

Optical metrology of off-axis aspherical diffraction gratings for the Solar-C/EUVST Grating Assembly

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ABSTRACT

The Solar-C mission aims at studying the physical processes driving coronal heating and the release and acceleration of the solar wind through spectroscopic observations in the extreme ultraviolet. It is led by JAXA with contributions from European countries and the US. The Extreme Ultraviolet high-throughput Spectroscopic Telescope (EUVST), its primary instrument, is designed to simultaneously observe the different layers of the solar atmosphere over a broad temperature range, from the chromosphere (0.01 MK) to the flaring corona (10 MK). It will provide measurements with significantly improved spatial and temporal resolution compared to previous EUV spectrographs. The spectral performance of EUVST relies critically on two high-precision aspherical diffraction gratings integrated into the EUVST Grating Assembly (EGA). The broad spectral range of the instrument requires the diffractive element to be formed by bonding two separately ruled sub-gratings. Since this bonding operation is irreversible, pre-bonding metrology is essential to verify that each sub-grating meets the stringent specifications prior to integration. We present the optical metrology approach developed at the Institut d'Astrophysique Spatiale (IAS) for the characterization of EGA substrates at key stages of the manufacturing process. The substrates present specific measurement challenges, including their off-axis aspherical figure and a relatively large tilt, both of which must be accurately handled to reach the required surface figure error of less than 5 nm RMS, with a 2.5 nm RMS best effort target. Surface figure measurements are performed with a Zygo Verifire interferometer. Radius of curvature, tilt, and departure from the nominal surface are derived independently of each measurement. Measurement procedures have been established and validated on the flight substrates, and results on a representative substrate are presented, showing surface figure error, radius of curvature, and tilt values within specification.

Keywords: Solar-C, EUVST, diffraction grating, optical metrology, Fizeau interferometry, surface figure error, aspherical optics

1. INTRODUCTION

What are the physical processes that occur in the lower corona that are responsible for the solar wind heating and acceleration? Answering this question requires observing directly in the region where the solar wind is formed, resolving the small-scale transient phenomena such as magnetic reconnection, waves, and rapid flows that are thought to drive coronal heating and solar wind acceleration.¹ This calls for high-resolution EUV spectroscopy, which alone gives simultaneous access to the velocity, temperature, and density diagnostics of coronal plasmas needed to constrain these mechanisms, with the spatial, temporal, and spectral resolution to capture their transient nature. The Solar-C mission aims at addressing these open questions through its core instrument, EUVST (Extreme Ultraviolet high-throughput Spectroscopic Telescope),² an EUV spectrograph designed to simultaneously observe the chromosphere, transition region, and low corona over a temperature range of 10^4 to 1×10^7 K, corresponding to a spectral coverage of 170–1600 Å. Its target performance includes a spatial resolution of 0.4 arcsec, a spectral resolving power of 5000–13500 depending on the channel which enables plasma velocity measurements to within a few km s^{-1} , and a cadence of 2 s at full spatial resolution.²

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The EUVST spectral performance relies on two aspherical diffraction gratings integrated into the EUVST Grating Assembly (EGA), whose design is led by the Institut d'Astrophysique Spatiale (IAS), as shown in Figure 1. This paper presents the first description of the optical metrology developed for the EGA substrates. The optical design of the EUVST telescope, within which the EGA defines the spectral performance, is described in Ref. 3. The requirement to simultaneously cover a wide range of line-formation temperatures imposes a broad spectral coverage, which is achieved through two sub-gratings ruled separately on two aspherized half-substrates with a relative tilt, then assembled into a single diffractive element. Any misalignment between the two half-substrates would directly degrade the focal plane quality and hence the spectroscopic performance of the instrument: precise geometrical and optical characterization of each half-substrate is therefore essential prior to assembly, which is irreversible.

2. SUBSTRATES AND MEASURED QUANTITIES

The EGA optical components are two octagonal substrates that correspond to the targeted wavelengths. The SW (Short Wavelengths) grating has a conic figure and covers the wavelength range from 17 to 21.5 nm. The figure of the LW (Long Wavelengths) grating is a generalized ellipse and covers a range from 69 to 127.5 nm. Both gratings are off-axis and tilted with respect to the optical axis and mechanical reference. The SW grating presents a larger tilt. This off-axis geometry is one of the main challenges faced during metrology. Four principal observables should be determined during the metrology process to verify that the optical shape fulfills all the stringent requirements. First, the surface figure error (SFE) should be measured to a nanometric precision as the requirement is of a maximum of 5 nm RMS. Second, the radius of curvature, nominally 516.823 mm for the SW substrate and 528.008 mm for the LW substrate, is determined with a relative precision under 0.05 %. Third, the surface tilt with respect to the mechanical axis, specified within 0.14° along X and 0.25° along Y, must be known to within 15 arcseconds to ensure the optical alignment with the other subsystems of the EUVST (CCD cameras and slit).³ Finally, the position of the vertex is a further parameter to characterize: its actual position may depart from the nominal by up to 0.05 mm along X and 0.2 mm along Y, and it must be measured to within 0.05 mm. The SFE, surface tilt and radius of curvature are decoupled and cannot be derived from a single measurement, each requiring a dedicated technique; the vertex position, by contrast, is obtained jointly with the SFE from the same aspheric fit.

Specific instrumentation is necessary to perform this metrology plan. We rely on a Zygo Verifire interferometer, with a F/3.3 spherical reference for the radius of curvature and the surface figure error and a flat reference for the measurement of the surface tilt. A central difficulty in the interferometric characterization arises from the aperture mismatch between the reference optics and the test surface. The Fizeau reference sphere provides an F/3.3 beam, whereas the physical diagonal of either substrate subtends an effective F/12 aperture at the interferometer. As a consequence, the measurement samples only a small zone of the reference wavefront near its axis, where its quality is better than over the full aperture. More fundamentally, the radius of curvature cannot be recovered from the SFE measurement itself: because the test surface is gauged against a reference sphere whose radius is set by the interferometer's transmission optics rather than matched to the substrate's nominal curvature, the power term of the interferogram is degenerate between the substrate's true radius and the axial positioning of the test setup. It therefore cannot be uniquely attributed to a radius error without an independent, absolute measurement. Conversely, once the radius is known from such an independent measurement, small residual errors in this value have only a second-order effect on the fitted SFE, since a least-squares aspheric fit largely absorbs this defocus term. This asymmetry is what makes the radius of curvature an observable that must be determined first, using a fundamentally different technique, before it can be used as an input to the SFE reduction.

The metrology plan and the substrate design requires the definition of three reference frames. The first one corresponds to the reference frame in which we perform the measurement, so that the Z direction is normal to the substrate and along the optical axis of the Zygo. The second reference frame is native to the substrate and defines its optical surface (form and tilt), with the origin at the vertex and the normal vectors $\xi x, \xi y, \xi z$ illustrated in Figure 2. The third reference frame is the mechanical reference frame, with the origin the point EGA-O in the drawing (Figure 1) and defined by the reference faces of the substrate. It is the reference frame in which we perform the computation to retrieve all parameters and in which we present the measurement of the surface figure error.

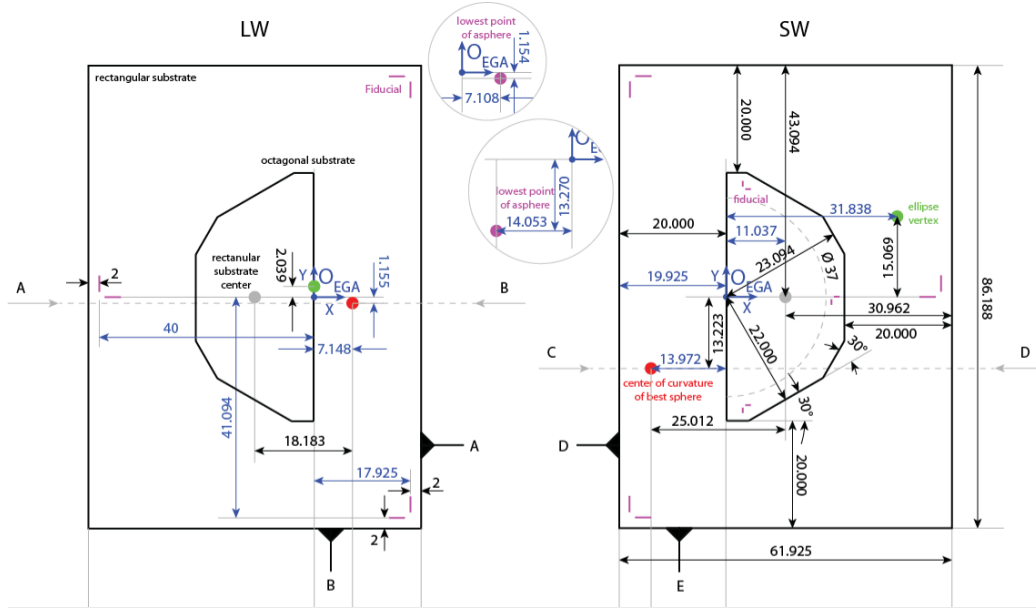


Figure 1. Geometry of the two EGA substrates, with the LW substrate on the left and the SW substrate on the right. Each substrate is an octagonal optical area on a rectangular blank, with the useful aperture, the fiducial, the ellipse vertex, the lowest point of the asphere, and the centre of curvature of the best-fit sphere indicated. The dimensions that define the optical surface and its position with respect to the mechanical reference faces are given in mm and degrees. These fiducials and reference features are used to register each measurement in the substrate reference frame.

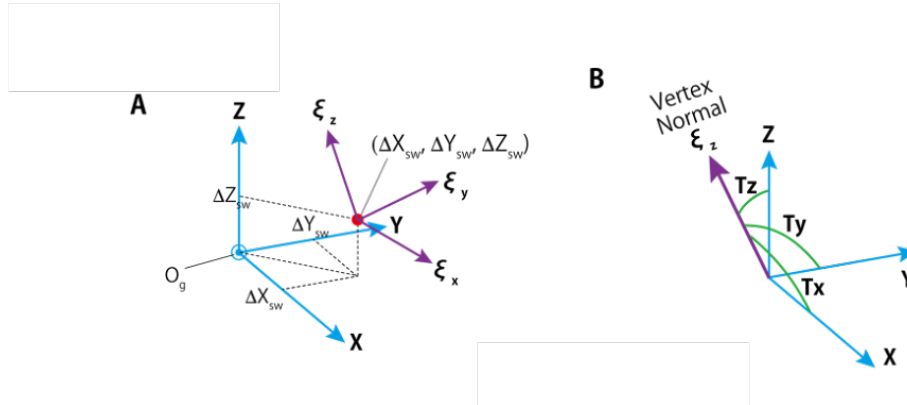


Figure 2. Reference frame of the SW substrate. Panels A shows the relationship between the coordinate to define the optical surface of the SW grating (hereafter SW coordinate, purple arrows with ξ_x, ξ_y, ξ_z) and the EGA local coordinate (light blue arrows with X, Y, Z). The surface of the SW grating is a conic (ellipse), with the origin of the SW coordinate system located at the vertex of the ellipse (red point in panel A), and the normal to the surface at the vertex is defined as ξ_z . The origin of SW coordinate is deviated by $(\Delta X_{SW}, \Delta Y_{SW}, \Delta Z_{SW})$ with respect to the origin of the EGA local coordinate (O_g). Panel B shows the schematic of angles (T_x, T_y, T_z) of the vertex normal of the ellipsoid ξ_z with respect to the EGA local coordinate (X, Y, Z).

3. MEASUREMENT PROTOCOL

The primary metrology instrument is a Zygo Verifire Fizeau interferometer, used with a flat reference for surface tilt measurements and a spherical reference for form and radius characterization. The spherical reference is specified at $\lambda/20$ PV ($\lambda = 632.8$ nm) over its full F/3.3 aperture. Because the EGA substrates subtend only an effective F/12 aperture, only the central zone of the reference wavefront is used, where its quality is in practice better than the full-aperture specification, relaxing one of the dominant contributions to the SFE error budget. The interferometer and the dedicated five-axis mount are shown in Figures 3 and 4.

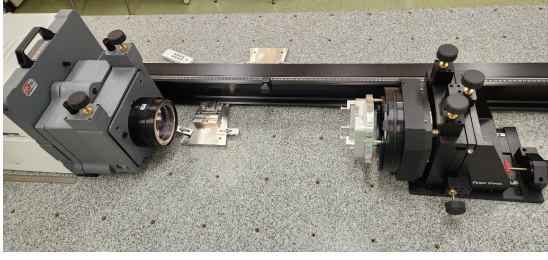


Figure 3. Zygo Verifire Fizeau interferometer, used with a spherical reference for SFE and radius measurements, and a flat reference for tilt measurements.

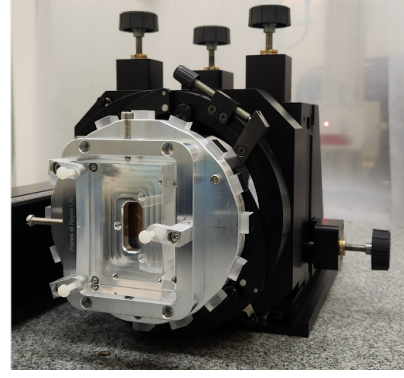


Figure 4. Five-axis rotating mount with specifically designed holder for the substrates.

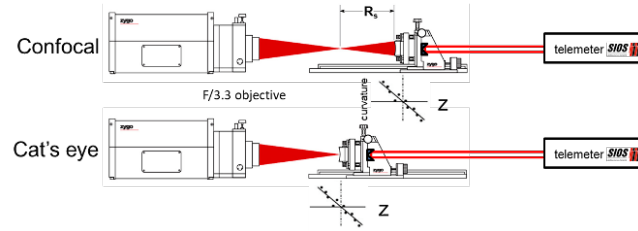


Figure 5. Schematic illustrating the principle of measurement of the radius of curvature

The three principal observables must be measured in a specific order. The radius of curvature is established first, because it cannot be derived from the SFE measurement: the test surface is gauged against an arbitrary reference sphere, so the power term of the interferogram does not give the absolute radius. The measured radius is nonetheless required for the SFE, since it fixes the nominal aspheric that is fitted and subtracted to yield the figure error. The tilt is processed last, as it depends on both the radius and the decentering derived from the SFE map. This sequential dependency structures the whole workflow.

The radius is obtained by translating the substrate along the optical axis between two autocollimation configurations (Figure 5).⁴ Absolute distance measurements at the sub-micron level are performed with a SIOS laser interferometric telemeter, used together with the Fizeau interferometer to track the substrate's axial displacement during radius measurements. In the confocal configuration, the center of curvature of the reference sphere coincides with that of the test surface; in the cat's eye configuration, it is placed at the surface vertex. The radius is the axial separation between the two, measured with the laser telemeter. The radius is thus obtained from a length measurement rather than from precise mechanical positioning. This procedure suits the long radii typical of EUV telescope optics.

Accurate SFE measurements contend with four systematic error sources. The residual spherical reference wavefront contributes ~ 0.2 nm RMS, small compared to the substrate defects and treated as a second-order correction. Instrumental noise (detector shot noise, parasitic reflections, coherent scatter) sets a noise floor. Most demanding, thermal gradients in the 0.8 m cavity give a direct phase error: 1 mK corresponds to ~ 1 nm of path length, imposing stringent environmental stability. Finally, mounting-induced stress may introduce low-order figure distortions that must be separated from the genuine form. These sources are mitigated by rotation, averaging over 16 azimuthal orientations in 22.5° steps (Figure 6).⁵ The first three sources are tied to the laboratory frame, not to the substrate, and are therefore averaged out by the rotation. Repeatable rotation is set by a crown of 16 pre-calibrated flat mirrors, a fixed autocollimator aimed successively at each one giving a rotation accuracy better than 10 arcseconds.

The surface tilt is the angle between the optical axis of the aspheric (the conic axis for SW, the ellipse axis for LW) and the normal to the back face. Rather than measuring it directly, the method exploits a geometric property of aspherics: a unique point exists where the local tangent plane is parallel to the back face

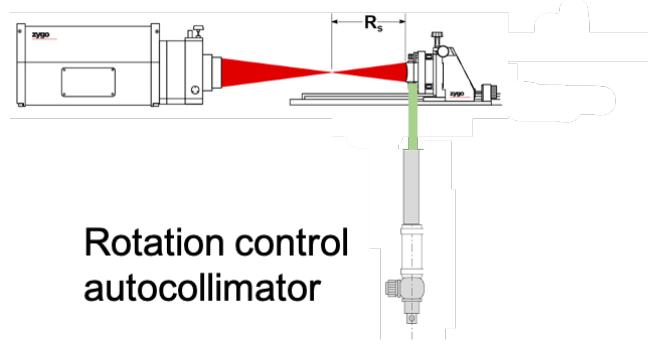


Figure 6. Setup for the surface figure error measurement, showing the rotation control autocollimator used to set the substrate at each of the 16 azimuthal orientations of the rotation-averaging sequence.

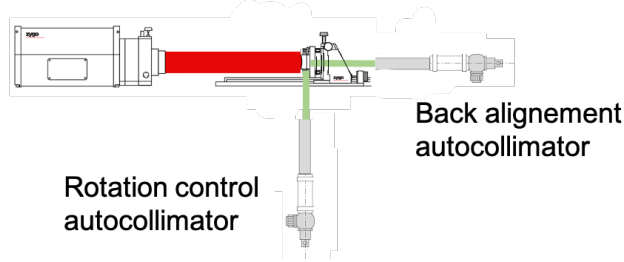


Figure 7. Setup for the surface tilt measurement in flat mode, showing the back-alignment autocollimator that sets the back face perpendicular to the optical axis and the rotation control autocollimator used at each of the 16 orientations.

(Figure 7). The location of this tangent point encodes the tilt, but it is sensitive to both the tilt and the lateral decentering; the decentering must therefore be known beforehand from the SFE analysis. The measurement uses the interferometer in flat mode. An autocollimator on the flat reference first sets the back face perpendicular to the optical axis. The substrate is then rotated in 16 increments on the same crown of mirrors, resting repeatably on a kinematic support, the back-face orientation being realigned after each rotation. At each orientation, 10 interferograms are acquired, the absence of drift across the series serving as the equilibrium criterion. Three orientations would suffice to locate the tangent point; the remaining thirteen over-constrain the fit and control residual mount and alignment errors.

In addition to the interferometric characterization of the optical surface, geometric measurements register the optical axis with respect to the mechanical reference frame and provide independent cross-checks. Angular measurements between reference faces are performed with two calibrated theodolites in autocollimation, leveled to better than 5 arcseconds. Edge lengths and fiducial positions are measured with an optical microscope and dedicated metrology software, sampling multiple points per edge.

4. DATA REDUCTION PIPELINE

The data reduction pipeline turns the raw interferograms, laser telemeter readings, and angular measurements into the three output observables. Its ordering follows the interdependencies established in Section 3: the radius is reduced first, the SFE second, and the surface tilt last (Figure 8).

The radius of curvature is processed first. The confocal and cat's eye interferograms are paired with the laser telemeter readings recorded at each configuration. At both the cat's eye and confocal positions the defocus term of the interferogram (the Power term reported by the interferometer) passes through zero; only the defocus is nulled, the surface figure still appearing in the confocal interferogram. Neither position is set mechanically: the defocus coefficient is read on either side of each null, where it changes sign, and the zero-crossing is recovered by linear interpolation of the defocus against the telemeter reading. The radius is the axial separation between the two interpolated positions.

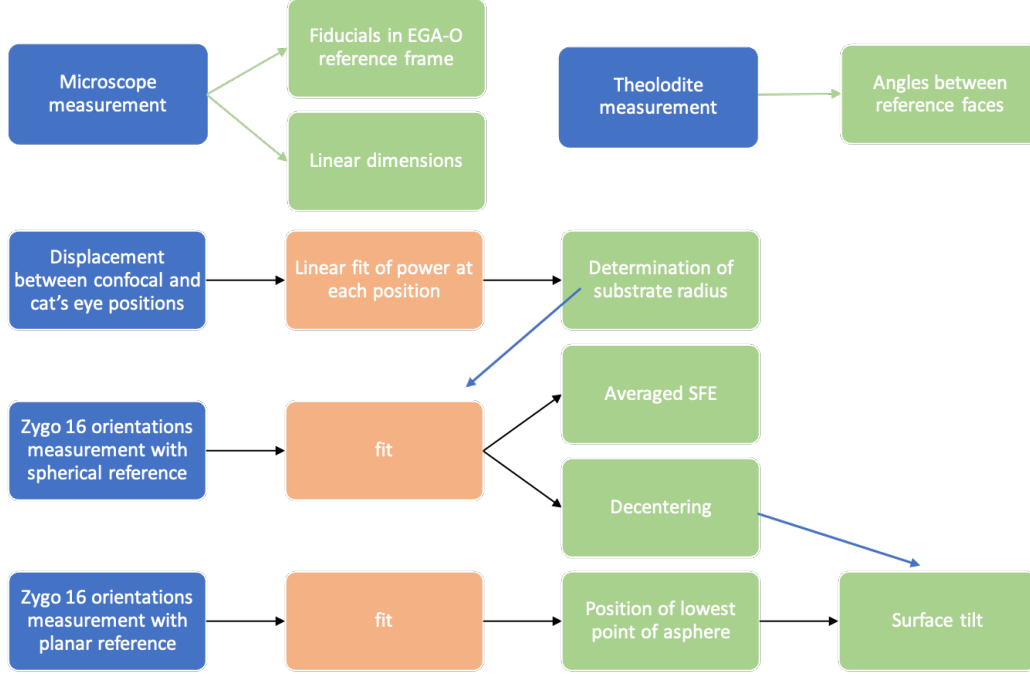


Figure 8. Flowchart of the data reduction pipeline, from raw interferometric maps to output parameters.

The SFE is then computed. Each of the 16 interferograms is registered into the substrate reference frame from the measured fiducial coordinates, which fix the in-plane position and orientation of the optical axis relative to the mechanical references. This registration is critical, since the aspheric fit residuals, and hence the SFE, depend directly on how accurately the optical axis is placed with respect to those references. The 16 registered maps are averaged. The radius obtained in the previous step fixes the nominal aspherical surface, which is then fitted to the averaged map. The best-fit asphere, a cone for the SW substrate and an ellipsoid for the LW substrate, is subtracted to give the SFE, reported as RMS and PV. The free parameters are the two coordinates of lateral decentering of the optical surface in the EGA-O frame, equivalent to the vertex position introduced in Section 2, which are propagated to the tilt analysis.

The tilt measurement is processed last, as it depends on the decentering obtained from the SFE analysis. Each of the 16 flat-mode interferograms is registered from its fiducials and fitted with a spherical cap whose summit locates the tangent point in that orientation, to about 1/10th pixel ($\sim 5 \mu\text{m}$ RMS). As the substrate rotates through the 16 orientations, the summits ideally lie on a circle. Fitting this circle by least squares returns its centre, which is the projection of the rotation pivot, and its radius. The pivot is kept as a free parameter rather than fixed to the substrate centre, because the residual misalignment between the flat reference wavefront and the back face cannot be measured independently and would otherwise bias the centre.

The tilt of the optical axis is then reconstructed from the tangent point and the vertex. We form the in-plane offset (dx, dy) between the vertex, located from the radius and SFE analysis, and the tangent point. On a surface of known radius R , this offset fixes the local normal at the tangent point: its in-plane components are (dx, dy) and its third component follows from the sphere equation, $\mathbf{n} \propto (dx, dy, \sqrt{R^2 - dx^2 - dy^2})$. This local approximation assumes that the Zygo line of sight corresponds to a pure dz displacement in the surface normal frame, whereas the actual measurement is a dr along the radius, related by $dz = dr \cos \theta$, where θ is the local surface tilt. At the measured tilt of $\sim 5^\circ$, this gives a relative error of $1 - \cos \theta \approx 4 \times 10^{-3}$, confirming that the spherical approximation has negligible impact on the derived tilt. The tilt angles α and β are the projections of this normal in the XZ and YZ planes, corresponding respectively to T_y (rotation about Y) and T_x (rotation about X) in Figure 2. The normal is finally mapped from the substrate native frame to the EGA-O frame through the

known rotation between them, so that the reported tilt is expressed against the mechanical references (T_x , T_y in Figure 2).

Dihedral angles between reference faces are obtained independently from the theodolite autocollimation measurements, and edge lengths and fiducial positions from the microscope. Both feed the registration steps above and serve as geometric cross-checks on the substrate.

For each substrate, the pipeline outputs the radius of curvature, the SFE map with its RMS and PV values, the surface tilt in the EGA-O frame, and the uncertainties propagated from the error sources of Section 3.

5. ILLUSTRATIVE RESULTS

Figure 9 shows a representative output of the pipeline on a flight substrate. The left panel is the raw form over the full substrate rectangle, dominated by the aspherical departure and the mounting features (164.83 nm RMS, 2525 nm PV). The central panel is the SFE over the optical useful zone, obtained after subtraction of the best-fit aspheric: the residual figure error reaches 3.02 nm RMS and 24.9 nm PV, with in-plane coordinates in mm and the height scale in nm. This value is within the 5 nm RMS requirement. A high-resolution inset over a sub-millimetre patch gives access to the micro-roughness, here 0.62 nm RMS.

The tilt reconstruction is illustrated in Figure 10. The tangent point is localized at each of the 16 orientations, its position on the spherical cap shown in the right panel; the summits define the off-axis position of the tangent point in the substrate reference frame, here $dx = -14.119$ mm and $dy = -13.130$ mm, with a dispersion across orientations of $\sigma_x = 0.061$ mm and $\sigma_y = 0.092$ mm. The tilt of the optical axis is then derived from this position and the decentering. For this substrate, the IAS measurement yields $T_y = 5.08506^\circ$ in the XZ plane and $T_x = 3.16024^\circ$ in the YZ plane, to be compared with the specification of $5.0952^\circ \pm 0.14^\circ$ and $3.15154^\circ \pm 0.25^\circ$, respectively. This corresponds to a deviation from nominal of 36 arcsec and 31 arcsec, well within tolerance.

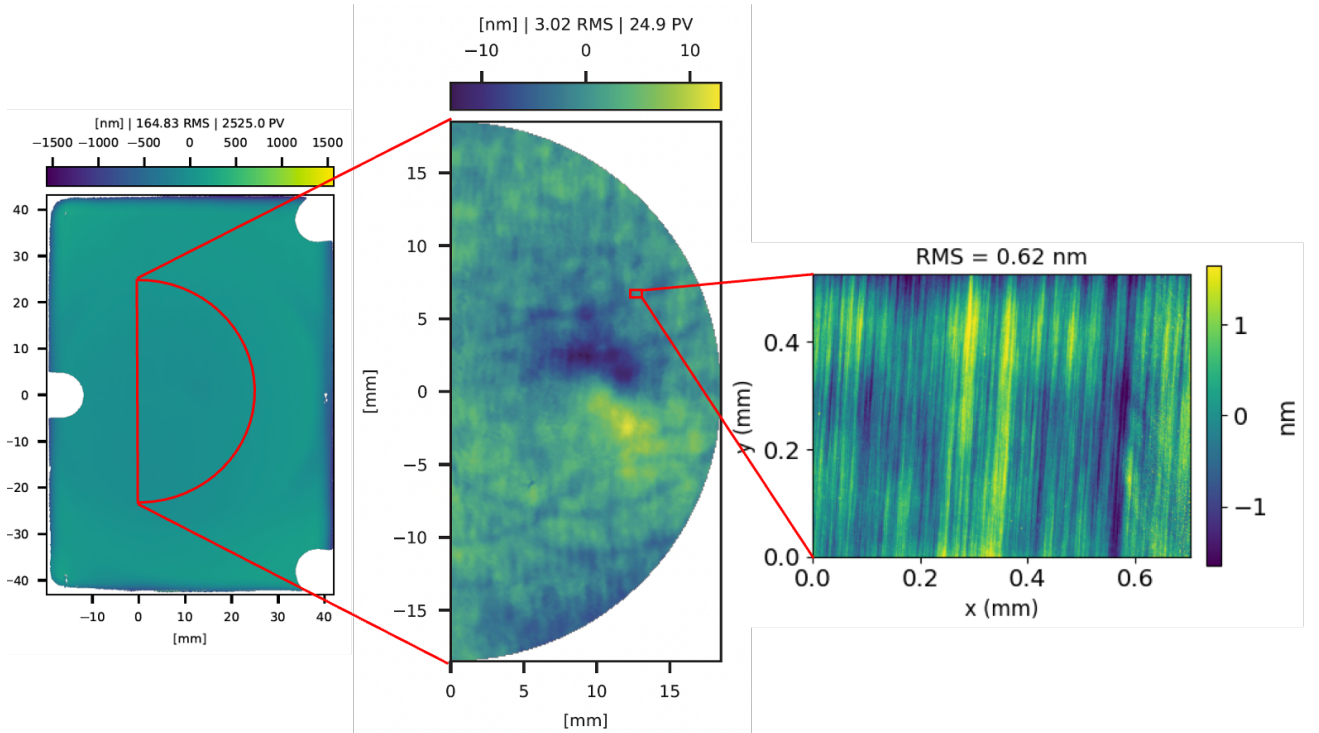


Figure 9. Example output of the pipeline on a flight substrate. Left: raw form over the full substrate rectangle, dominated by the aspherical departure and the mounting features (164.83 nm RMS, 2525 nm PV). Centre: surface figure error over the optical useful zone, after subtraction of the best-fit aspheric (3.02 nm RMS, 24.9 nm PV); in-plane coordinates in mm, height in nm. Right: high-resolution inset over a sub-millimetre patch giving the micro-roughness (0.62 nm RMS). All colour bars are in nm.

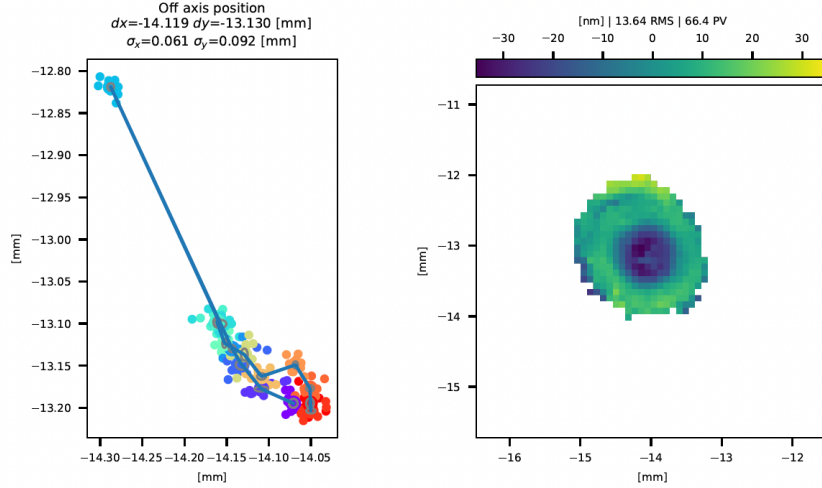


Figure 10. Tilt reconstruction on a flight substrate. Left: the tangent point localized at each of the 16 orientations (coloured markers) and the resulting off-axis position of the tangent point in the substrate reference frame, $dx = -14.119$ mm and $dy = -13.130$ mm, with a dispersion across orientations of $\sigma_x = 0.061$ mm and $\sigma_y = 0.092$ mm. Right: the corresponding spherical cap measured in flat mode (13.64 nm RMS, 66.4 nm PV); in-plane coordinates in mm.

6. CONCLUSION

The characterization of aspherical optical surfaces for space instrumentation cannot be reduced to a single interferometric measurement. We have shown that the geometric constraints imposed by the curvature mismatch between the reference optics and the test surface fundamentally decouple the surface figure, the radius of curvature, and the surface tilt, each requiring a dedicated measurement strategy. The combined approach presented here, rail translation interferometry with sub-micron telescope readings for the radius, rotation averaging interferometry for the form, and flat-mode tangent-point interferometry for the tilt, provides a coherent, traceable, and complete characterization of the EGA substrates for the Solar-C EUVST mission. The measurement sequence respects the interdependencies between observables and incorporates redundancy at each stage to control systematic and environmental errors. External validation against independent NANOMEFOS profilometry⁶ is planned, and the approach applies directly to other aspherical substrates for future EUV space instrumentation.

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