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SCIFLI HORIS Windowpane Optical Analysis

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Abbreviations

AR	anti-reflective
ASTM	American Society for Testing and Materials
BET	best estimated trajectory
CA	Clear Aperture
CFD	Computational Fluid Dynamics
ED	Engineering Directorate
EEV	Earth entry vehicle
FS	fused silica
HORIS	Hypervelocity OSIRIS-REx Reentry Imaging & Spectroscopy
ISO	International Organization for Standardization
JSC	Johnson Space Center
KSC	John F. Kennedy Space Center
LDTD	Laboratories, Development and Testing Division
LaRC	Langley Research Center
MTF	modulation transfer function
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification and Security Regolith Explorer
PSF	point spread function
PV	peak to valley
RMS	root-mean squared
SAMI	SCIFLI Airborne Multispectral Imager
SCIFLI	Scientifically Calibrated In-Flight Imagery
SN, S/N	serial number
SNR	signal to noise ratio
SRC	sample return capsule
TPS	Thermal Protection System
TWE	transmitted wavefront error
UV	ultraviolet
VIS	visible
WFE	wave front error

Nomenclature

$E(\lambda)$	White light source characteristics
k	Normalization factor for tristimulus calculation
$R(\lambda)$	Optical reflectance
$T(\lambda)$	Optical transmittance
$T1$	Haze measurement incident light
$T2$	Haze measurement total transmitted light
$T3$	Haze measurement scattered light by instrument
$T4$	Haze measurement scattered light by instrument and specimen
x, y	Chromaticity coordinates
$\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$	Standard observer characteristics
X, Y, Z	Tristimulus values
λ	Wavelength (nm)

Executive Summary

This NASA Technical Memorandum summarizes windowpane optical analyses for the OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification and Security Regolith Explorer) mission [1] supported by the SCIFLI (Scientifically Calibrated In-Flight Imagery) team [2] at NASA Langley Research Center (NASA LaRC). The SCIFLI team led a NASA multi-center team in characterization of fused silica (FS) and anti-reflective coated (AR-coated) sapphire materials for use as aircraft windowpanes. These materials were needed for the Hypervelocity OSIRIS-REx Reentry Imaging & Spectroscopy (HORIS) mission and were tested to generate performance parameters relevant to the flight environment. Some of the assessed parameters included optical quality, transmittance, reflectance, color balance, birefringence, transmitted wavefront error, wedge, and haziness of the windows.

In order to evaluate the material characteristics in a uniform manner, several criteria were held constant. For example, the physical dimensions of the test articles were held constant (i.e., 17-inch diameter aircraft windowpane and 2-inch diameter witness samples). In this way, the comparison of test results from one material specimen to another was invariant with regard to the manner in which the tests were conducted. This also reduced the variability in how the data were reported. As a result, the results shown in this report, including test data generated by NASA can be used for windowpane material evaluation and future material design trades. Window designers can use the data and the testing method along with the testing matrices to efficiently match material performance to their design and mission objectives and requirements. Standardized testing methodologies and data reduction procedures are described in this report. Unless otherwise noted in the data itself, all the windowpane materials were tested in order to characterize their performance for the HORIS mission.

One appendix has been included in this report. These include detailed wavefront interferograms of transmitted wavefront error and optical wedge used in the generation of aggregated material performance.

Background

NASA's OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification and Security Regolith Explorer) is the first U.S. mission to collect an asteroid sample and deliver it to Earth. Asteroid Bennu was selected for this mission for several reasons. Chief among them was its proximity to Earth and its size, both of which made it easier for a spacecraft to reach, orbit, and collect a sample from the asteroid. Bennu's carbon-rich composition, deduced by studying its spectral properties from Earth, also made it an attractive study target, particularly as scientists search for chemical markers that might have played a role in life's origins. In addition, scientists will be able to use data about Bennu's orbit to further study the Yarkovsky Effect, a force acting on a rotating body in space caused by the anisotropic emission of thermal photons, which carry momentum [1], or how sunlight and heat affect an asteroid's path, a critical factor in planetary defense.

OSIRIS-REx launched September 8, 2016, aboard an Altas V rocket from NASA's Kennedy Space Center, then reached Bennu in 2018. It spent two years in orbit as it mapped the asteroid's surface to help the mission team find the optimal spot for sample collection. Bennu proved to be rockier and rougher than the mission was designed for, making sample collection a much bigger challenge. Nevertheless, although two sites were selected, sampling the first, nicknamed Nightingale, was so successful that a second attempt was unnecessary. On October 20, 2020, the spacecraft successfully collected an estimated 8.8 ounces of material from the asteroid. After orbiting the Sun twice, OSIRIS-REx returned to Earth on September 24, 2023. Upon return, the capsule containing the Bennu sample separated from the rest of the spacecraft and entered Earth's atmosphere. The capsule parachuted to the Utah Test and Training Range (Dugway) where scientists retrieved it [3]. An extended mission will take the OSIRIS-REx spacecraft into orbit around the near-Earth asteroid Apophis in 2029 [4].

HORIS Mission

The Scientifically Calibrated In-Flight Imagery (SCIFLI) team at the NASA Langley Research Center collects real-time visual, infrared, and spectral data on vehicles while in flight. Doing so helps researchers gain insight into some of the most challenging questions in fluid dynamics, provides essential engineering data, and documents vital flight safety systems. With each successful mission [2], SCIFLI extends the experimental nature of wind-tunnel testing and computational aerothermal analysis by observing vehicles under real flight conditions. In addition to collecting these invaluable data, SCIFLI supports commercial and NASA missions by ensuring the safety of the vehicles and astronauts aboard. The topic of this report is a recent SCIFLI observation campaign supporting OSIRIS-REx, namely the Hypervelocity OSIRIS-REx Reentry Imaging and Spectroscopy (HORIS) mission. The HORIS mission included three ground imaging sites along with the four aircraft as shown in Figure 1.

The measurements and analyses goals for the observation campaign include the following:

1. Near-vehicle wake radiation measurements
   - UV–VIS (315–700 nm): N_2, NO, and NO_2 band systems
   - Plasma species radiative heating to leeward (payload) side of reentry vehicle
2. Broadband, low-noise shock-layer measurements
   - NIR–SWIR (700–2100 nm): Shock heated air species N, O, N_2, N_2+
   - Nonequilibrium electron number density: H_β VIS (486 nm)
   - Computational fluid dynamics (CFD) model validation and tool development for other Earth entry vehicles (EEVs)
3. Thermal Protection System (TPS) surface temperature analysis
   - VIS–NIR (400–950 nm): Broadband thermal emission from surface
   - TPS material response to allow validation of NASA CFD tools.
4. Trajectory reconstruction for best estimated trajectory (BET) derivation
   - NIR–SWIR (700–1800 nm)
   - Fielding multiple systems.

Overall mission goals:

1. Thermal emissions from the sample return capsule (SRC) surface and shock-layer during peak heat loading
2. Plasma species relaxation-related radiative heating to the leeward (payload) side of the reentry vehicle
3. Shock-heated air species and non-equilibrium electron number densities
4. High signal-to-noise ratio (SNR) data during a daylight entry event

These datasets were designed to help researchers better understand high-speed atmospheric entries and how the OSIRIS-REx capsule's thermal protection system functioned under extreme conditions. Given the stringent science goals for the mission, it was critical that the highest quality windows be installed on aircraft to permit the acquisition of imagery data in the desired optical spectral wavebands. Thus, a laboratory investigation was conducted to characterize the performance of various window candidates to achieve the HORIS mission objectives.

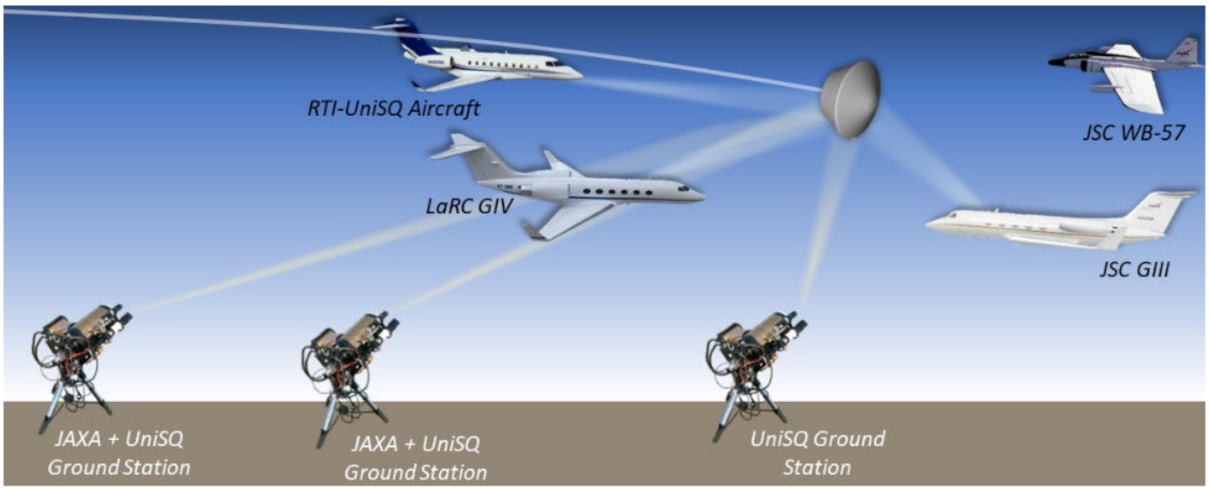


Figure 1. Four imaging aircraft and three ground imaging sites for science goals and imaging objectives of the HORIS mission.

Figure 2 shows examples of airborne imaging windows installed on Gulfstream aircraft stationed at NASA LaRC (tail number NASA 522) and Johnson Space Center (JSC) (tail number NASA 992), with the corresponding window frame assemblies shown in Figure 3. These assemblies incorporate a 17-inch diameter aperture and utilize single-pane optical windows. The choice of window enhances the quality of data collected in airborne imaging missions by utilizing a single pane element made of a highly transmissive material in the wavebands of interest (i.e., ultraviolet, visible, and midwave infrared). Due to the very long optical paths employed in the measurements (50–200 km away from the imaging target's trajectory), any improvement to window performance permits the acquisition of higher-quality data sets.

Figure 2. Fused Silica window utilizing a 17-inch diameter (16.4-inch diameter viewable area) with custom frames compatible with Gulfstream window ports and installed on a Gulfstream 4 Aircraft at NASA LaRC: (a) outside view, (b) inside view, and (c) in-flight view during a mission.

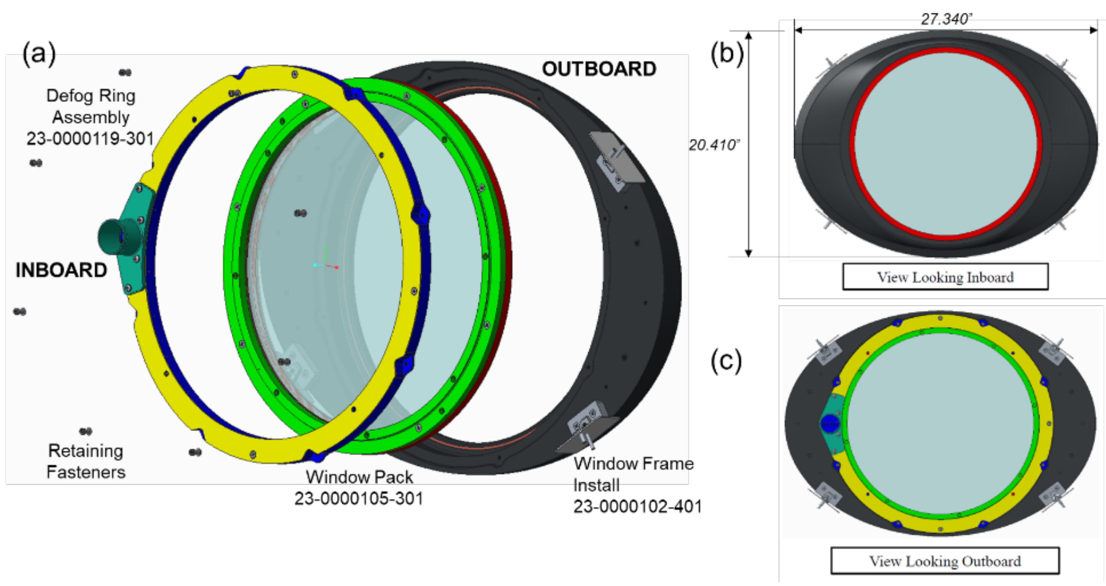


Figure 3. Optical window frames: (a) window frame assembly; outer frame (dark gray) is potted into the aircraft frame, and the window pack (green and red) is held into the outer frame with the defog ring (yellow and blue) and eight fasteners, (b) view looking inboard with dimensions, and (c) view looking outboard.

In early 2023, seven new, single-pane optical quality windows (six fused silica and one sapphire) were designed and acquired by SCIFLI specifically for the HORIS mission, where airborne imagery data were acquired during the reentry of the SRC as it landed in the Utah desert. The windows were designed to be compatible with the NASA Gulfstream aircraft, with installation in selected window ports as shown in Figure 4. The two NASA Gulfstream aircraft utilized airborne imaging systems similar to those shown in Figure 5.

Figure 4. External view of windows on NASA Gulfstream aircraft, left to right: original gulfstream window, previously designed acrylic "racetrack" shaped window, two new fused silica windows, and an original Gulfstream window.

Figure 5. Imaging systems installed in front of fused silica windows (in-flight).

Figure 6 shows 17-inch fused silica (FS) window pairing on LaRC GIV (N522NA) and JSC GII (N922NA). Each fused silica window is assigned a sixteen-digit serial number, marked on the edge of the window in indelible ink. The final five numbers, which will be used throughout this paper, are defined as 9yzz, where y =0 for an uncoated mirror and y =1 for a coated mirror and zz is a sequence number starting with the number 10. The six fused silica mirrors are numbered 9010 through 9015.

Figure 6. Payload and Window Pairing on (a) JSC GIII (N922NA) aircraft and (b) LaRC GIV (N522NA) aircraft.

Optical Metrology Overview

Optical metrology refers to a suite of measurements that use light to gather data regarding the physical properties of materials (or objects). The measurement techniques use light to interact with the material under study, and by measuring the characteristics of the light that is reflected, refracted, or absorbed by the material the optical properties of the material can be extracted. Typical measurands obtained for transparent materials include (1) transmittance, (2) reflectance, (3) color balance, (4) birefringence, (5) transmitted wavefront, (6) optical wedge, and (7) optical haze. These measurements are described in this section.

Transmittance, Reflectance and Color Balance: The purpose of spectral transmittance testing is to measure the optical transmittance as a function of optical wavelength across the visible and/or NIR spectral ranges, depending on the material under inspection [9-13]. The measurement is performed using a commercial spectrometer and spectrophotometer. The optical transmittance is the percentage ratio between the incoming and outgoing intensities of an optical beam as it propagates normally through a transparent specimen. The spectral transmittance of a material provides three important pieces of information:

1. It provides a direct measure of the degree of attenuation that the material will introduce the incoming optical intensity at every spectral component.
2. It provides the spectral reflectance, obtained computationally since normal reflectance is very difficult, if not impossible, to obtain using direct measures.
3. It provides a measure of the color balance, which is a quantity of how far a defined white input light will deviate in color as it propagates across the material.

Birefringence: The objective of optical birefringence testing is to measure the difference between two refractive indices along two orthogonal directions of a linearly polarized optical beam per unit length of the specimen thickness; i.e., the optical retardance per unit thickness of the specimen in centimeters (cm).

Transmitted Wavefront Error (TWE): The purpose of transmitted wavefront error (TWE) testing is to determine the change in wavefront of a defined input light beam as it passes through the specimen under inspection. The error in the transmitted wavefront provides important information on the optical performance of the pane material surfaces (see Figure 7). The test yields data for peak to valley (PV) TWE with piston, tilt, and defocus parameters removed and with only piston and tilt parameters removed. It also measures root-mean squared (RMS) TWE with piston, tilt, and defocus parameters removed and with only piston and tilt parameters removed. Using a Zygo (Middlefield, Connecticut) interferometer with a 6-inch size aperture, the point spread function (PSF) in addition to the modulation transfer function (MTF) of the material can be acquired. Note that the full optical transfer function is the Fourier transform of the PSF, and if needed, the phase information can be obtained as well.

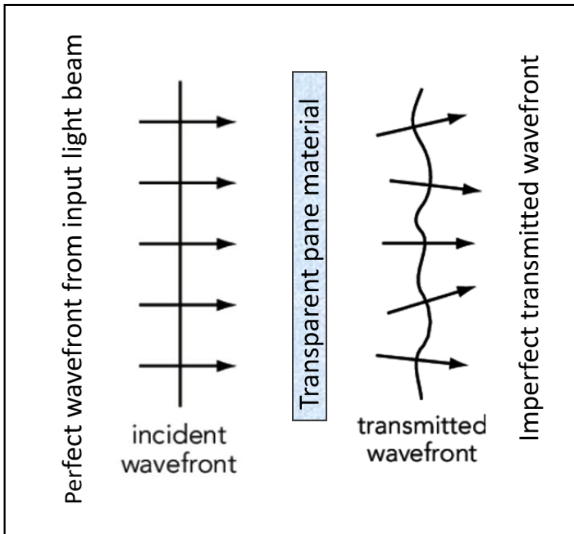


Figure 7. Schematic diagram of transmitted wavefront error principle.

Optical Wedge: Optical wedge is a measure of the parallelism between the two surfaces of an optical specimen within a defined viewing area. Typically, the wedge magnitude is obtained between the front and back surfaces of the specimen; i.e., this quantifies the net deviation of the specimen from parallelism. A Fizeau interferometer is the common instrument for measuring optical wedges.

Optical Haze and Clarity [10]: Optical haze measurements quantify the percentage of transmitted light that deviates from an incident beam direction by more than 2.5 degrees from the surface normal. The same measurement system that is used to measure haze can also measure optical clarity and luminous transmittance. Optical clarity is the percentage of transmitted light that is evaluated at angles of less than 2.5 degrees, and luminous transmittance is the percentage of the transmitted light that can be sensed by human vision, weighted by the human eye sensitivity curve. Commercial instruments are typically used for haze and clarity non-contact measurements.

Window Specifications

Figures 8 and 9 depict SCIFLI 17-inch diameter fused silica and anti-reflective- (AR-) coated sapphire optical window specifications. All the optical properties (transmittance, reflectance, color balance, birefringence, wedge, and haze) that could meet the mission requirements were specified. For scientific grade windows, typically the transmitted wave front error (WFE) (the amount of distortion of the wavefront through the window) should ideally be λ (lambda)/10 or less. Note that 1/10 waves are considered a standard for high-quality optics [11], [12]. Maintaining this requirement over the full 16.4 clear aperture by the vendor was challenging and the windows needed to be properly polished and/or coated to meet the performance specification. For the HORIS mission, NASA accepted a relaxed specification, better than λ/8, depending on how the measurements were obtained and handled. Specifically, NASA stated that for normal incidence viewing with piston, tilt, and defocus removed (the three most predominant aberrations), the RMS wavefront error over the window should not exceed λ/8 wave. This was a relaxed requirement versus the standard λ/10 standard; however, it was agreed upon since the mission was using an acrylic window as well.

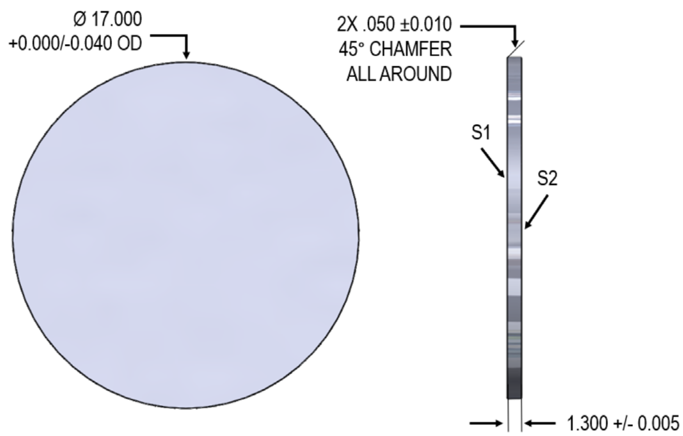
Items Desired:	Qty(6) 17-inch dia. Optical Grade Fused Silica Window
Material:	Corning 7980 Fused Silica
Shape:	Round, cylinder
Diameter:	D = 17.000” +0.000/-0.040
Clear Aperture:	16.40 inches +/- 0.01
Thickness:	1.300 +/- 0.005
Temperature Range:	-70°F / +150°F
Surface Finish:	All non-polished surfaces very fine-ground; ≥ 220 Grit Finish (0.5 – 1.0 Ra[micron])
Edge:	- All edges 0.05 +/- 0.01 X 45° chamfer (see Detail A on drawing *23-0000112.pdf*) - Edge chips shall conform to MIL-PRF-13830. Paragraph 3.7.9.2 - Maximum radius of 0.005” on edges, no sharp corners - Bevels may be polished to achieve wavefront requirements. 
Parallelism:	The two main surfaces of the window, “S1” and “S2,” shall be parallel within 0.002 inches
Transmitted WFE:	- The transmitted wavefront error shall be measured in collimated light at 632.8 nm with light transmitted over the full clear apertures designated on sides "S1" and "S2". (Lacking a full aperture interferometer, the interferograms can be stitched together. Minimum sub-aperture size of 6” diameter) - λ/10 waves peak to valley @ 632.8 nm at normal incidence across entire clear aperture
Surface Quality:	- Scratch/Dig = 60/40 on both sides “S1” and “S2” - Inspection report including map (preferably on transparent overlay) of scratches and digs to be provided with each window
Notes:	- Cracks are not acceptable anywhere on or in the window. - Qty(6) 2-inch diameter witness samples from same stock and thickness and finished to same quality shall be provided along with the window. - Optical characterization and transmission chart of the window provided with window delivery. Any Exceptions shall be discussed with customer

Figure 8. FS optical window specification.

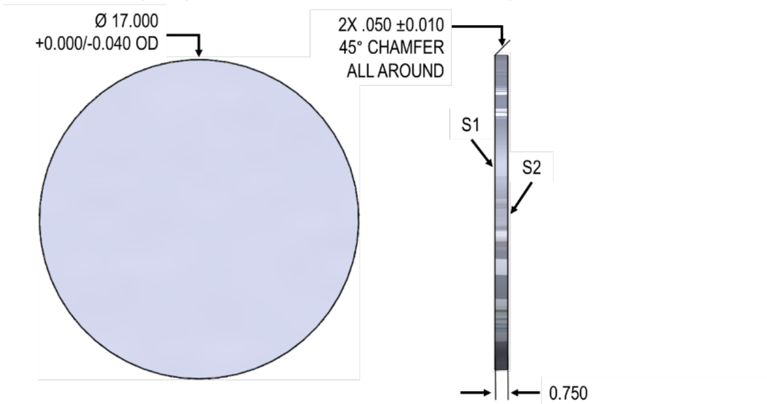
Items Desired:	Qty(1) 17-inch dia. Optical Grade Sapphire Window
Material:	Sapphire
Orientation:	C-plane, +/- 0.05 deg
Shape:	Round, cylinder
Diameter:	D = 17.000" +0.000/-0.040
Clear Aperture:	16.40 inches +/- 0.01
Thickness:	0.750 +/- 0.005
Temperature Range:	-70°F / +150°F
Surface Finish:	All non-polished surfaces very fine-ground; ≥ 220 Grit Finish (0.5 – 1.0 Ra[micron])
Edge:	- All edges 0.05 +/- 0.01 X 45° chamfer (see Detail A on drawing *23-0000106.pdf*) - Edge chips shall conform to MIL-PRF-13830. Paragraph 3.7.9.2 - Maximum radius of 0.005" on edges, no sharp corners - Bevels may be polished to achieve wavefront requirements. 
Parallelism:	The two main surfaces of the window, "S1" and "S2," shall be parallel within 0.002 inches
Transmitted WFE:	- The transmitted wavefront error shall be measured in collimated light at 632.8 nm with light transmitted over the full clear apertures designated on sides "S1" and "S2". (Lacking a full aperture interferometer, the interferograms can be stitched together. Minimum sub-aperture size of 6" diameter) - λ/10 waves peak to valley @ 632.8 nm at normal incidence across entire clear aperture
Surface Quality:	- Scratch/Dig = 60/40 post coating on both sides "S1" and "S2" - No visible inclusions, no visible scratches
Coating:	- Surfaces "S1" and "S2" shall have a hard dielectric antireflective coating applied over the full aperture. AR coating shall meet or exceed the following transmission requirements over the clear aperture: **BBAR coating from 0.31 – 5 µm with following:** ○ 0.31 to 0.6 um Rmax less than 3.5% per surface ○ 0.62 to 0.75 um Rmax less than 5.5%, Ravg less than 4.0% per surface ○ 0.8 to 0.95 um Rmax less than 6.0%, Ravg less than 5.0% per surface ○ 0.988 to 1.1 um Rmax less than 5.5%, Ravg less than 5.0% per surface ○ 1.28 to 1.35 um Rmax less than 5.0%, Ravg less than 4.0% per surface ○ 1.58 to 1.65 um Rmax less than 4.5%, Ravg less than 3.75% per surface ○ 2.18 to 2.3 um Rmax less than 5.5%, Ravg less than 4.75% per surface

Figure 9. Sapphire optical window specifications.

	○ 3.58 to 4.1 um Rmax less than 6.5%, Ravg less than 6.0% per surface ○ 4.58 to 5.0 um Rmax less than 6.5%, Ravg less than 6.0% per surface ○ Durability will be verified on simultaneously coated witness sample per MIL-PRF-13830B, C.3.8.2 (humidity), C.3.8.4.2 (moderate abrasion) and C.3.8.5 (adhesion). ○ All untoleranced surfaces: 200 grit or finer surface finish ○ Cosmetic quality, including surface quality, will be verified using MIL-PRF-13830B ○ Vendor will provide interferometric data that indicates conformance to the optical specifications. ○ Vendor will provide measured reflectivity of window surfaces or witness samples. - The coating specs should also include the range of angles of incidence, which is approximately -15° to 45° . A narrower nominal range of incident angles may be defined. - Anti-reflective coating applied to surfaces "S1" and "S2" may extend beyond the clear aperture. - Coatings shall meet the following requirements of MIL-PRF-13830B Appendix C Section 3.8 for: 1. Adhesion 2. Temperature 3. Severe abrasion 4. Salt solubility 5. Water solubility - All Specifications apply over the clear aperture only.
Notes:	- Cracks are not acceptable anywhere on or in the window. - Qty(10) 2-inch diameter **witness samples** shall be provided along with the window - Optical characterization and transmission chart of the window provided with window delivery. - Any Exceptions shall be discussed with customer

Figure 9 (continued). Sapphire optical window specifications.

HORIS Window Optical Metrology

HORIS candidate window optical characterizations were conducted at Kennedy Space Center (KSC) in the Metrology and Precision Measurement Alignment Lab. The SCIFLI team submitted six 17-inch diameter FS windows and six 2-inch diameter FS witness samples for testing. The windowpanes were categorized as Category A based on requirements defined in Ref. 14. Category A windows (Custom Optical Window Ports) are window-based customer-unique requirements developed on a case-by-case basis. The SCIFLI team compiled custom requirements for the windows and this information was relayed to the KSC Metrology Lab. The metrology testing matrix is summarized in Table 1. This section discusses specific testing methodologies that were used in characterizing the window performance.

Table 1. Window testing matrix for HORIS mission

Samples	Quantities Total / Pane Serial #	Wavelength	Transmittance, Reflectance and Color Balance Testing (Y/N)	Birefringence Testing (Y/N)	Transmitted Wavefront Error (TWE) Testing (Y/N)	Wedge Testing (Y/N)	Haze Testing (Y/N)
17 " dia. Fused silica (quartz) ‡	6 23-0000112-001-9010, 9011, 9012, 2013, 9014, 9015	320 nm-800 nm in 5 nm step sizes	Y	Y†	Y	Y	N
2" dia. Fused silica (quartz)	6 SN01, 03, 04, 05, 06, 07	180 nm-3000 nm in 5 nm step sizes	Y*	N	N	N	Y
17" dia. AR-coated sapphire	1	320 nm-800 nm in 5 nm step sizes	Y	Y	Y	Y	N
2" dia. AR-coated sapphire	1	180 nm-3000 nm in 5 nm step sizes	Y*	N	N	N	Y

* It was valuable to perform transmittance and/or reflectance testing on the 2-inch diameter witness samples (one of each type) because those can go to longer wavelengths. Otherwise, one would only have relevant information out to a 800 nm wavelength.

† Proposed to test one of the six windows.

‡ Six Corning 7980 FS (uncoated) windows of 17 ± 0.1 in diameter and 1.30 ± 0.05 in thickness and one c-plane sapphire window (both sides anti reflective-coated window of 17 ± 0.1 in diameter and 0.75 ± 0.05 in thickness. The witness samples were all 2-inches in diameter, with their thickness being the same as the flight windows. The average weight of the flight windows were 10.6 kilograms and 11.2 kilograms for fused silica and AR-coated sapphire ones, respectively.

Testing Instruments and Procedures: The instruments utilized in the KSC metrology lab are summarized in Table 2. The 17-inch diameter windowpanes were secured into a test fixture and protected around the edges using microfiber cloths that were certified for contact with spacecraft windows (Figure 10). All the windowpanes came from the manufacturer with an arrow drawn on the edge of the glass, as specified on the window mechanical drawings. The windowpanes were oriented in the same position when placed in the test fixture, with the arrows pointing towards the interferometer and in the 12 o'clock (vertical) position. The panes were tested for transmittance, reflectance, color balance, wavefront, and wedge. Birefringence testing was only conducted on one 17-inch fused silica windowpane—serial number 23-0000112-001-9015.

Table 2. KSC metrology lab instrument inventory

Measurement	Instrument	Model	Wavelength	Note
Transmittance	Visible Spectrometer	N/A	320–800 nm (5 nm/step)	*
Transmittance	NIR-VIS-UV Spectrometer	PerkinElmer 1050+ spectrometer	180–3000 nm (5 nm/step)	†
Reflectance	Derived from transmission data (450 nm – 800 nm)			
Color balance	Derived from transmission data (380 nm-780 nm)			
Birefringence		N/A	N/A	‡
Transmitted Wavefront Error	Interferometer	Zygo Interferometer 6/27/24 M94937	633 nm	§
Wedge	Derived from normal Zygo data Zernike sphere terms			
Haze	NIR-VIS-UV Spectrometer	PerkinElmer	380–780 nm	†

* Newport Oriel Cornerstone 260 1/4m Monochromater along with a halogen bulb, a chopper wheel, optics, and a photodetector custom built by Dr. Mark Nurge and Dr. Bob Youngquist

† Baseline measurements performed before tests and NIR-VIS-UV spectrometer for the Haze measurement was calibrated using the Transparent Plastic Haze Standards from HunterLab [13], [14].

‡ Custom built by Dr. Nurge and Dr. Youngquist

§ Calibrated on June 27, 2023

All six fused silica witness samples were tested for haze. One sample, SN01, was tested for luminous transmittance, color balance, reflectance, and haze. Due to the sample thickness (1.3-inch), the lens holder in the test chamber could not secure the sample for luminous transmittance and haze testing (Figure 11). For the luminous transmittance testing the samples were placed on a riser block covered with lens paper to protect the sample and elevate it to the correct aperture height. For haze testing, the sample was required to contact the aperture. To safely accommodate the sample in this position, it was necessary to apply Flashbreaker® tape to the sample's edge and the test chamber housing to ensure the safety of the sample. Flashbreaker® tape is certified to contact spacecraft flight windows and does not leave residue on the sample surface.

The 17-inch FS windowpanes were tested for TWE using a Zygo interferometer. The interferometer uses a 6-inch diameter aperture to take measurements on the surface of the windows to create a topographical map of the wavefront PV variation. The measurements were performed in a serpentine pattern with at least a 3-inch overlap between shots as shown in Figure 12. The testing was performed on the windowpane in three different positions. In the first test, the windowpane surface was normal to the aperture of the interferometer. In this configuration, a total of thirty-one images were captured (Figure 12a). Wedge measurements were derived from data collected in this configuration. The following configuration involved tilting the testing fixture to 30 degrees (Figure 13). In this configuration, 20 images were captured (Figure 12b). The windowpane was then rotated 90 degrees to the right, placing the arrow drawn on the edge of the windowpane at 3 o'clock. An additional 20 images were captured in this position (Figure 12c).

Figure 10. 17-inch FS windowpane mounted in test frame in normal (90-degree) position.

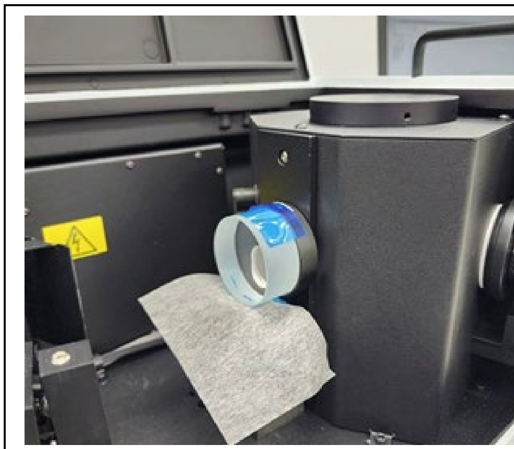


Figure 11. 2-inch FS witness sample shown during haze testing.

The 17-inch FS windowpanes were tested for luminous transmittance using a visible light spectrometer (380–800 nm) in 5 nm steps. Color balance and reflectance measurements were derived from the transmittance data. Birefringence measurements were taken using two light sources and two photodetectors set at specific angles. The luminous transmittance and birefringence measurements were taken with the testing fixture in the normal (90 degree) position. All 2-inch diameter fused silica witness samples were tested using the PerkinElmer 1050+ Spectrophotometer. The tests for luminous transmittance, color balance, and reflectance were performed using the NIR-VIS-UV spectrometer from the wavelengths of 180 nm to 3000 nm in 5 nm step sizes. The haze test was performed using an integrating sphere [10], [13].

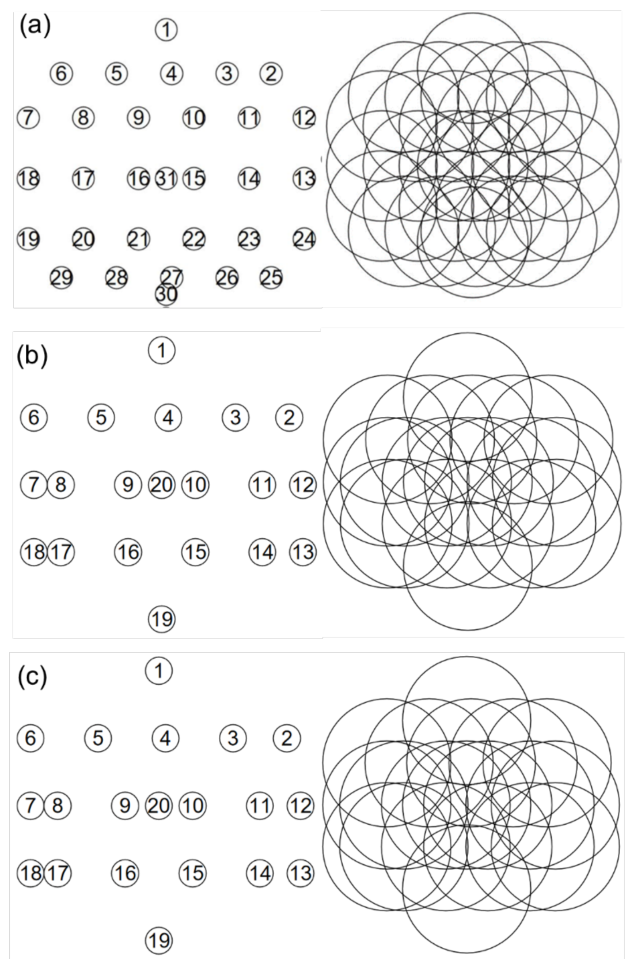


Figure 12. Scan plots and coverage maps of the interferometer uses a 6-inch diameter aperture to take measurements on the entire 17-inch diameter surface of the fused silica windows. (a) normal to the aperture position, (b) off-axis, and (c) 90 degree off-axis.

Only one 17-inch diameter sample (Pane Serial #: 23000112-001-9015) was proposed for birefringence measurements, by assuming that the witness samples were cut from the same billet as the 17-inch diameter windows. Birefringence is normally not an issue with glass and c-plane sapphire materials unless there is significant residual stress during the cutting. Similarly, haze testing was proposed to be performed only on witness samples, assuming the samples were of the same lot as the 17-inch diameter windows. For transmitted wavefront error testing, duplicate testing was not conducted on witness samples. Reflectance and color balance data were obtained from the measured transmittance spectra. For the color balance, it was decided to use the 1931 CIE Chromaticity Diagram [15] for the data processing[1]. Striae testing was not proposed for the windows.

The most useful information was measured using (a) for the aircraft windows and (b) for the witness samples. Overlapping data (380–800 nm visible wavelength) where possible allowed a level of confidence in using the 2-inch diameter witness sample results in the non-overlap region. For the AR-coated sapphire window, the vendor provided a window specification covering percent reflectance, not transmission, as the transmission is dependent on the substrate material property. Therefore, the reflectivity data was used to

The numbers to quantify the color shift are called the Chromaticity coordinates (x, y). They are computed through a given procedure that has been formulated in several published standards. The Chromaticity coordinates are normalized values of other numbers called the Tristimulus values (X, Y, Z) that are derived from the spectral transmittance data of the optical pane and the spectral characteristics of the preferred white light source, $E(\lambda)$, and of the standard observer, $x(\lambda)$, $y(\lambda)$, $z(\lambda)$.

evaluate how well the AR-coating met the specifications and could be compared to data provided by the vendor. Moreover, the transmission values were incorporated into the instrument model to determine the instrument reference transmittance for the spectrophotometer and for validation of the calibration. Calibration data with the window included in the optical path remained the baseline for further analysis of the data.

Figure 13. 17-inch diameter fused silica windowpane rotated 90 degrees, and the frame tilted at a 30-degree angle in preparation for wavefront testing.

Data Reduction: Data reduction is described as follows.

Transmittance, Reflectance, and Color Balance – The spectral transmittance data was obtained from the test measurement and plotted using an Excel spreadsheet. The spectrum covered a wavelength range from 320 nm to 800 nm with a wavelength increment of 5 nm. Using the spectral transmittance data and the spectral reflectance, the chromaticity coordinates shift (color balance) was calculated [9-13]. The spectral reflectance data was derived using

$$\mathrm{R}\ (\lambda) = 1 - \sqrt{T\ (\lambda)} \qquad (1)$$

where R is the reflectance and T is the transmittance in percent. The spectral reflectance computation was calculated for each material from the transmittance data and provided with the transmittance data in an Excel spreadsheet.

The numbers to quantify the color shift are called the chromaticity coordinates (x, y). They were computed through a procedure that has been formulated in several standards. The chromaticity coordinates are normalized values of other numbers called the tristimulus values (X, Y, Z) that were derived from the spectral transmittance data of the optical pane, the spectral characteristics of the preferred white light source, $E(\lambda)$, and the characteristics of the standard observer, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$. An excel spreadsheet was created with the following data: (1) spectral transmittance of the optical pane, $T(\lambda)$; (2) relative spectral power distribution of the illuminant, $E(\lambda)$, and the color matching functions of the observer.

The tristimulus values X, Y, Z are the amounts of three reference color stimuli, in a given trichromatic system, required to match the color of the stimulus considered, and defined as follows:

$$\mathrm{X} = k \int_{\lambda} E(\lambda)\, T(\lambda)\, \bar{x}(\lambda)\ d\lambda \qquad (2)$$

$$\mathrm{Y} = k \int_{\lambda} E(\lambda)\, T(\lambda)\, \bar{y}(\lambda)\ d\lambda \qquad (3)$$

$$\mathrm{Z} = k \int_{\lambda} E(\lambda)\, T(\lambda)\, \bar{z}(\lambda)\ d\lambda \qquad (4)$$

where $E(\lambda)$ is the relative spectral power distribution of a D65 day-light illuminant, $x(\lambda)$, $y(\lambda)$, and $z(\lambda)$ are the color matching functions for the CIE 1931 or 1964 standard observers, $T(\lambda)$ is the spectral transmittance of the optical window, and k is the normalized factor $k = 100 / \int_{\lambda} E(\lambda)\, \bar{y}(\lambda)\, d\lambda$.

For the 1964 standard observers, the color matching functions are often denoted by $x10(\lambda)$, $y10(\lambda)$, $z10(\lambda)$, and the related tristimulus values are represented as X_{10}, Y_{10}, and Z_{10}. Except for the spectral transmittance data that is extracted from the spectrophotometer measurement, all the other quantities are tabulated in the American Society for Testing and Materials (ASTM) and International Organization for Standardization (ISO) standards [9-13]. The chromaticity coordinates x, y, and z are defined by the following equations:

$$x = \frac{X}{X+Y+Z} \tag{5}$$

$$y = \frac{Y}{X+Y+Z} \tag{6}$$

$$z = \frac{Z}{X+Y+Z} \tag{7}$$

and the chromaticity coordinates (x, y) describe how a color shift is introduced from a standard illuminant by the optical material, as shown in Figure 14.

Transmitted Wavefront Error – The raw data obtained from the wavefront measurement were contained in a binary data file that was read and processed using a Zygo software package called MetroPro® [19].

Optical Wedge – Both the wedge magnitude and wedge angle/orientation were obtained from the Zygo interferometer MetroPro® data reduction system.

Birefringence – The birefringence data reduction was automated via the acquisition system and performed point by point measurements resulting in a sequence of optical retardation points plotted as a color contour map.

Optical Haze – A version of the approach described in ASTM D1003 was utilized for the haze measurements. Table 3 presents the equations that were used to extract optical haze, with sample values obtained from FS witness sample 01 shown.

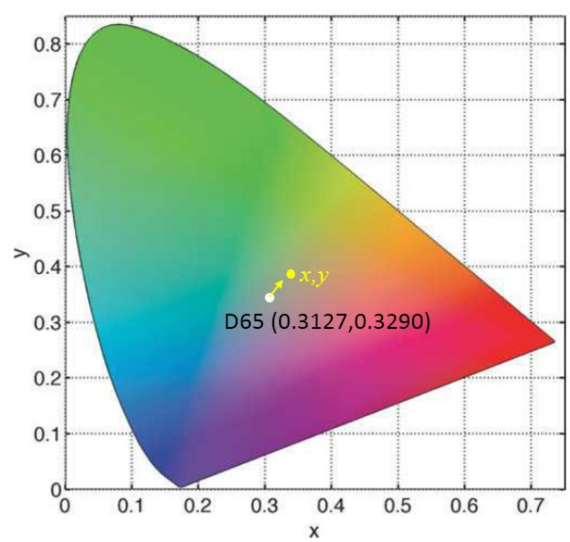


Figure 14. Color shift (x,y) from the D65 illuminant color coordinates on the 1931 standard.

Table 3. ASTM D1003 haze standard equations and sample values for FS witness sample SN01

Sample ID	ASTM D1003 Haze Standard	Values	Note
SN01	Haze =[(T4/T2) - (T3/T1)] * 100 (%)	0.01734	
	T1- Incident Light (No Sample, white plate in reflectance port)	1	Baseline
	T2- Total Light Transmitted by Specimen (Sample in transmittance position, white plate in reflectance port (total luminous transmittance)	0.9318	Y Sample and Instrument Scatter
	T3- Light Scattered by Instrument (No sample, light trap in reflectance port)	0.0141	K Part 1
	T4- Light Scattered by Instrument and Specimen (Sample in position, light trap in reflectance port (sample and instrument scatter))	0.0133	Y Instrument Scatter

Vendor Performance Data

The window vendors were required to provide NASA performance data that included as a minimum (1) surface inspection reports with defect maps, (2) inspection summary reports, (3) interferograms documenting the transmitted wavefront error (TWE), (4) interferograms documenting optical wedge (parallelism), (5) certificates of compliance with the specifications, and (6) certificates of conformance. These documents were provided by the vendor for the fused silica windows and are shown both in this section and in the appendices.

It is noted that the NASA-requested specifications were addressed but the TWE did not meet the requirements for transmitted wavefront specification. The actual measurements were as high as 0.174 waves PV. Given that a lower homogeneity grade of fused silica, the surfaces needed significant manipulation to adjust the TWE including inducing convex curves. Optical homogeneity refers to the degree of refractive index variation along the optical path of the optics. Variations in refractive index can distort the wavefront of light transmitted through the optical component and the fused silica's homogeneity is affected by bubbles and inclusions as shown in Figure 15. In the future, material of better homogeneity (λ /10 or less) would help the vendor and NASA meet the TWE specification that was quoted.

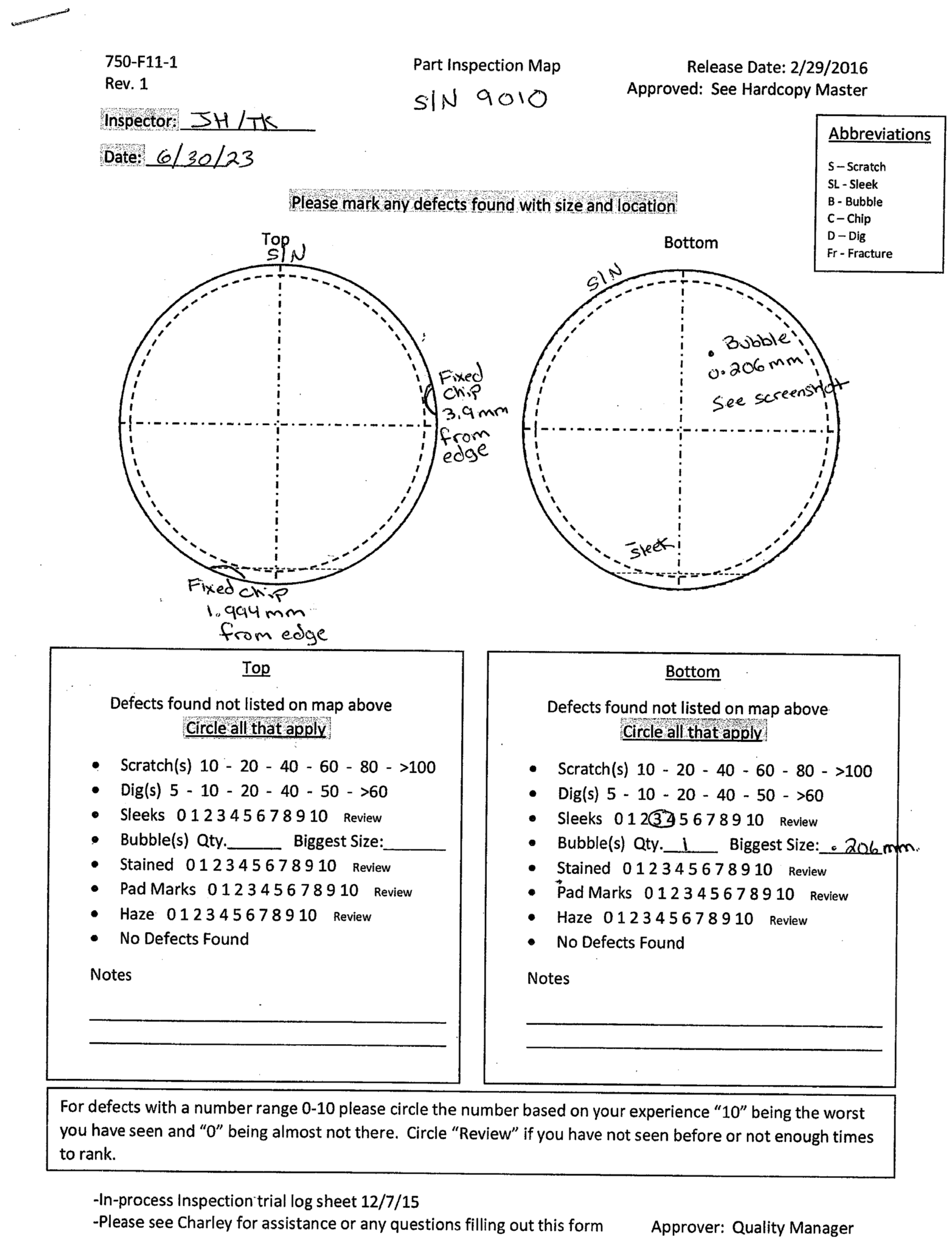
The fused silica window surface inspection report (S/N 9010) and window only figures (S/N 9011 – S/N 9016) from the vendor with defects identified are reproduced in Figures 15 and 16, respectively. Tables 4 and 5 summarize the TWE and optical wedge measurements conducted by the vendor along with the requirements and tolerances for the various measurands. With the exception of the TWE out of tolerance condition mentioned previously, all other performance data for the 17-inch FS windows were acceptable. There were no out of tolerances noted for the 2-inch FS witness samples. All of the windows and witness samples were considered cleared for further NASA in-house testing based on the vendor performance data.

Table 4. TWE and optical wedge performance data for 17-inch FS windows

			Actual Measurements						
Characteristic	**Dimension or Specification**	**Tolerance**	***9010***	***9011***	***9012***	***9013***	***9014***	***9015***	***9016***
OD	17.000	+/-0.040"	16.981	16.981	16.980	16.982	16.982	16.981	16.990
CT	1.300	+/-0.005"	1.302	1.302	1.302	1.303	1.302	1.302	1.304
TWE	<= 0.1 waves PV		0.117	0.120	0.118	0.127	0.175	0.114	0.073
Parallelism	<=0.002"		0.001	0.000	0.001	0.000	0.002	0.000	0.000366
Bevels Side A	0.04" to 0.06" FW @ 45 deg		0.050	0.048	0.050	0.050	0.050	0.050	0.050
Bevels Side B	0.04" to 0.06" FW @ 45 deg		0.049	0.048	0.049	0.050	0.050	0.050	0.045

Table 5. TWE and optical wedge performance data for 2-inch FS witness samples

			Actual Measurements					
Characteristic	**Dimension or Specification**	**Tolerance**	***SN01***	***SN03***	***SN04***	***SN05***	***SN06***	***SN07***
OD	17.000	+/-0.040"	1.993	1.994	1.994	1.993	1.994	1.994
CT	1.300	+/-0.005"	1.3025	1.3022	1.3020	1.3022	1.3022	1.3022
TWE	<= 0.1 waves PV		0.082	0.071	0.077	0.087	0.078	0.096
Parallelism	<=0.002"		0.0000	0.0003	0.0005	0.0002	0.0005	0.0004



750-F11-1
Rev. 1

Part Inspection Map

S/N 9010

Release Date: 2/29/2016
Approved: See Hardcopy Master

Inspector: JH/TK

Date: 6/30/23

Abbreviations

S – Scratch
SL - Sleek
B - Bubble
C – Chip
D – Dig
Fr - Fracture

Please mark any defects found with size and location

Top

Defects found not listed on map above
Circle all that apply

- Scratch(s) 10 - 20 - 40 - 60 - 80 - >100
- Dig(s) 5 - 10 - 20 - 40 - 50 - >60
- Sleeks 0 1 2 3 4 5 6 7 8 9 10 Review
- Bubble(s) Qty.______ Biggest Size:_______
- Stained 0 1 2 3 4 5 6 7 8 9 10 Review
- Pad Marks 0 1 2 3 4 5 6 7 8 9 10 Review
- Haze 0 1 2 3 4 5 6 7 8 9 10 Review
- No Defects Found

Notes

Bottom

Defects found not listed on map above
Circle all that apply

- Scratch(s) 10 - 20 - 40 - 60 - 80 - >100
- Dig(s) 5 - 10 - 20 - 40 - 50 - >60
- Sleeks 0 1 2 (3) (4) 5 6 7 8 9 10 Review
- Bubble(s) Qty. 1 Biggest Size: .206 mm.
- Stained 0 1 2 3 4 5 6 7 8 9 10 Review
- Pad Marks 0 1 2 3 4 5 6 7 8 9 10 Review
- Haze 0 1 2 3 4 5 6 7 8 9 10 Review
- No Defects Found

Notes

For defects with a number range 0-10 please circle the number based on your experience "10" being the worst you have seen and "0" being almost not there. Circle "Review" if you have not seen before or not enough times to rank.

-In-process Inspection trial log sheet 12/7/15
-Please see Charley for assistance or any questions filling out this form

Approver: Quality Manager

Figure 15. Fused silica surface inspection report for window S/N 9010. The handwriting says that 'fixed chip 3.9 mm from edge' and 'fixed chip 1.994 mm from edge' on Top image and 'bubble 0.206 mm' and 'sleek' on Bottom image.

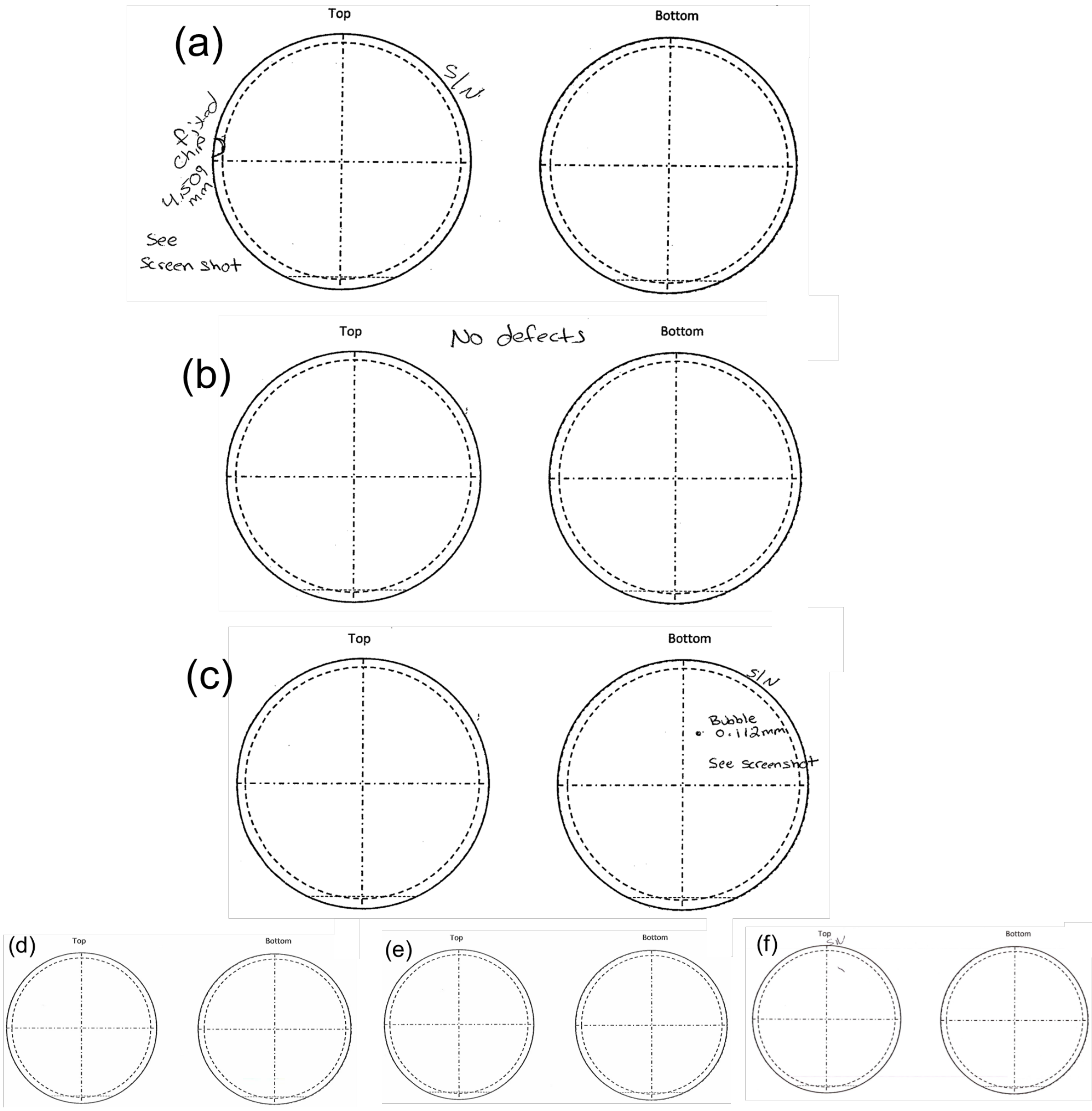


Figure 16. Fused silica surface inspection maps for window (a) S/N 9011, (b) S/N 9012, (c) S/N 9013, (d) S/N 9014, (e) S/N 9015, and (f) S/N 9016 with defects identified. The handwriting says that (a) 'fixed chip 4.509 mm' on and (c) 'bubble 0.112 mm'.

Windows Metrology Results

Figures 17–22 depict the 17-inch diameter FS windowpane testing results (included here for completeness) and consist of a summary of the data, transmittance and reflectance spectrum graphs, and a photo of the pane. One sample (pane SN 23-0000112-001-9015) contains a birefringence plot as shown in Figure 26d. In all cases, the transmittance and reflection spectra are uniform and essentially flat across the measured wavelength range of 380–800 nm. The color shift coordinates from the 1931 standard D65 illuminant color coordinates are remarkably similar between all the windows, with an average (X, Y) coordinate of (0.3130, 0.3193). The optical wedge for the windows did not exceed 0.04 arc minutes, and the TWE did not exceed 0.12 waves PV with piston and tilt removed from the measurement. Based on the vendor performance data coupled with the windows metrology results, the 17-inch FS windows were determined to be acceptable for use during the HORIS mission.

Figure 23 shows a summary of testing results for all of the 2-inch diameter FS witness samples (SN01, SN03–SN07, 1.3 in thick) including a full transmittance spectrum for one sample (SN01) and photos of a sample positioned for transmission measurements and in the test holder for haze measurements. The witness samples were the primary test articles for measurement of FS haze, and the haze measure did not exceed 0.02 for any of the samples. The transmittance spectrum depicts a fairly flat response over a wavelength range of 200–2000 nm, with a notched drop in transmission observed around 1350 nm. This drop is most likely due to the response of the light source in the photo spectrometer system.

Table 6 summarizes vendor-provided specifications for the panes along with the results of metrology testing conducted at NASA KSC. For scientific grade windows, the WFE, the amount of distortion of the wavefront through the window, should ideally be $\lambda/10$ or less. For the HORIS mission, NASA imparted a relaxed specification for WFE, better than $\lambda/8$. It is because the maintaining the requirement over the full clear aperture of the 17-inch diameter windowpanes was challenging and required the vendor to properly polish and/or coat the windows to meet the performance specification. Specifically, it was stated that for normal incidence viewing with piston, tilt, and defocus (the three most predominant aberrations) removed, the RMS wavefront error over the window would not exceed 1 wave.

Based on the results obtained from the laboratory metrology testing, it was concluded by the SCIFLI team that the FS windowpanes met the requirements for the HORIS mission.

Table 6. Summary of windowpane vendor specifications and KSC laboratory measurements.

Samples	Pane Serial # (23-0000112-001-xxxx)	Transmittance (both 17" windows and 2" witness samples)	Birefringence Testing (17" windows)	Transmitted Wavefront Error (TWE) Testing of 17" windows (vendor provided values as comparison)	Wedge Magnitude Testing of 17" windows (angle / °)	Haze Testing (2" witness samples)	Test Results
17 " dia. Fused silica (quartz)	9010	93.4 T%	Figure 32(d) map	0.107 (0.117)	0.01070 (25.02)	N	Pass
	9011	93.3		0.106 (0.120)	0.03332 (51.57)		
	9012	93.3		0.115 (0.118)	0.0278 (81.43)		
	9013	93.4		0.091 (0.127)	0.01188 (65.44)		
	9014	93.4		0.075 (0.175)	0.01671 (-18.99)		
	9015	93.4		0.074 (0.114)	0.01024 (2.11)		
2" dia. Fused silica (quartz)	SN01	93.3 T%	N	N	N	0.017%	Pass
	SN03					0.011	
	SN04					0.016	
	SN05					0.009	
	SN06					0.007	
	SN06					0.009	

The 17-inch diameter FS windowpane were subsequently installed on two NASA Gulfstream aircraft and used successfully in the airborne imaging campaign conducted during the OSIRIS-REx sample return capsule reentry to obtain meaningful thermal data on the capsule performance during entry and descent back to Earth in September 2023.

Aside from surviving the flight environment, the best evidence of the windows being successful is the absence of anything of note – Signal levels and spot sizes were consistent with expectations.

As examples, data taken by SCIFLI Airborne Multispectral Imager (SAMI) payload through the FS window (S/N 9011), there were no anomalies results that have indicated a non-uniformity in the window absorption or PSF. For LaRC GIV (N552NA), the viewing angles to the SRC required looking through different parts of the windows. While coordinated translation and rotation correct for part of this, it does not fully eliminate viewing through various parts of the windows. For SAMI payload specifically, there is no vertical translation, so different portions of the window are imaged through elevation. As the view slewed through the FS windowpane, we did not see any localized variation in the sky that would indicate differences in transmission. Again, there were no anomalies in the sky or SRC spectra that required an explanation linked to pointing angles based on the results analysis by the team. Similarly, the spot formed by the SRC on the image planes did not change in size or shape as the view moved around on the window. Moreover, for the CALSPEC and NIRSPEC payloads through the FS window (S/N 9013) in JSC GII (N922NA) aircraft, fiber fed spectrometers achieving single fiber illumination from the SRC. The consistency of this result over all view angles is another example of where localized variations in the windows would have cause issues in the data. While these instruments have smaller apertures than SAMI one and therefore view through a smaller portion of the window, there was no need in the lead up to the mission to identify local "sweet spots" to image through – the optical performance was as expected with no special attention to the window required. Additional analysis could be performed to specifically look at gradients in observed sky radiance and the spot size and shape, but there have been no indications that such analysis was necessary.

(a)

Pane Serial Number:	23-0000112-001-9010		
Pane Description:	17" Diameter Fused Silica Pane		
Window Thickness:	1.300in		
Window Thickness:	3.302cm		
Index of Refraction:	1.448673696		
Summary of Transmission Properties:			
Luminous Transmittance:	93.4%		
Photon Flux Reflectance:	3.3%		
Average Reflectance:	3.3%		
		x lower bound	x upper bounc
Color Balance X-Coordinate:	0.3129	0.3072	0.3186
Color Balance Y-Coordinate:	0.3293	0.325 ≤ y ≤ 0.375	
Normal Wavefront Properties:	0.107 (Average of PV - No Piston / Tilt)		
Summary of Wedge Properties:			
Magnitude of Wedge (arc minutes):	0.01070		
Direction of Wedge (°):	25.02		

(b)

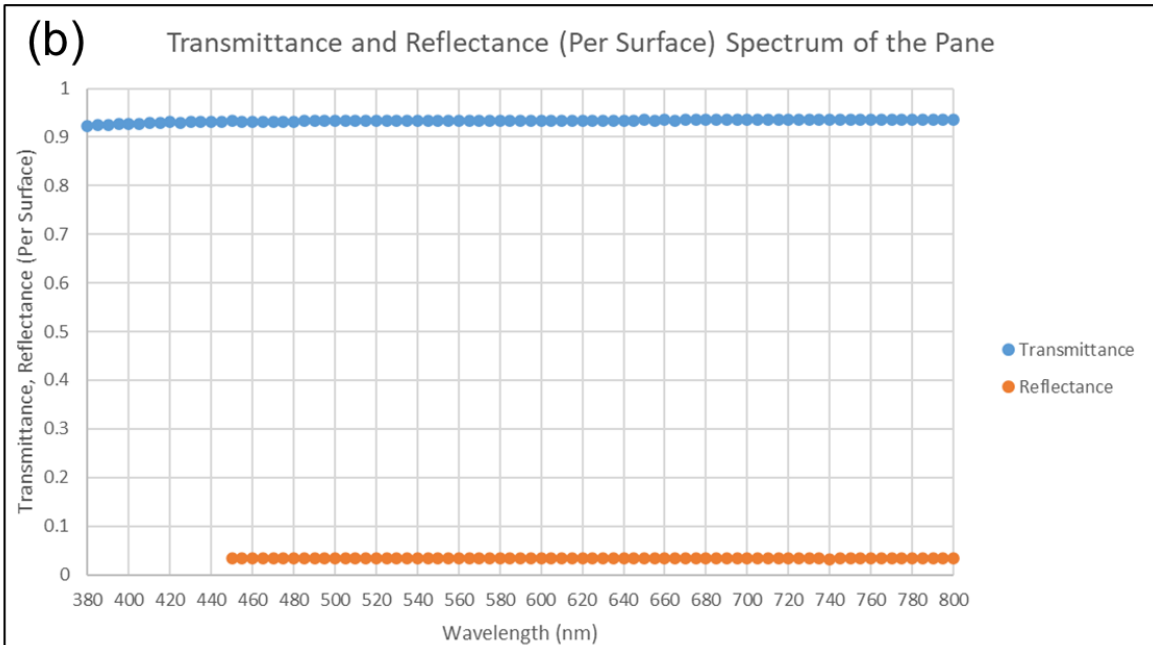


Figure 17. 17-inch FS window (SN: 23-0000112-001-9010) test results: (a) data summary, (b) transmittance / reflectance spectrum, and (c) photo of the test article.

(a) Pane Serial Number:	23-0000112-001-9011		
Pane Description:	17" Diameter Fused Silica Pane		
Window Thickness:	1.300in		
Window Thickness:	3.302Cm		
Index of Refraction:	1.453442921		
Summary of Transmission Properties:			
Luminous Transmittance:	93.3%		
Photon Flux Reflectance:	3.4%		
Average Reflectance:	3.4%		
		x lower bound	x upper bound
Color Balance X-Coordinate:	0.3129	0.3072	0.3186
Color Balance Y-Coordinate:	0.3293	$0.325 \le y \le 0.375$	
Normal Wavefront Properties:	0.106 (Average of PV - No Piston / Tilt)		
Summary of Wedge Properties:			
Magnitude of Wedge (arc minutes):	0.03332		
Direction of Wedge (°):	51.57		

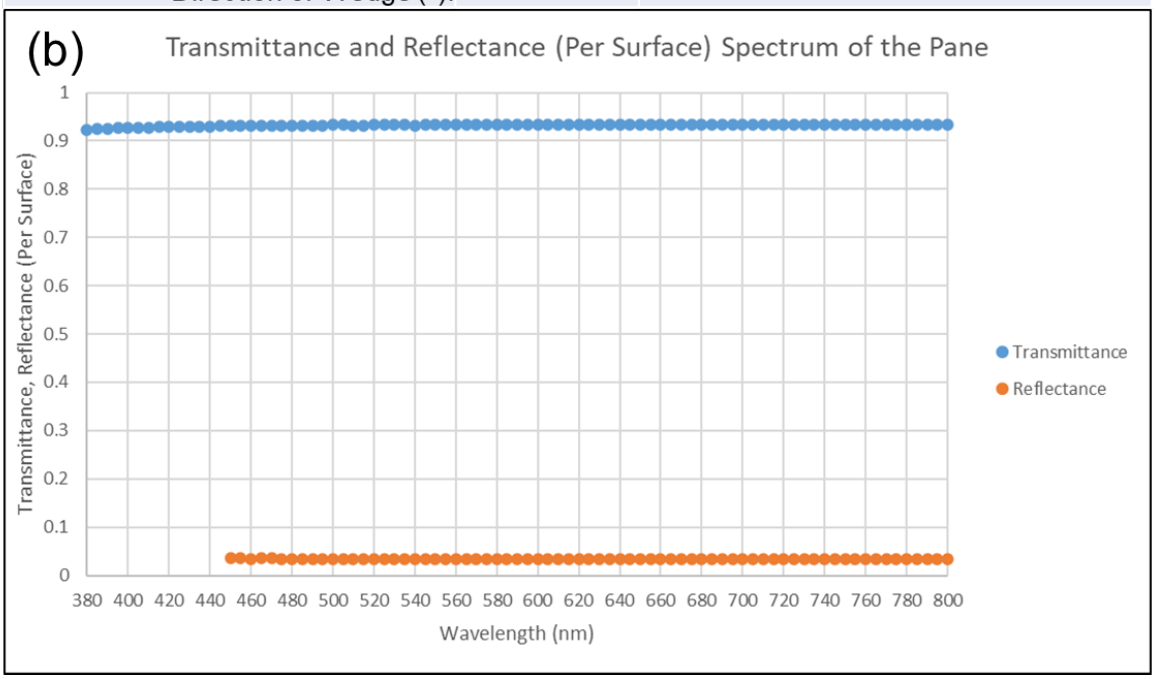


Figure 18. 17-inch FS window (SN: 23-0000112-001-9011) test results.

(a)

Pane Serial Number:	23-0000112-001-9012		
Pane Description:	17" Diameter Fused Silica Pane		
Window Thickness:	1.300in		
Window Thickness:	3.302cm		
Index of Refraction:	1.453896032		
Summary of Transmission Properties:			
Luminous Transmittance:	93.3%		
Photon Flux Reflectance:	3.4%		
Average Reflectance:	3.4%		
		x lower bound	x upper bound
Color Balance X-Coordinate:	0.3130	0.3072	0.3186
Color Balance Y-Coordinate:	0.3292	0.325 ≤ y ≤ 0.375	
Normal Wavefront Properties:	0.115 (Average of PV - No Piston / Tilt)		
Summary of Wedge Properties:			
Magnitude of Wedge (arc minutes):	0.02787		
Direction of Wedge (°):	81.43		

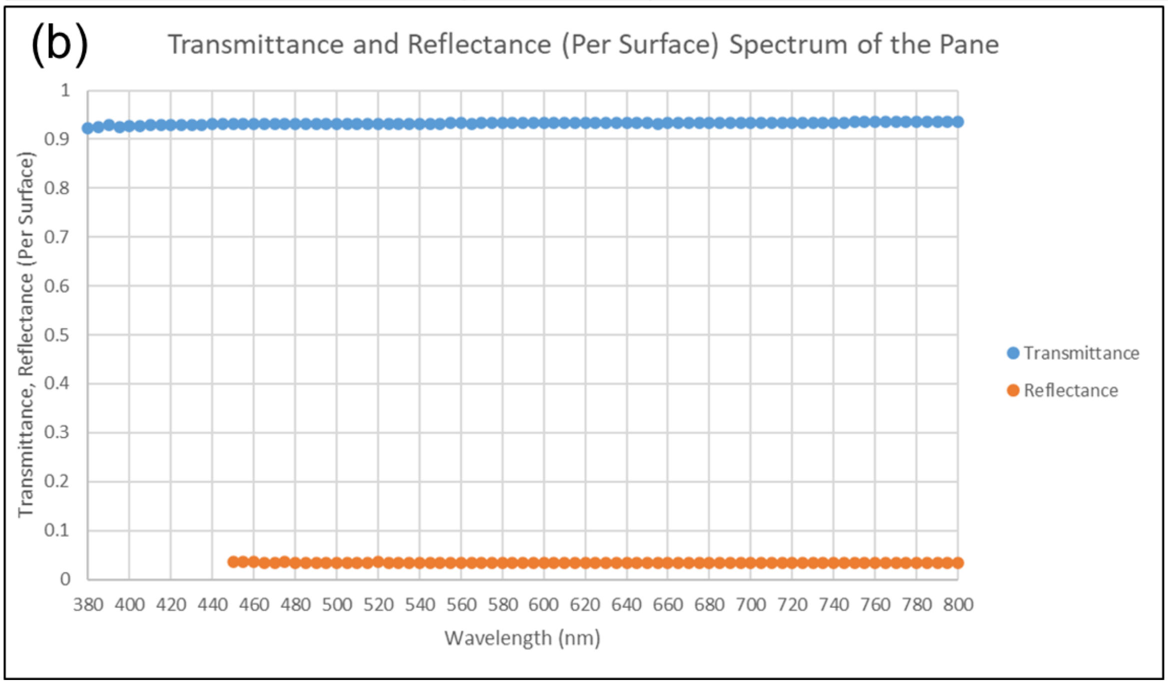


Figure 19. 17-inch FS window (SN: 23-0000112-001-9012) test results.

(a)

Pane Serial Number:	23-0000112-001-9013		
Pane Description:	17" Diameter Fused Silica Pane		
Window Thickness:	1.300in		
Window Thickness:	3.302cm		
Index of Refraction:	1.448673696		
Summary of Transmission Properties:			
Luminous Transmittance:	93.4%		
Photon Flux Reflectance:	3.4%		
Average Reflectance:	3.4%		
		x lower bound	x upper bound
Color Balance X-Coordinate:	0.3130	0.3072	0.3186
Color Balance Y-Coordinate:	0.3294	0.325 ≤ y ≤ 0.375	
Normal Wavefront Properties:	0.091 (Average of PV - No Piston / Tilt)		
Summary of Wedge Properties:			
Magnitude of Wedge (arc minutes):	0.01188		
Direction of Wedge (°):	65.44		

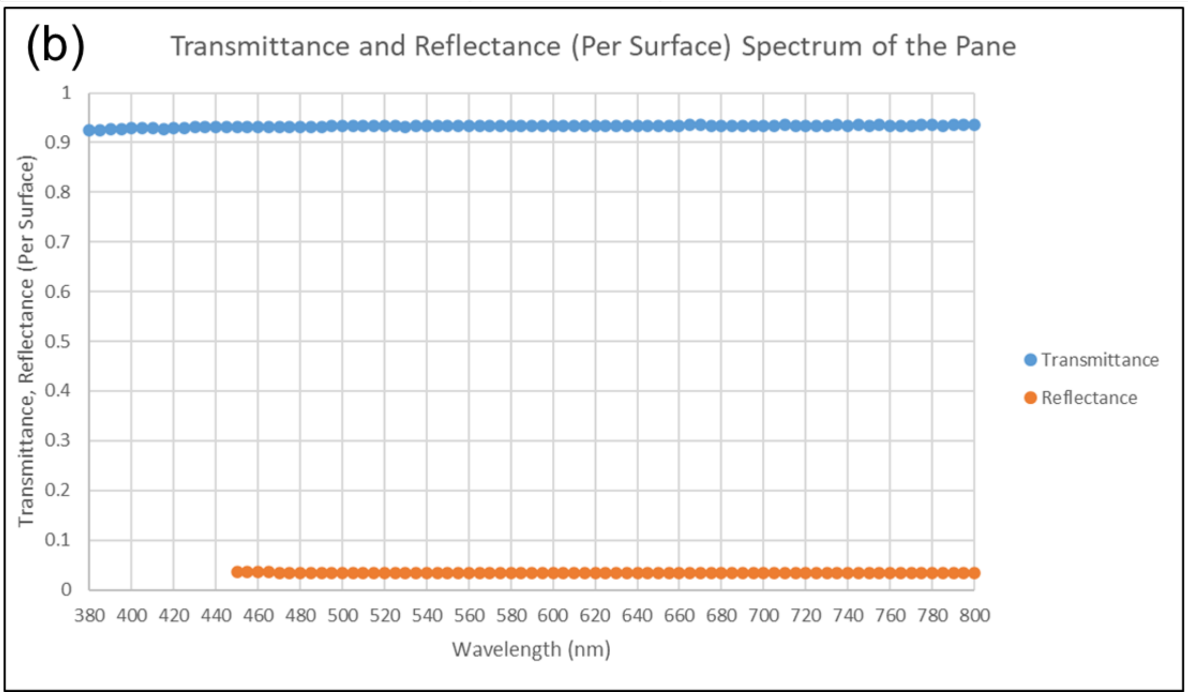


Figure 20. 17-inch FS window (SN: 23-0000112-001-9013) test results.

(a)

Pane Serial Number:	23-0000112-001-9014		
Pane Description:	17" Diameter Fused Silica Pane		
Window Thickness:	1.300in		
Window Thickness:	3.302cm		
Index of Refraction:	1.449860093		
Summary of Transmission Properties:			
Luminous Transmittance:	93.4%		
Photon Flux Reflectance:	3.3%		
Average Reflectance:	3.4%		
		x lower bound	x upper bound
Color Balance X-Coordinate:	0.3130	0.3072	0.3186
Color Balance Y-Coordinate:	0.3294	0.325 ≤ y ≤ 0.375	
Normal Wavefront Properties:	0.075 (Average of PV - No Piston / Tilt)		
Summary of Wedge Properties:			
Magnitude of Wedge (arc minutes):	0.01671		
Direction of Wedge (°):	-18.99		

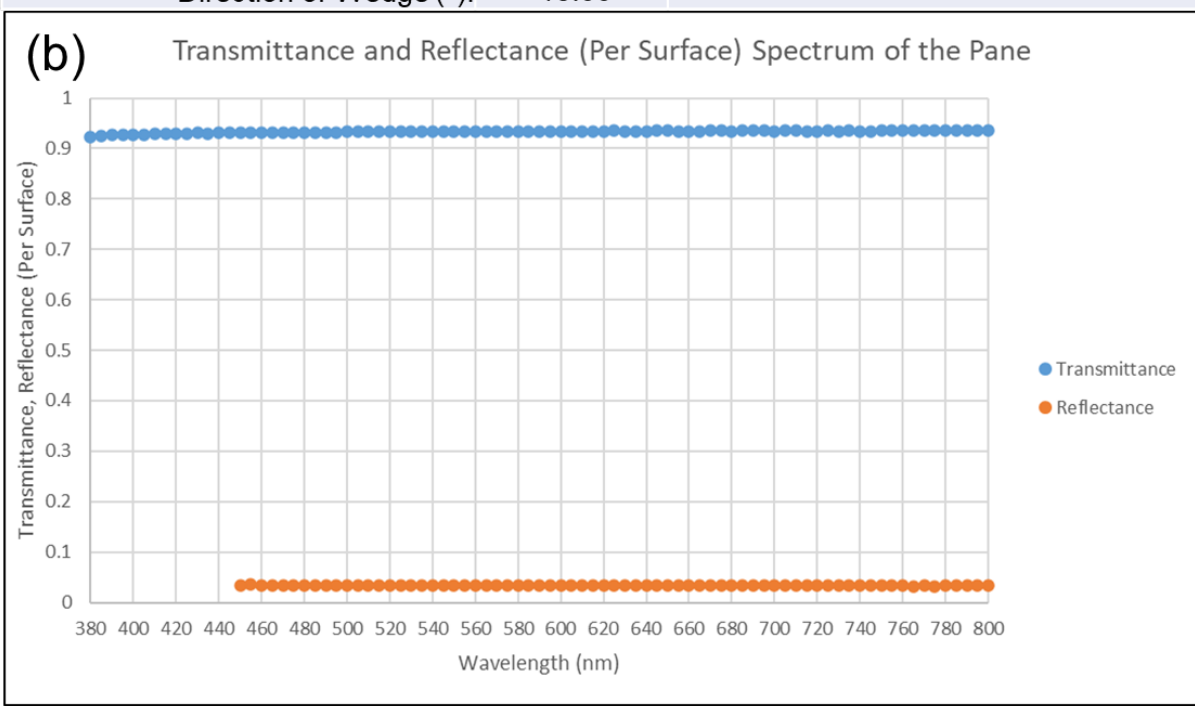
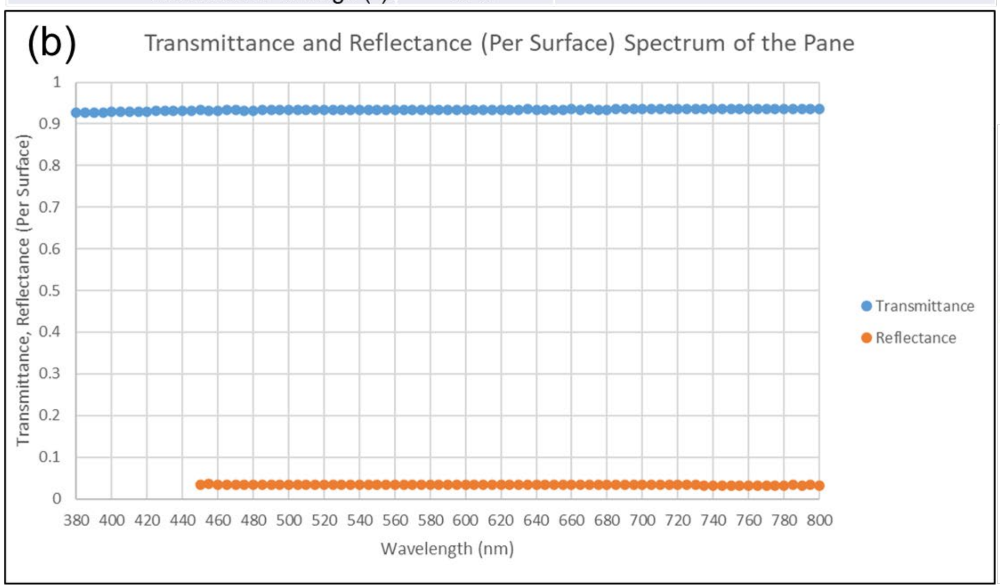


Figure 21. 17-inch FS window (SN: 23-0000112-001-9014) test results.

(a)

Pane Serial Number:	23-0000112-001-9015		
Pane Description:	17" Diameter Fused Silica Pane		
Window Thickness:	1.300in		
Window Thickness:	3.302cm		
Index of Refraction:	1.449926116		
Summary of Transmission Properties:			
Luminous Transmittance:	93.4%		
Photon Flux Reflectance:	3.3%		
Average Reflectance:	3.3%		
		x lower bound	x upper bound
Color Balance X-Coordinate:	0.3129	0.3072	0.3186
Color Balance Y-Coordinate:	0.3292	0.325 ≤ y ≤ 0.375	
Normal Wavefront Properties:	0.074 (Average of PV - No Piston / Tilt)		
Summary of Wedge Properties:			
Magnitude of Wedge (arc minutes):	0.01024		
Direction of Wedge (°):	2.11		



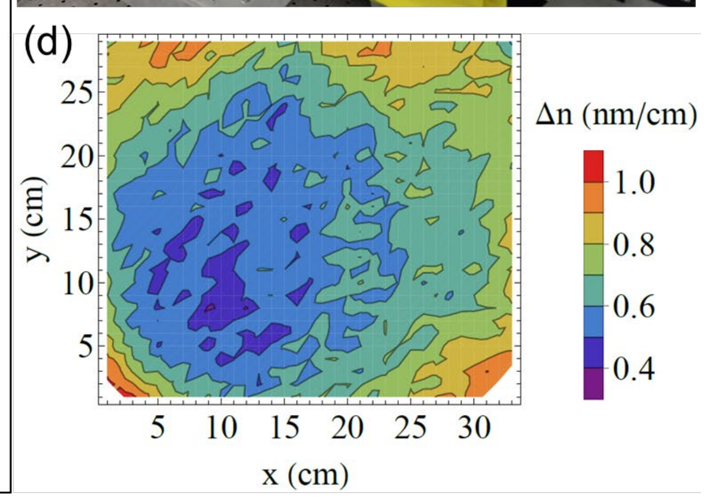
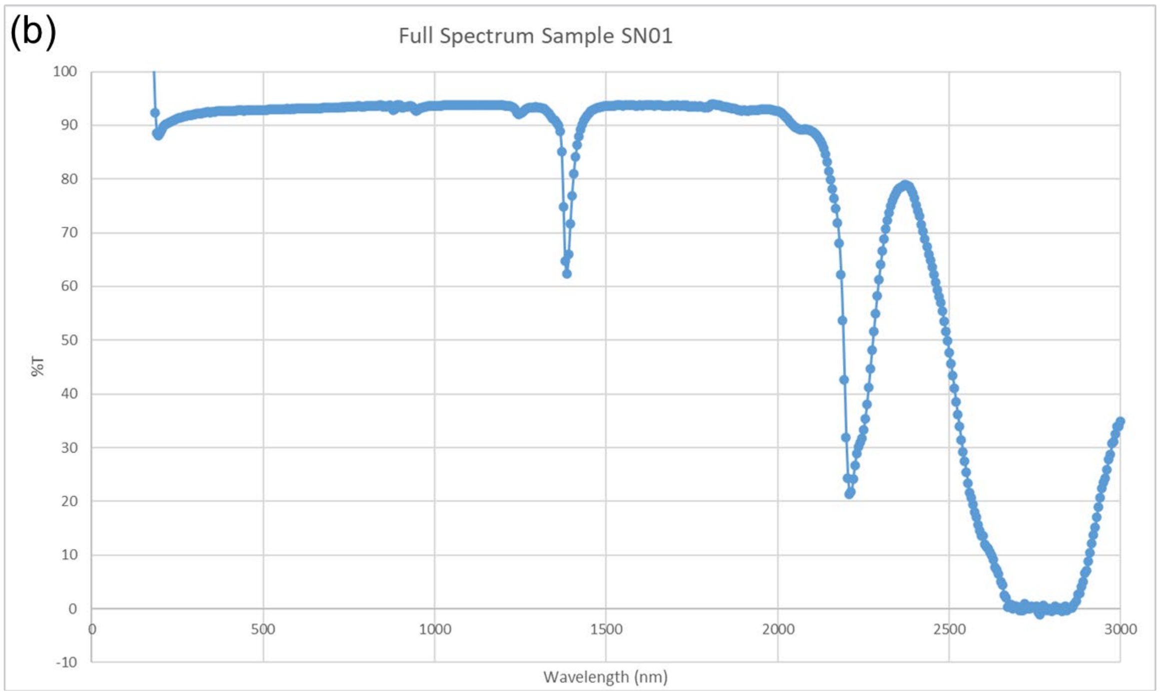


Figure 22. 17-inch FS window (SN: 23-0000112-001-9015) test results.

(a)

Summary of Haze Properties (%):			
Sample SN01	0.017		
Sample SN03	0.011		
Sample SN04	0.016		
Sample SN05	0.009		
Sample SN06	0.007		
Sample SN07	0.009		
Summary of Transmission Properties:		Only one sample (SN01) was tested for transmission per the testing matrix	
Luminous Transmittance Requirement (380 nm to 800 nm):		Note: Full transmission spectrum graph is shown (b)	
Sample SN01	93.0%	-	
Summary of Color Balance Properties:		-	
Sample SN01		x lower bound	x upper bound
Color Balance X-Coordinate:	0.3130	0.3072	0.3186
Color Balance Y-Coordinate:	0.329	0.325 ≤ y ≤ 0.375	



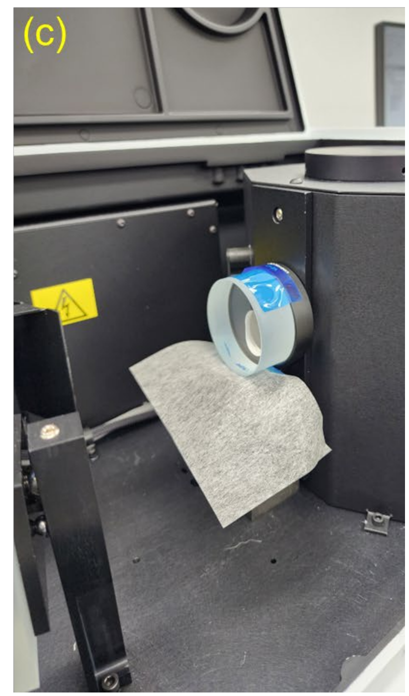


Figure 23. 2-inch diameter FS witness sample (SN01, SN03 – SN07, 1.3 in thick) test results: (a) summary of data, (b) full spectrum of SN01, (c) photo of sample positioned for transmission and haze measurements in test holder.

Summary

This report summarizes windowpane optical analyses conducted for aircraft windows designed and procured for the SCIFLI HORIS mission. Six 17-inch diameter FS windows were designed and purchased for use in airborne imaging campaigns for HORIS and subsequent. The FS panes were tested based on standard optical window characterizations including transmittance, reflectance, color balance, birefringence, transmitted wavefront error, optical wedge, and optical haze. For scientific grade windows, the WFE, the amount of distortion of the wavefront through the window, should ideally be λ/10 or less. 1/10 serves as a standard for high-quality optics. Maintaining the requirement over the full clear aperture of the windows was challenging and required the vendor to properly polish and/or coat the windows to meet the performance specification. For the HORIS mission, NASA imparted a relaxed specification for WFE, better than λ/8, depending on how the measurements were obtained and handled. Specifically, it was stated that for normal incidence viewing with piston, tilt, and defocus (the three most predominant aberrations) removed, the RMS wavefront error over the window would not exceed 1 wave.

Based on the results obtained from the laboratory metrology testing, it was concluded by the SCIFLI team that the FS windowpanes met the requirements for the HORIS mission. They were subsequently installed on two NASA Gulfstream aircraft and used successfully in the airborne imaging campaign conducted during the OSIRIS-REx sample return capsule reentry to obtain meaningful thermal data on the capsule performance during entry and descent back to Earth in September 2023.

Acknowledgements

1. Testing objectives and the data acquisition and processing sections are formulated based on work by Dr. Ken Tedjojuwono (LaRC Distinguished Research Associate), through internal NASA reports entitled: (1) Transmittance, Reflectance and Color Balance Testing in Support of the Window Material Database Test Plan, (2) Birefringence Testing in Support of the Window Material Database Test Plan, (3) TWE Testing in Support of the Window Material Database Test Plan, and (4) Wedge Testing in Support of the Window Material Database Test Plan.
2. The testing results section is expanded based "SCIFLI OSIRIS-REx Windowpane Optical Analysis Preliminary Draft" (Document ID: NASA-5557, Rev: Basic) written by Ian Rook and Thomas Gutierrez in the Laboratories, Development and Testing Division (LDTD) in the Engineering Directorate (ED) at the John F. Kennedy Space Center (KSC).

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Appendix A. Wavefront Interferograms for FS Windows

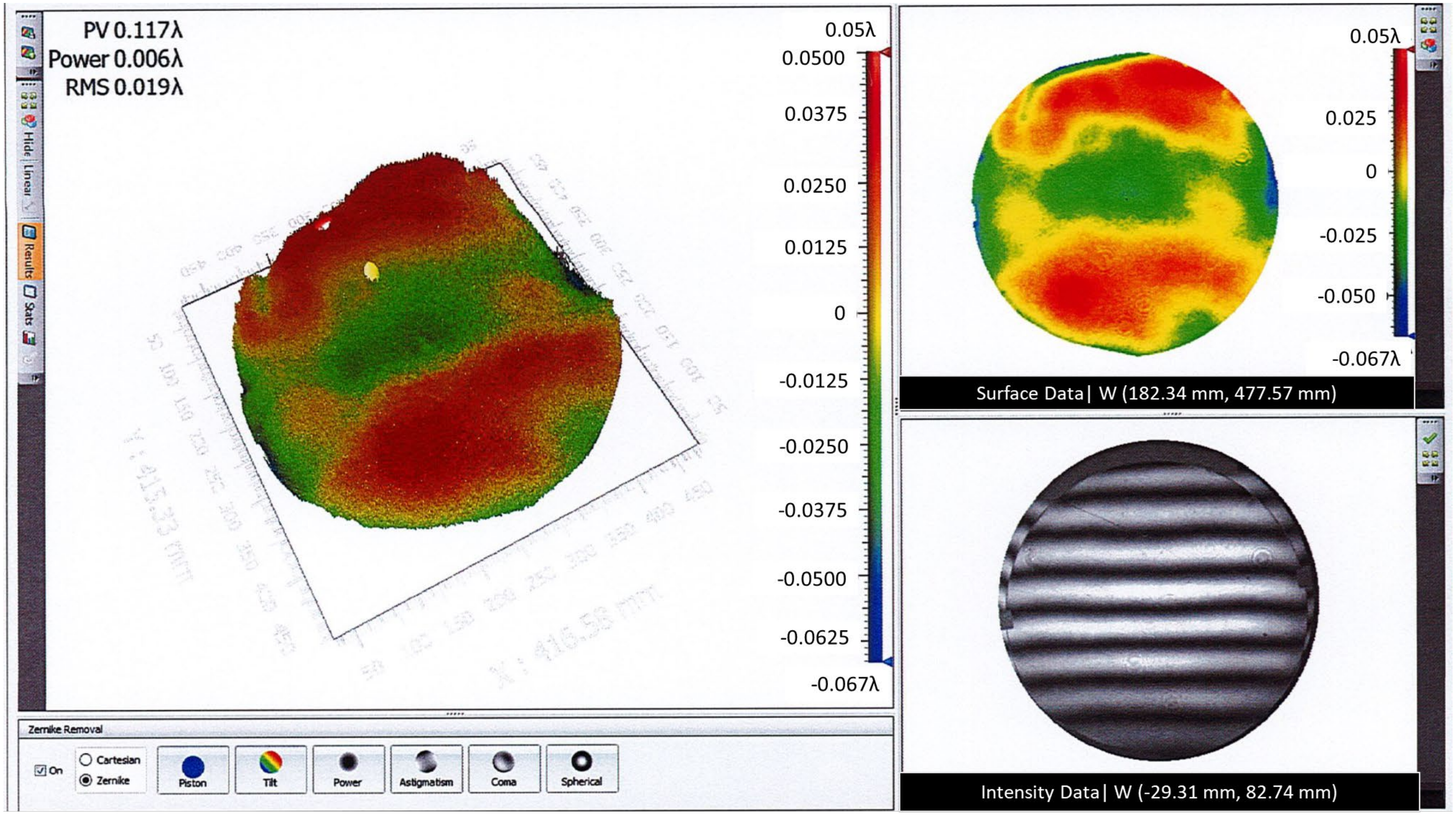


Figure A1. Interferogram for 17-inch FS window, SN 23000112-001-9010

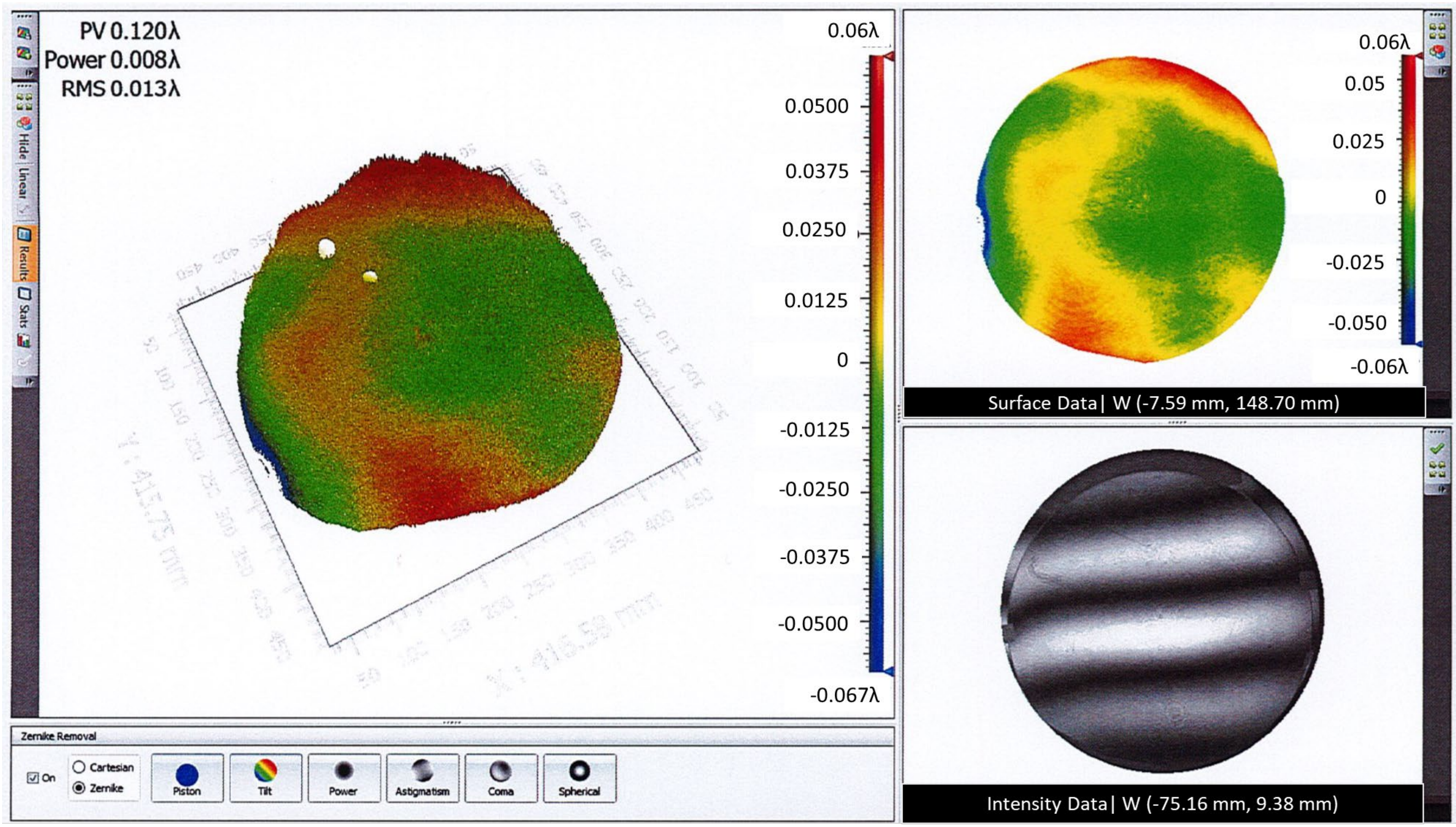


Figure A2. Interferogram for 17-inch FS window, SN 23000112-001-9011

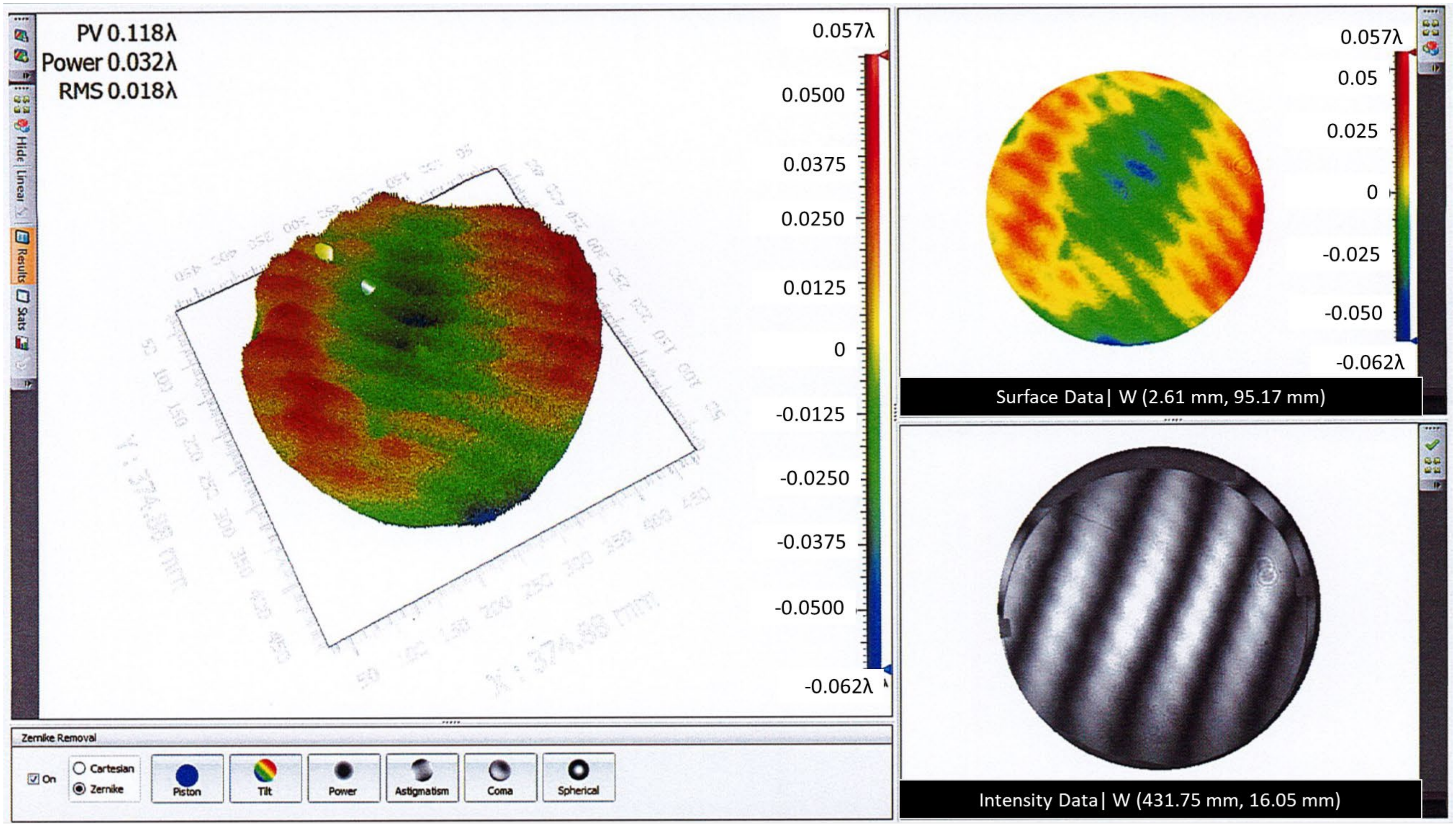


Figure A3. Interferogram for 17-inch FS window, SN 23000112-001-9012

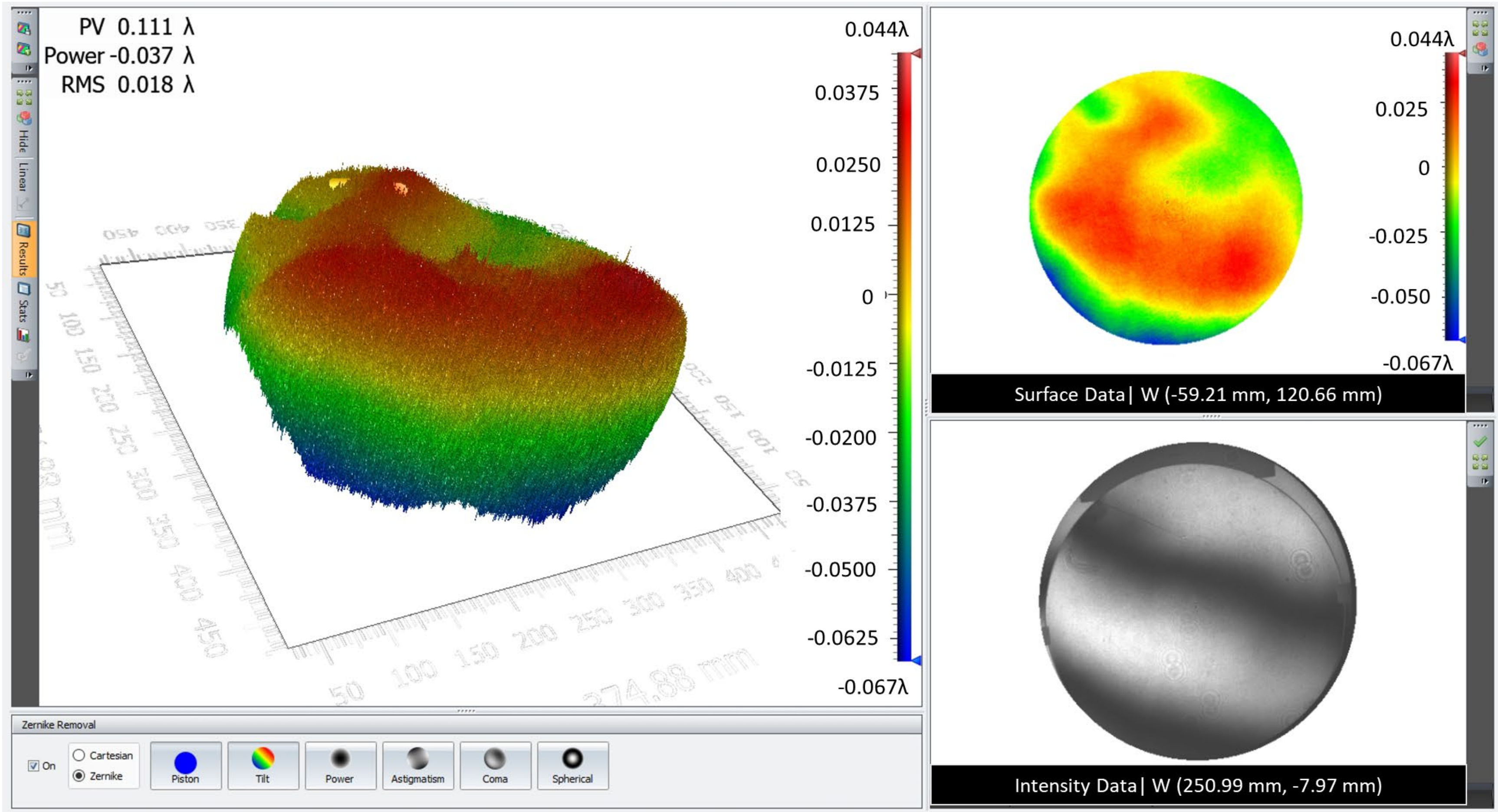


Figure A4. Interferogram for 17-inch FS window, SN 23000112-001-9013

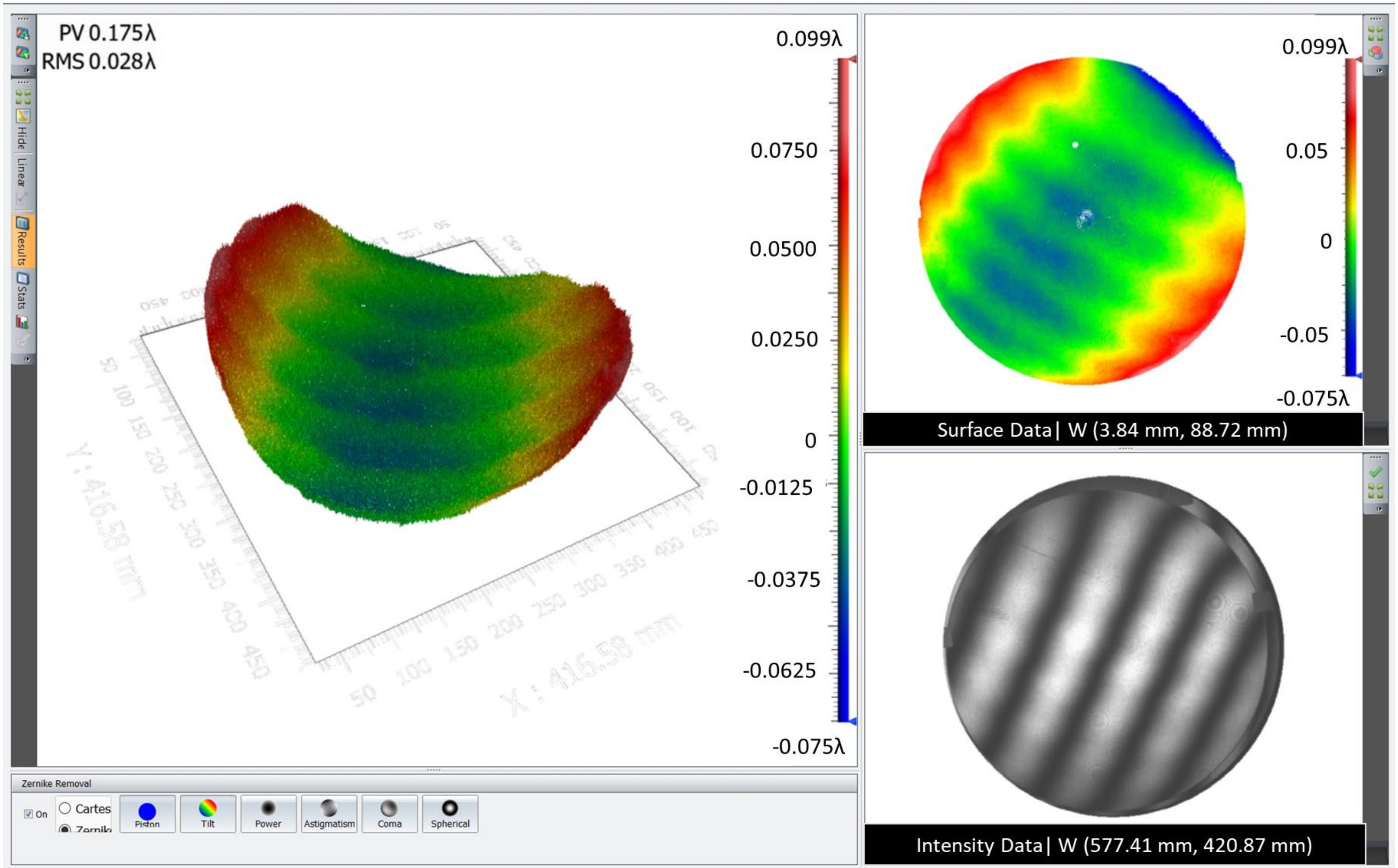


Figure A5. Interferogram for 17-inch FS window, SN 23000112-001-9014

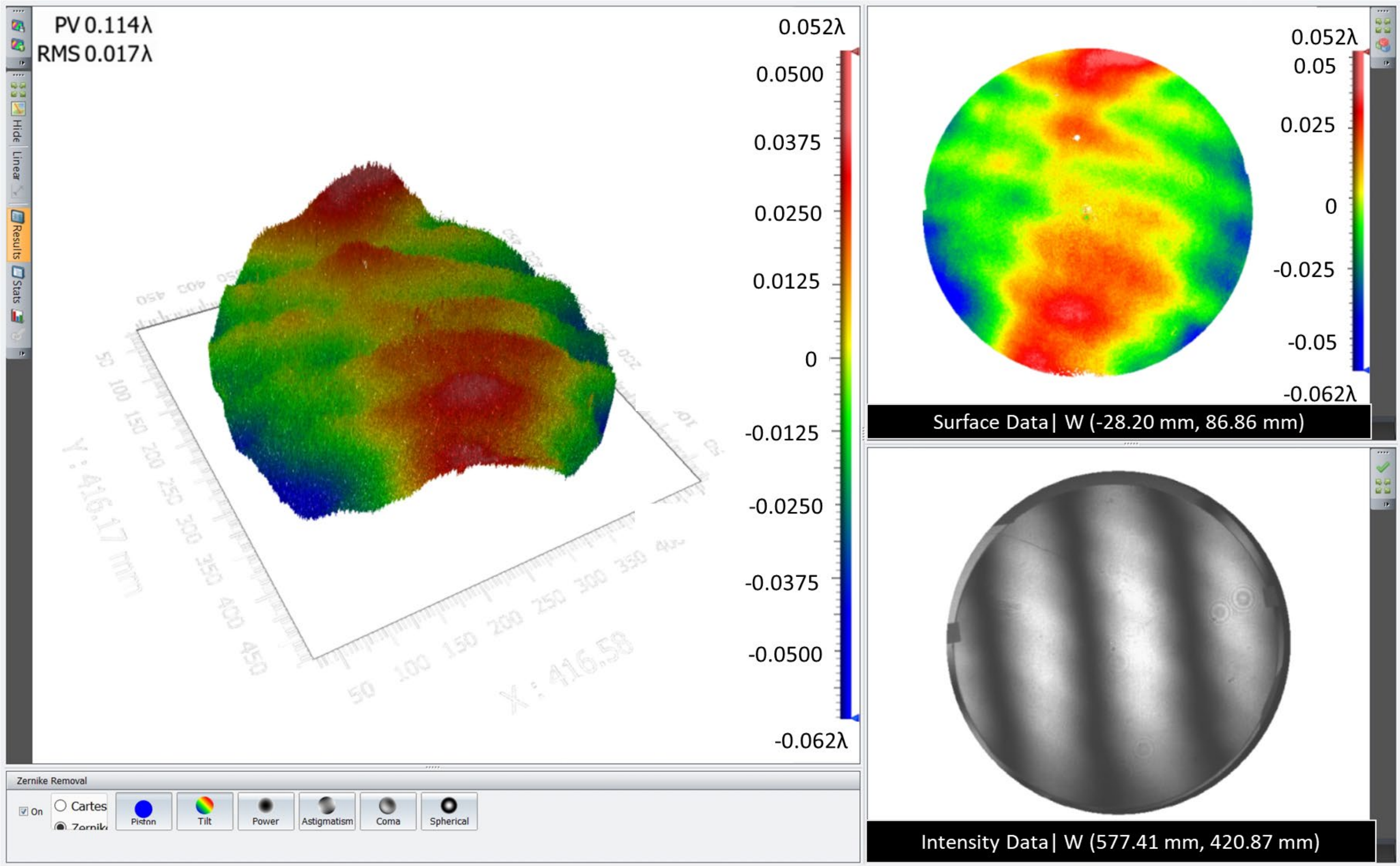
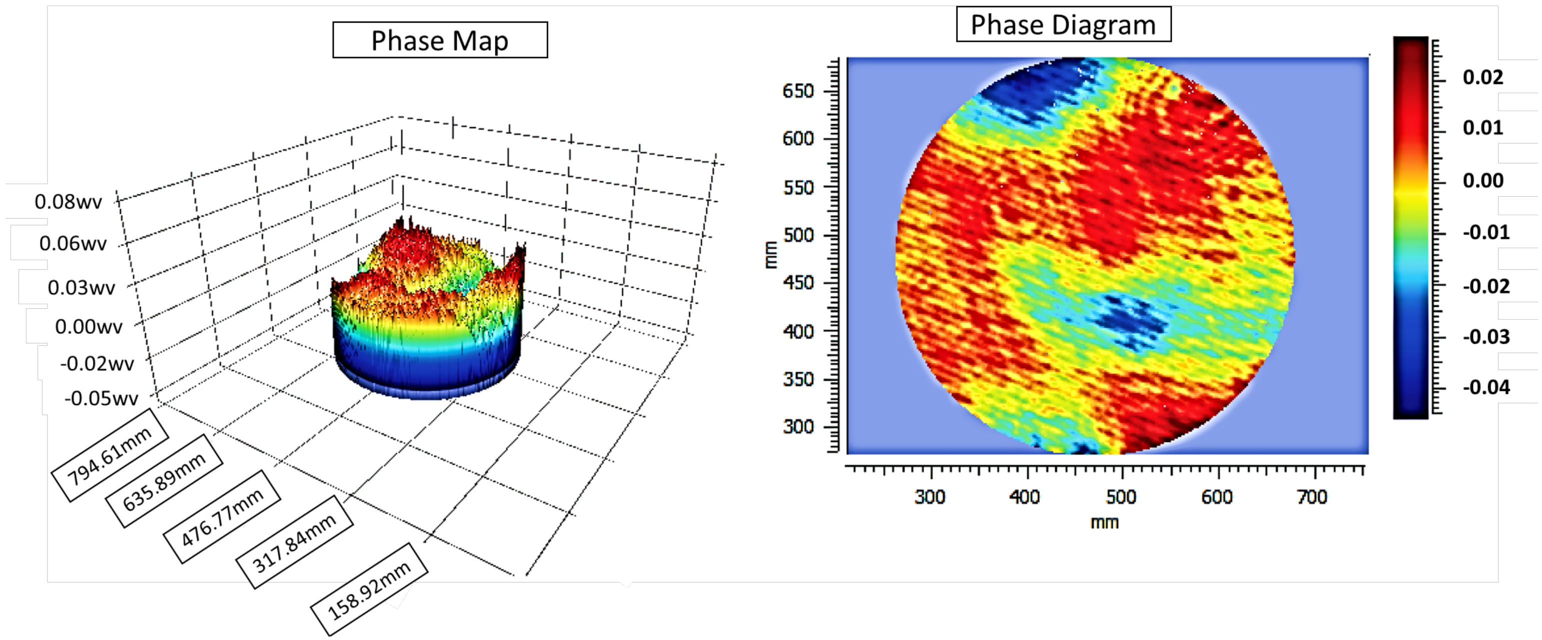


Figure A6. Interferogram for 17-inch FS window, SN 23000112-001-9015



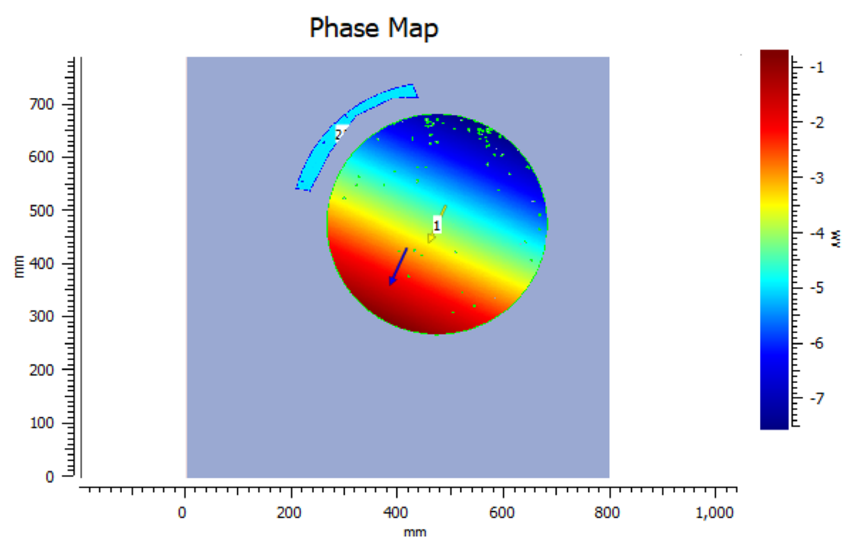


Figure A7. Interferogram result for 17-inch FS window, SN 23000112-001-9016

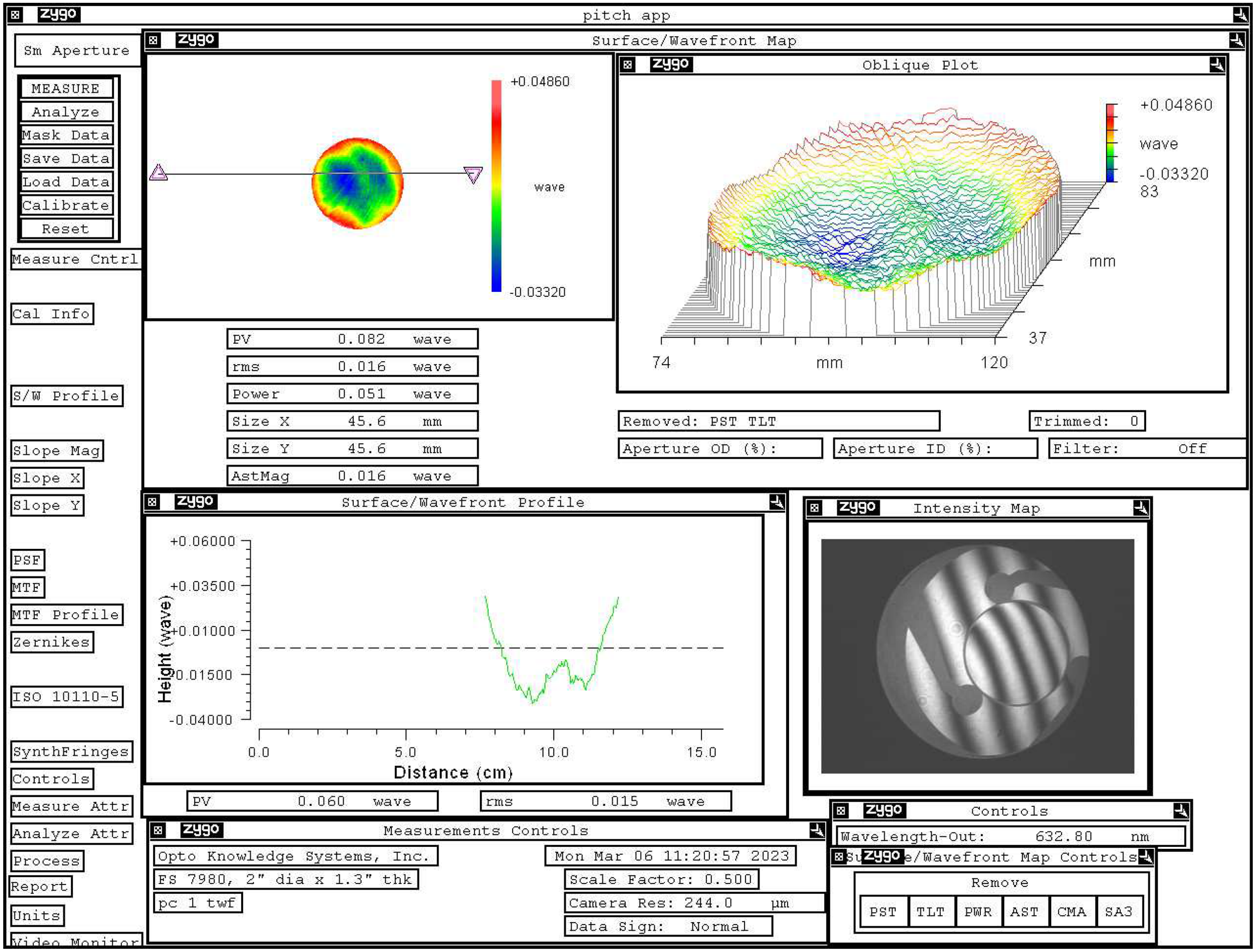


Figure A8. TWE Interferogram for 2-inch FS witness sample, SN01

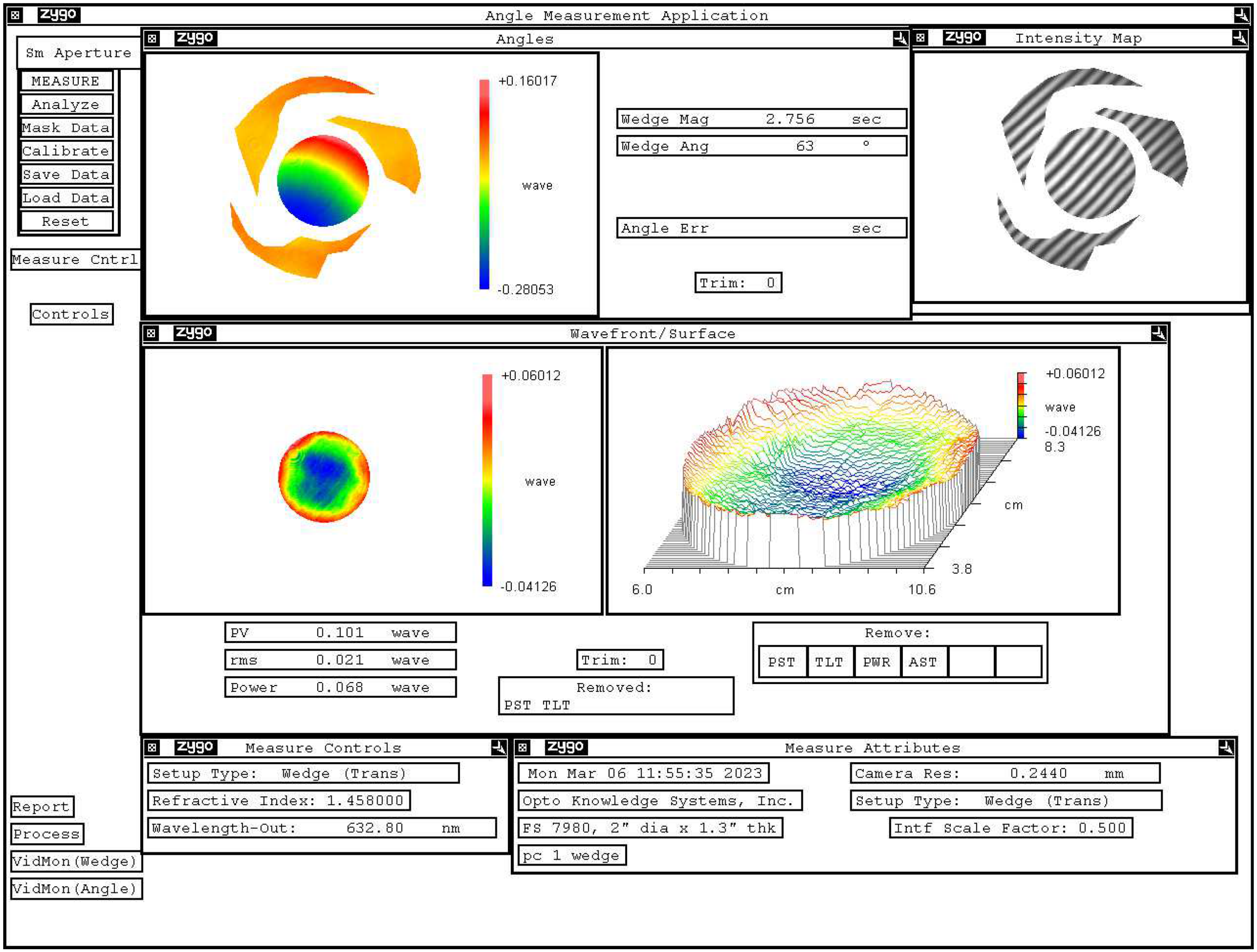


Figure A9. Wedge Interferogram for 2-inch FS witness sample, SN01

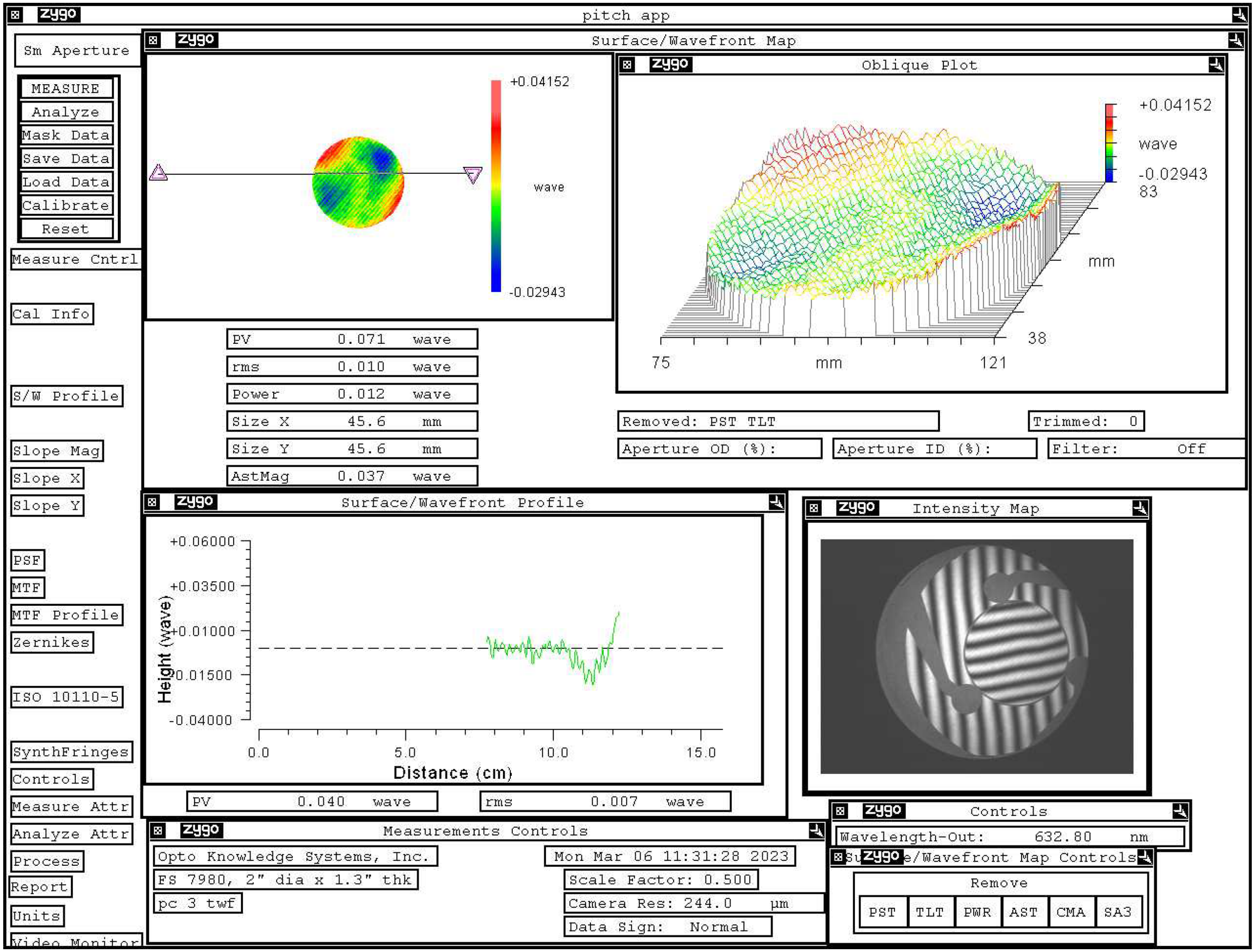


Figure A10. TWE Interferogram for 2-inch FS witness sample, SN03

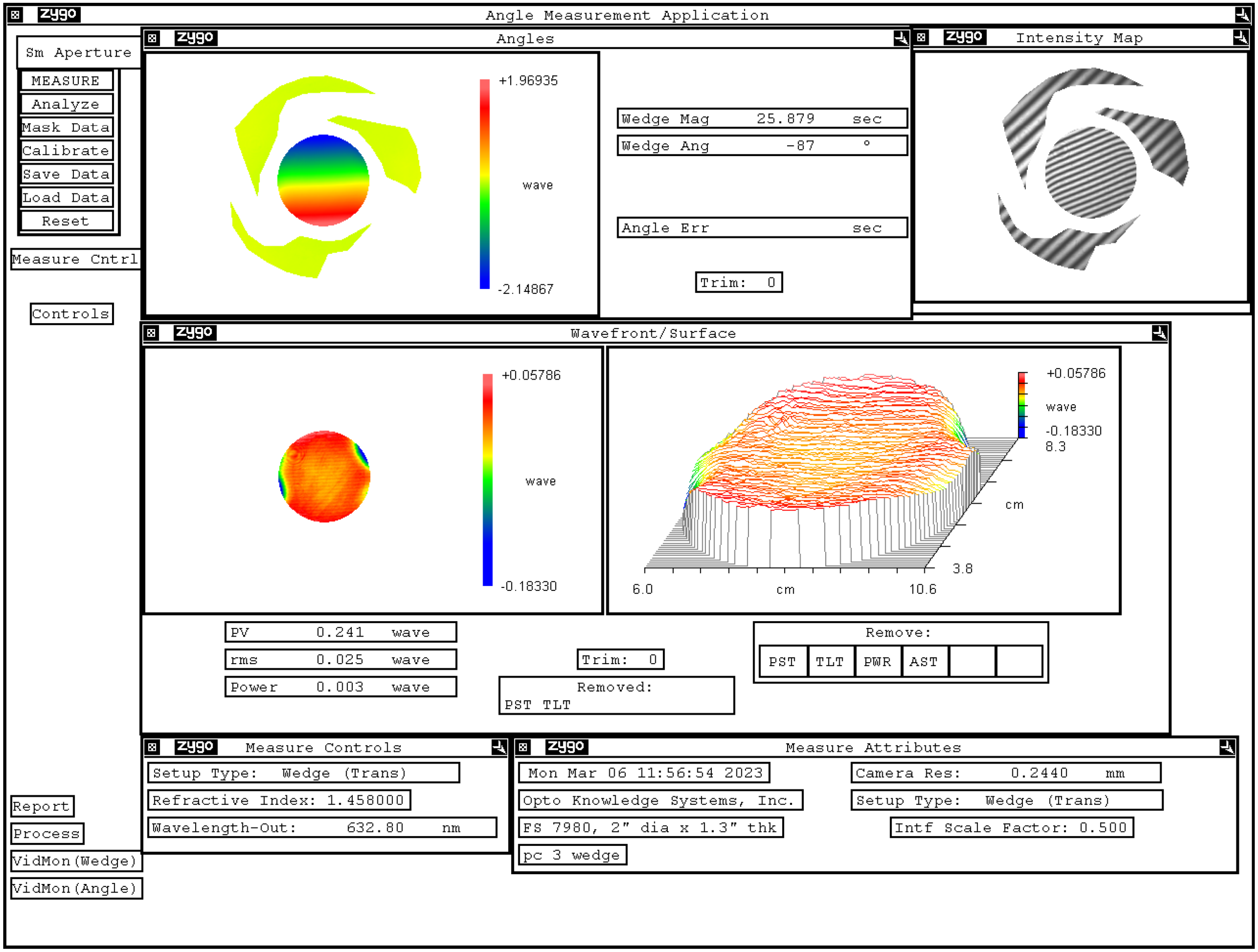


Figure A11. Wedge Interferogram for 2-inch FS witness sample, SN03

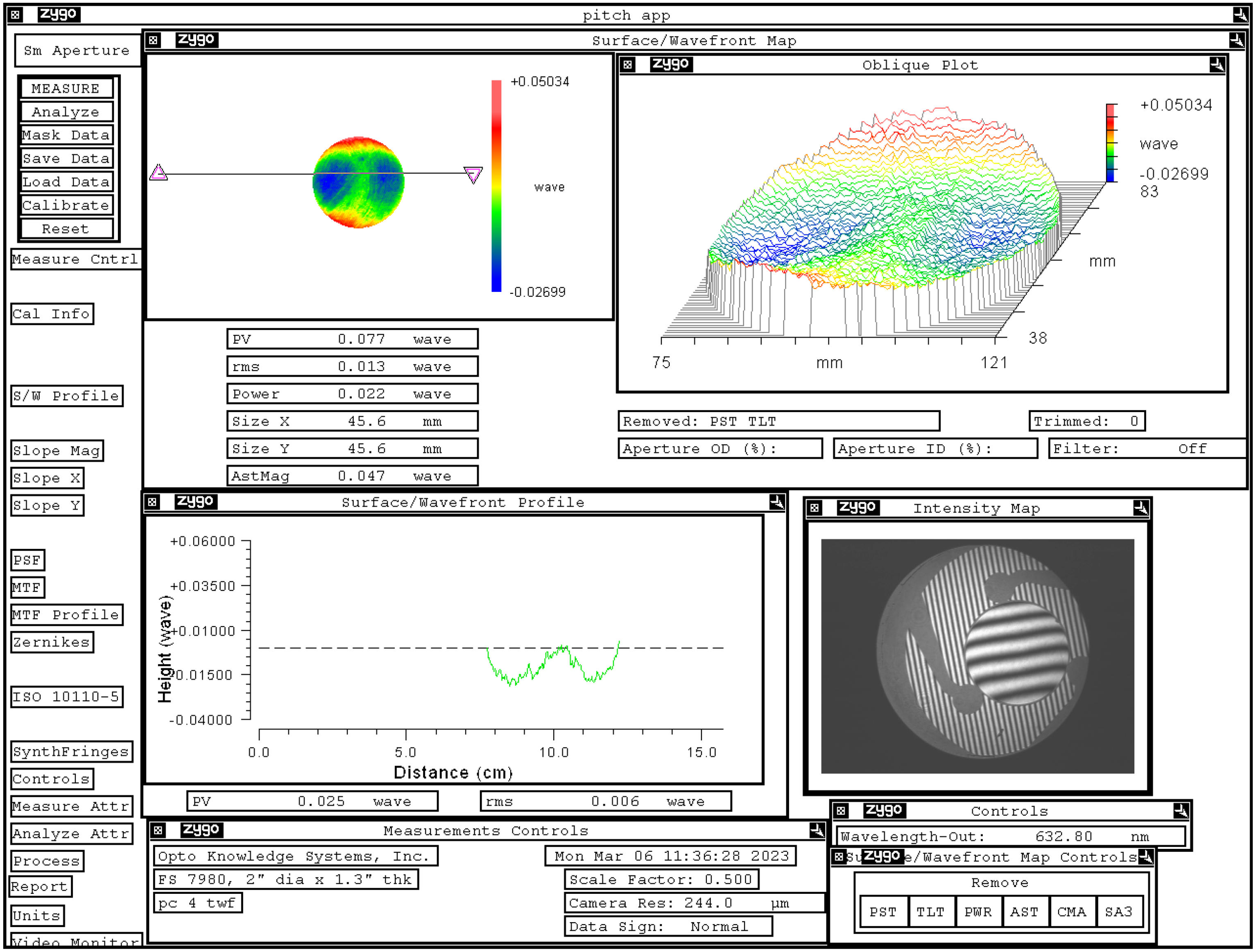


Figure A12. TWE Interferogram for 2-inch FS witness sample, SN04

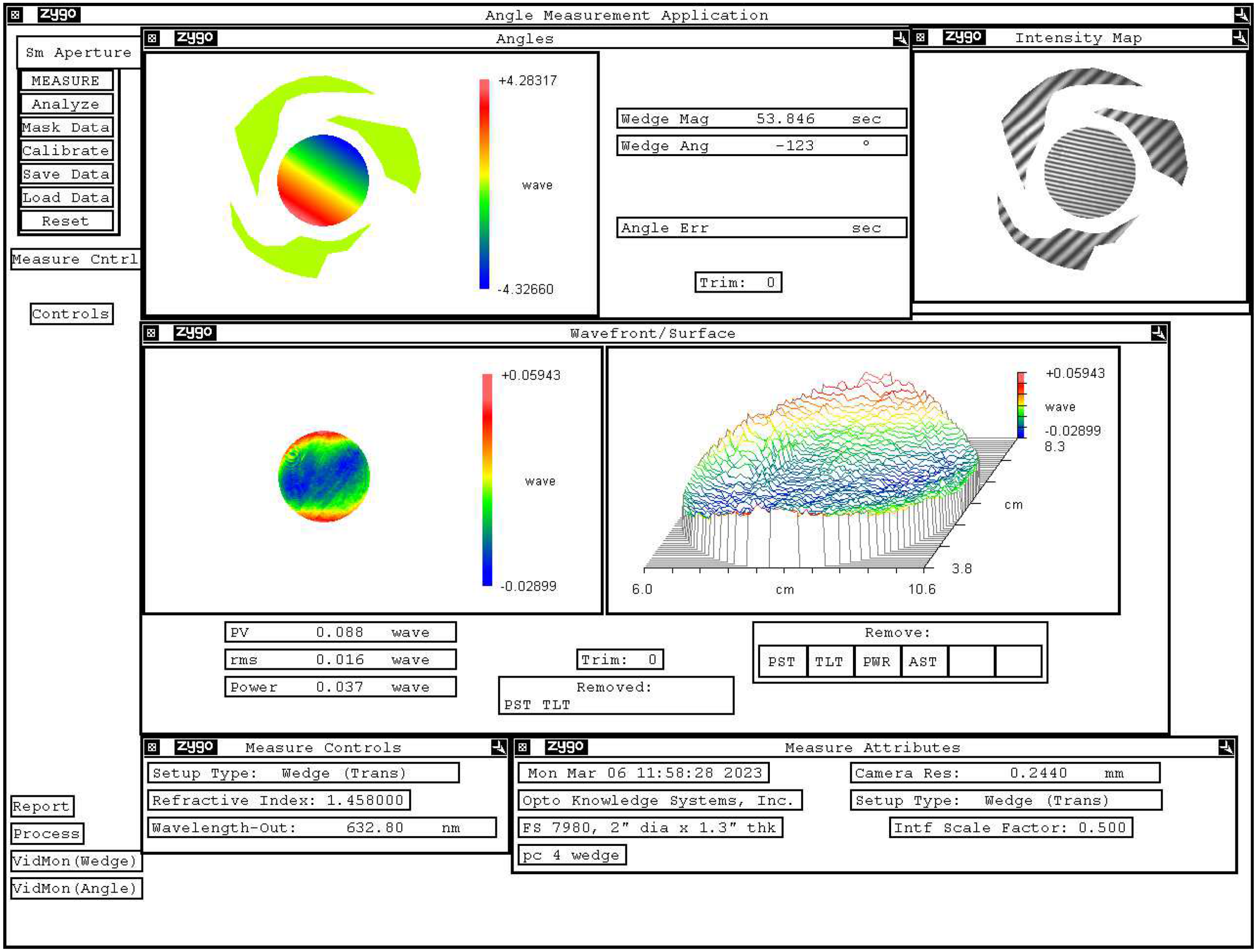


Figure A13. Wedge Interferogram for 2-inch FS witness sample, SN04

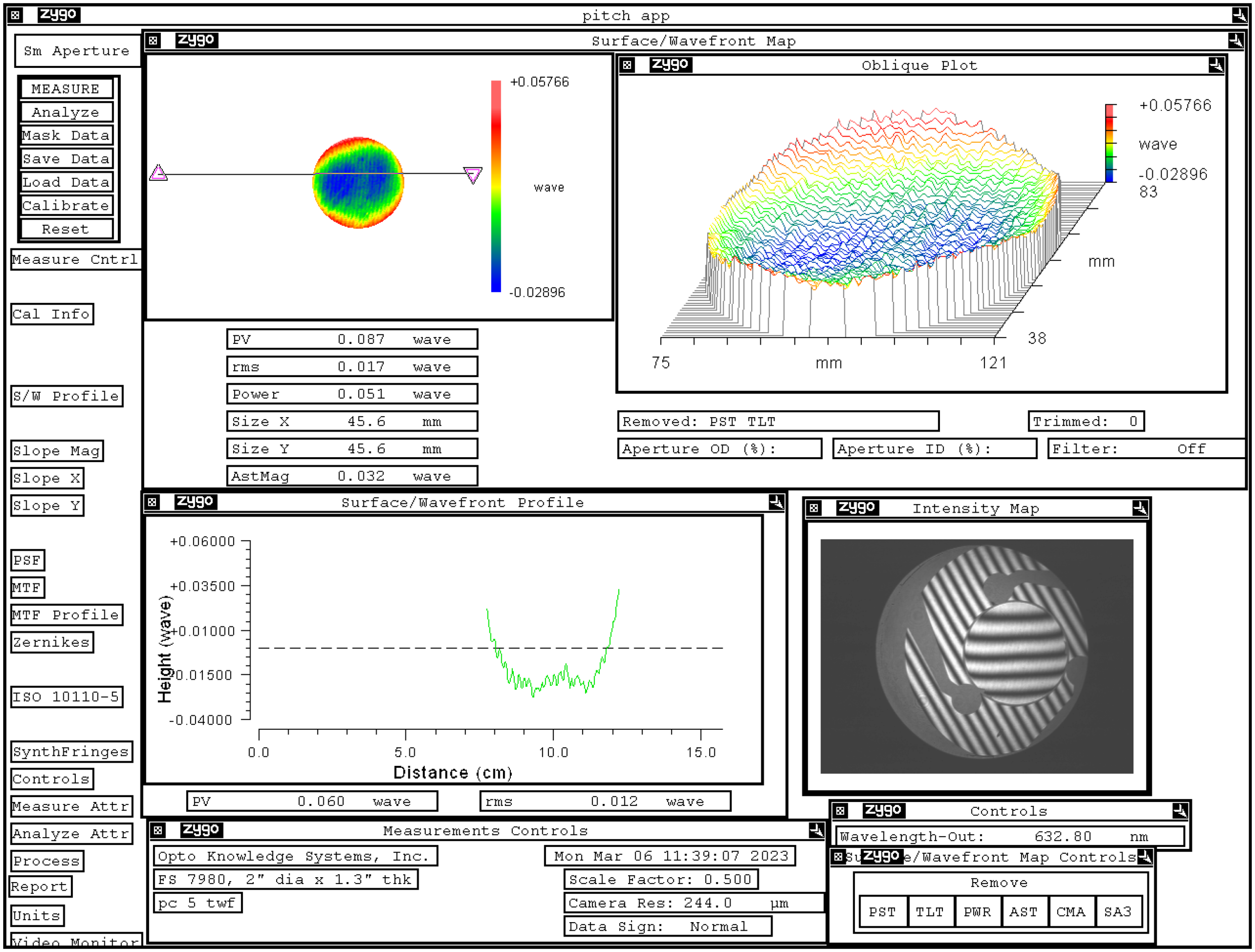


Figure A14. TWE Interferogram for 2-inch FS witness sample, SN05

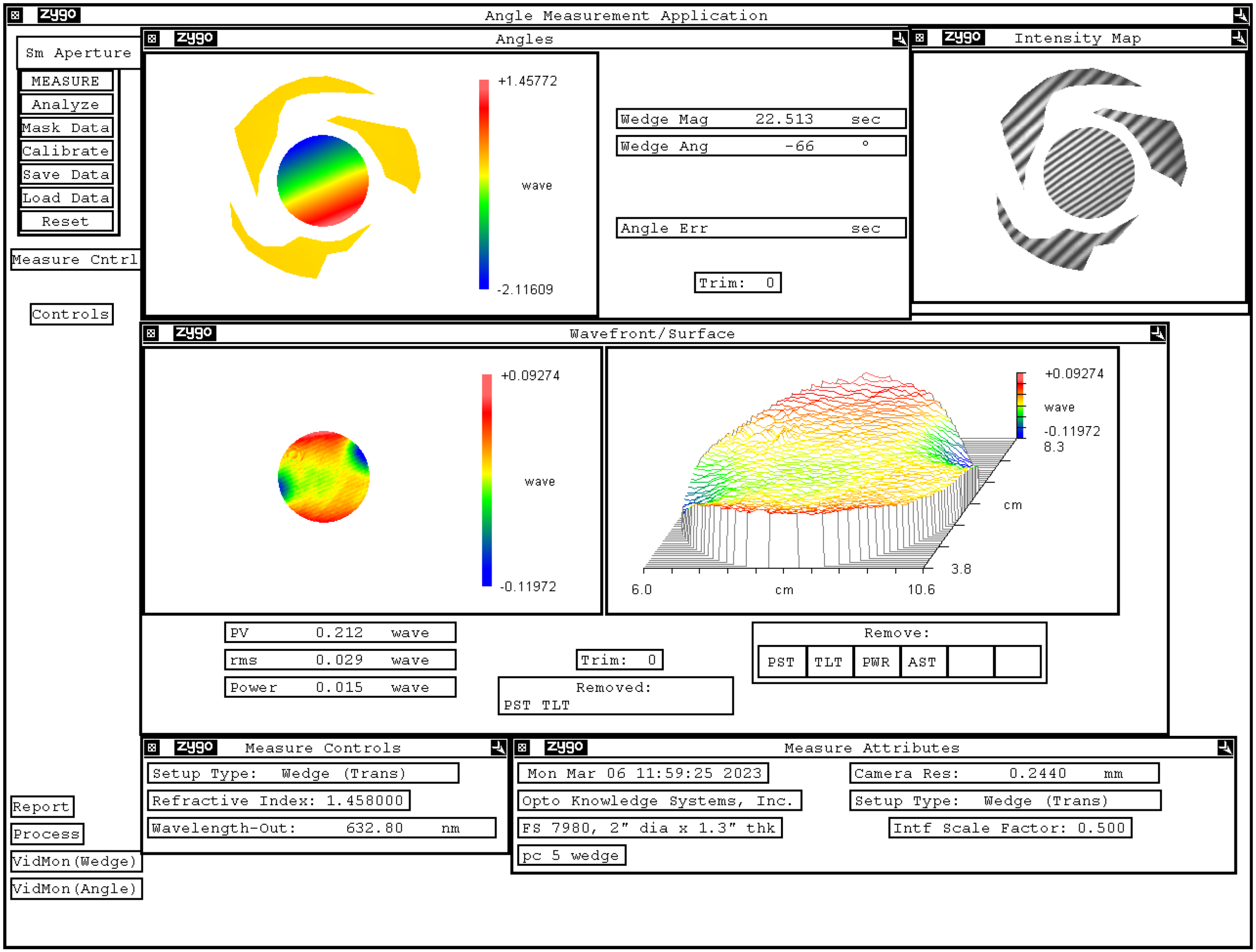


Figure A15. Wedge Interferogram for 2-inch FS witness sample, SN05

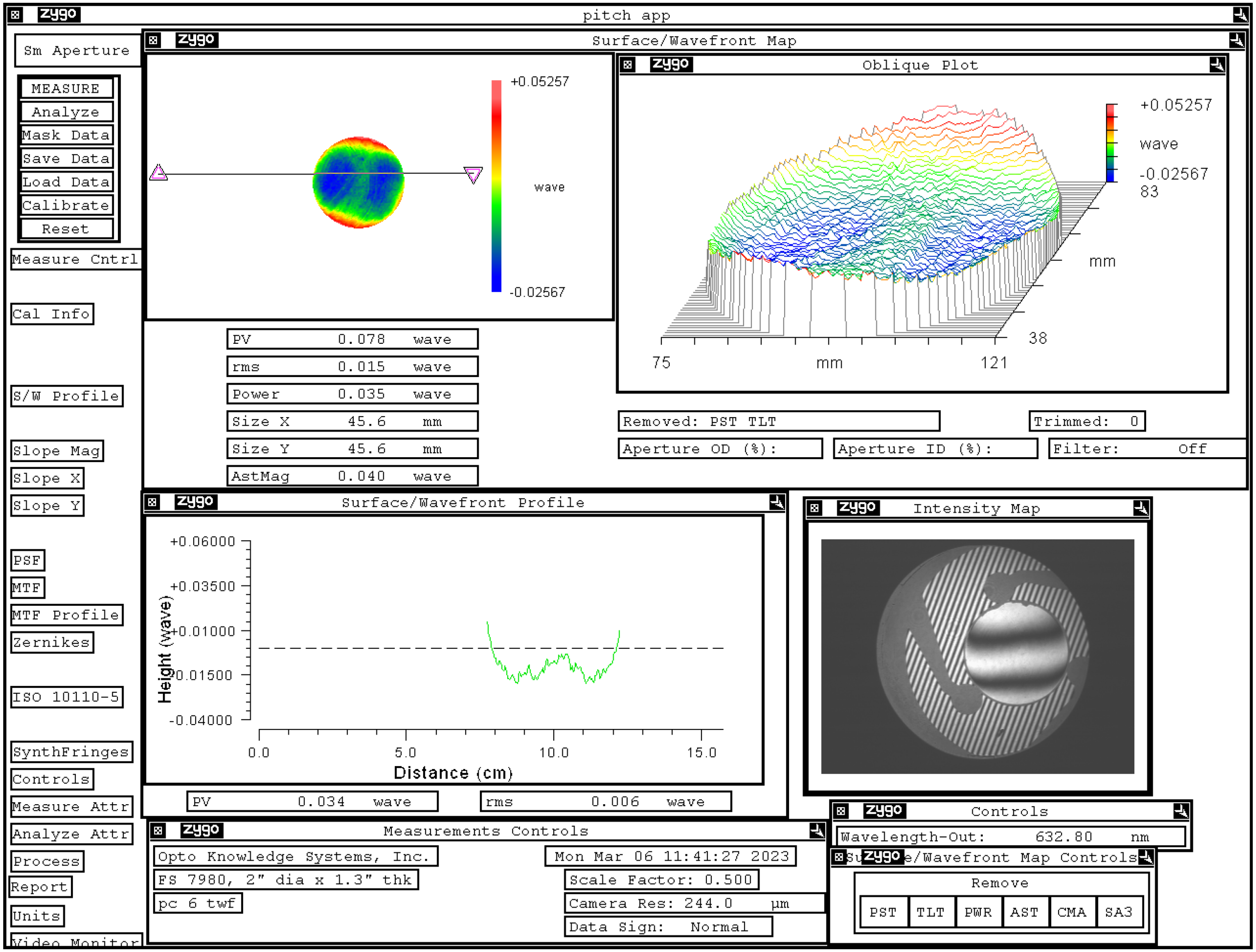


Figure A16. TWE Interferogram for 2-inch FS witness sample, SN06

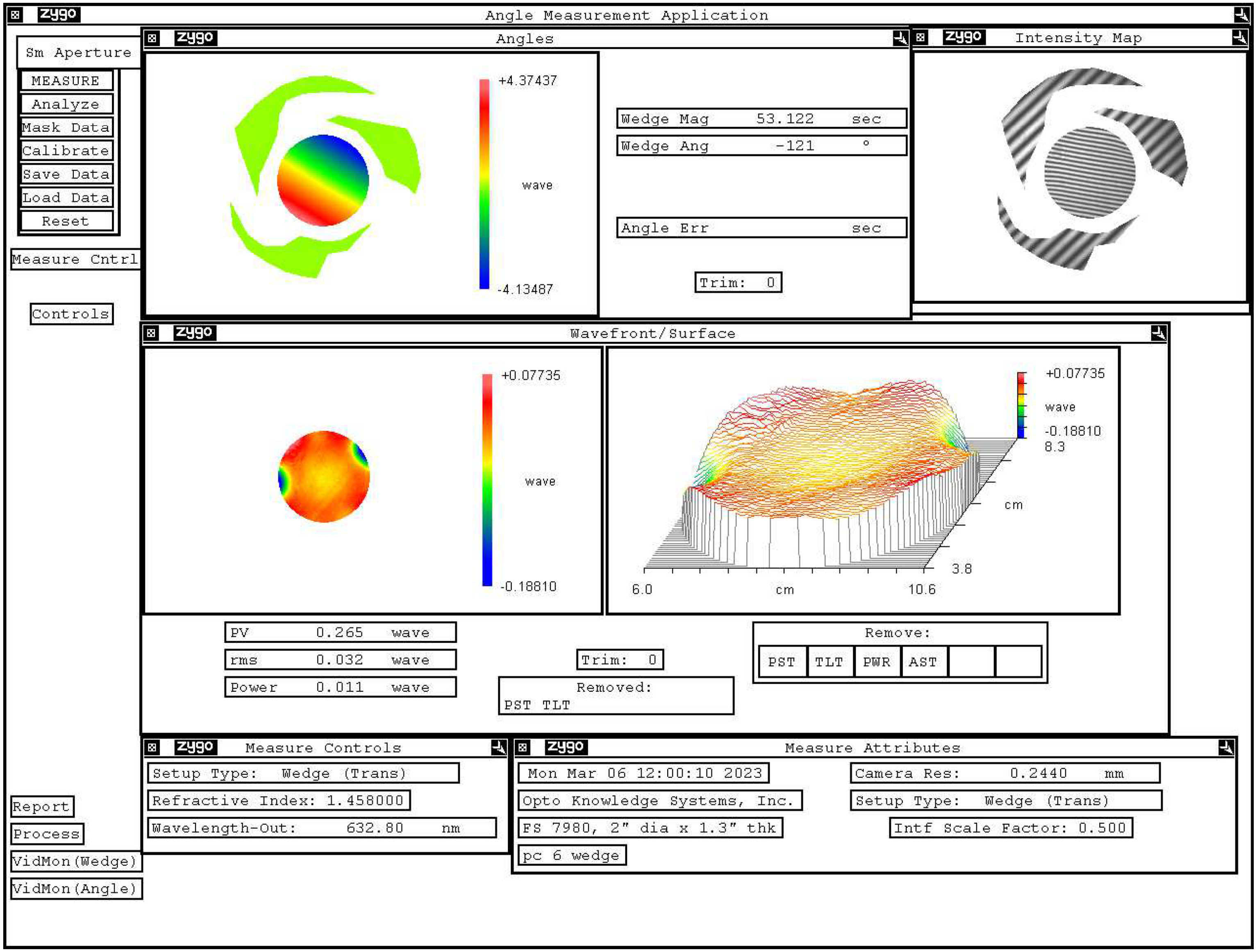


Figure A17. Wedge Interferogram for 2-inch FS witness sample, SN06

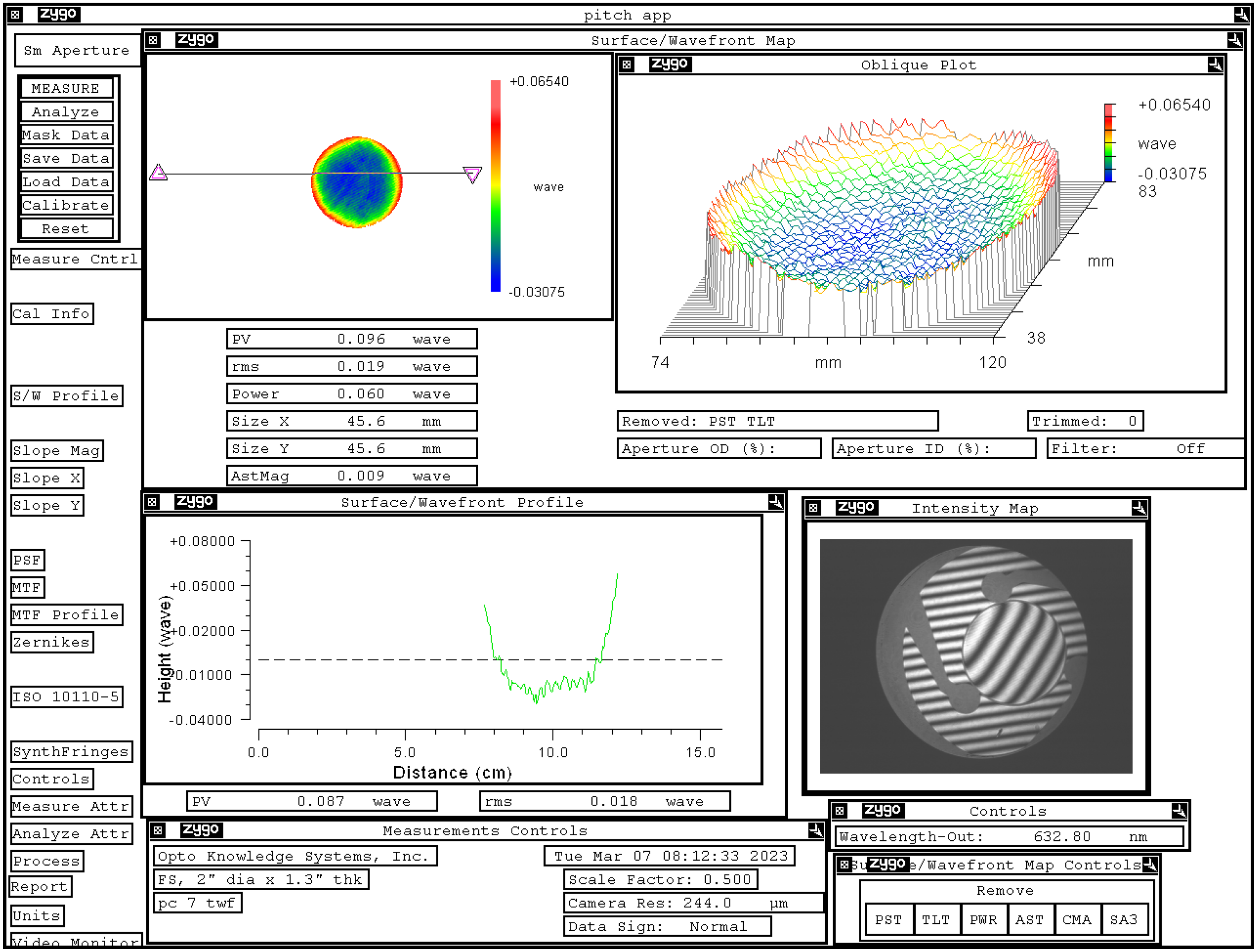


Figure A18. TWE Interferogram for 2-inch FS witness sample, SN07

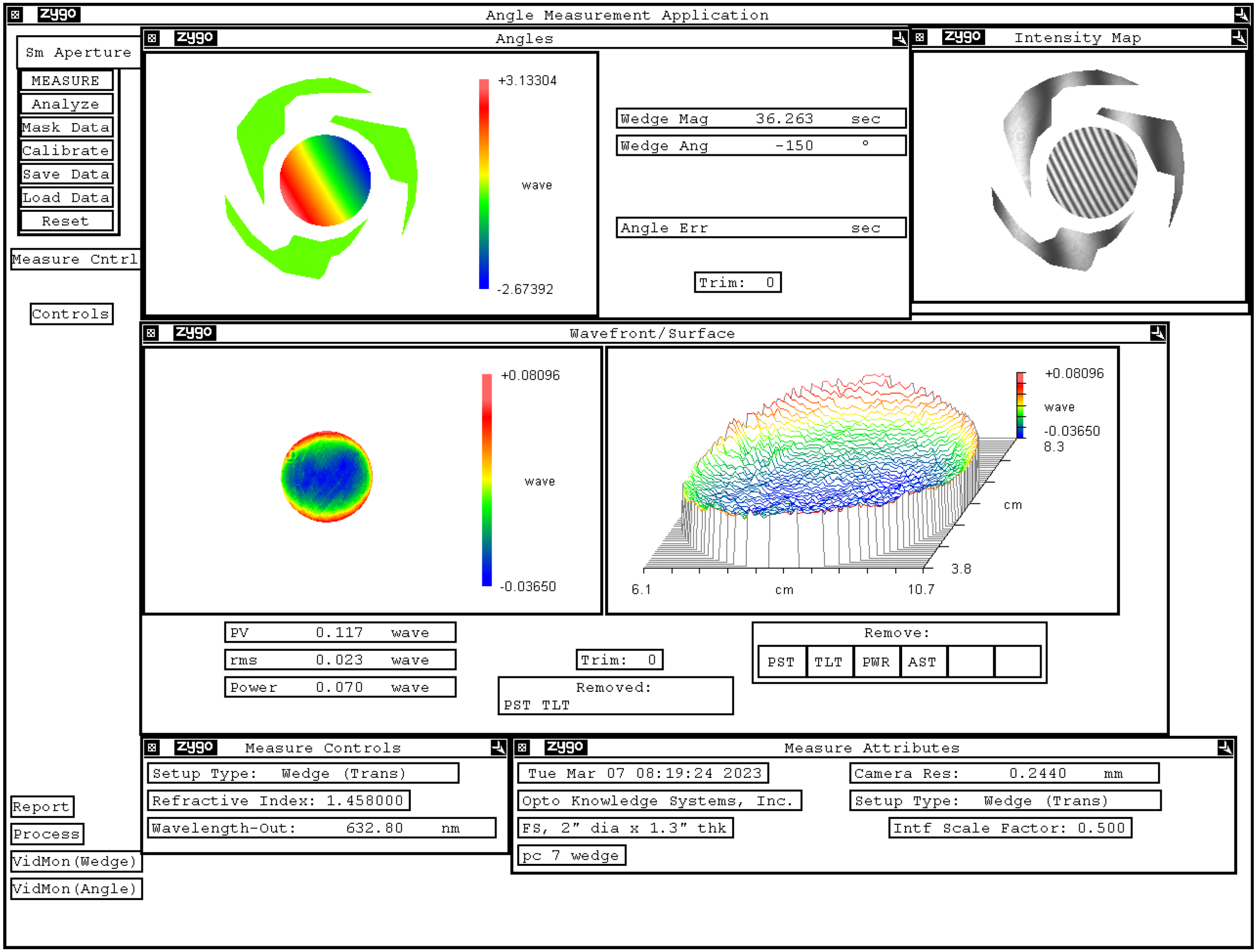


Figure A19. Wedge Interferogram for 2-inch FS witness sample, SN07