aluminum for the optics in the laboratory and vacuum system is probably optimistic. The best-guess at present would be between these two extremes.

The current CHARA tilt detectors are photomultiplier-based detectors working in the blue-visible. The throughput of the Array in this spectral range is a strong function of the assumed

characteristics. It should be possible to calibrate this region from the observed count-rates in the tilt detectors, but this has not been done at this writing.

5. GOLD COATINGS

Gold is the best red-infrared reflector. It is often not acceptable for astronomy because the reflectivity at 0.5 microns is only 60% and falling fast toward the blue. If the tilt tracking detectors are changed over to red-sensitive, CHARA could consider gold, since the only current "visible" requirement is for the alignment laser, and gold reflectivity at the laser wavelength is greater than the aluminum reflectivity. Gold does not adhere well, but can be applied to glass using a metal bonding layer. Bare gold has the highest broadband reflectivity, but is scratched easily. It might be appropriate for use in the laboratory and vacuum system, but not in the telescopes, which must be cleaned regularly. Protected gold could be used in the telescopes.

6. SILVER COATINGS

Fresh, bare silver is a very efficient reflector in the red and infrared. The theoretical reflectivity is shown in Figure 3.

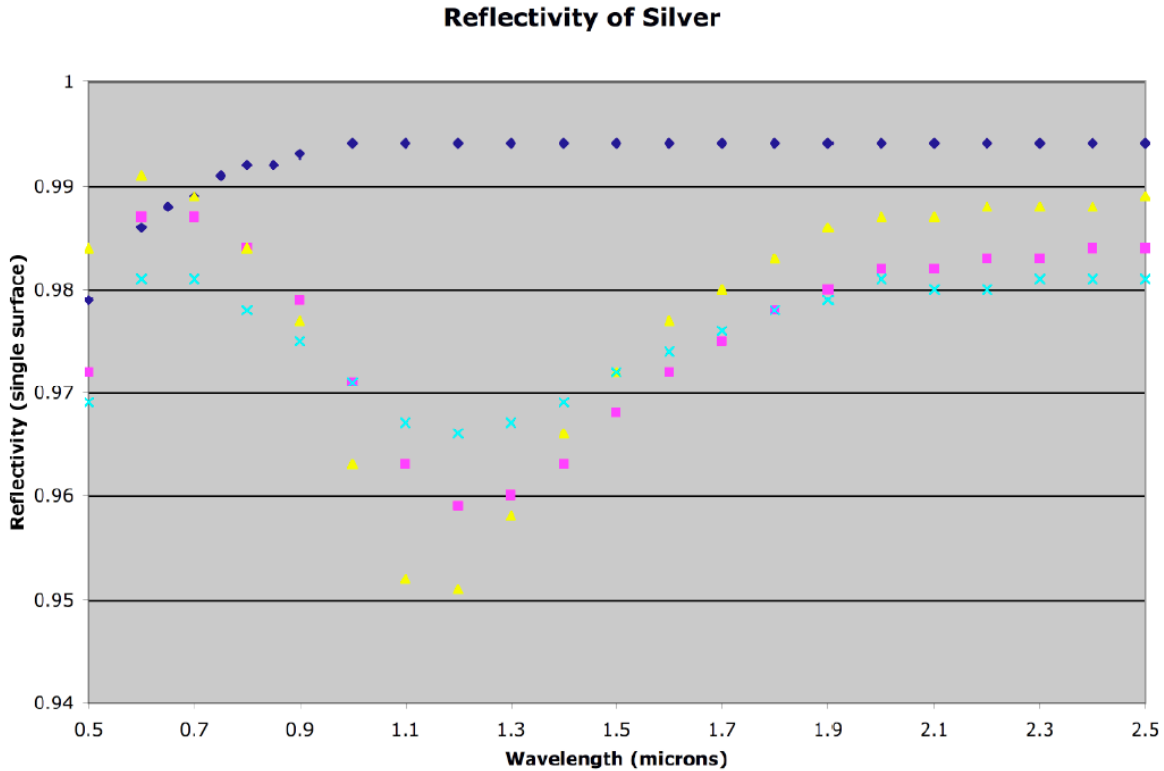


Figure 3. Fresh bare silver (upper curve). Below, ideal protected silver coating EM.2 from Newport, according to vendor specifications. The curves are for on-axis, and for off-axis in two polarizations.

Silver coatings are available from many vendors. Over-coated silver is sometimes called "Protected silver" and sometimes "Enhanced silver" - in the latter case, there is usually some augmentation of the reflectivity in some waveband - most commonly short-ward of 0.5 μm .

Figure 3 also shows reflectivity curves provided by Newport (private communication) for their ER.2 silver coating. Plotted are the normal reflectivity, and also the reflectivity at 45° AOI for the two polarizations. In this coating, the blue reflectivity has evidently been enhanced - perhaps this is the cause of the depression near 1 micron, which in fact actually drops below the fresh aluminum values for a short wavelength range. I'm grateful to Newport for being particularly responsive to requests for technical information.

Numerous vendors offer coatings with other prescriptions and characteristics. All seem to have more complex reflectivity variations than bare silver, and all seem to offer reflectivities less than bare silver. It might be mentioned here that of the many vendors for silver coatings, virtually none are willing/able to fully characterize their product. Most will not divulge information about the prescription of the overcoats. In many cases, the vendor's published reflectivity charts appear to be of uncertain accuracy, and usually represent calculated rather than measured values. The description of the coatings often differs from the charts

Silver Coating Technology

The classical coating technique uses an electron beam to evaporate silver. It is found, empirically, that this tends to form a somewhat porous coating. Due to crystalline structure, it tends to build up in columnar form. The interfaces between columns offer an avenue for moisture penetration, significantly reducing the coating lifetime.

Ion aided deposition (IAD) maintains a plasma cloud in a region of the coating chamber, and the coated piece is rotated alternately through the evaporating region and the plasma region. The plasma bombards the thin film and helps pack it down. In continuous plasma deposition (CPD), the bombardment is continuous. This packs the coating down and makes it even harder. Sputtering has been used successfully for applying silver in some prescriptions.

The temperature of the substrate is also a variable. Heated substrates are sometimes used to promote improved bonding of thin films. On the other hand, this may promote crystallization, and an unheated substrate may produce a denser coating.

Since silver does not stick to glass well, an interface material is used. A classical choice is chromium. It has been suggested that a metal-metal interface can shorten the lifetime of the coatings due to the chemical electric effect. Partly for this reason, some silver coatings are offered on a dielectric substrate.

For the protective overcoat, a variety of materials can be used, including quartz, sapphire, or thorium fluoride. Dielectric protective coatings are also offered.

Reflective Optics

Some manufacturers indicate that their coatings pass the MIL-SPEC MIL-M-13508C. This includes the following: exposure to 95+% relative humidity for 24 hours with no evidence of pitting or corrosion; 50 strokes with a cheesecloth with no sign of deterioration; five hours at -80° F and 5 hours at 160° F with no signs of deterioration; and a cellulose tape test with no part of coating removed. These show that the coating is not mechanically fragile.

The protected silver can still be attacked (probably by moisture containing sulfur) through pinholes in the protective coating, and from the edges of the coating. There have been anecdotal reports that some substrates can promote coating degradation, perhaps from internal impurities.

Although some of the coating options appear to offer reasonable certainty of long or even indefinite life, the possibility of eventual recoating must be considered. The features that make protected silver protected also make it difficult to remove. Obnoxious processes such as use of hot sulfuric acid (!) have been mentioned. Some vendors do not know how to remove their coatings and simply say that substrates must be re-polished before recoating.

10. PROTECTION OF SILVER COATINGS

Even protected silver coatings are not expected to last forever. However, there have been informal reports of some coatings having a lifetime of only 1-2 years. Usually these reports are associated with a particular vendor's products. It is probably difficult to draw any conclusions from anecdotal evidence (other than a need for caution) due to variations in substrate characteristics, handling and operating environment.

The process of applying thin film coatings involves a considerable number of parameters. There is preparation of the substrate; the ambient pressure, the cleanliness of the chamber and the purity of coating material, which will impact presence of impurities; the means of evaporation, which determine the density and speed of the application; and the temperature of the substrate and the options of ion or electron beam assist, which affect how the film adheres and crystallizes. Even experienced vendors do test runs to re-verify their setup and technique before each production run series. Much of the process is more in the nature of an art than a science, and it would not be surprising if some vendors had evolved significantly superior skills.

Damage to optical surfaces often involves the deposition of dust. Ambient humidity contributes a moisture content to the dust, and the liquid provides a medium for reactions on the optical material of bases (typical southwestern alkali dust), or acid (fumes from internal combustion engines). Hence a major step in protecting optics is preventing deposition of dust, and controlling humidity. This suggests the value of dust covers, with the importance growing rapidly in the more exposed areas. Some optical surfaces can be cleaned. This option should be thoroughly understood and implemented as feasible. Control of air moisture content, where possible, is also advisable, especially avoiding the very high levels sometimes encountered in the winter.

Sulfur is generally considered the most serious enemy of silver coatings. In the LA area, it can be expected that sulfur will be present in the atmosphere due to combustion of fossil fuels. It is possible to bring sulfur contamination into the Array area, even into the vacuum system, as a trace component in lubricants and rubber or related compounds, which may be dispersed by an out gassing process. Since the laboratory is a relatively closed environment, it may be worth looking into the availability of a simple means of removing trace sulfur contamination from the atmosphere. The charcoal filters in the air purifiers already in the optics area may serve this purpose - provided they are operated and maintained regularly.

It can be hoped that the reflective surfaces installed in vacuum will survive for a very long time. This is a good argument for keeping the CHARA system evacuated even when not in use. The system should be valved so that when opening one arm, other arms remain evacuated. When an arm is opened, it would be desirable to backfill with nitrogen and minimize the open time and the exposure to ambient conditions. If sufficiently rigorous protection procedures can be maintained, it may be possible to use unprotected silver coatings in the vacuum system, gaining perhaps 0.01 to .02 per reflection.

7. CHARA WITH SILVER OPTICS

The spreadsheet was updated with the assumption of silver optics. For this calculation, the Newport ER.2 coating was assumed since reasonably full and quantitative documentation was available.

In the throughput model, it was assumed that the telescope primary was fresh aluminum. All other optics were changed to fresh (ideal) Newport ER.2. This gives a fair estimate of the maximum improvement that could be hoped for with the Newport prescription. This is shown in Figure 4, with, for comparison, the predicted CHARA throughput for all fresh aluminum.

CHARA Throughput Fresh Al or Ag

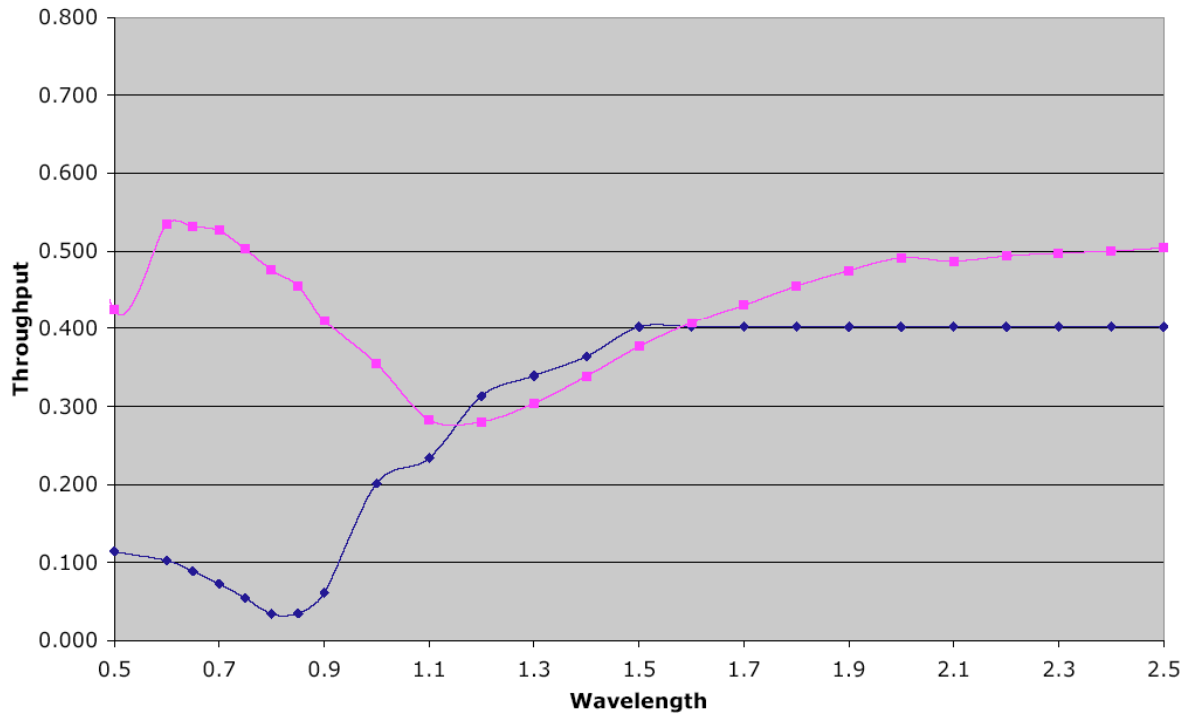


Figure 4. Predicted CHARA throughput with fresh aluminum everywhere, and with fresh overcoated silver everywhere except at the telescope primary. The jump at 1 mm corresponds to the different optical trains used in the visible and infrared arms of the facility.

In the visible, especially the red visible, the potential gain is great - as much as a factor of 10 or even more.

It is interesting to see that the promised improvement in the infrared is modest. In fact, in order to see dramatic infrared improvement, the system throughput would have to be improved to spectacular throughput values. However, it should be emphasized that the high predicted infrared throughput has not been confirmed.

Some other coatings might offer somewhat better performance in particular wavelength regions. Only bare silver would appear likely to perform better through much of the visible and the infrared.

8. SURVEY OF VENDORS

A survey of vendors was undertaken to determine which ones offered coatings of possible interest, and perhaps more important, which vendors were willing to help us evaluate their products adequately.

Two conditions are adopted, which help to limit the number of possible vendors. First, only U.S. vendors will be considered. This is purely for logistical reasons - many components will be coated - foreign shipment is an unreasonable cost-time-risk overhead. Second, only vendors that already offer high efficiency silver coatings will be considered.

The following list of questions and topics was developed for the vendor contacts.

- Does the vendor offer a high efficiency silver coating service for customer supplied lots of the mix required by CHARA?
- Experience coating ULE and Zerodur and coating astronomical telescope mirrors.
- Information about reflectivity: theoretical, actual.
- Information about polarization/phase: repeatability.
- Information about survivability.
- How is the coating removed?
- Availability of samples for testing?
- Size of a coating batch.
- Cost per batch.

The following vendors responded positively that they could fulfill the CHARA coating requirements, although in some cases only for smaller pieces.

- Coherent Inc, Auburn CA
- Computer Optics Inc. Hudson NH
- CVI Laser Corp, Albuquerque NM
- Denton Vacuum Inc, Cherry Hill NJ
- Deposition Sciences Inc, Santa Rosa CA
- Ealing, Rocklin, CA
- EMF Corporation, Ithaca, NY
- Evaporated Metal Films, Ithaca NY
- General Optics, Moorpark CA
- GM, Newport Beach CA
- Janos Technology Ltd, Townshend VT
- Lambda/10 Optics, Westford MA
- LLNL, Livermore, CA
- Majestic Optical Coatings, Clark, NJ
- Moonlight Optics, Peoria, AZ
- Newport, Irvine CA
- Omega Optical Corp, Brattleboro VT
- OPCO Laboratory Inc, Fitchburg MA
- Opticoat Associates, Chelmsford MA
- Quality Thin Films Inc. Oldsmar FL
- Rocky Mountain Instrument Co, Longmont CO
- Thin Film Devices Inc, Anaheim CA
- Virgo Optics, Port Richey FL

Reflective Optics

The vendor survey was initiated with the idea of undertaking procurement and testing of samples from a number of interesting sources. This aim was not followed up owing to uncertainties about completing meaningful tests and eventually, after the Array became operational with aluminum optics, doubts about the feasibility of staging the optics through a vendor for both initial and then replacement coatings.

9. VENDORS

(Here, as elsewhere in this report, CHARA cannot guarantee the accuracy or completeness of the information reported.)

Several of the vendors were familiar with astronomy applications. Coherent Inc did coatings for the Keck Echelle. Computer Optics has done work for Air Force Rome research lab. Deposition Sciences Inc developed coatings for Gemini. General Optics coated mirrors for Gravity Probe B. Opticoat Associates did coatings for the Keck AO system (and has done custom coatings for CHARA). LLNL has done coatings for Keck.

All vendors say they will not accept responsibility for damaged optics, even if they are negligent - although I know of one case in which a vendor replaced an expensive optic which was damaged.

Denton Vacuum, Inc

Denton has supplied silver coated optics to many observatories including IOTA and NPOI. The classic coating is called FSS99. It is offered in several options such as FSS99-500, which is optimized somewhat for reflection at 500nm (normally to the detriment of adjacent wavelengths). Anecdotally, the FSS99 coating is not sufficiently durable for use in the CHARA telescopes. IOTA reported very rapid loss of coatings on siderostats owing to inadvertent exposure to fog on one occasion. Mt. Wilson is a much damper site than Mt. Hopkins. NPOI has reported that substrates in exposed locations for 1 year had reflectivities as low as 70%. However, the FSS99 coating appears to serve indefinitely in protected conditions.

We don't have any data for the infrared from Denton. Keck has used Denton coatings, and supplied us with measured reflectivities that are a little hard to understand, but seem to show the FSS99 performing as well as gold in the 1-2.5 micron region (that would be about 0.99!).

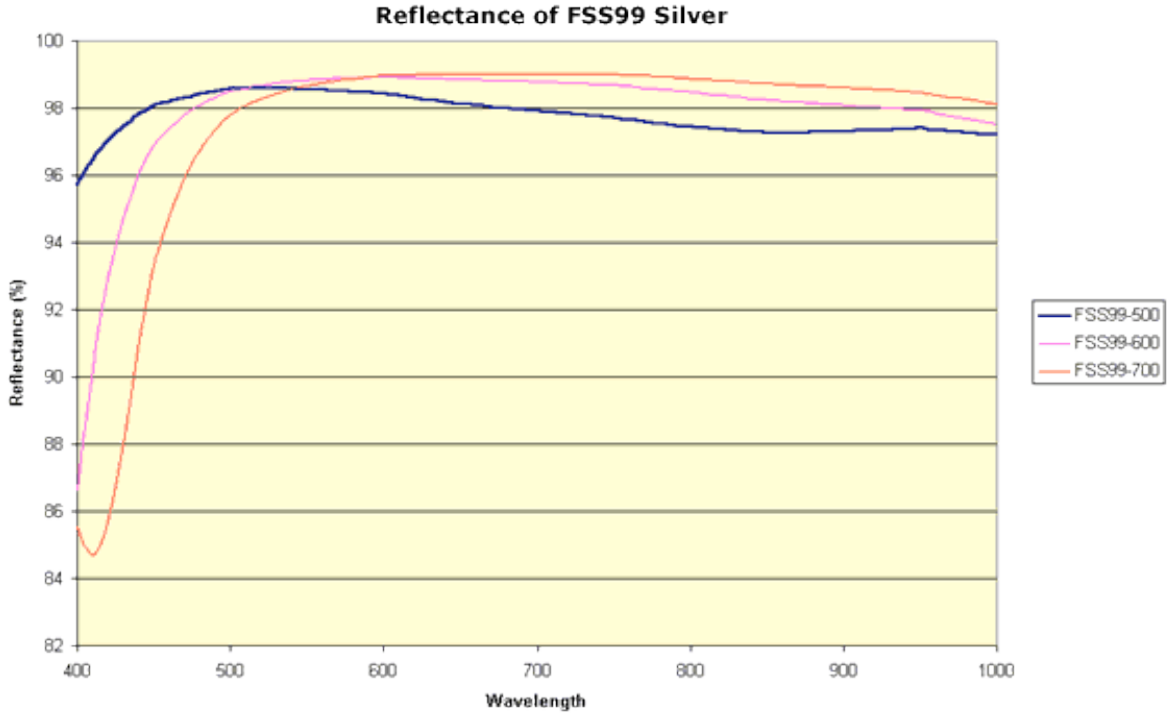


Figure 5. Performance of Denton coatings (supplied by the vendor).

A ROM estimate shows that it would cost about \$30K to do all the CHARA optics (not including telescope primaries and POP/End mirrors) if shipped in small lots. Perhaps a better price could be negotiated if the mirrors were grouped optimally.

The Denton WEB site shows a new coating, X-1, which is described as being more durable, passing a 24 hour salt fog test.

Denton is willing to strip the old aluminum coatings.

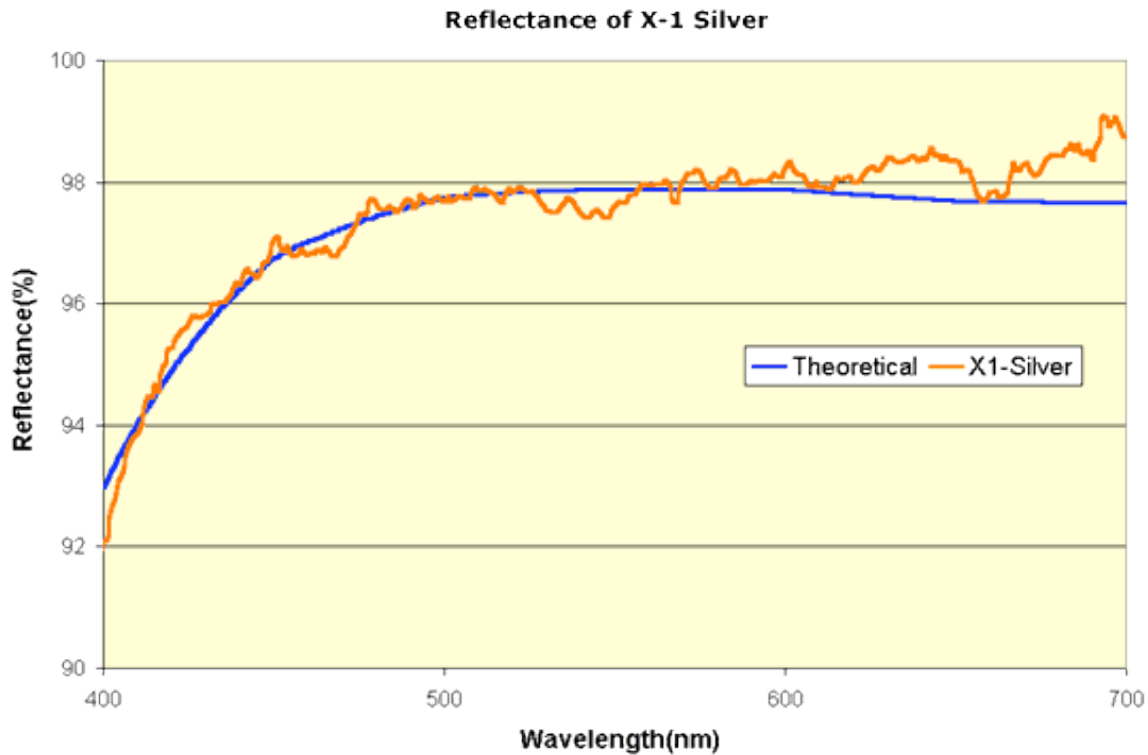


Figure 6. Denton coating X1-silver (computed and measured performance) provided by the vendor.

LLNL Engineering

Jesse Wolfe and David Sanders at LLNL have developed a protected silver coating that has a reputation for unusual durability. It is said to pass tests such as boiling salt water, acid and base tests, and hydrogen sulfide atmosphere. We do not have specifics on infrared reflectivity, although the literature claims average reflectivity greater than 95% from 300 to 2500nm. It has been used in astronomy.

The coating uses over and undercoats of NiCrNx, nickel chromium nitride, for toughness and to retard diffusion. Layers of SiO2 and Nb2O5 can be used to increase the reflectance at selected wavelengths. The coating can be stripped with sodium thiosulfate.

It is well known that LLNL is in a somewhat unusual situation with respect to providing technical services - I can't give an explanation does it justice.

The coating chamber can process whatever pieces can be mounted on a 26-inch circular plate. The processing cost is \$3K per run, whether it is productive or not. Normally one setup run is required for each "session", which may be either private or shared.

This coating may be the only one that could be considered a candidate for use in the exposed location of the CHARA telescopes. Although the work is provided for cost, the cost is high by

comparison to conventional vendors. Using this coating for just the telescope optics (through M9) would cost about \$18K, assuming that the runs went well. If there are problems, the customer pays for the additional runs at \$3K each.

LLNL would like the substrates stripped of aluminum and cleaned by the customer.

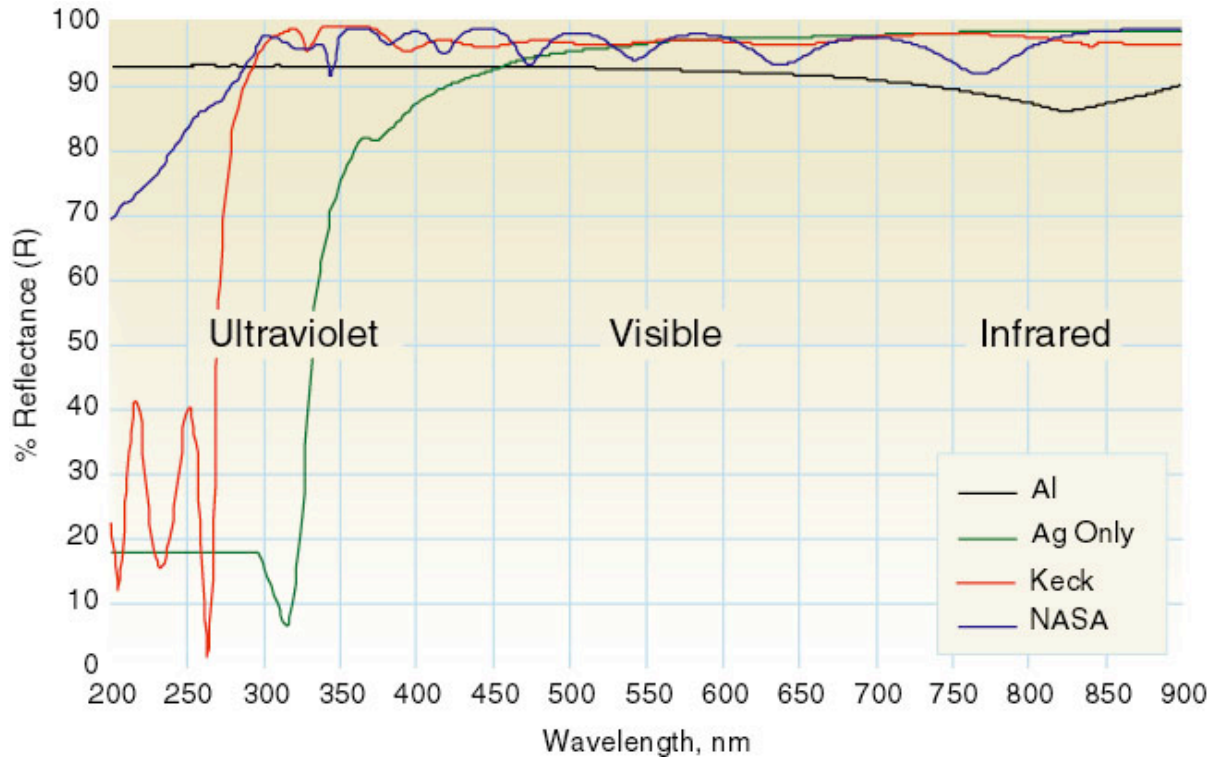


Figure 7. The reflectivity of coatings provided by LLNL engineering - their computed performance.

10. DO-IT-YOURSELF SILVER COATINGS

The Gemini observatory people have worked very hard to develop a silver coating that can be applied to an 8-m mirror. The method adopted employs a 3- or 4-layer coating, which addresses the issues of adhesion and protection. The technique uses relatively accessible technology that can be duplicated in a laboratory. The coatings do not have, or attempt to have, the best longevity, but make up for this with the capability to replace the coating on-site.

The basic equipment needed, in addition to a vacuum chamber, is a sputtering source for each material in the coating, and a thickness gauge. These are standard commercial products. The process does not require unusually high vacuum, heating the substrate, or other of the various exotic techniques mentioned above.

I have investigated the approximate cost of developing a silver coating capability at the CHARA labs. Angstrom Sciences provided the following estimate of the costs for equipping an existing vacuum system for applying the 3-layer Gemini coating.

Reflective Optics

In order to get a uniform coating on your 13" OD or smaller substrates, we would recommend a 24" long magnetron design. For this process, we would estimate that 3 magnetrons (100k) would be necessary and 2 power supplies (75K). We would suggest using pulse DC power supplies in this application. Assuming that you already have adequate cooling for the system (8 gpm- max.), additionally you will need the following; shutter and uniformity mask assembly (3 at 60k), gas inlet and controls (25k), pressure controls (10k), deposition monitor (15k), targets and bonding (10k), installation and set-up assistance, and training. You would also need some way of measuring reflectivity. This doesn't include tooling and fixturing that will be necessary (100-200k).

Total Estimate: \$295,000.00 (+) \$100,000-\$200,000.00 (tooling and fixturing)

Alarmed by this estimate, I contacted Maxime Boccas at Gemini, to enquire about a possible more modest approach to the problem. He suggested that a simpler system could be put together for a budget of order \$100K, with the following approximate distribution:

Three magnetrons (eg from Sierra Applied Sciences in Colorado): \$50K
Power supply with pulser (eg Advanced Energy, Huttinger, Glassman high voltage): \$15K
Shutter: \$10K
Tooling, fixturing: \$20K
Deposition Monitor: \$1.5K

These prices assume that a suitable vacuum chamber is already available.

11. RECOMMENDATIONS

The decision for or against enhanced reflectivity coatings should be made on scientific grounds - particularly on the importance of the improved visible-red throughput.

The major challenge for CHARA in taking advantage of a commercial coating would be removing and delivering the substrates to the vendor in a way that allowed the vendor to organize the runs cost-effectively. The only sensible way to stage the work would be to close operations and remove all optics at the same time. The down time would probably be of order 2-3 months. This could be reasonably phased as a winter shutdown.

If the decision were made to silver coat the optics, a compromise between cost and durability would be to use Denton optics for the laboratory environment, and LLNL for the telescope optics. From the price estimates obtained, it appears that the cost would be approximately \$50K.

While the coatings may have good longevity, it would be risky to assume that this is certain - since, in fact, the coatings would not have a meaningful guarantee for lifetime in the CHARA environment. The long term cost, in terms of cleaning and recoating optics, remains problematic. If the CHARA site turns out to be particularly hostile to silver coatings (not impossible) damage might be noted in less than a year.

The demonstration at Gemini of silver coating technology offers CHARA an approach to venturing into silver optics incrementally and with an assured backup at all times. The Mt. Wilson 100" chamber might be modified for this. The pressure profile used at Gemini necessitates pumping the chamber to around 10^{-6} Torr, for purposes of cleaning, then introducing a small amount of an inert gas (usually argon) to produce a plasma, bringing the pressure up to a few milli-Torr. The 100" chamber normally pumps down to $8 - 40 \times 10^{-6}$ Torr, which might be adequate.

REFERENCES

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