

TMT Segment Polishing Principles

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TMT recommends a segment polishing approach based on the successful Keck approach. The combination of Stressed Mirror Polishing (SMP) and Ion Beam Figuring (IBF) is believed to be the lowest cost approach to producing segments that meet TMT performance specifications.

This memo describes a version of the Keck approach that has been adapted to meet the unique needs of TMT. The steps outlined below briefly describe the process, motivation, and advantages of this process.

1. **GENERATION:** A circular meniscus blank (roundel) is generated using large tools at the blank manufacturer, or at a low-cost subcontractor like AGI.
2. **INSPECTION:** Polisher receives and inspects the roundel. This should include measurement of the glass birefringence along the perimeter approximately where the hexagon is to be cut. These measurements are described in the Blank Specification and are the responsibility of the blank supplier. Keck experience is that this measurement was well correlated with the amplitude of the warping of the segment when it was cut from the roundel.
3. **S2 FINISHING & OD PREPARATION:** The back surface (S2) is ground and polished using large tools to remove sub surface damage (SSD). The outside diameter (OD) may need to be processed also.
4. **INSPECTION:** The roundel is dimensionally inspected. If the wedge angle exceeds TMT requirements for the finished segments, it must be corrected either in a separate grinding operation, or during front surface (S1) grinding.
5. **PREPARATION:** The stressing fixture attachments are bonded to the roundel.
 - a. On Keck, the stressing forces were applied to the OD of the roundel. This is because the desired deformations (quadratics and cubics) are only naturally generated by forces and moments applied at the perimeter
 - b. The required warping influence functions are most easily calculated for a circular meniscus that is loaded at the OD.
 - c. Local distortions at the points of force application may be imprinted on the optic during polishing, so it is helpful to maintain good radial edge margin between the finished clear aperture and the attachments.

6. **S1 GRINDING:** The roundel is attached to the stressing fixture. The roundel is warped to the desired shape and then ground to a spherical shape rapidly using a large tool and loose abrasive. The large tool tends to make spherical shapes, and surfaces with minimal high spatial frequency errors. The ground surface should be measured in both the stressed and unstressed states. The difference should match the desired warping. If not, the stressing fixture should be adjusted and grinding resumed. After passing inspection in the un-warped condition, the roundel advances to polishing. Because the surface is naturally lacking in high spatial frequency errors, the measurements can be made with a multipoint profilometer. This profilometer must be properly calibrated against some trustworthy reference.

7. **S1 POLISHING (SMP):** The roundel is then warped again and polished into a spherical shape. When released, the part takes on the desired (inverse to the warping) aspheric shape. As with grinding, comparisons between the warped and un-warped surfaces should be made and suitable adjustments to the stressing fixture made to match the desired warping.
 - a. On Keck, large tools (approximately 80% of the roundel diameter) were used to remove material rapidly, and to produce smooth, ripple-free surfaces that strongly tend toward spheres.
 - b. Keck used multi-point profilometry to control the polishing process, with measurements being made while the roundel was on the polishing machine, in the un-stressed condition. The multi-point profilometer is rapid and therefore less vulnerable to thermal-induced drift.
 - c. The polishing iterations continue until the desired “hand-off” accuracy is reached. The hand-off accuracy is the cost-optimized surface figure goal that allows the part to be cut into hexagonal shape (“hexed”), mounted and finally figured at minimum overall cost.
 - i. For example: It is not cost effective to SMP the roundel to perfection if it distorts more than 1 micron peak-to-valley (P-V) during hexing and mounting, because these errors will need to be removed by a subsequent process.
 - d. Keck polishing experience was that occasionally low spatial frequency errors, mainly astigmatism and focus, may arise in the “spherical” polishing. These can be slow to remove. By amplifying them with the stressing fixture, the removal was much more rapid, saving time. When this technique is used, the removal must be watched closely, as one might overshoot the goal.

8. **HEXING and MACHINING:** The SMP attachments are removed, the roundel is cut into the desired hexagonal shape, and the “ears” (which contain the rolled edges on the roundel) are discarded. The center hole and edge sensor pockets are machined (by fixed-abrasive grinding) into S2, and the chamfers and other small features are added.
 - a. When the roundel is hexed, the residual stress in the blank is released at the cut surfaces, causing the blank to distort slightly. TMT anticipates this

effect to be 1 micron P-V or less, however, it will depend on the type of glass used. To date, TMT does not have sufficient statistics on springing of the different candidate glass types to absolutely quantify the effect; however, the Keck experience provides good insight.

- b. Keck found a strong correlation between measured stress birefringence and shape change due to hexing for Zerodur, with the dominant effect being power. Based on this, it was possible to anticipate a large fraction of the shape change, and polish the mirror with a compensating amount of power, thus largely mitigating this effect.
- c. The figure errors that result from SMP, Hexing, and Machining are not removed until after the segment has been mounted and tested as described in steps 9-11.
- d. After hexing and machining, a complete dimensional inspection of the polished mirror should be performed.

9. **MOUNTING:** After etching the center pocket bond surfaces to remove SSD, the pucks and diaphragm are bonded to the glass.

- a. Note that the pucks are bonded to the back surface of the mirror which has been polished and made SSD-free in step-3.

After the adhesive has cured sufficiently, the Segment Support Assembly (SSA) is installed and fastened to the pucks and diaphragm.

- b. TMT anticipates a modest distortion of the optic due to the mounting. This is primarily a focus error caused by small misalignments and pre-stresses at the bolted connections. This effect is expected to be on the order of 100-250nm PV. This effect needs to be removed by final figuring.

Following mounting, a complete dimensional inspection of the Mounted Segment Assembly should be performed.

10. **ACCEPTANCE TESTS:** The mounted segment is oriented zenith-pointing, and restrained in a manner that provides support load-paths similar to those in the telescope. For TMT, the segment is also cooled down to the mean observing temperature (2C) prior to, and during the acceptance test.

- a. The segment is tested zenith-pointing so that the 1g print-through can be measured and removed in subsequent figuring. This has the benefit of making the telescope performance optimum at the zenith, (where the seeing is the best), then allowing optical errors to increase away from the zenith, degrading telescope performance as the atmospheric seeing also increases, thereby minimizing the science impact of optical aberrations.
- b. The segment is tested cold so that the mount-induced and glass-induced thermal distortions that occur at 2C can be measured and removed by final figuring. Given the added expense of cold tests, it is important to measure the change from 20°C to 2°C and establish what fraction of this change is predictable, from mirror to mirror. If a sufficiently large fraction of the change is predictable, then cold tests on every segment may not be needed.

11. **FINAL-FIGURING:** Using the surface error map measured in step-10 as the input, the final figuring process is performed to reduce the surface errors and bring the segment into specification.
- a. Since the SMP process using large tools to polish the roundel and subsequent hexing has produced an optic that has a smooth, ripple-free surface, with excellent edges, it is vital to select a final figuring process that does not add ripple, or degrade the edges.
 - b. Keck successfully used IBF for final figuring specifically because it could correct the surface figure without introducing ripple or edge roll-off, while also providing high rates of convergence (very deterministic). In theory, another process could be used for this step if it had the same excellent characteristics as IBF, but TMT does not know of any other process that achieves the same desired results.
12. **ITERATE TO CONVERGENCE:** Steps-10 and -11 are iterated until the optic meets the TMT specifications. For Keck, one IBF “hit” was sufficient. For TMT, two or three IBF hits might be required, depending on the hand-off accuracy achieved, because the TMT specifications are tighter than Keck. The polisher can adjust the hand-off point in order to improve efficiency as the process becomes better understood during production. It may be advantageous to improve SMP accuracy in order to reduce IBF durations and test/figuring iterations in production.

SUMMARY

The Keck project successfully demonstrated the advantages of SMP and IBF, making a strong case that this is the best approach for polishing off-axis aspheric hexagonal mirrors for segmented primary mirror astronomical telescopes. The unique combination of requirements (smooth, accurate surfaces that are good right to the edge) requires a unique solution. The SMP and IBF process appears to be technically superior and highly cost effective; therefore it is believed to be the best approach for TMT.

APPENDIX – A

SMP Metrology Considerations

In order to rapidly and efficiently SMP the optics, it is essential to have a fast, accurate, and repeatable metrology tool that can be used in-situ during polishing. Keck used a linear one-dimensional (1D) array of 15 probes that was clocked (rotated) around the optic in order to sample the surface sufficiently to fit Zernikes and understand the corrections needed to converge the optic to the desired shape.

The following is a partial list of considerations related to in-process SMP metrology that need to be considered:

- **Accuracy and Repeatability:** The measurements must be accurate and repeatable. This suggests the following:
 - Detailed error analysis and budgeting is essential to establish the uncertainty in the measurements.
 - Stable control of the Radius of Curvature over time periods of years is needed.
 - Accurate indexing of the metrology instrument to the optic in the required degrees of freedom (DOF) is needed. For the highly aspheric segments, this indexing is critical and challenging. Both radial position (off axis distance) and clocking of the mirror about its own center are important. Small indexing errors will result in significant measurement errors, and therefore polishing errors.
 - Thermal stability of the instrument and the optic support system over the period of time required to make a measurement is important. At Keck, the instrument was “zeroed” against the spherical reference mirror before and after each measurement.
 - Stability of the instrument over long time scales is also important, typically accomplished using a stable, zero-expansion reference surface.
 - If the instrument contacts the optic, the forces introduced into the optic must be sufficiently small so as not to distort the optic.
 - The measurement probes must be stable, and calibrated both for zero point and over the operating range to high accuracy. Calibration to ~50 nm RMS is required.

- **Spatial Sampling Density:** The sampling density requirement for in-process metrology depends on the characteristics of the polishing process. If the polishing process inherently produces ripple-free surfaces dominated by low-spatial-frequency errors, then only a coarse sampling density is required. Conversely, a process that must be carefully controlled in order to eliminate higher spatial frequency errors requires a greater sampling density. The sampling density must be carefully matched to the process in order to minimize cost and assure figure control.

- **Support of the Optic:** The optic needs to be measured in both a stress-free state and in the warped configuration. During SMP it’s important that the mirror can

be measured both warped and un-warped, to ensure the warping amount is correct, and that the final mirror has the desired shape.

- **SMP Mount Effects:** If measured in-situ, as was done during Keck production, the SMP fixture needs to be able to float the part with low-distortion and with the stressing forces removed.
- **Speed:** The time consumed making in-process measurements is costly. The production is halted, the capital equipment is idle, facility overhead and marching army costs continue to accrue. It is essential that the in-process metrology be rapid as well as accurate. Simultaneous measurement with multiple probes is advantageous, as was demonstrated during Keck. For TMT one may consider the use of a 2D array of probes to improve through-put and accuracy, while also reducing thermal drift during the measurement.
- **Data acquisition and Processing:** To be efficient, the measurement data needs to be captured rapidly, processed to determine the shape of the optic, including Zernike fitting, followed by the determination of revised SMP fixture settings and polishing machine motions. This implies an integrated control system, specifically designed for TMT SMP.

APPENDIX-B

Acceptance Test Metrology Considerations

The Primary Mirror Segment Acceptance Test Metrology is one of the most critical and complex aspects of the TMT project. The performance of the Primary Mirror dominates the ultimate performance of the telescope, and the mirror segment metrology must be accurate in order to produce segments that meet requirements.

Generally:

The requirements for Acceptance Test Metrology are somewhat different than the requirements for in-process metrology described in Appendix-A. The Acceptance Test Metrology must be more accurate and have higher spatial resolution than the SMP process control metrology.

The Acceptance Test Metrology must also be performed at the mean observing temperature (2C), and the entire process, including cool-down, testing, and data processing must be sufficiently rapid that it can keep pace with the production flow. Considering that 2 to 4 tests cycles will likely be required for the final figuring of each segment, the throughput of the testing process is extremely important.

TMT currently specifies that every mirror segment be acceptance tested at 2°C, however, this will be costly. Given our desire to reduce cost, TMT may determine, after cold-testing some modest number of segments, that the thermal distortion effect is predictable. In this case, the thermal distortion would be compensated for during the figuring process, thereby eliminating a large portion of the cold testing. For purposes of quality control, it would still be necessary to cold-test segments periodically throughout the production program to assure that the compensation is correct.

Specifically:

The following is a partial list of considerations related to Acceptance Test Metrology that need to be considered:

- **Systematic Errors:** Systematic errors present a significant risk to the program because they are so difficult to detect, and the consequences are potentially so serious. This becomes even harder when one considers that the telescope requires 82 different mirror types, meaning that the test apparatus must be able to maintain accurate control of Radius of Curvature while also possessing sufficient dynamic range to measure the asphericity associated with all 82 types, without introducing significant systematic errors. Note: It is often useful to consider radius of curvature errors as surface errors, thus putting them on the same footing as other optical errors.

Systematic errors are difficult to detect and are especially dangerous because they can consistently provide incorrect data to control polishing. The worst case is that the optics may be carefully polished to the wrong prescription.

Systematic errors may result from several sources such as:

- design errors in the test apparatus & process,
- errors in the data processing and subsequent usage

- alignment errors within the apparatus, or between the optic and the apparatus,
- manufacturing errors in the test apparatus (for example: errors in the reference optics, calibration standards, or computer-generated hologram (CGH) errors),
- slow drifts of the apparatus (for example: thermal distortions, or creep), or
- other sources.

Depending on the type of systematic errors, these errors could potentially:

- impact every segment produced in the same way, or
- be type-specific (consistently impacting a segment type in the same way), or
- be slowly varying, and hence easily un-noticed, such as a thermal drift

This risk must be mitigated by careful design and analysis of the apparatus and process, including developing stable calibration standards, as well as the use of an independent segment test method, to cross-check the results. An actual segment may be a very useful reference to check against time varying drifts.

- **Random Errors:** Random errors are annoying and disruptive to the manufacturing process, but they are much easier to observe and manage. The design of the test apparatus should minimize the risk/impact of random errors. For example: large optical path lengths are likely to degrade repeatability hence increase the time needed to test. Vibration and thermal distortion may also result in uncontrolled random errors.
- **Error Budgets:** Careful design, analysis and error budgeting can reduce the risks due to systematic and random errors and this must be performed during the conceptual design of the test apparatus, and maintained throughout the program.
- **Spatial Sampling Density:** The spatial resolution for the Acceptance Test Metrology is specified in the Polishing Specification as 500x500, which corresponds to approximately a 3mm pitch. This is easily accomplished with optical interferometry, but much more difficult using profilometry. The required sampling density depends on the polishing process and the expected spatial frequency of the surface errors. Coarser sampling is only justified if it can be shown that there are no high spatial frequency errors that would be missed by the measurement. It is also the case that IBF is limited in the spatial frequency it can correct; therefore correcting high spatial frequency errors with IBF may not be possible. All these argue for making the mirrors as smooth as possible.
- **Support of the Optic:** For the acceptance test, the optic is supported on the Segment Support Assembly (SSA). This is the same mount that will be used to support the mirror segment in the telescope. The SSA provides a stable and highly repeatable support, thus easing metrology.

- **Accuracy and Repeatability:** The measurements must be accurate and repeatable. This suggests the following:
 - Detailed error budgeting is essential to establish the uncertainty in the measurements.
 - Absolute accuracy that is stable over time periods of years, including the radius of curvature. The serial production of segments thus requires excellent stability of all terms describing the segment surface.
 - Accurate indexing of the measurement apparatus to the optic in the required DOF. For the highly aspheric TMT segments, this indexing is critical and challenging. Small indexing errors will result in significant measurement errors, and therefore polishing errors.
 - Thermal stability of the instrument and the optic support system over the period of time required to make a measurement is important. This is particularly challenging at 2C.
 - Stability of the instrument over long time scales, typically accomplished using a stable, zero-expansion reference surface is also important. As noted earlier, some long term drifts may be calibrated out using a standard optic, such as a mirror segment.
 - If the instrument contacts the optic, the forces introduced into the optic must be sufficiently small so as not to distort the optic.

- **Speed:** As previously mentioned, the time consumed making these critical measurements is costly. It is essential that the final metrology be rapid as well as accurate. The measurement process must support the production rates at the minimum cost. Slower processes may suggest the need for multiple parallel measurement stations. This would increase cost and would increase the difficulty of ensuring that all segments will be part of the same global aspheric shape.

- **Data acquisition and Processing:** To be efficient, the measurement data needs to be rapidly captured and processed to determine the shape of the optic, including Zernike fitting, followed by the determination of a “hit map” that will direct the final figuring process.