

Sub-nm Freeform mirrors manufacturing

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ABSTRACT

Optical freeform surfaces offer significant advantages in optical performance and system compactness. However, aligning systems such as telescopes that incorporate freeform optics is less tolerant than with conventional designs like off-axis aspherics or Three-Mirror Anastigmat (TMA) systems. This means freeform surfaces must be manufactured with extremely high global form accuracy. For certain applications, sub-nanometer is required in terms of RMS wavefront error and surface roughness. The compact nature of these systems results in smaller freeform surfaces compared to traditional designs, which complicates polishing due to both the large deviation from a spherical shape and the reduced usable area. Conventional polishing techniques must be adapted to meet these demands. Moreover, measurement methods for these freeform surfaces need to be reassessed to ensure they achieve the necessary sub-nanometer accuracy to match their ideal theoretical profiles.

Thales SESO has developed a complete freeform manufacturing process starting from blank glass. This covers grinding, polishing, lightweighting, coating, integration, and testing. For smaller freeform surfaces, it is essential to tailor the manufacturing steps and tools accordingly. One major challenge lies in how to define the freeform surface beyond the useful area, a peripheral collar (extra-margin) must be established to facilitate proper polishing and prevent edge effects. Robust management of this extrapolated area is critical to avoid introducing additional manufacturing difficulties.

For the optical testing of freeform surfaces, Thales SESO has implemented a test setup capable of achieving 10 nm RMS wavefront error accuracy and optical axis measurement with 25 μm precision. As specifications for smaller freeforms become more stringent, down to 0.1 nm RMS, optical testing methods must evolve, requiring enhanced interferometric setups for absolute measurements, as well as the integration of stitching roughness measurements and profilers. By combining results from these various measurement techniques, Thales SESO can achieve sub-nanometer accuracy with high global form fidelity, enabling precise determination and control of the optical axis.

Keywords: Freeform, manufacture, polishing, measurement

1. INTRODUCTION

Thales SESO has demonstrated, through a self-funded prototype, the complete manufacturing and measurement of a concave freeform surface, from a blank substrate to nanometer-level surface error quality, including optical axis position measurements in an interferometric setup (ICSO 2024 – Freeform manufacturing challenges).

Since that demonstration, new requirements have emerged. First, convex freeform prototypes have been manufactured. More recently, Thales SESO has pursued high-performance freeform mirrors. The LISA telescope project, for instance, requires smaller mirrors (approximately 50 mm in diameter) with extremely strict wavefront error specifications over the science field of view. The requirement is typically expressed as < 1 nm Peak

-to-Valley WFE over a 10 mm diameter, corresponding to approximately 0.1 nm RMS WFE. Such challenging specifications introduce two critical questions:

1. How can these surfaces be measured with sufficient accuracy?
2. How can such small-diameter freeform surfaces be manufactured reliably?

2. FREE-FORM DEFINITIONS

Freeform surfaces can be defined in several ways, including point-data grids and polynomial representations such as NURBS, Legendre, or Zernike, in addition to standard aspheric forms. Once one representation is established, other representations can be derived through fitting procedures.

At Thales SESO, the freeform figure is typically modeled using standard aspheric shapes extended by Zernike polynomials, consistent with major optical simulation tools (OpticStudio, CodeV, ...). More recently, it has become necessary to extend freeform definitions to include (X, Y) translation offsets, applied directly to the freeform terms rather than only to the aspheric shape. Thales SESO has incorporated this capability into its models.

The deviation from a best-fit sphere is a global metric of optical manufacturing difficulty and can be quantified in terms of amplitude or slope (in Peak-to-Valley or RMS). However, this metric alone does not describe the actual challenges encountered in mechanical polishing. To better characterize polishing feasibility, Thales SESO developed a proprietary polishing criterion [1], based on curvature fluctuation, which provides a more realistic indicator of mechanical polishing difficulty.

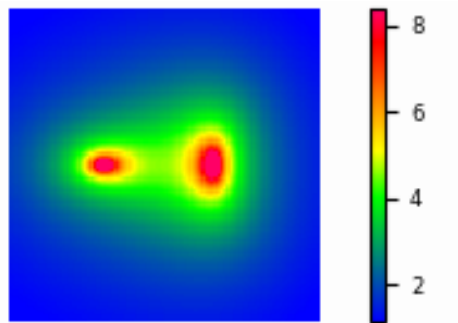


Figure 1. Example of polishing criterion map for a freeform surface. The lower the value, the higher the polishing complexity. Units are in millimeters. This criterion enables comparison across all other surfaces produced at Thales SESO (freeform and non-freeform).

For the LISA telescope mirrors, the system-level requirement is expressed as a minimal angular deviation within the field of view. This translates into a wavefront quality requirement of less than 1 nm Peak-to-Valley WFE across the field, which leads to a particularly demanding value of the polishing criterion.

3. METROLOGY CHALLENGES

Meeting the 1 nm Peak-to-Valley requirement, or equivalently 0.1 nm RMS WFE, requires substantial improvements compared with conventional metrology. Standard interferometry or high-precision profilometry typically provide accuracies on the order of ~10 nm RMS WFE. Therefore, techniques must be improved by roughly two orders of magnitude to confidently close the error budget at the target level.

Although freeform surfaces can be tested with Computer Generated Holograms (CGH), the resulting accuracy is often limited. Freeform mirrors are highly sensitive to positional errors, which makes conventional displacement-based error removal less robust when systematic uncertainties are not sufficiently below the residual figure error of interest.

Thales SESO has previously achieved 0.1 nm RMS WFE knowledge on large-radius spherical and large-diameter components for the Advanced Virgo experiment, using a Zygo MST interferometer with a 24-inch transmission flat (TF).

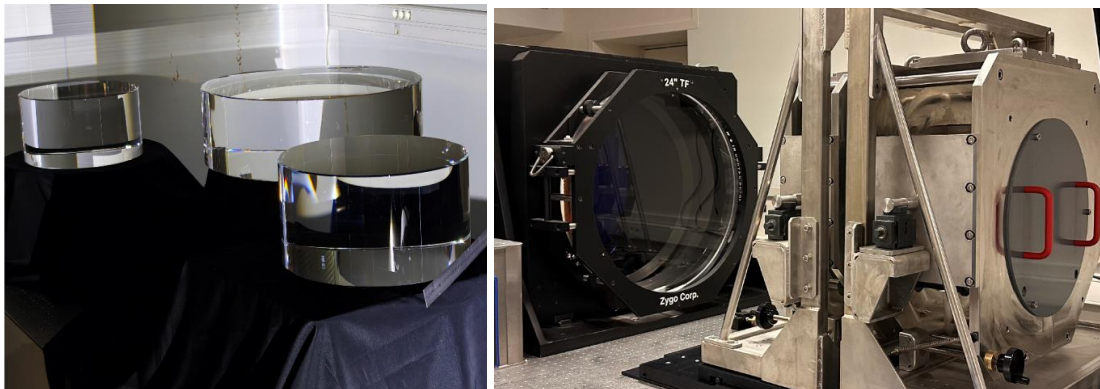


Figure 2. Left: IM and EM components of Advanced Virgo / Right: 24-inch Zygo interferometer for measurement of these components

In that configuration, the surfaces are almost flat (radius of curvature on the order of kilometers) and can be treated similarly to flat optics. As a result, the radius of curvature can be obtained directly from the WFE measurement.

The dominant source of bias in that setup originates from the Transmission Flat (TF). Characterization using a three-flat measurement method led to a systematic TF error of approximately 1.7 nm RMS, which is larger than the accuracy required for the sub-nanometer target.

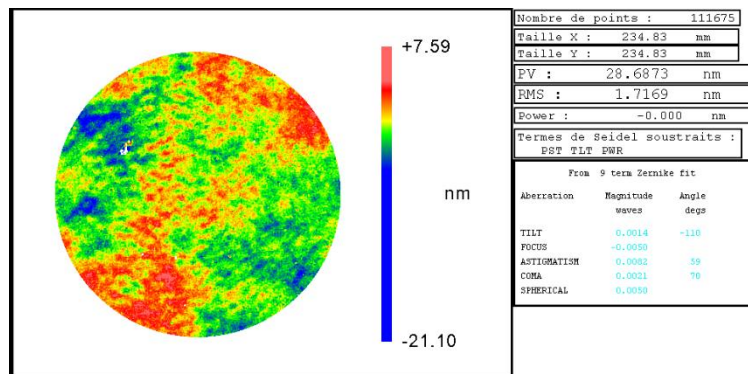


Figure 3. Three-flat measurements of TF

Instead of directly subtracting the characterized error map, Thales SESO uses a robust self-calibrating error removal method. This approach is adapted from stitching techniques used in X-ray mirror metrology (sub-pupils over long mirrors) and is extended to full-pupil measurement strategies. In practice, random but accurately known displacements are applied to the component in front of the TF. By averaging and iteratively estimating the residuals from translated-map subtraction, the systematic TF contribution can be extracted more robustly.

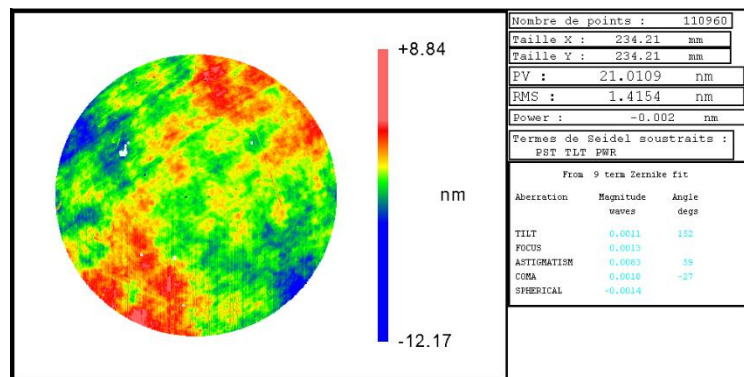


Figure 4. TF measurement after self-calibration error method

After subtraction of TF contribution and averaging unitary measurements, the EM performance is at 0.7 nm RMS.

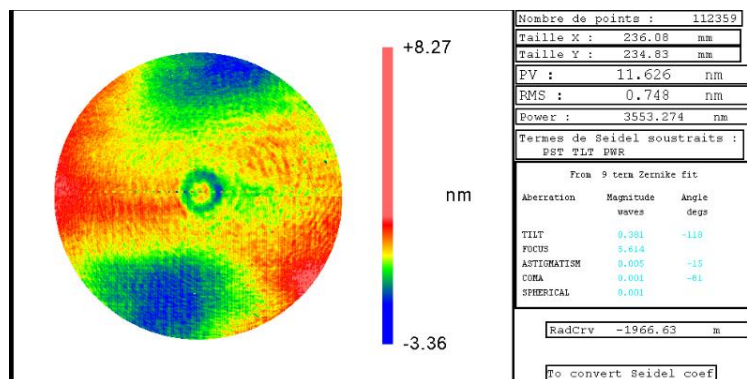


Figure 5. SFE map of EM component, after analysis

For the LISA telescope mirrors, the mirrors are relatively small (approximately 50 mm diameter), and the direct implementation of the previous measurement strategy is not feasible.

As an intermediate step toward LISA-relevant specifications, Thales SESO manufactures off-axis ellipsoid shapes with diameters similar to the LISA telescope mirrors for EUV applications. In that qualification work, a 0.1 nm RMS WFE measurement accuracy is achieved using a method inspired by Advanced Virgo and adapted to a vacuum environment with a double-focus working setup.

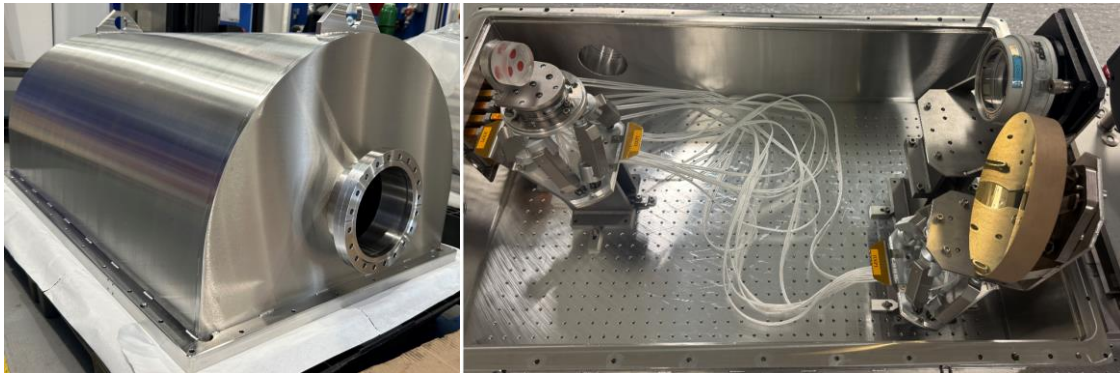


Figure 6. Left: Vacuum chamber / Right: double-focus interferometric test setup in the chamber

First, a Transmission Sphere (TS) generates a first focus point, and the diverging beam is then reflected by the off-axis ellipsoid. A second focus point is then generated in space. A spherical return mirror is placed such that the second focus point corresponds to the desired spherical radius of curvature. This method uses under-vacuum hexapods to apply controlled displacements. The first measurement, performed under vacuum, is to characterize the TS error using the self-calibrating error removal with a standard spherical mirror.

The Zygo interferometer is located outside the chamber. A wavelength-shifting solution is used to create the interferometric reference so that the chamber window does not contribute to the final WFE measurement. In the final configuration, the spherical mirror is used again to perform the self-calibration error removal. At the end of the process, WFE maps are obtained after subtracting the contributions associated with the test sphere and the reference (TS) characterization.

For the EUV project, roughness bandwidth requirements also demand lateral resolution and global form consistency. A stitching-based roughness measurement using a x10 objective on a Bruker instrument provides high lateral resolution (approximately 2 μm per pixel in the demonstrated example) and delivers global, rather than only residual, freeform sag data. This roughness measurement produces WFE maps consistent with those obtained from the interferometric test setup.

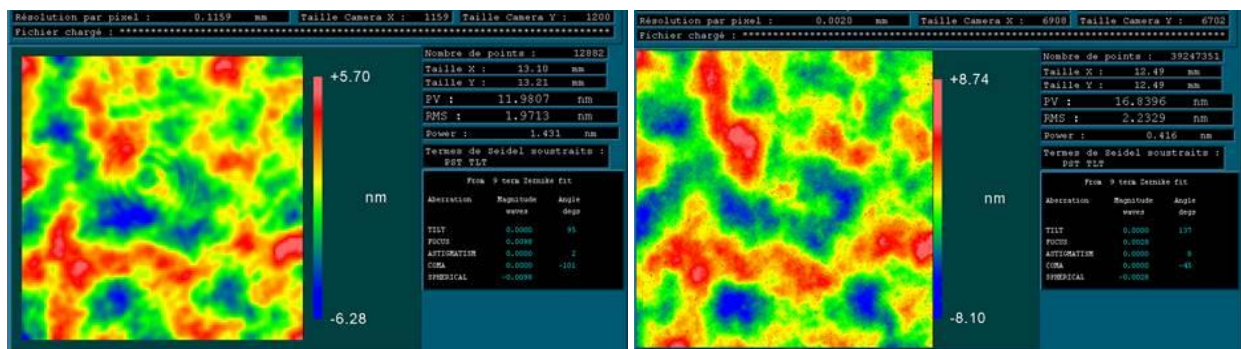


Figure 7. Left: interferometric test setup / Right: stitching roughness

The main advantage of stitching-based roughness is the ability to capture both global and local form, enabling extraction of the complete freeform sag with high lateral resolution.

4. MANUFACTURING AND POLISHING CHALLENGES

Thales SESO uses customized polishing machines originally designed for large optics and therefore equipped with large polishing tools. For smaller freeform mirrors, these machines are less suitable, requiring smaller tools and possibly the acquisition or development of new equipment. While 5-axis CNC polishing machines are available, demonstrating that they can achieve comparable roughness and performance to large-format solutions remains a critical qualification step.

Manufacturing also requires the inclusion of peripheral collar outside the useful aperture to avoid edge effects induced by mechanical polishing. This collar must be incorporated into the defined freeform surface, which necessitates surface extrapolation. Extrapolating freeform surfaces is challenging: a straightforward extension of Zernike and aspheric terms from the initial definition often leads to a significantly harder polishing criterion on the additional surface area. Current efforts therefore focus on developing extrapolation methods that minimize polishing difficulty and produce manageable additional surfaces, while ensuring geometric continuity of amplitude, slope and curvature across the boundary and maintaining smoothness.

Conventional extrapolation approaches (polynomial or FFT-based methods for example) do not satisfy all of these requirements simultaneously. To maximize the degrees of freedom during extrapolation, Thales SESO uses a grid-based sag method. In this approach, the sag is fully defined point-by-point in the useful area, and the extrapolated collar points are defined through constrained interpolation rules.

This grid-sag definition had to be implemented in production: previously, only an aspheric and Zernike definition was allowed. The ability to control the collar correctly is essential to decrease the risk of tool marks and unwanted local modes near the boundary. On the collar extrapolated zone, linear interpolation is used to generate the points required for manufacturing control.

From an optical simulation perspective, the collar is not required at the instrument level. However, at the manufacturing level, the collar must be included in the CGH definition, for the first interferometric measurements. Therefore, manufacturing-oriented freeform datasets must be supported by optical simulation software. This grid-sag definition is now supported in optical simulation software, enabling a coherent link between the optical definition and the manufacturing control strategy.

5. CONCLUSION

Sub-nanometer freeform mirrors impose stringent requirements that affect the full production chain: definition, extrapolated collar handling, polishing feasibility, and metrology uncertainty management. Standard metrology methods at the ~10 nm RMS WFE level is not sufficient for closing an error budget targeting ~0.1 nm RMS WFE. Therefore, Thales SESO has developed a dedicated metrology strategy combining

- absolute-capable interferometric test configurations,
- self-calibrating error removal principles
- stitching-based roughness measurements to recover global freeform sag with high lateral resolution.

On the manufacturing side, achieving the required global form quality and surface finish for small freeform apertures requires process adaptation, including smaller tooling capability and a controlled strategy for defining and polishing a peripheral collar to avoid edge effects. The introduction of grid-based sag definitions supports practical fabrication and improves the manufacturability of the extrapolated region beyond the useful aperture.

By integrating these advances, Thales SESO can reach sub-nanometer-level accuracy with high global form fidelity, ensuring consistent optical-axis and figure control from design intent to manufactured hardware for demanding telescope architectures.

REFERENCES

- [1] Christian du JEU, Julien FOUREZ, Hassan El HANDRIOUI, Matthieu GILLES, “Definitions of criteria for assessing feasibility and measurability of freeform surfaces,” Proc. of SPIE Vol. 11175 1117510-13 (2019)