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Comparison of laser and $C0_2$ snow cleaning of astronomical mirror samples

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ABSTRACT

The cleaning of mirrors in large, remote telescopes is essential if these telescopes are to meet their performance goals, including low (2%) thermal emissivity in the infrared. Aluminum-coated mirror samples, which were naturally or artificially contaminated with materials representative of those at observatories, were cleaned with a UV laser beam or CO_2 snow. Cleaning effectiveness was determined from studies of residual particle densities and size distributions (measured from low-magnification optical imaging). For exposures under two weeks both laser and CO_2 cleaning yield comparable results; however, for longer exposures (up to three months) UV laser cleaning is about twice as effective in our tests. At the laser energy densities required for effective cleaning, no surface changes or damage was observed even after cleaning the same spot 200 times. For 8-m class telescopes, the annual consumption cost of sufficiently pure CO_2 is comparable to the capital cost of a UV laser. Both methods clean such surfaces in less than one day. Two attractive features of laser cleaning are that the method can be fully automated and run frequently without significant cost of manpower or expendables, and that by focusing the laser beam tighter it can be used to strip old surface coatings prior to recoating.

1. BACKGROUND

Bare aluminum-coated mirrors in astronomical telescopes degrade over time after being exposed to their local environment This degradation is caused by both molecular contaminants (e.g., organic films and inorganic chemicals) and particulates (e.g., dust) adhering to the mirror surface, and by tarnishing of the aluminum coating. The degradation leads to a decrease in mirror reflectivity, and an increase in light scattering and infrared (IR) emissivity.

Typical procedures for *in situ* cleaning of the primary mirror include washing the mirror or using a spray-on plastic coating that can be peeled off. These can temporarily improve the mirror performance. However, these techniques are not always 100% effective and they can cause other problems. For example, evidence obtained at the National Optical Astronomy Observatories suggests that water cleaning may actually accelerate tarnishing. Peel-off cleaning films appear to trap water under the aluminum coating which can cause early flaking of the coating from the substrate. Being able to reach the interior of the 8-m primary mirrors for cleaning using these conventional techniques also poses serious logistical problems.

CO_2 snow[1] is one possible candidate being considered for cleaning 8-m class telescopes. This snow can be generated by expelling pressurized liquid CO_2 from **a** nozzle at which point it expands, undergoes a phase change, and becomes snow crystals. The size of these crystals depends on the geometry of the nozzle, but for 1-mm apertures the crystals will be about I mm in diameter. Particulates on the mirror surface are blown away through impact with the crystals which eventually sublime directly to the gas phase. This process is very gentle to the mirror surface because the crystals glide over the mirror on a cushion of CO_2 gas that continually sublimes off the crystals. In order to avoid leaving any residue on the mirror surface it is important to use very pure CO_2 (>-99-99%). One limitation of this technique is that it cannot remove molecular contaminants as confirmed in CO_2 snow cleaning tests performed at STI.

Laser cleaning is another possible candidate for cleaning mirror surfaces that was initially developed for cleaning semiconductor wafers.[2] UV laser light has been shown to be particularly effective at removing both particulate and molecular contaminants.[3] Typically, the laser light from a pulsed UV laser is scanned in a raster pattern across the surface to be cleaned. The cleaning process relies on several physical mechanisms. Removal of molecular contaminants uses a combination of photochemical dissociation where the molecular bonds of the contaminants and the weak contaminant-metal mirror molecular bonds (typically several eV) are broken by the UV laser light, and photothermal processes where the contaminant preferentially absorbs the UV light and vaporizes whereas the highly reflective metal coating tends to absorb much less. This latter effect means the laser energy density (fluence) needed to clean the mirror is generally not very high and is well below the damage threshold of the mirror surface. Particulate removal is accomplished through direct absorption of the laser light leading to vaporization and generation of a photoacoustic stress wave in the mirror substrate that breaks the electrostatic bond between the mirror surface and the particulate and causes the particulates to literally bounce off the mirror. Water droplets and other small corrosive droplets should also be efficiently removed in the same fashion. A pulsed laser is essential to stimulate this photoacoustic effect.

Depending on the amount and type of contamination, it may be necessary to use an optical homogenizer to convert the output from the UV laser into one with a uniform (±5%) laser beam profile on the mirror surface. This is because normal laser beam profiles, e.g., Gaussian profiles, do not have sufficient energy in their outer edges to remove the contaminants, but this energy can still cause partial conversion and charring of hydrocarbon deposits. These deposits are difficult to remove with subsequent passes of the cleaning beam. Fortunately, as reported later in this paper, when the contamination is primarily particulates and is not severe as is the case for astronomical mirrors, then effective laser cleaning is almost certainly feasible without the use of a homogenizer.

Ideal lasers for UV laser cleaning are excimers, which are readily available commercially. They generate short pulse (20-100 ns) light in the UV at pulse energies more than adequate for this application. The excimer laser uses a rare gas/halogen gas mixture as its lasing medium with wavelengths available at 193, 248, 308, or 351 nm. For the work discussed in this paper a XeCl excimer laser is used whose output wavelength is 308 nm.

Another advantage of excirner lasers is that the output beam is already incoherent. This means it is relatively easy to obtain a uniform beam profile by sending the laser beam though a homogenizer without problems with interference and diffraction fringes occurring in the homogenized output hewn. Even without using a homogenizer, there are excimer lasers available whose output beam profile is already fairly uniform.

Lastly, excimer lasers are capable of high pulse repetition rates (100-1000 Hz). Typically 3-4 shots per beam spot size on the mirror are needed for cleaning. (This is to help generate the surface photoacoustic waves.) Hence, a high repetition rate directly reduces the cleaning time. Estimates based upon available commercial lasers are that an 8-m mirror can be laser cleaned in less than 8 hours including set up and shut down of the laser cleaning system.

The relative costs for laser and CO_2 snow cleaning of 8-m class telescopes are discussed later in this paper.

2. DESCRIPTION OF LASER AND C02 SNOW CLEANING EXPERIMENTS

2.1 Mirror test samples and contamination procedure

The mirror test samples consist of 4-in (10.2-cm) diameter polished silicon wafers coated by ~1000Å of aluminum. These were provided by the Gemini 8-Meter Telescopes Project who also arranged for some of the samples to be naturally contaminated (i.e., exposed to ambient air flow) at the UKIRT observatory on Mauna Kea, Hawaii. Pairs of mirrors were exposed to the same environment as the UKIRT primary mirror for exposure times from 3 to 84 days. These mirrors were shipped back to the mainland where one of the pair of mirrors was laser cleaned and the other one was CO_2 cleaned.

Clean mirror samples were also shipped to STI Optronics, Inc. (STI) and artificially contaminated with finely crushed soil (primarily volcanic rock) obtained from Mauna Kea. The size and distribution of the dust particles were selected to simulate the natural contamination observed on mirrors exposed for approximately 2 weeks. A special system was developed that allowed controlled, reproducible contamination of the mirror samples. These officially contaminated mirrors were then used to optimize the laser cleaning parameters and to characterize the CO_2 cleaning performance.

2.2 Description of laser cleaning test apparatus

A schematic of the laser cleaning system assembled at STI for test cleaning the mirror samples is shown in Fig. 1. The laser is a commercial excimer laser manufactured by Lambda Physik and, as mentioned earlier, operated on XeCl. The rectangular output from the laser is converted into a square shape by sending the laser beam through a cylindrical lens telescope. Attenuators are placed in the laser beam path to control the laser energy incident on the mirror sample. The actual amount of energy delivered to the sample is measured using a calibrated beam splitter that deflects a small portion of the laser beam to a power meter. An optical beam homogenizer can be positioned in or out of the beam path before the beam reaches the mirror sample. The lenses in the expansion telescope are repositioned when cleaning without the homogenizer to provide a focused spot size on the mirror surface similar to that achieved with the homogenizer. For the work presented here the laser spot size on the mirror is approximately 6 mm x 6 mm. This size is measured by using a CCD camera to view the laser beam striking a UV fluorescent glass plate.

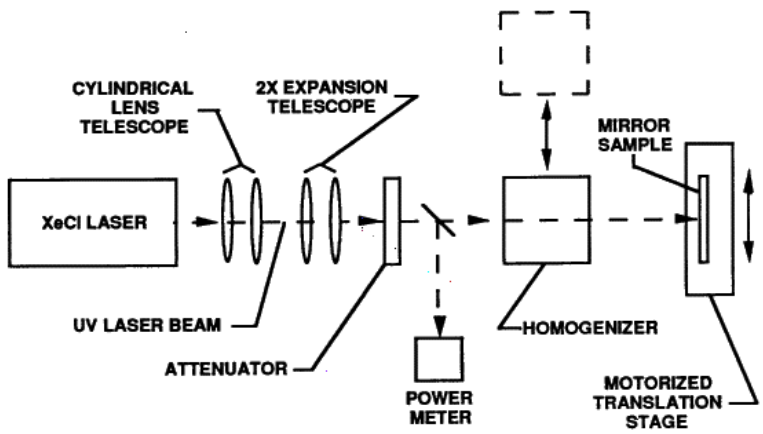

Fig. 1. Schematic of laser cleaning experimental system.

The mirror surface is held in a vertical position on top of a motorized translation stage with the surface facing normal to the oncoming laser beam. This stage translates at a constant speed in the horizontal direction. The number of shots per cleaning site is adjusted by varying the laser pulse repetition rate. Vertical translation of the laser spot on the sample is done manually with typically ~25% overlap between the horizontal rows cleaned by the laser. Dry air is gently blown downward over the mirror surface during the laser cleaning process. This air flow prevents the laser-expelled dust particles from resettling on the mirror surface, but the flow is not strong enough to remove contaminants off the mirror.

The laser fluence ranged from 0.33 to 0.38 J/cm^2 for the data presented in this paper with little difference in cleaning behavior noticeable within this fluence range. Laser cleaning scans are done using 4 shots per cleaning site. Tests are also performed using 2 and 3 scans (i.e., 8 and 12 shots per cleaning site, respectively).

The laser fluence for effective cleaning is approximately 3-4 times lower than the threshold for observation of any mirror coating changes which would indicate the onset of laser damage of the aluminum coating. Separate tests where the laser repeatedly cleaned the same area of **a** mirror sample 200 times revealed no visual changes to the coating. The laser also did not appear to worsen or change any existing surface damage on the mirror coating.

2.3 Description of particle measurement system

In order to provide quantitative information on the effectiveness of the laser and C02 snow cleaning methods, a particle measurement system was developed based upon detecting the scattered light from the dust particles on the mirror surface. A schematic plan view of this system is depicted in Fig. 2. Light from a high-intensity microscope lamp illuminates the mirror sample. Specular reflection from the mirror is directed away from the CCD camera so that only scattered light enters the camera. Thus, if the mirror sample is perfectly clean, the camera, which views an approximate 3 cm x 3 cm area on the mirror surface, sees only a dark image. Contaminants on the mirror surface cause scattered light that can be easily seen. The entire system is enclosed in a box to prevent extraneous light from entering the camera.

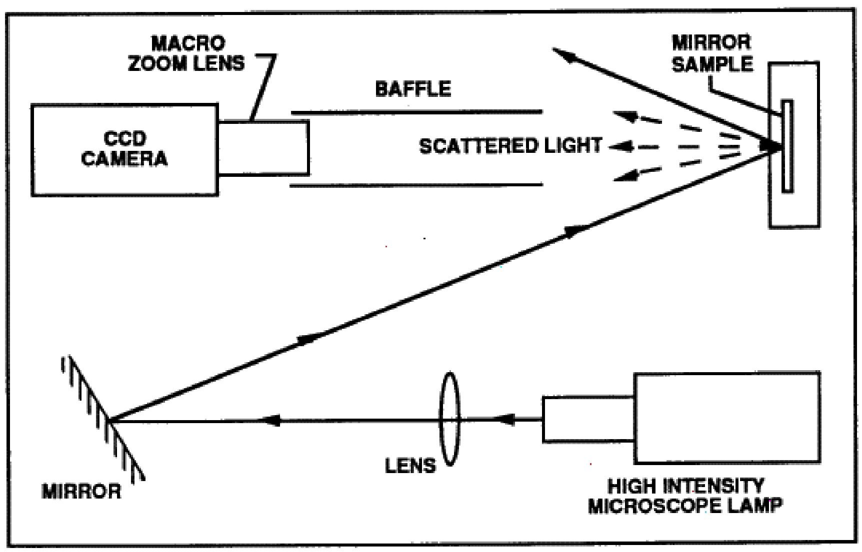

Fig. 2. Schematic plan view of particle measurement system for detecting contaminants on the mirror sample surface.

2.4 Description of data reduction method

The video images of the scattered light from the mirror sample are analyzed following the steps shown in the flow chart given in Fig. 3. A copy of the raw video image is sent through a 5 x 5 median filter. The purpose of this filtering process is to generate an image that excludes the bright points of light due to the dust particles, but retains any background signal. This filtered image is then subtracted from the raw video image to provide an image of the isolated particles. The size of the neighborhood for the median filter and the threshold of the video signal which indicates the presence of a particle were chosen by visually inspecting sample images to verify that the smallest particles detectable by this system (-25 µm) were not being eliminated during the filtering process.

Once the particles have been isolated a separate software program counts the number of particles and sorts them by size. The data output is the number of particles per unit area, the area of the mirror covered by particles, and the distribution of particles by size. Since the naturally contaminated mirrors included particulates and an unknown amount of molecular contamination and surface damage (e.g., pits and scratches), generally the area of the mirror covered by particles is presented in our results with the understanding that "particles" also includes molecular contamination and surface damage. Of course, while the laser can remove both particulate and molecular contaminants and CO_2 snow can only remove particulates, neither technique can do anything about surface damage.

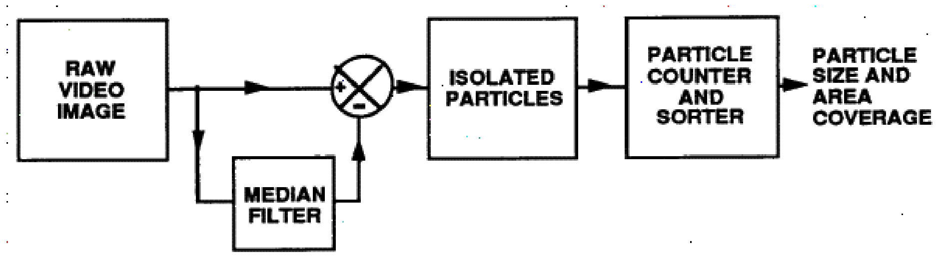

Fig. 3. Flow chart for analysis of mirror sample video images.

In Figs. 4(a) and 4(b) are examples of raw video images of a naturally contaminated mirror before and after laser cleaning, respectively. Figures 4(c) and 4(d) are the reduced data of the images shown in Figs 4(a) and 4(b), respectively, at the point in the data reduction process designated by "Isolated Particles" shown in Fig. 3. A single pixel corresponds to a particle dimension of approximately 25 gm.

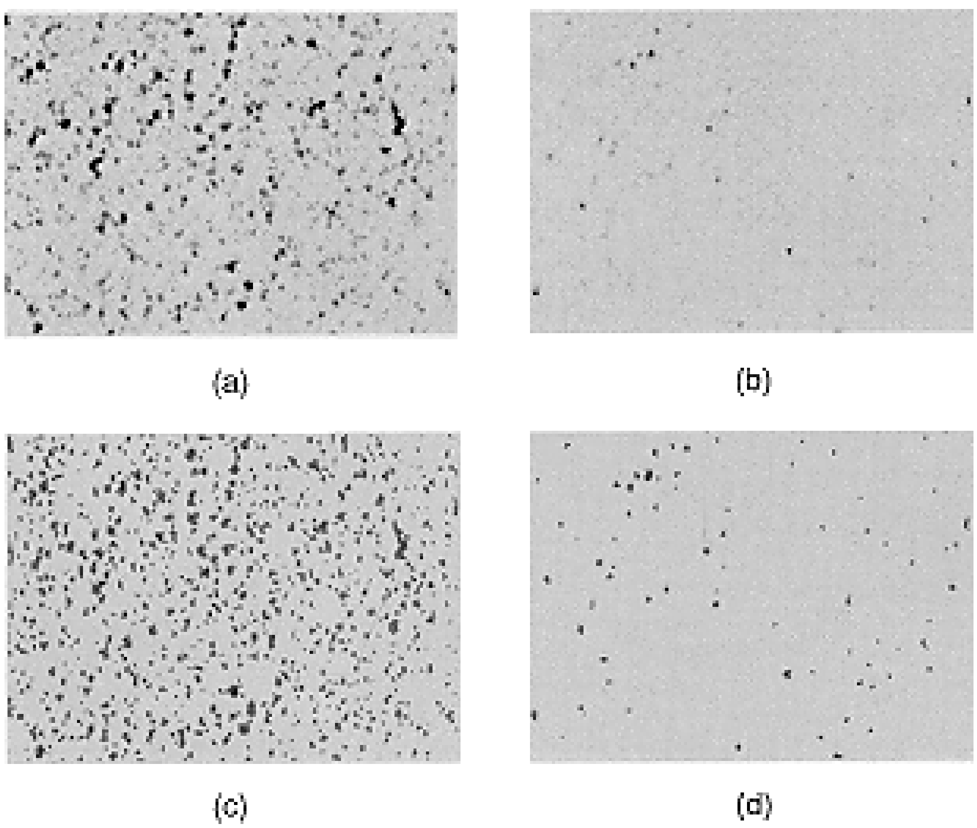

Fig. 4. Examples of raw and reduced video image data. (a) Raw video image of naturally contaminated mirror [21 days exposure]; (b) Raw video image of laser cleaned mirror shown in (a) [0.38 J/cm^2, 12 shots/site, no homogenizer]; (c) Reduced data of image (a) showing isolated dust and mirror imperfections; and (d) Reduced data of image (b).

The CO_2 snow cleaned mirrors are analyzed in a similar fashion. However, since these were CO_2 snow cleaned at the Gemini Project office, video images of the before cleaning condition were not obtained. Instead, comparisons were made using the contaminated mirror pair that was eventually laser cleaned. This should still provide a valid comparison since the pair of mirrors were contaminated at the same time.

3. EXPERIMENTAL RESULTS

Plotted in Fig. 5 is the mirror area covered by particles and mirror imperfections before and after laser or CO_2 snow cleaning as a function of days of exposure on Mauna Kea. For less than about 2 weeks exposure, both methods yield comparable results and dramatically reduce the amount of contamination. (As explained later, the data at 21 days exposure may be mislabeled.) For exposure durations greater than about 2 weeks, laser cleaning performs significantly better than CO_2 snow cleaning by roughly a factor of two. Laser cleaning using 8 shots/site (i.e., two scans at 4 shots/site) does improve the cleaning slightly over only 4 shots/site, but there appears to be less benefit with using a third scan (i.e., 12 shots/site). These data were obtained using a homogenizer, the results are similar if a homogenizer is not used demonstrating that a homogenizer is not necessary for this application.

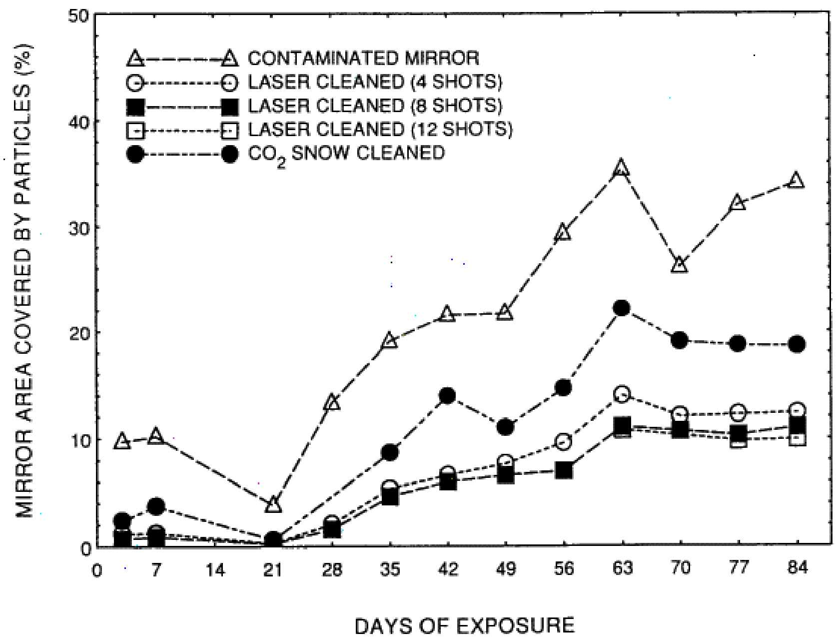

Fig. 5. Comparison of laser and CO_2 snow cleaning performance on naturally contaminated mirror samples. Plotted is the total mirror surface area covered by particles and mirror imperfections as a function of exposure days.

The data also indicate a steady increase in contamination level over time and a corresponding reduction of cleaning effectiveness for both techniques. Visual inspection of the contaminated mirrors revealed the presence of scratches and pits, and molecular contaminants (e.g., water spots) whose frequency appeared to increase with length of exposure. Hence, the decline in cleaning effectiveness may be partially due to an increase in mirror imperfections. The fact that molecular contaminants appear to take longer to accumulate on the mirror surface may help explain why CO_2 snow is less effective at cleaning the long exposure time mirrors. Electron microscope analysis of the mirror surfaces is planned to better understand the effects of long term exposure.

As an aside, the contaminated mirror data in Fig. 5 does not always increase monotonically with time as would be expected. This does not make sense. We suspect that the exposure times of some of the mirrors may have been mislabelled. Even if this were true, it does not change the overall trend demonstrated by the data, nor the basic results of our comparisons between laser and CO_2 snow cleaning.

In separate tests from this program, Gemini personnel measured the IR emissivity of the mirrors samples before and after laser or CO_2 snow cleaning.[4] A similar trend was observed where both methods improved the emissivity by about the same amount for exposures less than ~2 weeks, but for longer exposure times the laser cleaning significantly out performed the CO_2 snow cleaning.

4. DISCUSSION

The data indicate that laser cleaning performs better dm CO_2 snow cleaning for exposures greater than about 2 weeks. It also indicates that weekly cleaning is advisable since the mirror can become appreciably contaminated in only 7 days. Therefore, the cost effectiveness of each technique needs to be considered. The capital costs for an excimer laser are larger than for a CO_2 snow cleaning system; although, depending on the size of the CO_2 storage tank at the observatory and the type of CO_2 snow delivery system that is used, the capital costs for a CO_2 snow cleaning system may not be insignificant. The nozzle for delivering the CO_2 snow must be kept fairly close to the mirror surface (-30 cm) to achieve satisfactory cleaning performance. Because of the large force on the nozzle due to the CO_2 discharge, manually holding the nozzle close to the mirror surface runs the risk of accidentally hitting the surface with the nozzle. Hence, some mechanical support system would need to be constructed to permit holding the nozzle close to the surface and reaching the center areas of the mirror. As explained below, a laser cleaning system can be relatively simple in design because the laser beam can be easily directed over long distances.

Surprisingly, the operation costs for cleaning an 8-m mirror with CO_2 snow can be quite large. Based upon CO_2 cleaning studies performed at STI, the amount of CO_2 needed to clean the entire mirror area can be estimated. For an 8-m mirror this is approximately 730 lbs. As mentioned earlier, it is necessary to use at least 99.99% pure CO_2, which costs about $1.60 per pound. 1 Hence, a single cleaning of an 8-m mirror will cost $1,168 in just CO_2 costs. This does not include the cost of transporting the CO_2 to the observatory. Monthly materials costs are close to $5,000 assuming weekly cleaning. At this rate the capital cost for a laser can be paid off in less than 1.5 years. These estimates also do not include labor costs, which would be -1 man-day per cleaning

In contrast, the only major materials cost for operating the laser is the excimer gas fill, which is approximately $140 per fill and lasts for about 107 shots. This means a single laser cleaning of an 8-m mirror costs less than $38 in materials. In separate work,[5] a conceptual design has been developed by STI for a semiautomated laser cleaning system that can be run by a single operator. Thus, Mm CO_2 snow cleaning the labor cost for laser cleaning is -I man-day per cleaning.

This same study produced several approaches for removing the laser-expelled dust during the cleaning process. Probably the simplest is to point the telescope near the horizon such that the primary mirror surface is near perpendicular to the floor. The laser cleaning system would be located on the floor near the distal end of the telescope with the laser beam directed towards the primary mirror. The dust on the mirror is removed and swept off the mirror surface by scanning the laser beam from top to bottom of the mirror. Fans along the cradle of the mirror help blow the laser-expelled dust downwards.

A possible additional role for the laser cleaning system is stripping old mirror surface coatings prior to recoating. This stripping process for the 8-m class mirrors using conventional acid wash solutions can be problematic and for dielectric overcoats, which are being considered, it may be a serious issue. Focusing the laser beam tighter on the mirror surface causes near instantaneous heating of the mirror coating that creates a small plasma around it. This heating and plasma formation detaches the coating from the substrate, and the short-pulsed nature of the process imparts enough momentum to cause the coating material to pop off the substrate. This process should not damage the substrate surface. Tests on the aluminum coated mirror samples used during these experiments indicate that a fluence of 2.2 J/cm^2 is needed to remove the coating in a single shot. Lower fluence can be used if multiple laser shots are used to remove the coating.

6. CONCLUSION

Laser cleaning appears to be a viable method for cleaning large diameter primary mirrors. Its advantages over CO_2 snow cleaning include improved cleaning of both particulates and molecular contaminants, improved emissivity recovery, a relatively simple delivery system, and significantly lower operating costs. In addition, the same laser cleaning system can be used to strip off old mirror coatings prior to recoating.

7. ACKNOWLEDGMENTS

The authors wish to acknowledge and thank Keith Raybould, Ruth Kneale, and Fred Gillett for providing the contaminated and CO_2 snow cleaned mirror samples, and for their assistance during this program. This work was supported by the National Science Foundation under grant number AST-9115804.

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