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Comparison of Laser and $C0_2$ Snow for Cleaning Large Astronomical Mirrors

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ABSTRACT. Contaminants on large astronomical reflecting surfaces (hereafter "mirrors") can significantly degrade their reflectivity, IR emissivity, and light-scattering properties. We will show data that the emissivity and scattering can degrade appreciably after just a few days or weeks. A safe, effective, and inexpensive cleaning technique, preferably one that can be used *in situ*, is especially important for 4- to 8-m class mirrors. Two cleaning methods CO_2 snow and pulsed ultraviolet (UV) lasers, offer the potential to satisfy these needs. Our primary purpose is to compare the two methods, and highlight their advantages and problems. Also, since the UV-laser cleaning technique is a new one, we describe how it works and how it may be implemented. We found that UV-laser cleaning removes contaminants that standard CO_2-snow-cleaning techniques do not remove as well or not at all. After 2-4 weeks of exposure, Al-coated-mirror samples placed under the mirror covers of the UKIRT telescope on Mauna Kea and the 4-m telescope on Kitt Peak were cleaned about twice as effectively by the UV laser than the CO_2 snow, based upon the amount of contamination left on the mirrors. For long exposure times, the laser cleaning also restores the thermal emissivity better than the C02 snow. While a CO_2-snow delivery system can be less expensive than a UV-Iaser-cleaning system, the operation costs for cleaning a large-diameter mirror with CO_2 snow can be substantially greater than the costs to run the laser. Unlike C02 snow, laser cleaning can be applied no matter what the local humidity. The ease of both methods facilitates frequent use; however, the cost of the CO_2 may eventually limit its usage.

1. INTRODUCTION AND BACKGROUND

Reflecting surfaces of astronomical mirrors degrade once they are exposed to natural contamination in their local environment, principally dust, molecular contaminants (e.g., pollens, oil films, water spots), and a combination of water humidity and reactive gases (e.g., H_2S) that can lead to tarnishing. Functionally, these problems lead to decreased efficiency of the telescope through the loss of reflectivity (as much as 1% per month), added thermal emissivity, and increased scattered light.

Telescopes now being designed and built impose additional performance requirements on large mirrors and the methods used to maintain their performance. For example, some telescopes have or are being optimized for operation in the thermal infrared (TIR). Any opaque particles or molecular contaminants add to the TIR emissivity of the surface, which in turn significantly increases the TIR background levels seen by detectors. For the Gemini 8-m Telescopes Project, a goal of 2% TIR emissivity has been set (Mountain et al. 1994). This goal requires a very clean silver surface since, as we will show later, ordinary exposure to contamination rapidly degrades the emissivity.

Studies needing very high dynamic range, such as studies of the solar corona and the search for planetary systems or brown dwarfs around stars, are very susceptible to increased background light caused by scattering on reflecting surfaces. This is especially important for telescopes with superpolished optics. For example, the performance goal for a 4-m solar coronographic telescope is a scattered light intensity of 10^{-6} of the solar disk at 1 arcsec=2.54 cm from the limb (Beckers 1994). Data obtained at the National Solar Observatory's 40-cm coronograph (Abraham

1991) indicates that scattering increases at a rate of ~I% per month, so that constant cleaning may be essential. However, the application of traditional cleaning techniques in the tightly enclosed telescope tube may prove to be very difficult.

Traditional *in situ* cleaning methods include washing the reflecting surface with water or other liquid solvents, or using a spray-on, peel-off plastic coating. The many risks and indirect costs (i.e., labor) of using these methods are such that they are used infrequently (~annually), which means the telescopes are generally operated in less than pristine conditions. There are also secondary problems with both methods. Data obtained at Kitt Peak National Observatory (Abraham 1991) suggests that water cleaning may accelerate tarnishing. Under certain conditions the application of peel-off cleaning films can trap water under the film. For this reason Kitt Peak Observatory has ceased to use the peel-off cleaning films. Both of these techniques become increasingly intractable for large-diameter mirrors. Until recently, the only alternative to cleaning has been recoating. For very large mirrors the costs and risks of recoating motivates a search for better *in situ* cleaning techniques.

More recently sprays of CO_2 snow have been used for cleaning telescopes. The method relies on impulsive forces from CO_2 crystals to knock particulates from the surface (see Sec. 2.1). For many observatories this method is far easier and safer than the traditional cleaning techniques, and is very effective at removing dust. It also can be easily scaled to clean large-diameter mirrors. Consequently, CO_2 snow is rapidly becoming the method of choice against which other methods are compared.

In this paper we discuss a new technique, pulsed ultraviolet (UV) laser cleaning, and compare it with CO_2-snow cleaning. The technique was developed initially for cleaning semiconductor wafers (Zapka et al. 1991) and has been very effective on small-diameter mirrors (Osiecki and Magee 1990). The technique is generally safe on any reflecting surface; although, like all other cleaning methods, its efficiency depends on the nature of the contaminant. Both CO_2-snow- and UV-Iaser-cleaning techniques are described in the next section. We explain how the laser cleaning method works, how the method might be applied to astronomical mirrors, and describe the evaluation criteria for comparing it with CO_2 snow. In Sec. 4 the results obtained from cleaning test samples are summarized. A brief comparison of expected operational performance is discussed in Sec. *5*.

2. CO_2-SNOW AND UV-LASER-CLEANING TECHNIQUES

2.1 CO_2-Snow Cleaning

CO_2 snow is 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 is on the order of the nozzle diameter (typically I mm). Particulates on the mirror surface are blown away through impact with the crystals. The CO_2-snow blast can be directed at the mirror surface at either near-normal incidence or at a high angle of incidence (the former was used during our experiments). The snow quickly sublimates, so the particulates glide over the mirror surface on a cushion of gas. The process is simple and fast [the 3.5-m mirror at Apache Point Observatory is cleaned in about 30 min (Klaene 1995)] and can be generally done with a minimal amount of set-up and clean-up effort.

However, the method has certain limitations and constraints. In order to avoid leaving any residue on the mirror surface it is important to use very pure CO_2 ($\geq$99-99%) (Zito 1990); although, as explained later this has not been the expenence of all users. The method must be used under conditions of low ambient humidity in order to avoid moisture condensation on the cooled mirror surface. Molecular contaminants and very small dust particles, which adhere with a relatively high force per mass and can lie under thecushion of gaseous CO_2, are not as effectively removed. Other issues will be discussed in Sec. 5.

2.2 UV-Laser Cleaning

Light from a pulsed UV laser is scanned across the surface to be cleaned in a raster pattern. Several physical mechanisms operate simultaneously. Bonds that cause molecular contamination to adhere to the surface, typically a few eV, are broken by the UV photons. Also, relatively absorptive surface contaminants preferentially absorb the UV light and photothermally vaporize, whereas the highly reflective mirror coating is unaffected. This means that the laser energy density or "fluence" needed to clean the mirror is well below the damage threshold of the coating.

Water droplets and other types of absorptive films can be efficiently removed. Particulates are removed by both photothennal vaporization and by generation of a photoacoustic stress wave in the mirror substrate which breaks the bonds that hold dust particles on the surface and causes them to bounce off the mirror. A pulsed laser is essential to stimulate this photoacoustic effect.

Commercial excimer lasers are excellent candidates for cleaning astronomical mirrors. They use a rare gas/halogen mixture to generate UV light (λ=193-351 nm). For the work on Al-coated surfaces reported in this paper, a XeCl laser is used whose output is 308 nm (4.0 eV). Silver, whose reflectivity is relatively low at this wavelength, could be more safely cleaned using a XeF laser at 351 nm (3.5 eV).

We find that a minimum of 2 pulses or "shots" per laser spot size on the mirror are needed for thorough cleaning. Hence, the cleaning time is controlled by the pulse repetition rate. Commercial excimer lasers are capable of generating pulses of adequate fluence at 100-1000 Hz. For example, a 200-Hz laser at 2 shots per site can clean an 8-m mirror in less than 2 hr. The rate at which expendables (the rare gas/ halogen mixture) are consumed is very small so operating costs are low. Moreover, the scanning process is easily automated, meaning that the risks to and costs of personnel are n-tinimal. There is no risk of residual films even in high ambient humidity. Therefore, once installed these attributes of laser cleaning actually encourage very frequent application.

One potential problem with laser cleaning is that an inadequate fluence can bake molecular contamination onto the surface. For this reason a laser beam with fairly uniform illumination is needed. Commercial excimer lasers with adequately uniform beams are available. Even more uniformity is possible by using an optical homogenizer and taking advantage of the inherent incoherence of the excimer laser beam.

Although UV-laser cleaning can be quite practical to implement, the primary issue is its performance relative to other methods, such as CO_2 snow. Since lasers have not come into use in observatories, comparative evaluation studies are most efficiently approached through small-scale experiments in the field as well as laboratory tests.

3. CO_2-SNOW AND UV-LASER CLEANING EXPERIMENTS

In this section we present a description of a series of comparative tests of CO_2-snow and UV-laser cleaning. Laboratory results are also presented. As explained later, the criteria for evaluation are the relative amount of contamination left on the surface and the recovery of the TIR emissivity. The results of field tests are deferred to Sec. 4.

3.1 Mirror Samples and Contamination Procedures

The mirror test samples consist of 10.2-cm (4-in) diameter polished silicon wafers coated with ~1000Å of aluminum provided by the Gemini 8-m Telescopes Project. Gemini personnel arranged for some of the samples to be naturally contaminated in the ambient air flow at the UKIRT observatory on Mauna Kea. Pairs of mirrors were exposed for 3, 7, 14, 21,..., 84 days.

Another set of samples was placed next to the primary mirror in the 4-m Mayall Telescope at Kitt Peak. These were exposed to natural contamination during the early summer when airborne pollens are at their annual peak. The types of rock dust at Kitt Peak are characteristic of those at many sites throughout the U.S. Southwest and somewhat different than the characteristic basalts and carbonates at Mauna Kea.

Other clean mirror samples were artificially contaminated at STI Optronics (STI) with finely crushed soil (primarily volcanic rock) obtained from Mauna Kea. The size and distribution of the dust particles was controlled to simulate that found on naturally contaminated samples exposed for ~2 weeks at the same site. These artificially contaminated samples were used to optimize the laser-cleaning parameters. It was found that these lab-prepared contaminated mirrors could be cleaned more thoroughly than their natural counterparts, presumably because of dust application under dryer lab conditions. Consequently, these artificially contaminated samples were not used to compare the relative effectiveness of the various cleaning techniques.

3.2 Laser-Cleaning Test Apparatus

A schematic of the laser-cleaning system used in the lab at STI for cleaning the mirror samples is shown in Fig. 1. The rectangular output from a commercial XeCl laser (Lambda Physik Model EMG-201) is converted into a square beam using cylindrical lenses. The beam energy is monitored with a beam splitter and energy meter. Attenuators control the fluence incident on the target. The laser spot size is ~6mmx6 mm. A beam homogenizer, which provides ±5% illumination uniformity, was used for most of the cleaning; however, as explained later it was determined that the homogenizer is not likely to be necessary for effective cleaning of the naturally contaminated mirrors.

The mirror surface is held in a position perpendicular to the horizontal laser beam with the mirror translated at a constant horizontal speed during cleaning. The number of shots per sample area is controlled with the laser-pulse repetition rate. Vertical translation is done manually with ~25% overlap between cleaning sites. A gentle stream of dry air is used during cleaning to prevent dust from resettling on the surface.

Except as noted, the laser fluence ranged from 0.33 to 0.38 J/cm^2 for the data presented in this paper. Little difference in cleaning efficiency is noted within this range. Most tests were conducted with 4-8 laser pulses per cleaning site.

3.3 Optimization of Laser-Cleaning Parameters

The two most relevant parameters that effect the optimization of pulsed UV-laser cleaning are the laser fluence and the number of pulses, or "laser shots" per site on the mirror. Tests performed on the artificially contaminated mirrors indicate that laser-cleaning efficiency levels off after two or three shots per site. We adopted 4 shots per site for our experiments since it allows this parameter to be fixed at a level where it no longer influences the results. Similar tests show that little additional benefit is derived if the laser fluence is greater than ~0.4 J/cm^2 per shot (with 4 shots per site). Therefore, cleaning was done at fluences below this level.

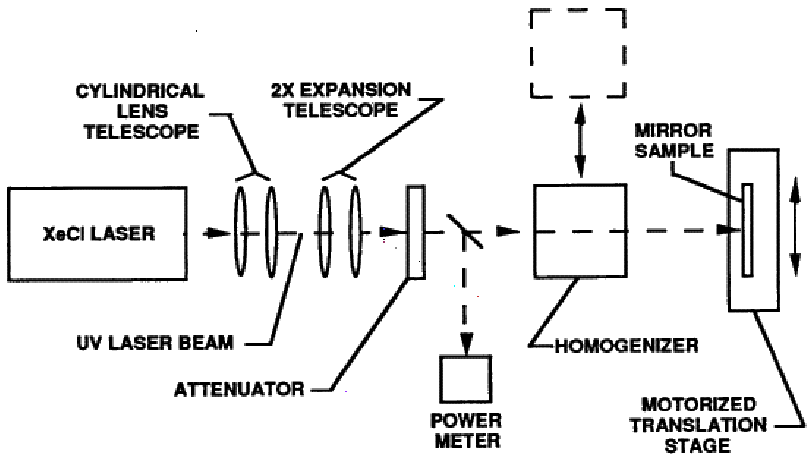


Fig. 1 - Schematic of UV laser cleaning experimental system.

Note, the cleaning effectiveness tends to gradually decrease with lower laser fluence. For example, a fluence of 0.2 J/cm^2 tends to remove roughly 50% less than a fluence of 0.4 J/cm^2 . This implies that lower laser fluences may still be effective especially if the mirror is not very contaminated because it is cleaned frequently. This has both cost advantages (a smaller laser can be used) and safety advantages to both the mirror coating and personnel. Hence, the fluence levels quoted in this paper should not be viewed as necessarily the minimum values needed to achieve satisfactory cleaning.

Another potentially important parameter is the laser wavelength. We elected to fix the wavelength at 308 nm since the efficiency of the laser is highest for XeCl gas. There is no reason to expect that the cleaning efficiency varies with wavelength unless the surface being cleaned is not highly reflective at that wavelength. (In this case, the surface coating may be susceptible to damage by the energy absorbed from the laser beam.)

The minimum amount of overlap between scanning rows depends on the uniformity of the beam at the cleaning surface; the overlap is smaller for more uniform illumination. Effective cleaning with a homogenizer requires approximately 25% overlap. Without the homogenizer the beam has more rounded edges, and so an ~50% overlap was used.

3.4 Surface Safety Tests

An uncontaminated mirror sample was exposed to varying amounts of laser fluence. The onset of any physical changes to the coating was monitored visually using a bright light source and microscope. (The onset of physical damage typically occurs when the laser beam partially melts the coating, which then immediately resolidifies. This resolidified coating generally is not as smooth as the original coating and will manifest itself under bright light illumination.) It was found the onset for coating changes occurs at approximately 3-4 times higher fluence than needed for laser cleaning. At 6-7 times the cleaning fluence level (e.g., ~2.4 J/cm^2) the aluminum coating is removed by the laser beam. (Note, mirrors used to direct laser beams can last indefinitely as long as the laser fluence is below the threshold for onset of damage.) Hence, the laser fluence levels needed to clean the mirror are well within the normal operating range of the mirror. (Since any laser-cleaning system would be designed to utilize the maximum output energy of the laser, and the focusing telescope used to control the size of the laser-cleaning spot on the mirror would be designed to be only strong enough to provide the minimum spot needed, there would be no danger of accidentally depositing more laser energy than that needed for cleaning.)

The effect of possible damage or cumulative changes due to repeated laser cleaning of the mirror surface was investigated by repeatedly cleaning the same area of a mirror sample 200 times. No visual changes to the coating were observed. The laser also did not appear to worsen or change any existing minor surface damage on the mirror coating. These results are consistent with the previous statement regarding being below the damage threshold and with the fact that similar types of mirrors are used in laser applications where the laser beam may reflect off the same spot on the mirror for millions of shots with no adverse affects whatsoever.

We should emphasize, however, that under certain circumstances there is a chance that the laser beam could exacerbate existing coating damage. These circumstances would include those in which the adhesion of the coating to the substrate was weak. (The adhesion of the aluminum coating to the silicon substrate used in this work appears to be stronger than similar types of coatings on fused silica.) Therefore, it is important to test clean a mirror sample with the actual mirror coating on the intended substrate material in order to determine the safe operating range for the laser fluence.

During the cleaning tests, the laser beam is scanned across the entire surface of the silicon wafer, including the edges where the Al coating meets the edge of the wafer. On a microscopic scale this edge is very rough. No degradation of the Al surface is seen even after repeated scanning.

In earlier experiments, a polyurethane surface covered with black paint was subjected to laser cleaning in order to determine whether normal cleaning procedures might damage painted baffles, support struts, or dome walls. No degradation of the black paint layer was discernible. Hence, although the laser beam, which reflects off the primary mirror during the cleaning process, will strike the inside dome walls and telescope frame, this will not cause any harm.

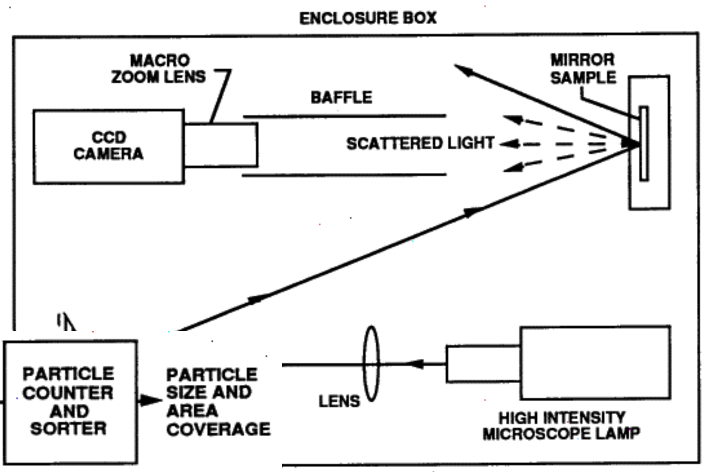
3.5 Surface Assessments Methods

The cleaning criteria reflect the primary goal of this study: a comparative study of various cleaning techniques. Our methodologies characterize the differences in the states of surfaces after various cleaning techniques have been applied. Thus, for example, the assessment of the *absolute* mirror reflectivity was not measured since special, highly accurate equipment is needed to measure the small changes expected over just a few weeks of exposure. Nonetheless, one measured absolute parameter, the TIR emissivity, is a good index of the absolute reflectivity because emissivity and reflectivity are highly correlated for any mix of particles, and, as will be shown, small increases in emissivity are easier to detect than small changes in reflectivity.

In addition to absolute TIR emissivity, we used a simple technique that allows us to (1) characterize and compare the gross optical state of a surface, and (2) to measure the distribution of the majority of particle sizes that adhere to the surface. A schematic plan view of the system is shown in Fig. 2. Light from a high-intensity microscope lamp illuminates the sample at a constant illumination angle. A CCD camera is mounted obliquely to the sample so that no specular reflection is observable from an approximate 3 cm x 3 cm viewing area. Hence, only scattered light is detectable. The spatial resolution of the video camera is about 25 μm at the sample.

The image from the camera shows bright pixels where scattered light is detected and darkness otherwise. Processing of the image follows the steps shown in Fig. 3. A copy of the raw image is first sent through a 5x5 median filter yielding a background image free of bright points of light arising from scattering by small particles and other contaminants. This background image is then subtracted from the original image. The result is converted to a 1-bit image using an intensity threshold selected by visually inspecting the samples to verify that the smallest particles were not being eliminated and that artificial detections were not being introduced. These parameters were kept fixed during all the measurements.

The success of this procedure is illustrated in Fig. 4. Figures 4(a) and 4(b) show two raw video images of one sample exposed for 21 days at Mauna Kea before and after laser cleaning, respectively. Figures 4(c) and 4(d) show the corresponding processed images at the processing stage designated "Isolated Particles" in Fig. 3.



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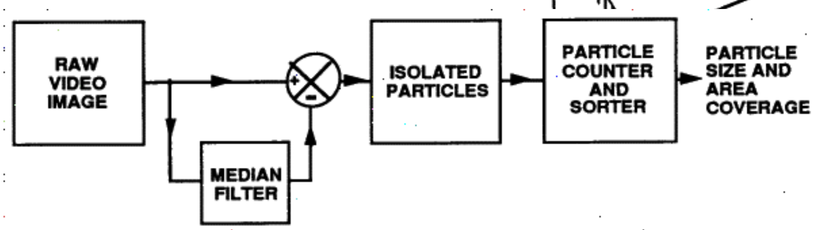

Fig. 3 - Flow chart for analysis of mirror sample video images.

Subsequently, the 1-bit images are processed to determine the number of pixels per unit area in which scattered light ("spots") are detected. For example, the software finds the average amount of scattered light seen in Fig. 4(c) (before cleaning) is 2.3×10^3 pixels/cm^2; whereas, Fig. 4(d) (after cleaning) has $<0.36 \times 10^3$ pixels/cm^2 . Although the absolute mirror reflectivity could not be measured accurately, we can say with some certainty that ~85% of the initial contaminants were removed. The software also computes a histogram of the spot diameters.

Although the system is very sensitive for the detection of dust, it should be noted that several factors limit the absolute accuracy and physical interpretation of the pixels/cm^2 parameter. First, any particle smaller than ~25μm that causes the detection of a spot in the video image is counted to be 1 pixel= 25μm in size. Also, the apparent size of a particle can appear bigger than its actual size depending on the illumination condition (e.g., brighter illumination tends to increase the apparent size). Consequently, the area corresponding to the pixels is a substantial overestimate of the actual area covered by dust and other contaminants. Second, small particles in adjacent pixels are assumed by the algorithms to be a single larger particle. These crowding effects are not significant in most video images, and no correction for crowding effects was applied. Finally, we note that rock dust is not optically black, which is why scattered light is detectable by the video camera. Hence, the covering of the surface by the dust is not the same as (1-reflectivity); although, the two variables have a monotonic, but probably nonlinear relationship to each other. Despite these limitations, the use of this measurement provides a means of quantifying the *relative* effectiveness of a cleaning method with the understanding that small particles, which may not contribute significantly to reflectivity loss or emissivity, tend to be overemphasized.

The mirrors also contain pits and scratches that cause scattered light. The software does not attempt to distinguish between surface blemishes and contamination. Although these scars affect the reflectivity and emissivity of the surface, obviously they cannot be removed by any cleaning process. Even a perfect cleaning process cannot restore the performance to pristine conditions, and recoating is eventually necessary.

The TIR measurements are described elsewhere (Kneale and Raybould 1994). A LN_2-cooled InSb photometer measures the sample thermal emission at 3.96μm. The measured TIR emissivity is the ratio of the output voltage

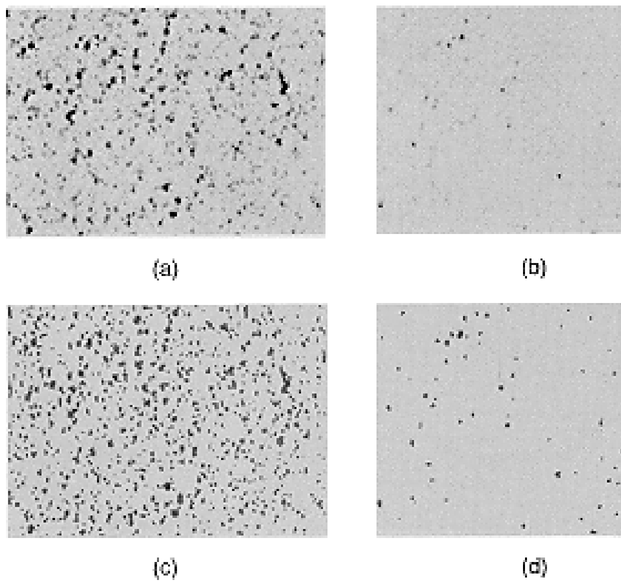

Fig. 4 - Examples of raw and reduced video image data. (a) Raw video image of naturally contaminated mirror [21 days exposure]; (b) raw video image of laser-cleaned mirror shown in (a) [0.38J/cm^2, 12 shots/site, no homogenizer]; (c) reduced data of image (a) showing isolated contaminants and mirror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

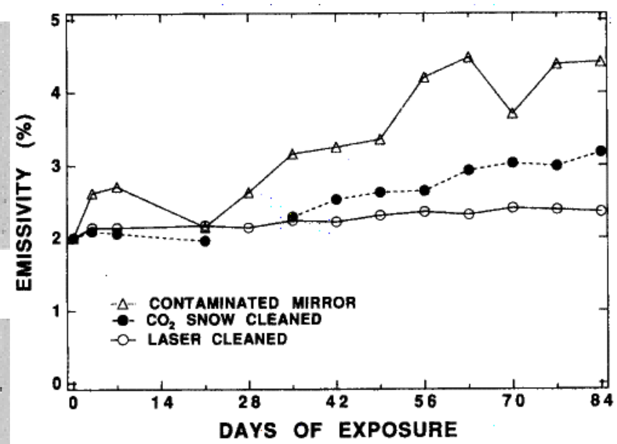

Fig. 6 - Thermal infrared emissivity results obtained by Gemini (Kneale and Raybould 1994) for the laser and CO_2-snow-cleaned mirros given in Fig. 5.

from the detector when it is viewing the sample to the detector voltage measured from a reference ambient blackbody, after subtraction of instrumental bias from both voltages.

3.6 Sample Handling Procedure

The pair of samples returned from Mauna Kea after exposure to contamination were sent directly to the Gemini Project Office where their TIR emissivity was measured. One sample was CO_2-snow cleaned and its emissivity remeasured. Both samples were then sent to STI where the remaining contaminated sample was laser cleaned and the pixels/cm^2 parameter for both mirrors was measured using the video system. Both samples were returned to Gemini and the emissivity of the laser-cleaned mirror was measured. Although not an optimum procedure, it did provide two independent measurements of the mirror characteristics. The evaluation of cleaning methods is valid provided that the contamination of a pair of samples exposed for the same duration are identical.

Samples exposed at Kitt Peak were handled somewhat differently. The sample pairs were returned directly to STI where they were either laser or CO_2-snow cleaned, and analyzed with the video system. While the emissivity was not measured for these mirrors, it was verified that both mirrors experienced the same amount of contamination. Thus, the assumption of identical contamination used for the interpretation of samples from Mauna Kea appears to be justified.

4. EXPERIMENTAL RESULTS

The results obtained for CO_2-snow and laser cleaning of the samples returned from Mauna Kea are summarized in Fig. 5. The average number of light-scattering pixels per cm^2 before and after cleaning is plotted as a function of exposure duration. The onset of contamination is apparent after about a week of exposure. It is quite clear that for exposures of two weeks or less the performance differences between the two cleaning methods are not significant. For longer times the laser is roughly two times more effective. Unlike the lab tests we find that there is a slight advantage to using more than 4 shots per cleaning site.

We offer only speculative explanations for the differences between the two cleaning methods. Preliminary results of scanning electron microscope (SEM) measurements of the post-cleaned surfaces indicate that CO_2-snow cleaning removes fewer of the molecular contaminants and 50-100 μm-sized dust particles. For longer exposure times, neither method completely restores the reflecting surface to its original pristine state. Visual inspection reveals that

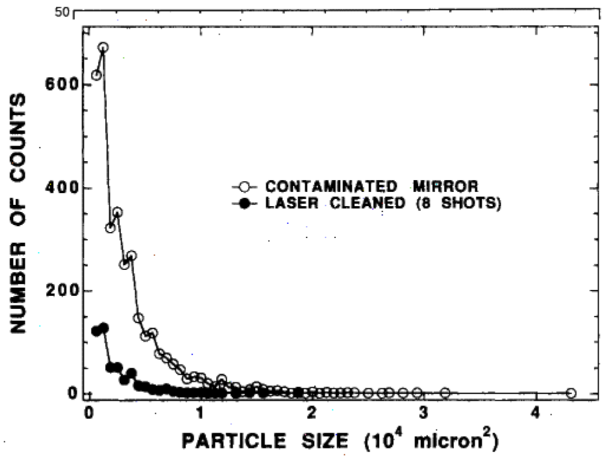

Fig. 7 - Contaminant size distribution before and after laser cleaning of a naturally contaminated mirror sample (21 days) using 0.41 J/cm^2 and no homogenizer. Note that some of the large contaminats may have been molecular contaminants, such as water spots.

Fig. 5 - Comparison of laser- and CO_2-snow-cleaning performance on naturally contaminated mirror samples exposed at Mauna Kea, Hawaii. Plotted is the average number of pixels/cm^2 of scattered light (see text for explanation) from particulates and molecular contaminants as a function of exposure days.

scratches and pits become more prevalent with exposure length. This observation plus a possible accumulation of tenacious types of particulates and molecular contaminants, and a slow buildup of tarnished metal may all limit the long-term effectiveness of all cleaning methods.

A complete understanding of the physics and chemistry of the formation and stability of surface contamination and defects is outside the scope of the present study.

As an aside, the data in Fig. 5 indicate the contamination did not increase monotonically. This is most unexpected and counterintuitive. The simplest explanation is that two of the samples, those at 21 and 70 days exposure, were accidentally mislabeled. No matter what might have affected these few aberrant data points, the trends are quite clear and the empirical results stand. (Note, the 21-day-exposure mirror in Fig. 5 is different from the 21-day-exposure mirror referred to in Fig. 4.)

Figure 6 shows the TIR emissivity results for the same samples (Kneale and Raybould 1994). The increase in emissivity tracks the pixels/cm^2 data plotted in the previous figure. Both cleaning techniques almost completely recover the emissivity for the first two weeks. The laser-cleaned samples appear to asymptotically approach an emissivity of 2.3% after 12 weeks; whereas, the CO_2-snow-cleaned samples show an emissivity of 3% that is still increasing almost linearly at the end of the exposure period. Comparing the emissivity and pixels/cm^2 data in Figs. 5 and 6, we speculate that smaller particles contribute less to the emissivity than to the detection of scattered light. (See also the preceding discussion of the secular characteristics of Fig. 5.)

The laser-cleaning data given in Figs. 5 and 6 were obtained using a beam homogenizer. Separate laser tests with and without the homogenizer were performed on naturally contaminated samples from Mauna Kea. No significant differences in TIR emissivity and light-scattering characteristics were seen in the comparison tests.

Particle size histograms measured from the analysis of video images are shown before and after cleaning with a laser in Fig. 7. Both large and small particles are removed; however, most of the remaining particles are small whose size is probably below the 25μm resolution of the video images. This same type of behavior has been seen in other studies of laser cleaning (Zapka et al. 1991) and helps explain the fact that pristine conditions are not maintainable either by CO_2-snow or UV-laser cleaning.

Figure 8 shows the results of the scattered-light evaluation conducted on samples exposed at Kitt Peak. The results are generally consistent with those shown in Fig. 5 for the samples exposed at Mauna Kea. However, the higher cleaning efficiency of the laser process emerges from the data even before two weeks elapse. The apparent decline in the rate of contamination before cleaning is because of the summer shutdown, which was interrupted only to observe the collision of SL9 fragments on Jupiter for a few days. Note that the amount of contamination increases monotonically over time as expected.

The errors bars in Fig. 8 are derived from variations in results obtained at several different locations on the samples. Many errors bars are smaller than the plotting symbols. We expect that similar magnitude errors bars are likely to characterize the data from the samples exposed at Mauna Kea.

5. COST AND IMPLEMENTATION COMPARISONS

As part of this research effort we also surveyed the CO_2-snow-cleaning experience of users at APO, CFHT, IRTF, Keck, and MMT. A typical CO_2-snow delivery system consists of someone on a raised platform who manually sprays the surface with CO_2 snow emitted from a wand and nozzle. A wand and nozzle system specifically designed for applying the CO_2 snow can be purchased for about $1,500, including a cart for the CO_2 bottle. The amount of labor varies depending on the size of the mirror, but for a large mirror such as the 10-m Keck it may require about -6 manhours.

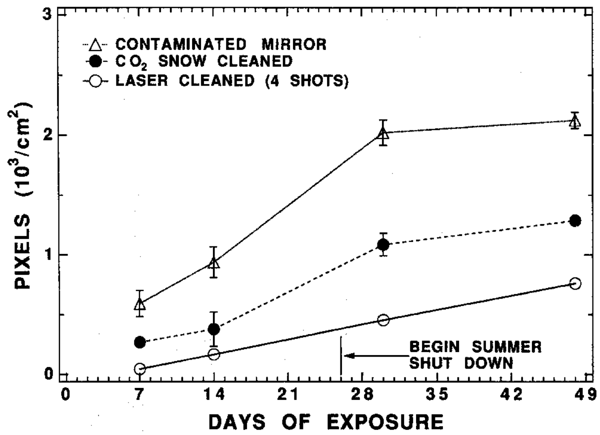

Fig. 8 - Comparison of laser and CO_2-snow-cleaning performance on naturally contaminated mirror samples exposed at Kitt Peak, Arizona. Plotted is the average number of pixels/cm^2 of scattered light (see text for explanation) from particulates and molecular contaminants as a function of exposure days. (See text for explanation of shut down indicated on the figure.)

There are very few problems with applying the technique. The amount of force from the CO_2-snow discharge is small enough that an operator can hold the wand close to the mirror surface without danger of accidentally striking it. The wand can build up significant static charge; therefore, it is important to ground the wand and/or the mirror to protect nearby sensitive electronic equipment. Breathing unsafe levels of CO_2 does not appear to be an issue. Some users (CFHT and IRTF) have also verified Zito's claim that it is important to use at least 99.99% pure (Grade 4) CO_2 to ensure no residues are left on the mirror surface; whereas, other users (Keck and MMT) have found that 99%-99.5% purity works satisfactorily[1]. The uniformity of the cleaning does depend on the technique of the operator and the type of cleaning head used, and can affect the amount of CO_2 consumed. (In general, more unifon-n cleaning tends to require more CO_2 snow usage.) Lastly, the technique cannot be used when the humidity is >80% because of condensation problems.

The technique can be quite effective if applied regularly and frequently. Emissivity data taken at the IRTF (Toomey and Hall 1994), shows that cleaning with CO_2 snow every 2 weeks reduced the rate of emissivity growth by an order of magnitude to ~0.05%/month. This rate appears smaller than the apparent rate indicated by the emissivity data of Fig. 6; although, it is difficult to make a direct comparison because the mirror samples in Fig. 6 were not cleaned every 2 weeks.

The emissivity of the 3- and 7-day exposure CO_2-snow-cleaned mirrors grew at a rate higher than the IRTF results. Cleaning with CO_2 snow monthly, Keck has noticed an increase of reflectivity of typically 1% with changes as large as 3% observed (DiVittorio 1995).

Several users believe that frequent cleaning is necessary with a minimum interval being 2 weeks. Weekly or even daily cleaning may be appropriate at times, especially during dusty or stormy periods. Frequent cleaning appears also important for IR observations, which are particularly sensitive to the increased en-tissivity caused by contaminants on the mirror (Toomey 1995; Kindred 1995). With less-frequent cleaning users notice the same build up of contamination on the mirror surface that we observed over long exposure periods. As we also observed, these are subsequently more difficult to remove with the CO_2 snow.

The cost for expendables depends upon the purity and amount of CO_2 used per cleaning. Our survey revealed some variations probably due to differences in the rate that users apply their CO_2 snow. For example, the IRTF (Toomey 1995) uses a little less than one bottle of 99.99% pure CO_2 per cleaning of their 3-m mirror at a cost of ~$120 per bottle. This gives a cost per cleaning of <$17/m^2 . The CFHT requires approximately 14 kg (30 lbs) of Grade 4 CO_2 at a cost of roughly $3/lb to clean their 3.6-m mirror (Magrath 1995). This translates to a cost of -

[1] Although Keck has been using lower purity C02, there are plans in the near future to change to Grade 4 in order to avoid possible contaminants (DiVittorio 1995).

$9/m^2 . Keck uses 3 bottles of CO_2 to clean their 10-m mirror (Mason and DiVittorio 1995). Using a cost of $120 per bottle for Grade 4 CO_2, this implies a cost of -$4.6/m^2 ; however, as mentioned earlier, Keck is able to use 99% pure CO_2, which reduces the cost by a factor of 2-3.

If we use these CO_2 expenses to estimate the cost for CO_2-snow cleaning the 8-m Gemini mirror, we find the cost per cleaning ranges from a low of $230 to a high of $850. If we assume weekly cleaning, this implies an annual cost for CO_2 of $11,960 to $44,200. Gemini has made their own estimate and calculates that approximately 91 kg (200 lbs) of CO_2 is needed to clean their mirror at a cost of about $400 per cleaning, or $20,000 per annum for weekly application (Kneale and Raybould 1994). Hence, the cost of CO_2 for cleaning large-diameter mirrors could be significant if used frequently.

A plan to automate the CO_2-snow-cleaning process using a nonretractable rotating cantilevered system has been proposed for the ESO 3.5-m NTT telescope (Giordano and Torrejon 1994). Another proposal to mount a CO_2-spray system on the mirror covers is under consideration by Gemini (Kneale and Raybould 1994). The spray is directed across the surface by raising and lowering the covers. An automated delivery system should be easier to operate repeatably and safely, and will probably provide more uniform cleaning, but it will be more expensive to construct than a manual one.

It is only possible to conjecture about the best ways to implement a laser-cleaning system. The beam can be automatically directed at the primary mirror by computer controlled steerable mirrors, so the engineering issues are not especially difficult. The laser might be located near the enclosure wall where the view of the primary mirror is unobstructed. Besides the laser, a focusing telescope and a PC to control the mirrors are needed. A ventilation system to carry the released particulates away from the mirror surface may also be needed; however, by simply scanning the laser beam from top to bottom of a horizon-pointing mirror it may be possible to "sweep" the particles towards the floor. The need to protect personnel from exposure to the beam is essential, but simple methods (e.g., ordinary clothing for skin protection and standard safety glasses for eye protection) are in common use in industrial applications.

The cost of expendables is very low for a laser system. Cleaning an 8-m mirror requires less than $3x10^6$ shots. A single XeCl refill costs about $140 and lasts for 10^7 shots; however, a refill can be stretched much further if more shots are used even after the nominal lifetime of the gas mixture is exceeded. Cleaning costs total roughly $2,000 per year exclusive of labor assuming weekly cleaning. The capital cost of the laser is about $80,000, but the costs and performance of excimer lasers are improving as commercial applications for them proliferate.

6. CONCLUSION

Both CO_2-snow and pulsed UV-laser cleaning are convenient and effective ways to clean large mirrors. They operate in very different ways. Laser cleaning delivers photons directly to the surface where bonds between contaminants are effectively broken. Photoacoustic stress waves from the pulsed beam and photothermal vaporization are important at removing particulates, molecules, and thin films of water or oils. CO_2 snow relies on impulsive forces to knock particulates loose and is not likely to be as effective at removing small particles or other types of molecular contamination.

Field tests using samples contaminated at Mauna Kea and Kitt Peak clearly show that UV-laser cleaning outperforms CO_2-snow cleaning by as much as a factor of two in the long run. The quantitative advantages of laser cleaning are most dramatic for controlling TIR emissivity.

Cost and implementation issues are not likely to be decisive in selecting between the two methods. Any such decisions can be made on the basis of performance and reliability.

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