

Mirror Recoating of Large Primary Optic

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Abstract

Over the course of 2021, the Air Force Research Laboratory and the site's contractor, Boeing, recoated the primary mirror of the Department of Defense's largest optical telescope. The Advanced Electro-Optical System (AEOS) has a 3.67m primary mirror as part of its Cassegrain design. In order to maintain excellence in Space Domain Awareness (SDA) data collection, the primary mirror is periodically stripped of its reflective coating and recoated with a new bare aluminum coating. The purpose of this paper is to provide insight into the details and challenges of the large mirror recoat process required to maintain sensitive SDA telescope instrumentation in top working condition. This paper will cover the end-to-end process to include assembly of mechanical lifting equipment, critical lifts of the large optical assemblies, dis-assembly of the mirror cell, stripping/cleaning the optic, application of the new coating, and reassembly of the telescope. Also included are the challenges of maintaining clean room conditions throughout the process, ensuring little or no residue remains on the mirror post stripping/cleaning, achieving positioning of the mirror within the cell to within a few thousandths of an inch during reassembly, aligning 84 axial and 48 lateral actuators supporting the mirror, and ultimately returning the telescope and all sensor packages to operations. The result of the recoat is improved reflectivity and reduced scatter.

Background

The current AEOS 3.6m telescope has a yoke and azimuth bearing. Its mirror is a thin meniscus Zerodur® substrate with an aluminum coating. To properly maintain quality viewing data, the substrate must be recoated periodically as determined by the Space Force operations team. Separate mechanical and optical teams worked in conjunction to remove the primary mirror from its mount, transport it to a cleaning station, strip the old aluminum coating, coat the clean substrate, and transport the primary mirror back to its original location and configuration. This delicate operation involved approximately 1 year of planning and 4 months of execution.

Preparation

Prior to beginning de-integration of the 3.6m telescope, all of the existing recoat tooling needs to be gathered into the Mirror Coating Facility (MCF). Once gathered, the hardware must be organized, inspected, and assembled into the respective lifting fixtures. Each of these lifting fixtures uses a mirror cell & substrate simulator to load test all of the lifting hardware. These load tests ensure each fixture is properly assembled, structurally sound, and interfacing correctly with the telescope structure. A full dry run must then be performed within the MCF. This dry run consists of standing up a telescope simulator with i-beams to construct a structure with identical interfaces with a height matching the 3.6m telescope. The main purpose of this simulation is to ensure the team understood each part of the process for de-integration and to ensure smooth operations on the telescope.

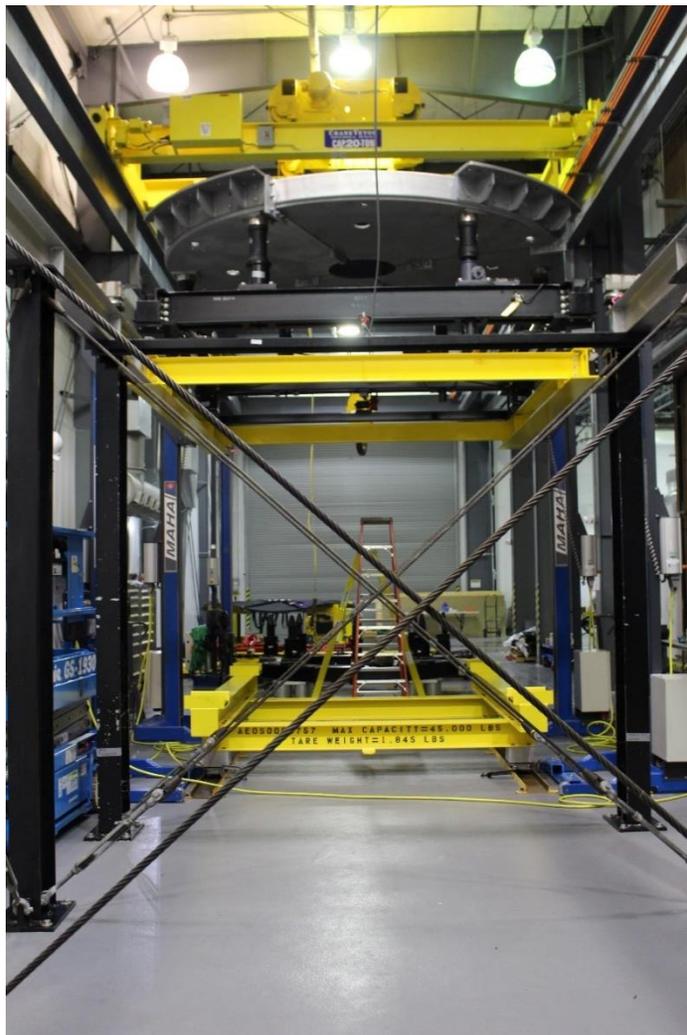


Figure 1- Simulation in the MCF

In addition to the tooling & operational preparations, the AEOS building requires preparation. The facility normally uses a passenger elevator to allow easy transportation of equipment & personnel between the floors, however this elevator has a 4000 pound capacity with a limited surface area. In order to transport the mirror cell into the MCF, the passenger elevator must be removed from the elevator system's structural beams and the Heavy Lift Platform (HLP) brought into service. The HLP is capable of transporting 40,000 lbs between the floors but moves at approximately an inch per second.

With the HLP in service, the recoat team transports the de-integration equipment to the 4th floor for assembly connected to AEOS. Once assembled, a final verification test is completed by transporting the mirror cell mass simulator to the 4th floor, engaging the lifting jacks, and simulating the majority of the de-integration with the mass simulator. This critical final step verifies that the equipment is properly installed, has clearance to all of the telescope sensor packages & facility, and that the team understands the subtle differences between the workspaces on the 4th floor and the MCF.

With all required tooling relocated to the 4th floor, the optical team begins cleanroom preparations to the MCF. This involves creation of a temporary vestibule for personnel entry and exit to minimize introduction of dust, sealing off all exterior doors, vacuuming and mopping of the entire facility, and beginning 24/7 operation of multiple HEPA filtration units throughout the space.

With all preparation and simulations complete, the team begins the process by locking out and tagging each of the hazardous systems such as the azimuth and elevation motors, as well as the mirror support system. This is the first step in removing the telescope from service prior to mirror cell removal.

Telescope De-integration

The AEOS telescope's optical path architecture is a Cassegrain design. Using a rotational tertiary mirror, light is directed to either various sensors on the elevation axis structure or directed down a coudé path to experiment rooms on the 1st floor of the facility. In order to remove the primary mirror, this tertiary mirror must be removed as it is located on a structural stalk extending from the center aperture of the primary mirror. Removal of the tertiary mirror is a delicate operation as the mechanical team is working within the structural trunnion box that holds the primary mirror in place. The team is located within inches of the primary mirror surface during removal. The tertiary mirror removal fixture is installed onto the telescope, with the truss structure and the primary mirror trunnion providing support. The removal fixture is essentially a one directional mobile crane that supports the tertiary mirror, then relocates it outside the azimuth base of the telescope for lowering to the 4th floor.

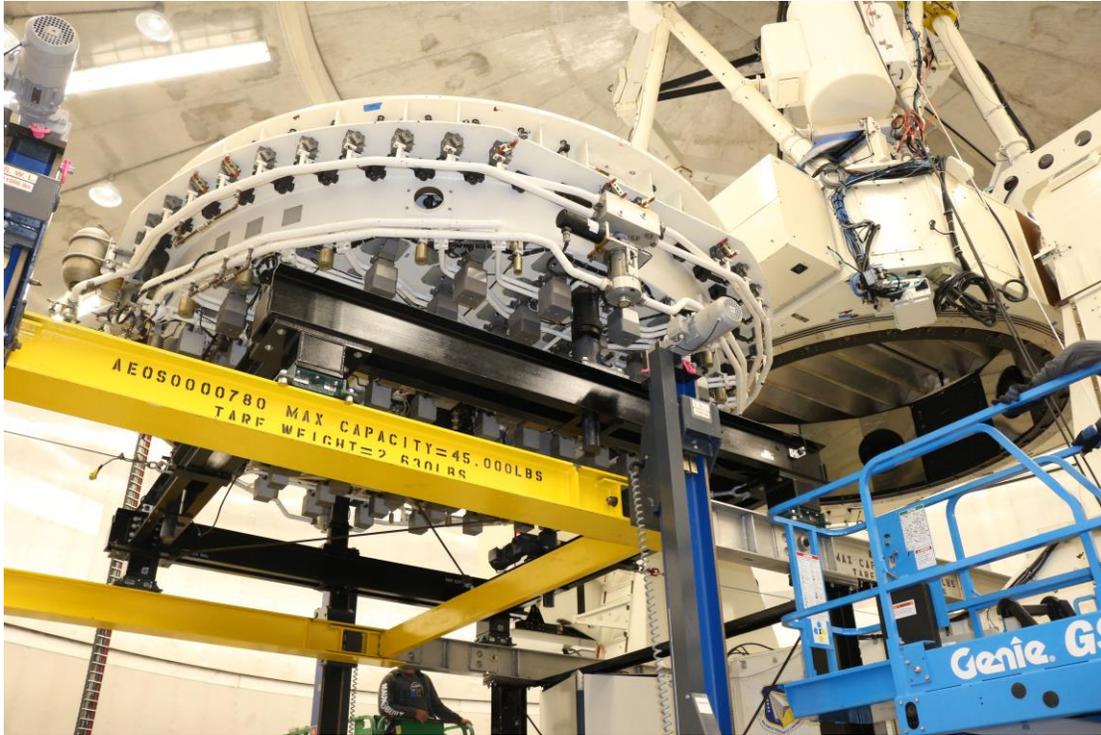


Figure 2 - Mirror Cell Removal from Telescope

With the tertiary mirror removed, the telescope is pointed at zenith where it will stay for the remainder of the recoat. There are multiple mirror support system electrical lines that require de-integration between the elevation axis and the mirror cell. These are labeled, disconnected, and stowed. The telescope is braced to ensure it does not move during the mirror cell de-integration. With all hardware in place, the mirror cell removal cart is brought under the mirror cell. The cart uses industrial roller bearings and i-beams as a linear rail to remove the cell from the azimuth base of the telescope. The cart interfaces with the primary mirror cell via three industrial screw jacks that raise and lower the mirror cell from the elevation axis structure. Once the screw jacks are supporting the mirror cell, all structural fasteners connecting the axis structure to the mirror cell are removed. The team lowers the jacks and verifies no Foreign Object Debris (FOD) or hang-ups from the stowed cables. At this point a ballistic cover is installed to protect the primary mirror's optical surface. Once the all-clear is called, the mirror cell begins the translation to the larger MAHA jacks. The MAHA jacks are 10,000 lbs industrial truck jacks that raise and lower the primary mirror cell to the HLP. Once the MAHA jacks have lowered the mirror cell to the HLP, they are removed from the structure and relocated to the 4th floor. Finally, the mirror cell is lowered to the 1st floor for further processing.

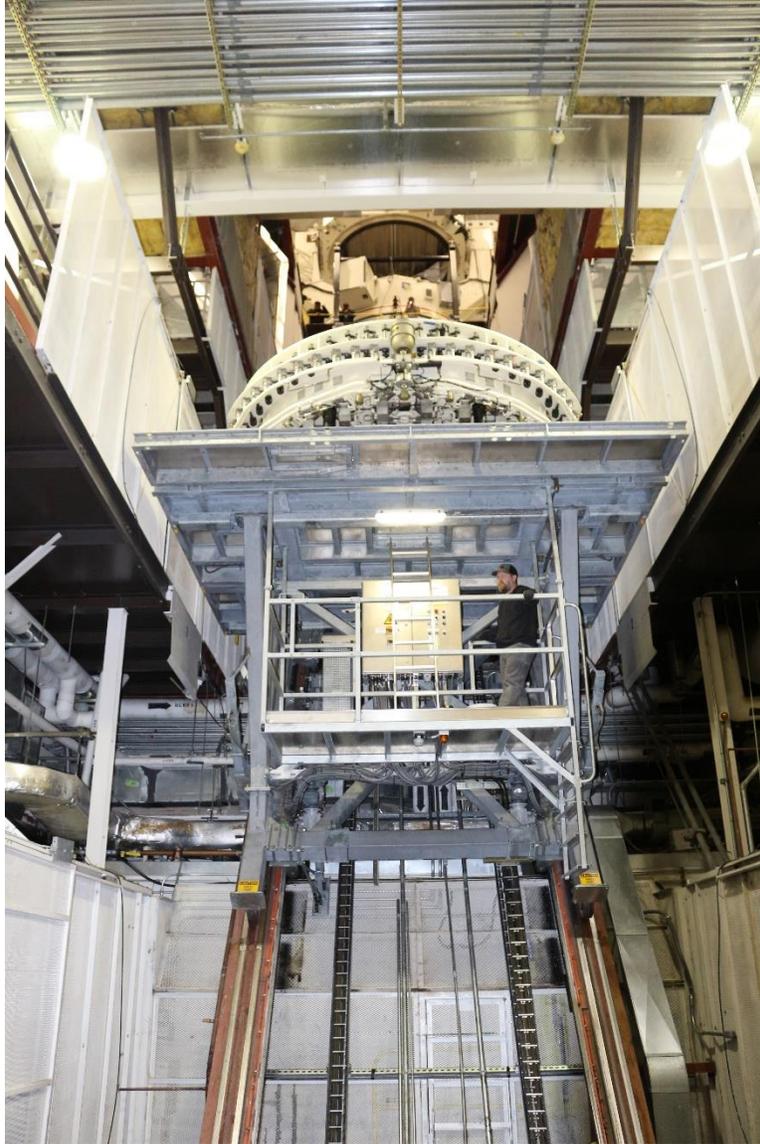


Figure 3- Transportation of mirror cell from 4th floor to 1st floor

Mirror Substrate Removal

With the mirror cell on the 1st floor, the Operations team begins by lifting the mirror cell onto the air bearing transportation cart. This cart has four large air bearings which use high air pressure to create a small amount of vertical lift between the mirror cell handling cart and the floor. The floor is lined with thin aluminum plates to allow a smooth surface for the air bearings to maneuver. This arrangement allows the Operations team to relocate the mirror cell around the MCF along the path lined with aluminum with great ease despite the large amount of weight. This is the first of two ‘full weight’ lifts used as part of the mirror substrate removal. This ‘full weight lift’ is approximately 38,000lbs. The air bearing transportation relocates the mirror cell from the lift room into the MCF processing area. The mirror extraction fixture is located within the processing area. The second full weight lift is performed to transition the mirror cell from the air bearing cart to the extraction fixture. This extraction fixture uses ‘poker stands’ support the mirror cell while it is extracted from the substrate. Measurements are taken at various datum locations between the mirror cell and the substrate to establish a baseline during integration after recoat. Prior to the extraction, the labor-intensive task of mirror support de-integration is performed. This system has 48 lateral (around the mirror) and 84 axial (on the back of the mirror) actuators to support, position, and maintain the primary mirror’s proper figure. Each of these actuator interfaces must be removed from the bonded pads on the primary

mirror. This task requires precise motion while working within tightly confined spaces to prevent damage to the mirror substrate. With all 132 actuator interfaces removed, the mirror substrate is lowered with the MAHA jacks. During this lowering process, the poker stand interfaces with the back of the primary mirror to provide support. The mirror cell is lowered down to floor level while the mirror substrate remains suspended at approximately 8 feet of height. The primary mirror cell will remain in this lowered state for the remainder of the recoat process.

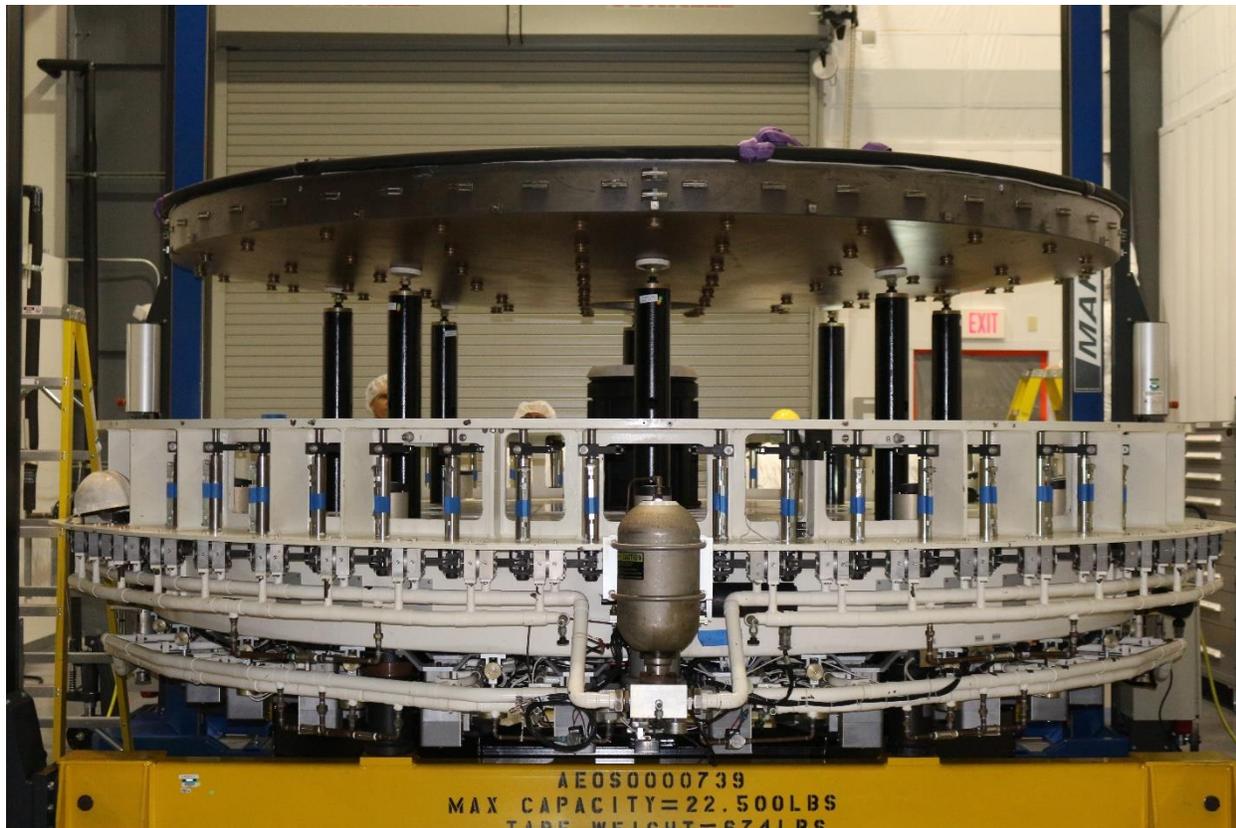


Figure 4- Separation of substrate from mirror cell

The mirror substrate is then lifted via the substrate lifting fixture into the strip & wash area of the MCF. This fixture has 8 arms that are positioned under the substrate. The team must maneuver the fixture concentric with the mirror substrate, lower the fixture around the mirror, then position the arms under the substrate. This is an orchestrated process requiring extreme precision on a 20 ton crane. Once the mirror substrate has been relocated to the strip and wash stands; the meticulous process of stripping and cleaning the mirror begins.

Cleaning, Stripping, Recoating, Inspections, and Preparations – Overview

Utmost care in handling of the exposed polished surface of the Large Optical Substrate (LOS) is paramount. After removal from the support structure and protective covers, anything that comes into contact with the optical surface can alter and permanently diminish its quality.

Cleaning of the previous coating is the first step in the process. The key to this is to remove all contaminants that could cause harm to the optical surface – without causing harm during removal. All persons involved must realize that a speck of sand, volcanic dust, or similar particles that are not evacuated off of the surface can and may become objects that will leave permanent scratches and/or streaks in the surface during other steps of the process. Using compressed air or nitrogen should be avoided as it can have the effect of driving the contaminants into the surface, similar to sand-blasting.

To achieve the required level of cleaning, pure solvents, pure water (deionized (DI), distilled / reverse-osmosis purified), clean gloves, and clean wipes are necessities.

Cleaning, testing, and preparation of the coating chamber is equally important to achieving a high quality finished product; though there is drastically less risk of damage, a failed coating will require significant rework (costing weeks of person-hours and a non-trivial amount of observing time).

Beyond contaminants on the optical surface or in the coating chamber, the work space that the coating chamber and LOS are housed in must also be prepared and cleaned so as not to introduce new damaging particles throughout the process.

Inspections are required at multiple phases of the processes for several reasons. First, to note intrinsic damage to the optical surface underneath the previous coating. Second, to note the status of the previous coating and show relative performance of the new coating in comparison to the old. Lastly and most importantly, to clearly parameterize the outcome of the entire effort.

Facility Preparation

It is imperative to maintain a clean environment where the cleaning and stripping of the substrate will take place. All efforts to reduce contaminants during this process should be taken. A general starting point would be to clean the entire area in which the handling and various processes will occur; also to continuously run HEPA air filtration units and particle counters to verify the cleanliness of the room.

All steps of the procedure make it necessary to wear cleanroom suits, booties, hairnets, and face masks. During the final steps of the process eye protection should be worn, as blinking your eyes can expel tiny particles of debris and droplets while in proximity (during inspection activity) to the cleaned substrate. A vestibule to don cleanroom gear should be utilized; this should be attached to the intake of a HEPA filtration unit, with the exhaust in the clean volume. This will provide a negative air pressure area to capture dust, lint and debris that will be introduced into the atmosphere when donning suits.

The floors of the room that will be used need to be rigorously cleaned, as simply walking on them will stir up contaminants. The common practice of floor cleaning with mops should be avoided as it inherently redistributes debris back onto the floors. Anything shy of using the following steps to clean the floors will be insufficient in the cleaning process. The first step is to inspect the floor for any 'unique' debris that cannot be removed with a HEPA vacuum alone (such as aged duct tape) and come up with a specific removal plan. Next is to carefully vacuum the entire area, ensuring that no area is missed. Starting from one side of the room, section off an area to be flooded with water and then scrubbed with a cleanroom mop, while not allowing the water to dry. Once the soil is in suspension, use a wet/dry vacuum with HEPA filtered exhaust to pick up all the soiled water. Next, use a sticky roller to verify that the cleaning has achieved the desired outcome across the entire area.

Once the substrate is completely stripped, it is extremely vulnerable to contamination. Anything that lands on the surface and is not removed before coating will become part of the coating in some undesirable way. During the 2021 recoat, a contaminant-free shield (known as the "Drumhead Cover") was fabricated and placed directly over the freshly cleaned and prepped substrate, with contact only along the outer edge (this is outside the clear aperture). The "Drumhead Cover" allowed time to perform the remaining steps of the coating process in the proper sequence without unnecessary pressure. This cover was manufactured significantly ahead of time and staged to be ready the moment the substrate cleaning and drying was complete.

Drumhead Cover

This cover is a newly established method to prevent contamination of a freshly cleaned substrate and avoids the use of (problematic) snow cleaning. A cover is fabricated using certified clean room plastic. The nature of this plastic is critical: it is folded in half and guaranteed that the interior surface of the folded plastic sheet is free from particles. The vital detail to this setup is to assemble it in such a way that the interior of the folded plastic is not exposed to

any contamination until it is put in place on the substrate. It should be placed on top of the substrate immediately after the final step of cleaning. This will give particulate from the atmosphere limited time to settle onto the surface.



Figure 5- Drumhead Cover Assembly

The frame of the cover is a torus of PVC pipe with a major diameter that is a few inches larger than the substrate diameter. This hoop is a frame onto which the cleanroom plastic is stretched. All of the components, as well as the area for assembly, should be thoroughly cleaned. If the substrate is larger than the width of the roll of folded virgin cleanroom plastic, several sections will need to be attached together with Kapton tape. The sheets should not be unfolded, but instead cut at the seams and taped together; this will minimize contamination and allow a large enough section. It cannot be stressed enough to maintain the cleanliness of the two inside surfaces of the cleanroom plastic; an understanding of this needs to be clear with all personnel involved. After the double plastic sheet is completed, the pvc ring is placed on top of both sheets. The top sheet is then cut to a size roughly twelve inches larger radially than that of the pvc hoop. Cutting triangular sections out of the upper plastic from the larger diameter plastic sheet terminating an inch or so from the outer diameter of the hoop will facilitate pulling individual sections up and over the hoop to be taped onto the top of the plastic.

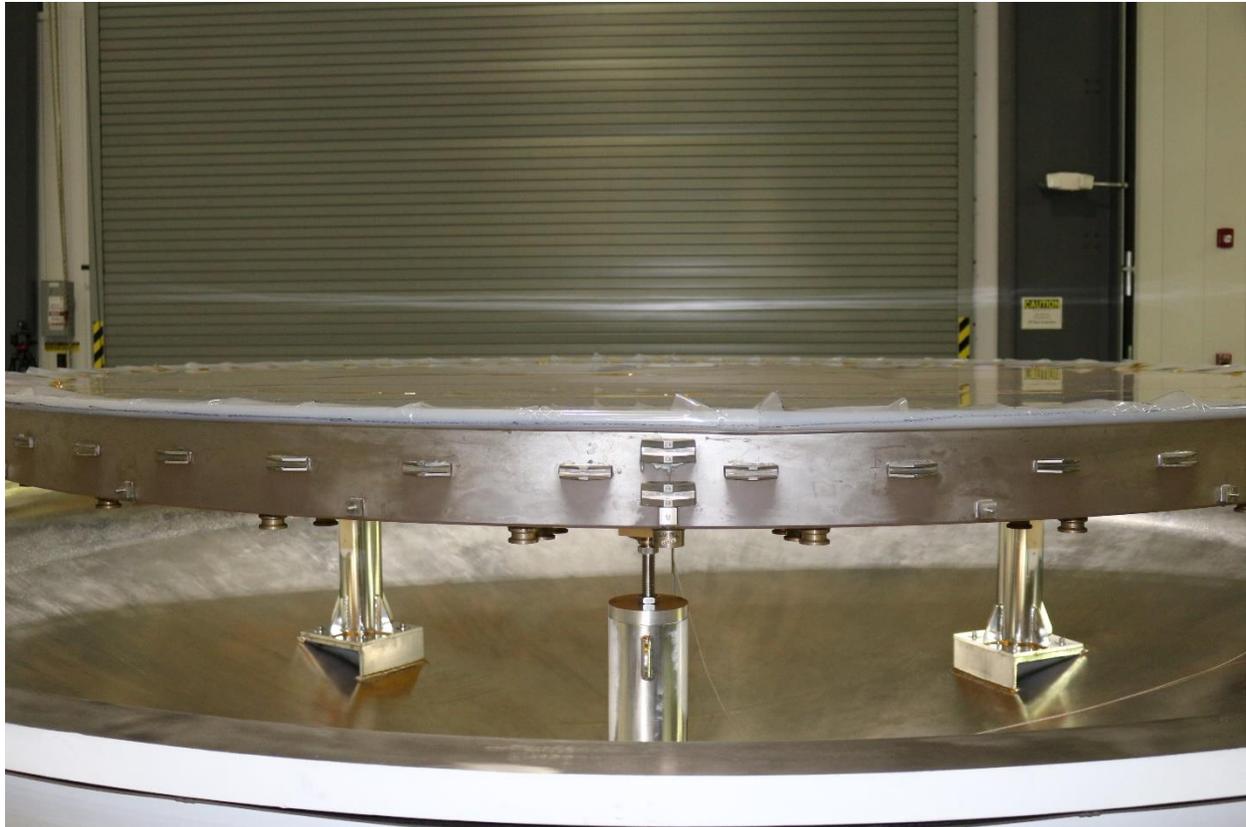


Figure 6- Drumhead cover over substrate

Coating Chamber Prep

It is paramount that the coating chamber is cleaned directly prior to each use. Such a cleaning will prevent contamination. This cleaning should commence a week prior to the coating run. Filaments are removed, shields and other panels to be cleaned are removed, and all surfaces are wiped down several times by hand to remove the majority of particulates that have accumulated during and since the previous chamber use. Ports that have sacrificial inner windows (which get incidentally coated) can be removed during cleaning to strip them of the incidental coating from the last coating run. Crystal thickness sensors, although able to be used several times over, should also be changed out, as they are a very low priced commodity.

To assist in eliminating particulates trapped inside the atmosphere of the coating chamber, a plastic skirt is attached to the upper flange of the chamber bell and is draped to the floor. Plastic is also laid on the floor underneath the upper chamber. A HEPA filter bank is placed inside this skirted volume to recirculate the internal atmosphere, scrubbing the area of particulate. It is a good idea to stir up more particulate from the internal walls of the chamber to get it into suspension in the air so that the HEPA filter can trap as much as possible. A particle counter is placed inside the chamber at the same time to record the progress.

While the chamber is being scrubbed of particles, the cryo-pumps need to be regenerated. The key to this is to do it many times, with the first being well in advance (possibly by many weeks) of the coating run. Follow the determined procedure to regenerate these cryo-pumps, purge them with ultra-high-purity dry nitrogen followed by rough pumping each day. After a pump-down, the rate of rise in pressure should show a decrease every cycle, as well as achieving a lower equilibrium pressure while sitting idle. This continued step down on achieved vacuum is an indicator that the low vacuum level will be maintained during the aluminum deposition.

As a final step, the lower bowl of the chamber should be thoroughly cleaned with an appropriate HEPA filtered vacuum, wipes, and solvents. Any particulate in the bowl may get stirred up as the pressure inside the chamber is changed during various phases of the actual coating process. Once cleaned, the bowl will be ready for the substrate

to be lowered inside, with the mirror cover still resting on top. As with the substrate “Drumhead Cover,” the bowl could be cleaned well in advance and covered with a similar-style dust cover, to be removed immediately before use.

First Inspection – Pre-cleaning

Before any work is done to clean and strip the surface of the LOS, the mirror should be inspected and quality recorded in a defined and planned style. This includes backside illumination with visible light sources of roughly-known intensity (to assess pinholing at end-of-life), front illumination using visible and UV light sources of known intensities and at prescribed or recorded angles (to assess existing damage to the coating or substrate), appropriate scale references for relevant photographs, and using cameras that have fine control over exposure duration. Calibrated light sources that can be casually photographed during inspection for instant calibration at various camera settings should be prepared. These camera calibration points could be as simple as integrating spheres illuminated with known intensities of known wavelengths. A support structure that extends over the substrate to aid in photograph collection should be avoided, as such a structure would almost certainly add to the contamination of the surface.

Pinhole artifacts as well as other blemishes are commonly found after a coating run. For a bare aluminum coating, these can widen over time depending on environmental conditions. These pinholes are found during inspection by shining a bright light through the bottom of the substrate while observing and taking pictures from above the coating. This is also an opportunity to gage how evenly distributed the coating has been applied by observing how much light passes through. With defined light sources, known substrate composition, and somewhat-calibrated cameras, this transmitted intensity can give an estimate of the remaining thickness of the coating.

Cleaning and Stripping

Prior to starting this process, everyone involved must understand that it is critical for the substrate to remain wet until it is hand dried at the very end. It is also important to understand that there is a rinse with deionized (DI) water between every step. Gently flushing the surface with high-purity distilled or reverse-osmosis purified & deionized water is the first step as it will dislodge and carry particulate away. The next step is to use a neutral pH mixture of soap and DI water, the soap helps hold debris in suspension away from the surface and assists in evacuation when rinsed away. After being satisfied that all contaminants suited to these two methods are removed, it is time to advance to a slightly more aggressive method to remove more stubborn debris. Using the same soap and water mixture along with large sterile cotton pads to lightly dab the surface of the substrate while applying only the weight of the wetted bulk cotton without agitation provide a means to gently encapsulate debris within the cotton, care must be taken to not redistribute harmful debris: the cotton is discarded after only a few contacts with the substrate. Once it has been established that the cotton soap step has been accomplished and another rinse has been performed, it is time to prep the surface for the Green River (an acid mixture) stripping step. This consists of laying clean wipes onto whole surface to be stripped, followed by pouring the solution gently onto the wipes. The purpose of the wipes is to maintain as much contact with the aluminum coating being stripped so that the mixture can dissolve it. A byproduct of this action is the forming of bubbles under the wipes; these will create contact gaps that do not allow the chemical action to proceed. Dabbing these bubbles with another acid wet wipe resolves the issue. After reapplying the solution to areas that need more attention to dissolve aluminum, a close inspection of the substrate is performed to ensure nearly all aluminum has been removed. The substrate is then rinsed again, removing the Green river solution and any debris generated in this process. Next, calcium carbonate is sprinkled over the entire surface of the substrate followed by pouring a solution of KOH onto the calcium carbonate. Using large sterile cotton pads soaked with the slurry the team walks slowly around the circumference of the substrate while using making a figure eight pattern on the surface and applying a five pound total force while doing so. Since each person involved will do this slightly differently it will ensure good coverage. The slurry should be applied a total of three times. This process will help scrub clean and remaining contamination and aluminum coating. A solution of nitric acid is poured over the substrate to flush away all calcium carbonate after the previous step, followed by flushing with DI water while periodically testing runoff with pH strips until a neutral pH value is achieved. Drying is followed by using lint free tech wipes. This is a process where each person involved is handed two wipes by an assistant and lays the pair down on a portion of the wet substrate followed by laying a gloved hand on top applying pressure as they pull the pair of

wipes towards themselves with the remaining gloved hand. The pair of wipes are then discarded and this action repeats until the substrate has been dried thoroughly.



Figure 7- Application of wet wipes

There is great scrutiny to the final wipe with pure ethyl alcohol and Tek wipes. The method is to fold a Tek wipe into a triangular form, hold it in one hand while applying a one inch spot of alcohol onto the center of the opposing side followed by applying that to the substrate in a rotational pattern. The theory is that the alcohol will be applied and removed along with any contaminants immediately. The problem of this action is that by doing so you inherently risk the possibility and increase the probability of smearing contaminants over a larger area. Maintaining the purity of alcohol, wipes, and the gloves holding them can be a challenge. Another option is to only wipe with a clean Tek wipe that has DI water applied in the same method, as this lowers the risk of spreading contaminants.

Second Inspection – Post Cleaning

After the final stage of cleaning, a spot check is performed. This can be with a traditional “black breath” or a DI water steam generator. Either will generate a patch of fog which is then observed for features such as streaks that will become permanent in the final coating and will impede good adhesion of the aluminum. Flashlights and bright light sources should be used as a visual inspect, with pictures quickly taken of anything notable such as scratches or streaking that cannot be overcome. When the substrate is as clean as achievable, the substrate should be protected with the “Drumhead Cover” to reduce time pressure and allow chamber preparation.

Final Chamber Preparation and Substrate Loading

The chamber now needs the filaments and shields loaded. The HEPA filter inside of the skirted chamber volume should now be attached to the skirt to allow fresh air to enter the filter and create positive pressure inside of the skirted area. This helps keep personnel inside to stay cool and also promotes particulate to be evacuated with the

positive pressure. The pre-wicked filament should remain in their argon flooded storage vessels right up to the time of being installed. The rule is to not allow them to be exposed to an atmosphere containing oxygen for more than three hours prior to coating, as it will cause the bare aluminum to oxidize and become an impurity during the deposition. In the case of the chamber being used, there are 120 filaments that need to be installed. To install all 120 filaments in a timely fashion, two double sided ladders with two personnel, donning cleanroom attire, on each would be handed filaments by a fifth person in charge of opening the filament jars one at a time and handing them out. This made it possible to install all filaments within half an hour. Once installed, each filament is individually torqued down to specification by one individual while others move ladders around to get to the remaining filaments. This should take another half an hour only using up a third of the allowed time.



Figure 8- Substrate in route to coating chamber

After the chamber is fully-prepped witness samples are installed. The lower bowl (with substrate) is moved into place. As the substrate is being moved into position underneath the upper chamber, the “Drumhead Cover” is gently lifted up off of the substrate but held in place. This allows it to serve as a cover and prevent falling onto the surface as the bowl is moved underneath. The chamber is then lowered and closed to be pumped down with the roughing pump.

Coating

There are two further critical points to achieving a high-quality coating: a successful ion glow discharge, and reaching extreme vacuum levels during the entirety of the coating run. Roughing the chamber the chamber pressure down to low vacuum of 1×10^{-3} Torr, followed by going even lower with a turbo pump to low negative 5’s prior is the starting condition. Once this level of vacuum is achieved, a small amount of pure oxygen is introduced with a purge valve. This brings the vacuum back up to low negative 3’s. This is where a proper ion glow discharge will be achievable. Initiating the high voltage power supply when in this range provides a good glow discharge and toggling the purge of oxygen will help find the correct subjective balance between a bright glow versus arcing which must be avoided. The oxygen plasma shreds residual organics on the substrate, increasing their vapor pressure and causing

them to “boil” off; these organics would otherwise interfere with adhesion. Once the glow discharge is complete, return to using the turbo-molecular pumps to lower the vacuum level of the chamber. In conjunction, the sorption pumps should be loaded with LN₂ and the cryo-pumps should be started. Once the cryo-pumps have reached the goal temperature it is time to actually coat the substrate.

Opening the sorption pump valves will almost instantaneously lower the vacuum level to the coating target of 1×10^{-7} . Once reached, the crystal monitors should be zeroed and the filament high current power supplies should be started. Gently raising the current to the filaments 5 amps at a time and holding for one minute intervals allows for even heating of the filaments. This continues until all filaments are glowing uniformly and the crystal monitors are showing no deposition. Other coating runs have used a more rapid increase in filament temperature and had significantly worse results. One observation on our most recent coating run was a pressure rise *followed by a pressure drop* during this slow warmup; this could be related to cleaning the filaments of contamination. It is proposed that the next coating run should include a warmup of the filaments before the glow discharge to further suppress contamination.

Once deposition is occurring at a rate of 1-2 angstroms a second, the current is increased to a deposition rate of 20 angstroms per second for a couple seconds. It is then increased again until deposition is occurring at a rate of 50 angstroms per second. Once the target thickness of 1100 angstroms is achieved, the high current supplies are turned off.

After this process is complete, the coating is allowed to cool for a brief period of time. Then a low speed venting of the chamber to atmosphere is started with clean dry nitrogen. It takes several hours before the chamber is back to atmospheric pressure and may be opened up to verify the results.

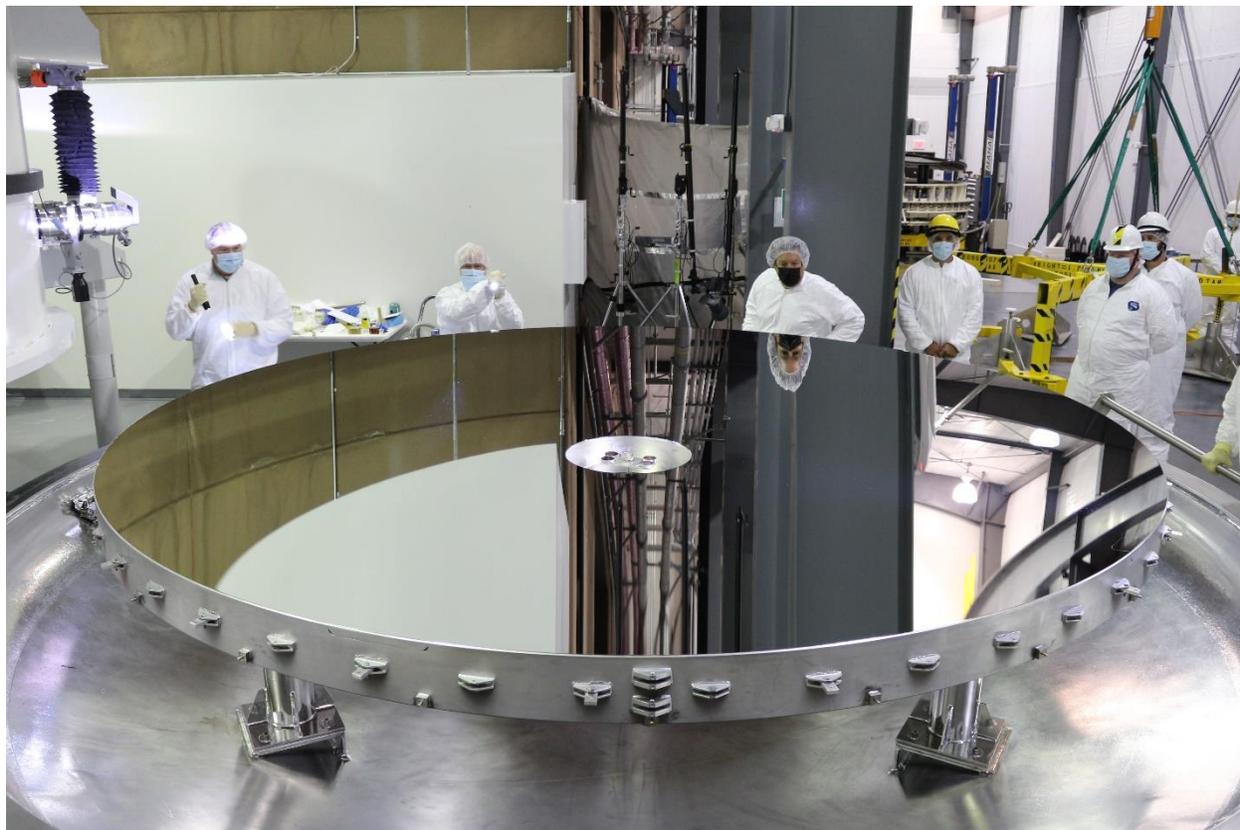


Figure 9- 2021 Mirror Leaving the Coating Chamber

Final Inspection

Following the same structure as outlined above, more pictures are collected to record the outcome and parameterize the results as outlined below.

Results

There are a total of 5 qualitative/quantitative tests that were performed on the primary mirror and witness samples to ensure the performance characteristics of the recoated 3.6m Primary Mirror. In order to establish requirements for each of these categories, the previous recoat results were taken as a threshold with superlative results defined as an objective requirement. The 5 tests are defined below with a brief description of how each test was performed.

The test categories are as follows:

- **Reflectivity/Scatter**
 - Surface reflectivity was measured in approximately 30 locations over the mirror per wavelength using the Konica-Minolta CM-700d Spectrophotometer.
- **Pinholing**
 - While shining a bright light from behind the mirror, pinholes were observed in the coating. The number of pinholes larger than 0.5mm were tallied over select areas on the mirror surface. The same method was used to tally witness sample pinholes except with the use of a microscope
- **Staining/Appearance/Cleaning**
 - Using bright lights, the mirror surface was quality inspected from the front. Inspections were performed for: consistency, leftover chemical residue, stains, splotches, patches and wipe/drag lines.
- **Adhesion**
 - ISO 9211-4 was used for additional detailed guidance on the technique used to perform the adhesion measurements. A series of 15 measurements, 10 with Scotch Tape #810 and 5 with Scotch Tape #600, were collected outside of the clear aperture of the mirror surface. A piece of 3M Scotch Tape 810, measuring approximately 25mm, was firmly pressed against the coated surface edge ensuring no air bubbles are present between the tape and the mirror surface. A small end of the tape was left unattached to the surface. While holding the unattached end of the tape, a slow pull of the tape was performed at an angle perpendicular to the coated surface at a rate of 2-3 seconds per 25 mm.
- **Uniformity**
 - The thickness of select witness sample coatings was measured using an interferometer.

Using the tests outlined above, the team performed extensive characterizations of the primary mirror coating after removal from the coating chamber and relocation back to the strip and clean area. After these lifts were performed, the team set up all of the lighting required to adequately capture pinholing, staining, and any other surface defects. Table 1 shows a comparison between the previous mirror coating and the 2021 recoat for a quantitative perspective on the significantly enhanced coating of 2021. The observations of the 2021 recoat overall showed drastic reductions in both pinholing and staining over the entire surface of the mirror substrate. This can be directly attributed to the enhanced cleaning and processing procedures outlined above.

Table 1 - Mirror Pinhole Photos

Previous Recoat pinholing	2021 Recoat pinholing
	

One of the most worrisome tests to perform is that of the tape test as there is a potential for damage to the fresh coating. This test consists of putting various adhesive level scotch tape onto the mirror surface and pulling at specific rates to verify that the aluminum coating is well adhered to the substrate. Figure 10 shows one of the tape tests results with no aluminum being pulled off of the mirror.

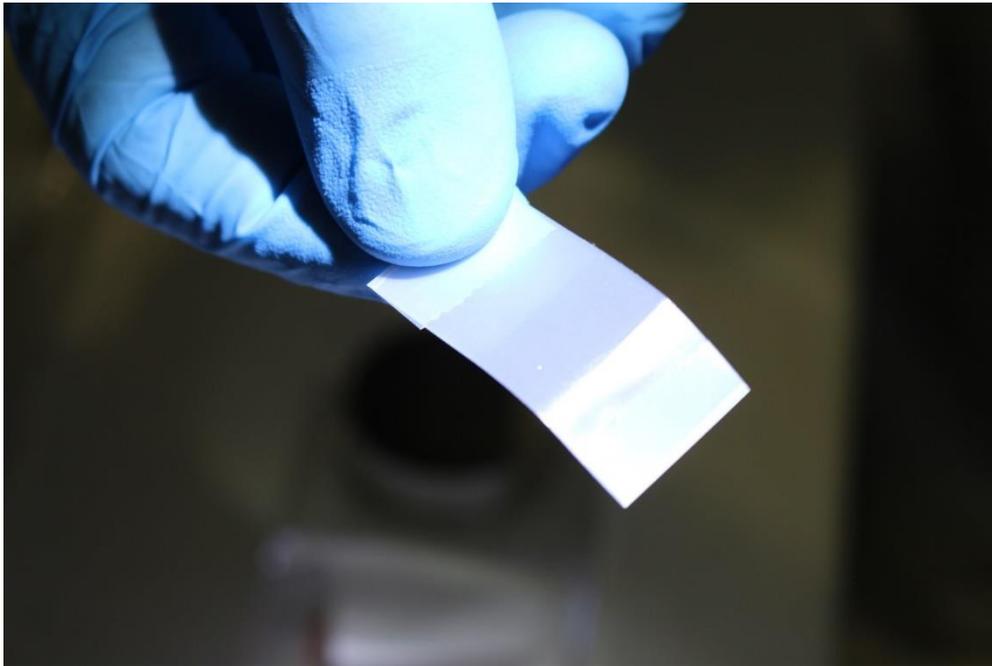


Figure 10 - Mirror Inspection Tape Test Sample

For measurement of reflectivity, scatter, and thickness, a combination of witness samples and on-mirror measurements were performed. The witness samples are used as on-mirror measurements are exceedingly difficult due to the size of the mirror. Witness samples are easily relocated to the measurement equipment. These samples were located throughout the coating chamber including within the interior of the center aperture and radially surrounding the primary mirror to ensure representative results for the entire primary mirror. The results of these witness samples are outlined below.

REQUIREMENT	THRESHOLD	OBJECTIVE	RESULT
Average Reflectivity (700 nm)	≥ 88.0% at 700 nm	≥ 90.0% at 700 nm	88.84 at 700nm
Average Reflectivity (400 nm)	≥ 90.0% at 400 nm	≥ 92.0% at 400 nm	93.53 at 400nm
Average Scatter (700 nm)	≤ 1.00% at 700 nm	≤ 0.30% at 700 nm	.23% at 700nm
Average Scatter (400 nm)	≤ 1.50% at 400 nm	≤ 0.50% at 400 nm	.30% at 400nm
Adhesion	< 1% of each pull area	No aluminum lost per pull	No aluminum lost
Average Thickness	900 - 1400 Angstroms	1100 - 1300 Angstroms	949 Angstroms
Average Uniformity	≤ ±100 Angstroms	≤ ±50 Angstroms	30 Angstroms deviation

The 3.6m Primary Mirror Recoat team exceeded expectations. The baseline goal was to produce an aluminum coating that met or exceeded the previous coating. As an additional statistical baseline, performance data from the previous coating was compared to the 2021 coating. The 2021 coating exceeded the previous coating in every performance category. The coating was such an improvement over the prior effort that the Boeing team received team awards and was heralded by noted industry experts.

Re-Integration

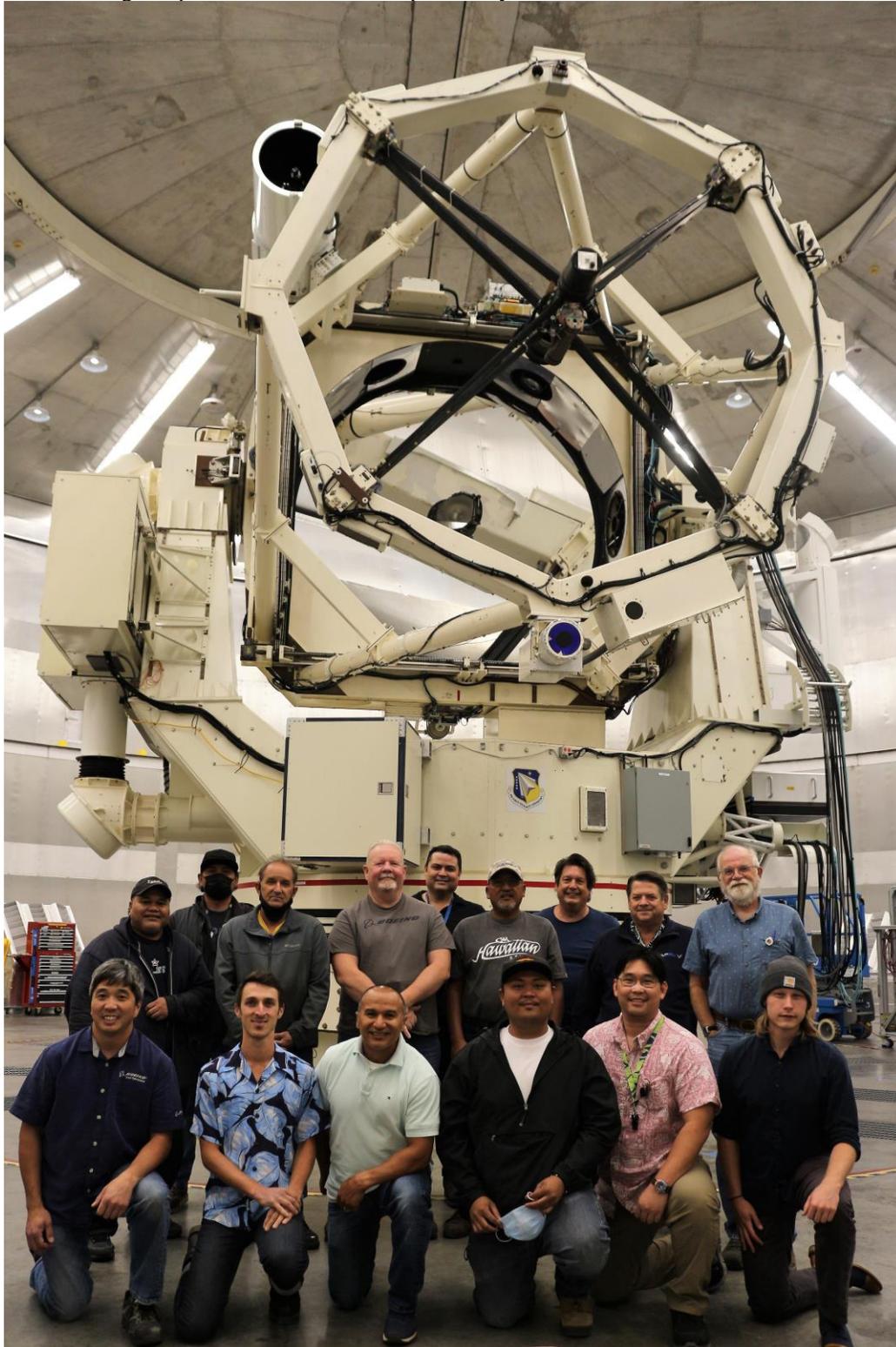
After completion of the inspection on the mirror wash stands, the mirror substrate began its journey back to the telescope. The majority of this work is a reverse-order of the steps outlined previous. The steps outlined in this section are portions that differ from the de-integration.

Once the mirror substrate has been reinstalled within the mirror cell, the mirror is floated on the hydraulic support system at the pre-removal measured heights. From this location, the radial measurements are verified to ensure the mirror has been re-installed at approximately the same location as prior to removal. There are a number of mechanical adjustments that can be performed to help relocate the mirror should the mirror not be perfectly centered. These adjustments are far easier to perform with the mirror cell at ground level than after integration on the telescope, hence the reason for this initial verification. With the mirror location verified to match the previous measurements, the mirror cell is brought to the 4th floor where it is fully re-integrated onto the telescope.

After mechanical & electrical integration is completed. The primary mirror support system is activated. The engineering team performed a system check-out where tip/tilt, piston, lateral position, and hysteresis are verified at various mirror angles. The various angles are required as the mirror support system uses the lateral supports while at horizontal and the axial supports at zenith. By taking measurements for location & pressures within the hydraulic system, the engineering team verifies that the system is performing as expected. During these checkouts, there are a number of strain gauges and measurement locations that give the team verification that the mirror support system is working correctly and unintended stresses are not being applied to the mirror. If final adjustments to the mechanical supports are required, the team must use a scissor-lift to access difficult locations to make adjustments. During the 2021 recoat, the team had to make a single adjustment to one of the mirror support locations. Fortunately, this single change did not require re-adjustment of the entire support system.

With the primary support system integration & verification completed, the telescope is ready for on-sky checkout. The on-sky checkout process begins with figure control modeling. This process requires the use of one of the on-telescope sensors, a Shack-Hartmann wavefront sensor. This sensor puts an array of lenslets at a pupil. Each lenslet of the array creates a focus that will move away from nominal if the wavefront covered by that lenslet is tilted. By going on-sky and looking at how each of these foci is shifted, the system is able to make adjustments to the primary mirror's shape and location as well as the secondary mirror's lateral and longitudinal location, as well as its orientation. All of these parameters are adjusted over the course of many observations at a variety of elevations

across the sky to minimize distortions. Should the system find that the secondary mirror requires more adjustment than the electro-mechanical system can provide, the AEOS telescope has manual adjustments that can be performed to relocate the secondary mirror center location. During the 2021 recoat, the engineering team had to make a .052” change to the secondary center location in one axis to ensure the secondary had enough range of travel. With the figure control modeling completed, the AEOS telescope is ready for SDA data collection.



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