

James Webb Space Telescope primary and secondary mirror segment assemblies cleaning: a quantitative assessment

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ABSTRACT

The James Webb Space Telescope Primary Mirror Segment Assemblies (PMSAs) and Secondary Mirror Assembly (SMA) were cleaned at the Johnson Space Center (JSC) in January 2018. In order to quantify the effectiveness of the cleaning, the same cleaning process was performed on the PMSA and SMA traveling witness wafers. These wafers have accompanied their respective mirror segments from their arrival at the Goddard Space Flight Center, through transport to JSC, and ultimately their exposure in Chamber A for cryogenic testing. The traveling wafers were analyzed using an Image Analysis automated microscope both prior to and after the cleaning. The resulting data showed that the PMSA wafers' Percent Area Coverage (PAC) reduced by 83.5% on average, from 0.1524 PAC to 0.0251 PAC. The SMA wafer's PAC decreased by 97.2%, from 0.1194 PAC to 0.0034 PAC. Further analysis of the particle size bins was completed in order to calculate their particle distribution slopes. The slope of the PMSA wafers increased by 0.025 on average, and the SMA wafer slope increased by 0.066. This indicates that the ratio of large to small particles slightly increased after the cleaning across all mirror segments. Visual inspections of the wafers and the flight PMSAs and SMA showed considerable and comparable particulate coverage improvements, thus leading to the conclusion that the average PAC on the PMSAs and SMA improved by the same factor as their respective wafers.

Keywords: JWST, mirror, contamination, percent area coverage, cleaning, NASA, optics, image analysis

1. INTRODUCTION

The James Webb Space Telescope (JWST), shown in Figure 1, is an infrared telescope that will observe some of the furthest objects and earliest events in the universe, including exoplanetary systems, the formation of galaxies, the birth of stars, and the interstellar medium. The observatory will also aim to fill in specific chronological gaps in the timeline of the origin of the universe.

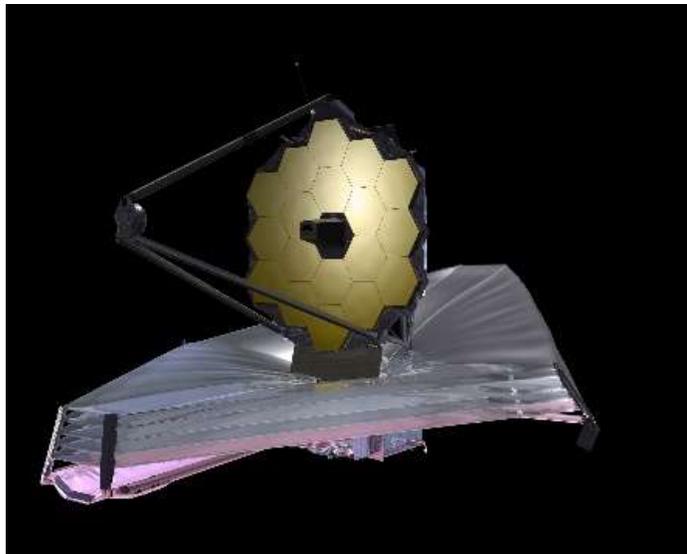


Figure 1. James Webb Space Telescope computerized rendering. (Credit: NASA)

The external optics of the JWST Optical Telescope Element (OTE), seen in Figure 2, include a 6.5 m Primary Mirror (PM) comprised of eighteen Primary Mirror Segment Assemblies (PMSAs) (left) and one 0.7 m Secondary Mirror Assembly (SMA) (right). These mirrors are constructed of a beryllium substrate and are gold-coated. They work together to reflect incoming light to the four instrument systems within the Integrated Science Instrument Module (ISIM).



Figure 2. The JWST OTE: Primary Mirror (Left) and Secondary Mirror (Right). (Credit: NASA/Chris Gunn)

These mirrors carry strict surface contamination requirements at each phase of JWST's Integration and Test (I&T) program that are driven by performance capability and stray light control requirements on orbit and at end-of-life.¹ Additionally, the absence of an enclosure for the optics presents a unique challenge in maintaining sufficient cleanliness. Therefore, a contamination Percent Area Coverage (PAC) budget was determined and instituted for the program. Because of the exposed optical surfaces and long I&T timeline, the cleanliness upkeep of the optics is crucial for proper operation of the telescope and fulfillment of mission objectives.

The integration of the OTE began in late 2015. Prior to integration, the PMSAs and SMA were stored in large, stainless steel containers that were hermetically sealed and kept under constant gaseous nitrogen (GN_2) purge. They were removed from these containers for alignment measurements and reinstalled thereafter. Eventually, the PMSAs were integrated onto the backplane with a composite cover that shielded the optical surfaces from contamination fallout. The covers were then removed on April 25, 2016 in preparation for ISIM integration with the OTE. Beginning at that time, the PMSAs were exposed to the environments at Goddard Space Flight Center (GSFC), Johnson Space Center (JSC), and inside the telescope's shipping container. The SMA, however, was kept covered as often as I&T activities allowed.

Witness fallout wafers accompanied the individual mirror segments throughout I&T activities. The wafers were installed inside the storage containers upon arrival at GSFC and each wafer's exposure was managed in accordance with the exposure of its respective mirror segment. Upon integration with the OTE, each wafer was deployed on a portable cart and placed as close to the mirrors as possible in order to follow the OTE throughout the cleanrooms. In certain situations when the primary mirror was inverted, the wafers could be covered to simulate the reduction in fallout accumulation. They could remain covered until the primary mirror was rotated to another orientation where the optics were subject to environmental fallout. This system allowed for an accurate portrayal of actual mirror segment fallout accumulation.

2. CLEANING PROCEDURE DEVELOPMENT

2.1 Cleaning procedure collaboration

A Ball Aerospace Technology Corporation (BATC) team developed the cleaning procedure for the JWST PMSAs and SMA in collaboration with the JWST team both at their facility and at JSC. Experiments were designed by the BATC team in order to determine the most effective cleaning method that presented the least risk to the flight hardware. The BATC and JWST teams utilized silicon particle fallout wafers from NASA and Northrop Grumman Aerospace Systems (NGAS) with a variety of predetermined levels of contamination. The needed levels were determined by the calculated cleanliness ranges of the PMSAs and SMA at this time.

The test fallout wafers were scanned using a standard Image Analysis (IA) technique for particulate and residual cleanliness prior to any cleaning activity in order to confirm baseline numbers. They then underwent one of two cleaning methods and were rescanned to determine post-cleaning results. The IA data was used to calculate the improvement.

2.2 Image analysis of particle fallout wafers

Particle fallout wafers are processed through an IA system consisting of a Leica DM6000M microscope connected to a Sentech STC-TC202USB Color Progressive CCD camera, a Marzhauser Wetzlar stage, and a Clemex Tango Motorized Stage Controller and Joystick. The system is controlled by Clemex Vision 7.08 software. A fallout wafer is placed on the microscope stage and manually focused at 3 points. The software commands the microscope to navigate the wafer while the camera captures numerous images. The system can recognize particles and fibers of various sizes as small as 5 microns. The software then performs cleanliness level calculations to determine total PAC, particle counts and size distributions, and fiber counts.²

All fallout wafers used were 10.2 cm in diameter. The total scan area of each wafer was 47.1 cm² at a nominal magnification of 50x.

2.3 Cleaning methodologies

Two potential brush cleaning methods were performed on the test fallout wafers. Winsor & Newton Cotman Water Colour Series short handle nylon brushes were used to remove particulate from the surfaces of the wafers. The brushes were initially extracted for Non-Volatile Residue (NVR) before arriving at JSC. They were wetted with a distilled solution of heptane and isopropyl alcohol (HIPA) and dried with a non-shedding wipe just prior to use. This was repeated on each brush just prior to cleaning each test wafer.

The first method involved brushing across the entire surface of the test wafers in a unidirectional pattern toward the wafers' straight edges. The second method began by repeating the brushing pattern from the first method. There was a concern, however, that particulate could accumulate near the straight edge. Therefore, an additional perpendicular swipe was included in an effort to remove any accumulated particulate. These methods are portrayed in Figure 3.

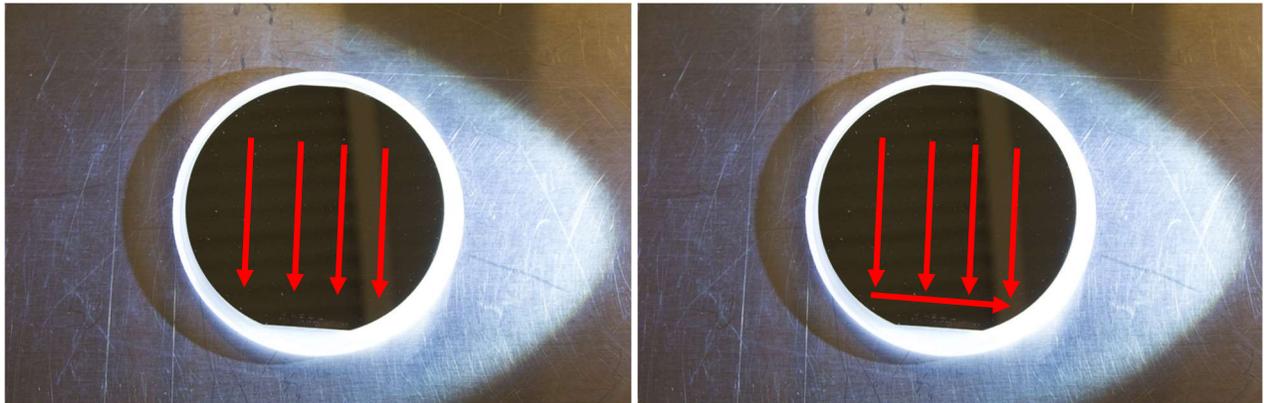


Figure 3. Portrayal of the brushing patterns of the first (Left) and second (Right) methods. (Credit: NASA/Chris Gunn)

A procedure for spot-cleaning was also developed to remove large fibers, adhesive residue, large particles, and evaporation marks from the PMSA and SMA optical surfaces that were not removed by the brushes. The process included the use of multiple organic solvents and deionized water to remove the contaminants. Features that could not be removed were documented. Details regarding this procedure have been published by the BATC team.³

2.4 Cleaning trials results

The test results of the first method are detailed below in Table 1.

Table 1. First method test trial data.

Sample ID	Scan Event	PAC	Delta (%)	Number of Objects	Delta (%)	NVR (Å)	Delta (%)
NGAS 4	Pre-Cleaning	0.0990	77	5946	72	2.3324	5.54
	Post-Cleaning	0.0230		1663		2.2031	
NGAS 5	Pre-Cleaning	0.7873	91	106385	88	2.5314	2.14
	Post-Cleaning	0.0732		13920		2.4771	
11_30_16_01	Pre-Cleaning	0.0193	95	1319	80	2.1890	-1.90
	Post-Cleaning	0.0010		240		2.2305	

The data showed an average reduction in PAC by 87%, number of objects by 78%, and ellipsometry-detected NVR by 1.93%. No particle accumulation was observed along the straight edges of the wafers.

The results of the second method are detailed below in Table 2.

Table 2. Second method test trial data.

Sample ID	Scan Event	PAC	Delta (%)	Number of Objects	Delta (%)	NVR (Å)	Delta (%)
NGAS 3	Pre-Cleaning	0.0091	78	1687	66	1.9988	1.98
	Post-Cleaning	0.0020		572		1.9593	
NGAS 6	Pre-Cleaning	0.0379	69	7886	65	2.0101	2.12
	Post-Cleaning	0.0012		2784		1.9659	
11_30_16_40	Pre-Cleaning	0.0151	99	1336	86	2.1997	0.50
	Post-Cleaning	0.0002		181		2.1887	

The data showed an average improvement in PAC by 82%, number of objects by 72%, and ellipsometry-detected NVR by 1.56%.

The results indicated that the brushing technique would remove approximately 84.8% of the particulate contamination present on the mirror segment optical surfaces. To determine the mirror PAC reduction after cleaning, this procedure was reproduced using the first method on their witness wafers as detailed in Section 4. Changes in molecular contamination were negligible, so the wafers were not processed with the ellipsometer before or after cleaning.

2.5 Flight hardware cleaning remarks

Despite the fact that the first method delivered slightly better average results than the second method, the additional perpendicular swipe was performed on the flight mirror segments to ensure that particulates would not migrate into gaps between the individual elements. Because the surface area of a flight mirror is much larger than that of a fallout wafer, there was a higher possibility of particulate contamination build-up. This step aided in reducing any risk of particulate migrating into any interior surfaces.

The PMSAs and SMA were cleaned by BATC personnel with JWST team support at JSC. Observations and lessons learned from the cleaning event are detailed in the BATC team's publication.³ The cleaning was considered to be an important success by Project Management.

3. BACKGROUND OF WITNESS WAFERS

Each PMSA and the SMA has been accompanied by a 10.2 cm silicon particle fallout wafer to monitor accumulated contamination throughout the respective mirror segment's exposure during the I&T phases of JWST after delivery to GSFC. The mirror segments arrived inside hermetically sealed shipping containers that were opened for receiving inspections upon delivery. During these inspections, the particle fallout wafers were affixed to stages inside the containers to track accumulation as pictured in Figure 4.

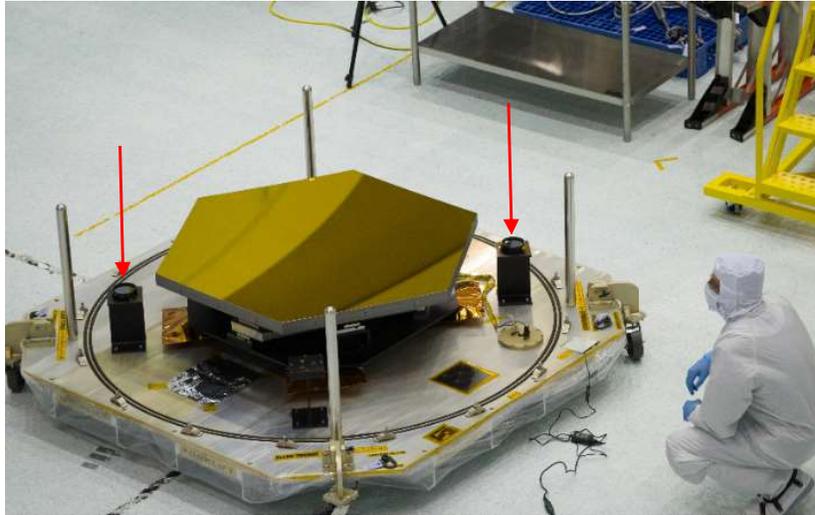


Figure 4. Particle fallout wafers affixed to stages inside a mirror segment's storage container. (Credit: NASA/Chris Gunn)

The mirror segments arrived at GSFC with provided initial cleanliness data, but the wafers began in a clean state. Therefore, any determination of a current cleanliness PAC thereafter would require the addition of the mirror segment's initial condition (PAC_o):

$$PAC = PAC_o + PAC_{wafer} . \quad (1)$$

As the mirror segments were processed throughout the various I&T phases at GSFC and JSC, the monitoring wafers were exposed to the same environments. These included multiple cleanrooms and a cryogenic vacuum chamber, both at ambient and vacuum. Surrogate fallout wafers were used for shipment between facilities (PAC_{ship}) and certain mechanical tests (PAC_{MT}) due to a lack of available space inside the shipping container and test facilities. Data from the surrogate wafers must then be added in as well when determining current cleanliness levels:

$$PAC = PAC_o + PAC_{wafer} + PAC_{MT} + PAC_{ship} . \quad (2)$$

The mirror segments were not always in a horizontal, face-up orientation, but the monitoring wafers needed to remain in that orientation in order to be safely deployed. Therefore, vertical (v), inverted (i), angular (a) and combination (r) orientation factors could be applied to the formula to adjust for dynamic accumulation rates based on orientation. For instance,

$$PAC_{center} = PAC_o + rPAC_{PMSAwafer} + vPAC_{MT} + iPAC_{ship} \quad (3)$$

$$PAC_{wing} = PAC_o + rPAC_{PMSAwafer} + vPAC_{MT} + vPAC_{ship} \quad (4)$$

$$PAC_{SMA} = PAC_o + rPAC_{SMAwafer} + iPAC_{MT} + aPAC_{ship} . \quad (5)$$

The PM was stowed for center-to-center shipment, and in this configuration, the wing mirror segments were vertical while the center mirror segments were inverted. Therefore, two equations are needed to describe the different states. Calculations for the SMA also require adjusted orientation factors due to its angular position.

Attempts at determining definitive values for these orientation factors, however, have been unsuccessful. Numerous experiments exposing wafers side-by-side in various orientations for given durations have given inconsistent results. Determining a definitive value for r becomes even further complicated given the numerous orientation changes of the mirror segments during integration. To remain conservative in calculating current PAC values, the orientation factors were simply applied with a value of 1.

All wafers were cleaned following the cleaning of the mirror segments.

4. CLEANING OF THE FALLOUT WAFERS

Cleaning of the particle fallout monitoring wafers occurred throughout the duration of the cleaning of the PMSAs and the SMA. The wafers were exposed to the same brush cleaning method used on the JWST flight optics, but spot-cleaning using other techniques was omitted. The brush cleaning involved unidirectional strokes with careful surface contact while each wafer was held at a 45° angle, as seen below in Figure 5.

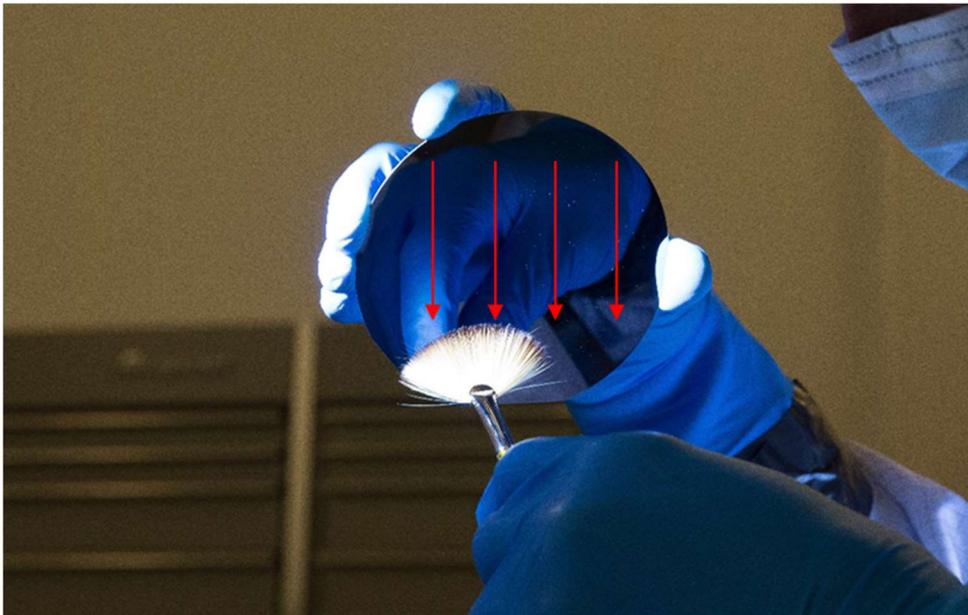


Figure 5. Brushing of wafer in a unidirectional manner. (Credit: NASA/Chris Gunn)

The angle aided in the delicateness of the contact in an effort to avoid any smudging of residues that may be present on the wafers' surfaces and provided stability to balance friction between the brush and the wafer.

Spot-cleaning of the wafers was ultimately omitted for a few reasons. The removal of spot-contamination on the PMSAs and the SMA, in general, does not result in a significant decrease of the PAC of the mirror surfaces because of the large sizes of the PMSAs and the SMA. On the much smaller surface of a wafer, however, spot-cleaning would greatly affect the measured PAC of the wafer and could elicit misleading results. Spot-cleaning also involved the use of additional solvent that could alter any residues that may be present on the wafers' surfaces. Smudging could also skew PAC data into providing misleading results both due to scale and the likelihood of the Image Analysis system to detect smudge marks as significantly large particles.

5. RESULTS

5.1 Image analysis data

Each particle fallout wafer was processed through the IA system just prior to and just after they were cleaned. A summary of data analyzed to determine the cleaning's effectiveness is presented in Table 3.

Table 3. Image Analysis results for the particle fallout wafers.

Optical Component	Scan Event	PAC	Number of Particles	Average Particle Size (μm)	Number of Fibers
PMSA (Average)	Pre-Cleaning	0.1524	16087	27	319
	Post-Cleaning	0.0251	1603	14	21
SMA	Pre-Cleaning	0.1194	19015	16	158
	Post-Cleaning	0.0034	647	11	9

The data show that the PMSA fallout monitoring wafers' PAC decreased by an average of 83.5%, and the SMA fallout monitoring wafer's PAC decreased by 97.2%. The data also show vast reductions in the total number of particles, the average particle size, and the total number of fibers across the entire set of fallout wafers. The predicted improvement determined from the test trials was matched.

The wafer associated with the mB7 mirror segment, however, showed a smearing after the cleaning that was not present on any of the other wafers. This was caused by an overly wet brush. This smearing was picked up by the IA system and misleadingly increased the final PAC of that wafer. If the mB7 mirror segment wafer is omitted from the data then the average PAC for the PMSA wafers improved by approximately 87.3%.

A determination of the NVR reduction on the fallout wafers was not attempted because of the negligible differences obtained during the procedure development trial scans. The current predicted NVR levels of the flight mirror segments were also substantially below the allowable upper limit, so these measurements would have provided little value.

5.2 Particle size distribution calculations

Particle size distribution is a crucial factor in stray light analysis and, therefore, an important element in the determination of surface contamination requirements for the JWST optical surfaces. Particles varying sizes and concentrations will impact an optical system's ability to properly collect, focus, and transmit light. Known or predicted particle size distributions allow for technical adjustments of flight optics and modeling.

In order to determine predictions of particle coverages for the flight mirror segments after cleaning, the specific particle size data must first be classified in standardized bins for proper difference calculations. The ultimate goal of this series of calculations is to show the change in particle size bin volumes and not to directly offer a current status of the particle size distributions on the flight mirrors. The data obtained by the fallout wafers cannot fully account for all particulate contamination on the flight mirror segments because the cumulative fallout monitoring wafers were not witness to the entire lifespans of each flight mirror segment. They only represent specific phases, as previously stated. Data for initial conditions, mechanical testing at GSFC, and all transportation activities after delivery to GSFC must be included and appropriately adjusted in any calculation attempting to determine the current particle size distributions of the flight mirror segments.

However, the results obtained by analysis of the fallout wafers still offer a quantified improvement factor that can be applied to other relevant data sets to determine further predictions. The results also allow for the calculation of a prediction model slope and cleanliness level that can be used to extrapolate data to relevant surface areas and provide predictions under the given circumstances. In this case, the relevant surface areas would be those of the flight PMSAs and SMA.

Slope and cleanliness level designation calculation steps are detailed in IEST-STD-CC1246.⁴ Essentially, the particle bins are recalculated by removing the upper bound and extrapolating to a standardized area. The new numbers are plotted on a log-log² scale of particle size (x) vs. particle concentration (N) equal to and greater than the stated size. The slope is determined by the best-fit line and is often expressed as an absolute value $|m|$ despite being predictably negative:

$$\log N = m \log^2 x .$$

While IEST-STD-CC1246 provides a standard slope of 0.926, JWST fallout monitoring data shows that an adjusted, unique slope is needed to properly predict particulate cleanliness levels. Hard data disagreed with the standard projection, so new slopes were determined from the fallout monitoring wafers. The new slopes are shown below in Table 4 and are depicted in Figure 6 and Figure 7.

Table 4. Calculated slopes for the PMSAs and SMA using pre-cleaning and post-cleaning data.

Optical Component	Scan Event	Slope $ m $	Delta
PMSA (Average)	Pre-Cleaning	0.365	0.025
	Post-Cleaning	0.340	
SMA	Pre-Cleaning	0.375	0.066
	Post-Cleaning	0.309	

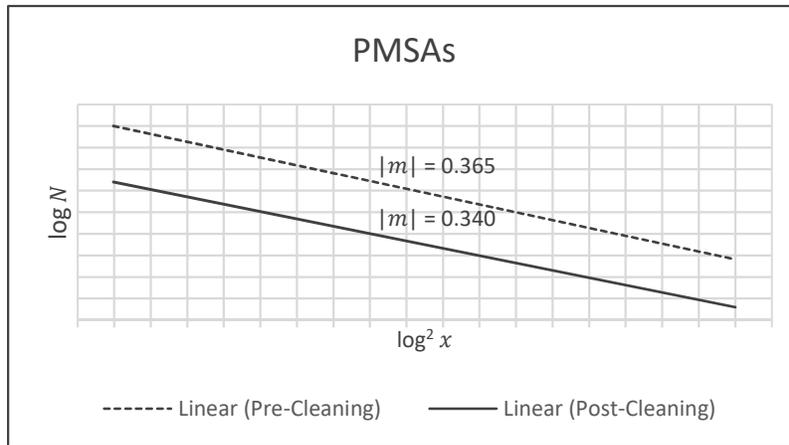


Figure 6. Depiction of the average pre-cleaning and post-cleaning slopes for the PMSAs.

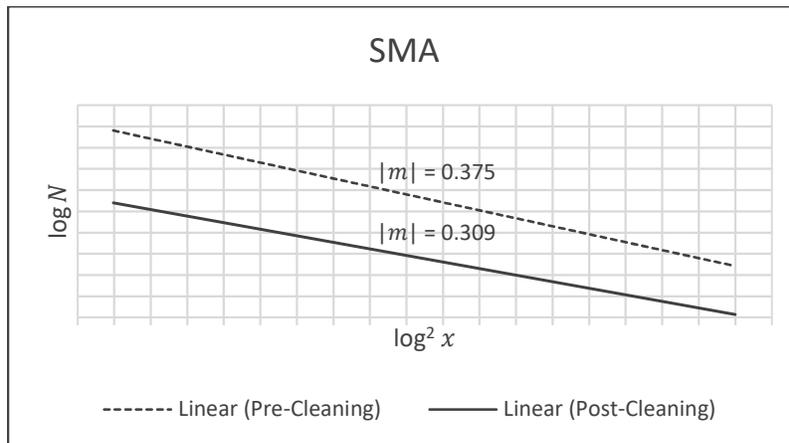


Figure 7. Depiction of the pre-cleaning and post-cleaning slopes for the SMA.

6. DISCUSSION

6.1 Interpretations

The average PACs of the cumulative PMSA and SMA fallout wafers for before and after cleaning determine the overall effectiveness of the cleaning activity. The average of the particle size bin slopes of the wafers show the change in distribution predictions over a scaled area.

The fallout wafers, as previously stated, were also only tracking the flight mirror segments for specific stages of their lifespans. In order to calculate estimates of the current PAC of the optical surfaces, the initial conditions, data from previous mechanical testing at GSFC, and all transportation activities after delivery to GSFC must be considered. However, because these activities occurred prior to the cleaning of the mirror segments, any contamination accumulated during these periods would have also been subject to the cleaning activity. Therefore, cleaning improvement factors for the PMSA (γ) and SMA (δ) should also be applied to the other PAC data:

$$PAC_{\text{center}} = \gamma(PAC_o + rPAC_{\text{PMSAwafer}} + vPAC_{\text{MT}} + iPAC_{\text{ship}}) \quad (6)$$

$$PAC_{\text{wing}} = \gamma(PAC_o + rPAC_{\text{PMSAwafer}} + vPAC_{\text{MT}} + vPAC_{\text{ship}}) \quad (7)$$

$$PAC_{\text{SMA}} = \delta(PAC_o + rPAC_{\text{SMAwafer}} + iPAC_{\text{MT}} + aPAC_{\text{ship}}) . \quad (8)$$

The increases in average particle size bin slopes for the PMSA and SMA wafers indicates that the ratio of large to small particles slightly increased after the cleaning for all mirror segments. This does not, however, indicate that large particles were omitted from the cleaning or were deposited during the cleaning process. It simply means that smaller particles were removed in higher concentrations.

Post-cleaning visual inspections of the fallout wafers and of the flight PMSAs and SMA showed considerable and comparable particulate coverage improvements. This lends credence to the belief that the average PAC of the PM and SMA likely improved by the same factor as their respective fallout wafers.

6.2 Limitations

The flight PMSAs and SMA are not necessarily free from unique contaminants such as smears, particles, and residues, so these interpretations should not be considered perfect. The flight mirrors did receive spot-cleaning of large fibers, stuck particles, and adhesive spots that their respective fallout wafers did not receive, but the spot-cleanings were not all-encompassing. Many items remained on the optical surfaces at the end of the cleaning activities. Therefore, these results are limited for use as a general conclusion and not as hard evidence.

The surface coating difference between the fallout wafers and the flight mirror segments may have also played a role in how particulate was removed. The assumption was made that since the fallout wafers were exposed to the same conditions as the flight mirror segments during various ambient and cryogenic vacuum integration and testing then the particulate observed should be the same. However, there was no way to imitate the flight mirror segments' coating on the existing fallout wafers, so discrepancies may exist.

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