Understanding the PV Specification

Introduction

An array of non-standard, arbitrary practices are frequently used in the optics industry to demonstrate conformance of a part to the traditional peak-to-valley (PV) specification. Some of these practices include filtering, trimming, masking, and spike removal. The problem with any of these techniques is that they are time consuming and the result lacks consistency between instruments and operators.

PVr is a new measurement result that significantly reduces the large variations that often occur when using PV. As a specification for optical surfaces PVr is independent of detector and operator differences, making it a robust specification that provides essentially the same result over a wide range of measurement conditions.

Defining Traditional PV

By definition, peak-to-valley is the height difference between the highest and lowest points after removal of nominal form (i.e., the best fit plane for a flat, best fit sphere, etc). The ISO Standard for "Preparation of drawings for optical elements and systems", ISO 10110 does not define use of standardized filtering. It also does not specify any minimum sampling. Using the ISO interpretation, the PV value should be reported as the PV of all the pixels that encompass the clear aperture of the optic. It is questionable whether this interpretation of PV is reasonable, reliable, and robust. With variations in metrology equipment, test conditions, and operator techniques, a consistent result must be established.

Problems with PV

A robust PV parameter would represent a reliable PV measurement that does not vary between different instruments having different spatial resolutions and different noise characteristics; but this is not the case with traditional PV. To understand just how significant this "measurement divergence" can be, the following example is from a paper by Kemp and Pantley from Alpine Research Optics.[1]

"...ARO purchased optics from several major catalog suppliers. The table lists the results of interferometric testing of a few of these samples, and highlights the need for obtaining proof of performance. In the worst case, an optic specified as λ/10 had an actual surface figure of only λ/5."

Refer to the table below.

- Traditional PV has limitations when used as a surface specification
- PVr overcomes the limitations, providing a robust specification providing the same result over a range of conditions.

Diameter	Substrate Material	Clear Aperture	Specified Surface Flatness	Measured Surface Flatness
2.000	BK-7	85%	λ/10	λ/9
2.000	BK-7	90%	λ/10	λ/5
2.000	UV Fused Silica	80%	λ/10	λ/8

Table 1: Comparison of samples using interferometric testing

Certainly, there are a number of possible sources of error in these measurements. PV is frequently increased erroneously by outliers and artifacts of the measurement which the metrologist is confident are not associated with the surface under test. Methods for removing those outliers from the measurement result are not standardized.

Manipulating PV

Note: All graphics referenced in this section are shown on the following pages.

For generations, opticians have performed implicit filtering when using test plates. Current practice throughout the industry is to apply judgment about edge effects, diffraction, ghosts, etc. PV specifications are commonly met by applying reasonable – but frequently undocumented and not standardized filtering, trimming, masking and spike removal. Removal of an on-axis hot spot up to 30 pixels in diameter is common practice.[3]

Traditionally, manipulation of the surface data occurs if the test part does not meet its PV specification. Typical adjustments to the result begin with the trimming of diffracting edge pixels. Then, if an on-axis bulls eye is driving PV, it is masked out. Next dirt and defects caused by forward propagation or artifacts in the interferometer are masked. All of these steps are reasonable but arbitrary. A different operator will usually obtain a different result. A change to an interferometer with a higher or lower resolution camera will also produce a different result.

Interferometer software typically contains features that opticians can use to help pass PV specs. "Spike remove" is totally reasonable when the cut-off is set at 7.5 x rms, or perhaps lower, although 3X seems questionable[4]. The argument that polishing processes cannot leave spikes is reasonable, but does not extend to coated surfaces where a trapped dirt particle will likely exist.

Spike remove is designed for isolated pixels. Dirt and diffracting edges (including fiducials) can also drive PV. Another approach is the elimination of pixels by truncating the histogram of points. This approach has been formalized by some instrument manufacturers who offer PV based on a percentage of the histogram. Figure 5 shows surface data for an aplanat, and Figure 6 is a histogram of heights.

Evaluating PV by truncation of the histogram requires some agreement as to how the truncation should be performed. Applying judgment to the data of Figure 4, one might determine that a small number of on-axis points (hot spot?) drive the "Valley,"and these points should be removed. Again, this is reasonable but arbitrary. Automating truncation requires choices: remove an equal number of pixels from either side of the histogram, or equal heights? Figure 5 shows the change in PV with equal height truncation until 99.7% of points remain (+/-3 sigma for a normal distribution, which this is not).

Introducing PVr

PVr is a newly defined parameter[2] that is related to imaging and is robust over a range of instruments. Briefly, PVr for circular apertures is defined as:

$$PVr = PV_{36\ Zernikes} + 3 \times \sigma_{36\ ZernikeResid} \tag{1}$$

where the first term in Equation (1) is the PV of the surface generated using the 36 term Zernike fit to to the data and the second term is 3 times the rms of the residual after fitting and removing the 36 terms.

Example 1 – 12-inch Flat

Figure 1 shows data for a 12 inch flat measured at ZYGO. The measured PV is 126 nm, driven by some obvious outliers. Figure 2 shows the result of an experienced metrologist performing the typical "clean-up" of outliers. The metrologist spent some time masking and removed ~1% of the data, to reach a PV of 32 nm (~λ/20). The PVr application in ZYGO's MetroPro software calculates a PVr from the initial measurement of PVr 23.6 nm, with ~0.1% of the data points excluded from the range of PVr.

In reviewing the data summary chart, it is obvious that the use of the PVr result provides significantly more surface data and therefore provides a more valid representation of the actual surface. Notice that the PVr calculation retains more than 25X more data points than the manually manipulated result.

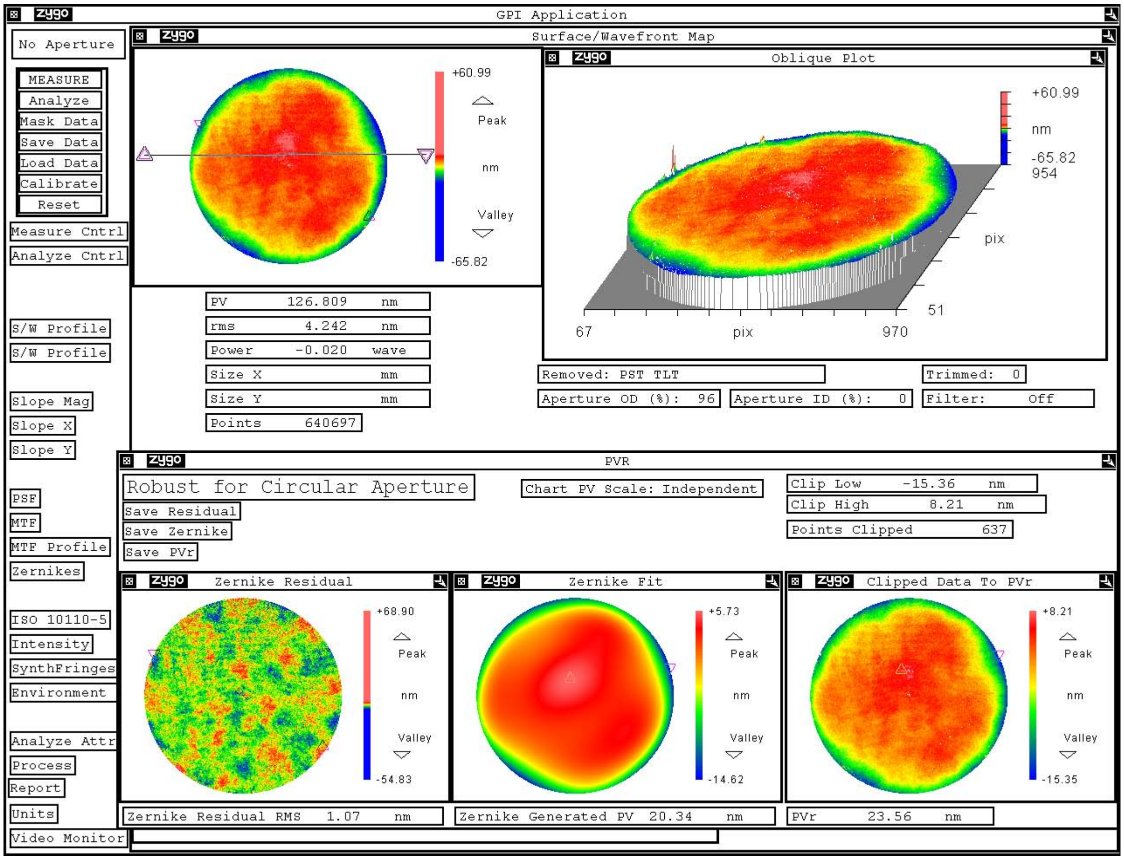
Example 2 – the λ/40 wave surface

The data shown in Figure 3 is for an optic with a λ/40 specification (that ZYGO purchased). Figure 3 shows the ~300 x 300 pixel test data (in black and white) that was shipped with the part from the vendor. The surface was measured at ZYGO using a ball-averaging absolute test (Figure 4). Simply using PV, this is a ~ λ/20 surface (31 nm); PVr is less than 10 nm, and the part would pass the PV specification of 15 nm with a 4 sigma spike removal or a 3x3 low pass averaging filter.

Conclusion

While PV has historically been used for surface specification in the optics industry, it is a parameter without clearly defined standards. The PV result is directly affected by detector size, system noise, and operator variability. Adjustments or corrections for any of these considerations involves some degree of subjectivity, making PV a less than ideal choice for surface specification.

PVr has been proven to demonstrate excellent correlation of measurements made by different users on different systems with a variety of camera resolutions. For this reason, ZYGO recommends the adoption of PVr as a surface specification for the majority of optical surfaces currently specified with PV.



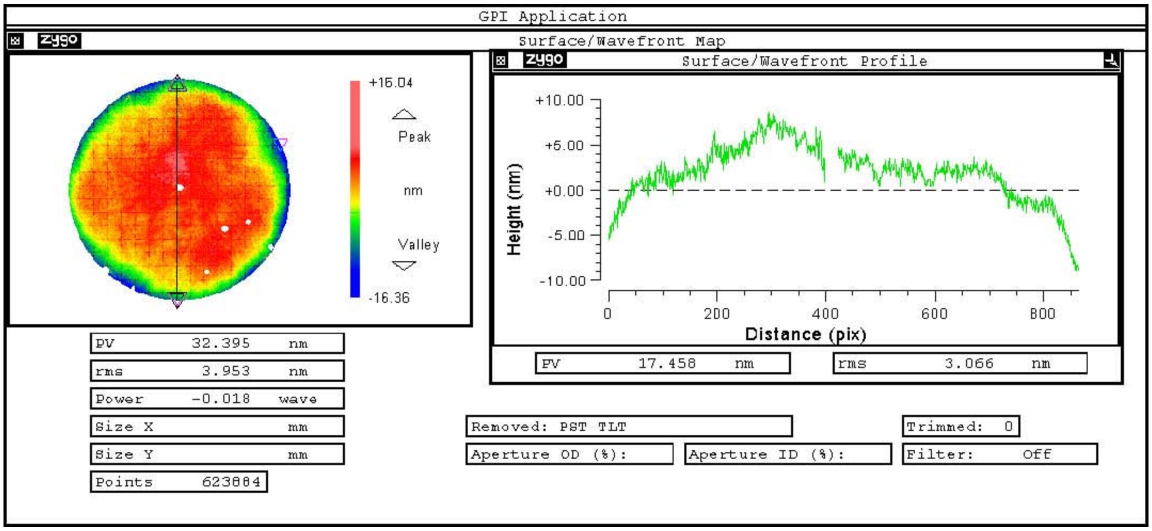
PV 126.809 nm
rms 4.242 nm
Power -0.020 wave
Size X mm
Size Y mm
Points 640697

Removed: PST TLT
Trimmed: 0
Aperture OD (%): 96
Aperture ID (%): 0
Filter: Off

Robust for Circular Aperture
Chart PV Scale: Independent
Clip Low -15.36 nm
Clip High 8.21 nm
Points Clipped 637

Zernike Residual RMS 1.07 nm
Zernike Generated PV 20.34 nm
PVr 23.56 nm

Figure 1: ZYGO measurement of a 12 inch flat.



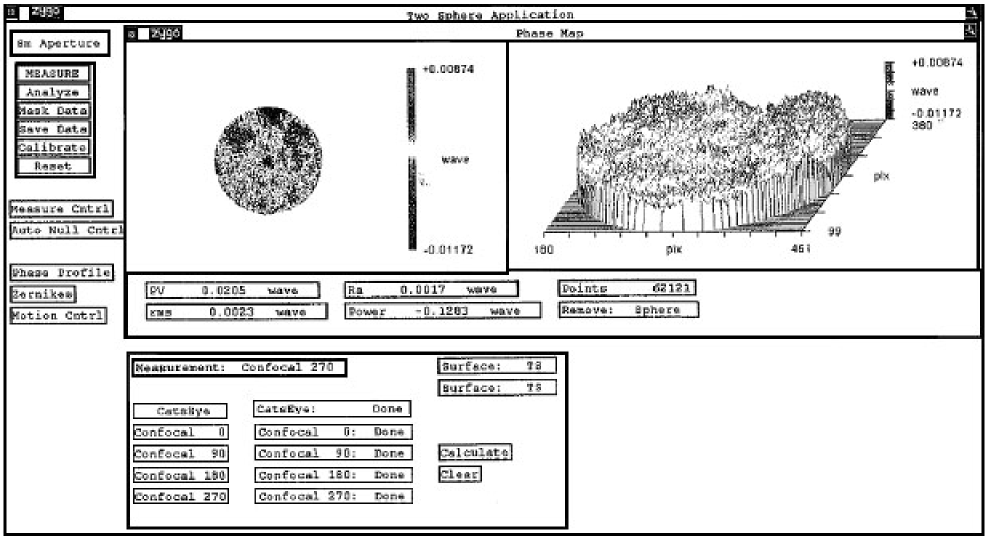
PV 32.395 nm
rms 3.953 nm
Power -0.018 wave
Size X mm
Size Y mm
Points 623884

PV 17.458 nm
rms 3.066 nm

Removed: PST TLT
Trimmed: 0
Aperture OD (%):
Aperture ID (%):
Filter: Off

Figure 2: Manual masking of data of Figure 1.

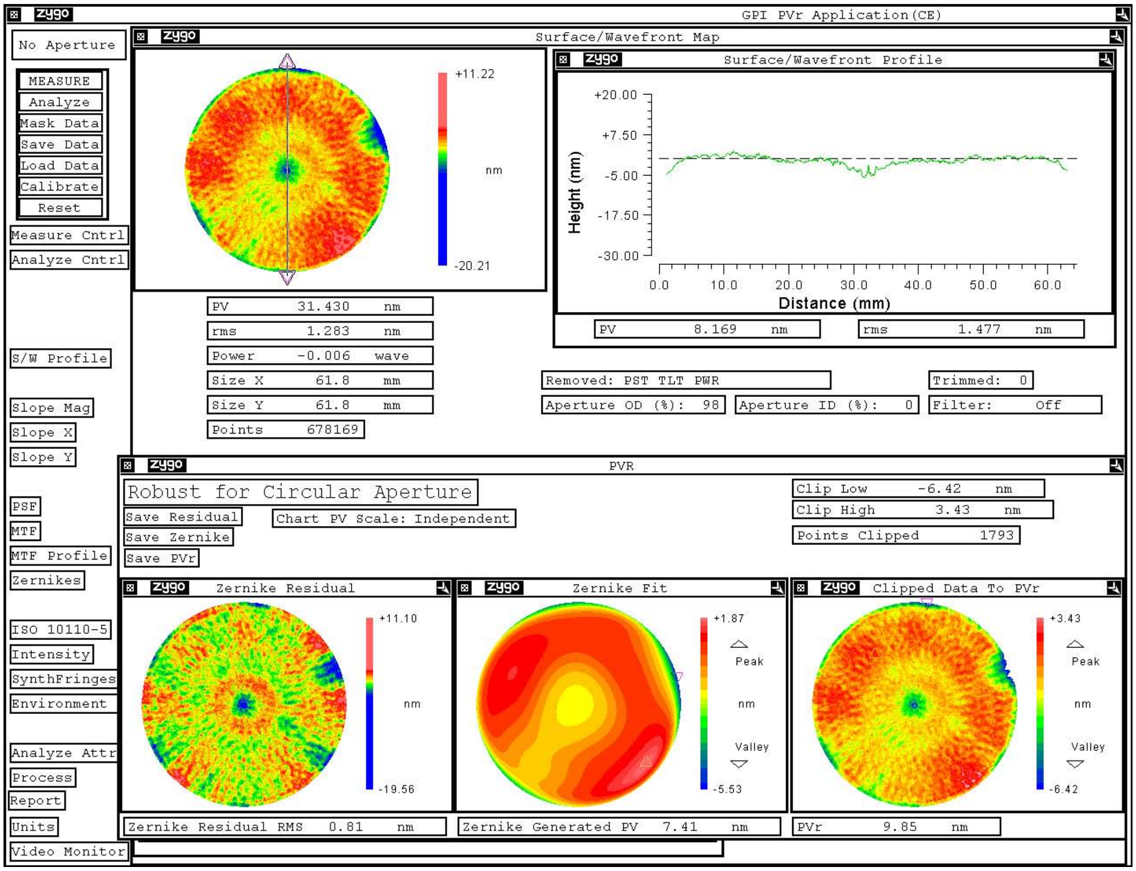
Measurement Method	Result	Number of Points
Direct – High Resolution	127 nm	640,697
Manual Adjustment (e.g. masking)	32 nm	623,884
PVr	24 nm	640,060



PV 0.0205 wave
rms 0.0023 wave
Ra 0.0017 wave
Power -0.1283 wave
Points 62121
Remove: Sphere

Measurement: Confocal 270
Surface: T8
Surface: T8
CatsEye: Done
Confocal 0: Done
Confocal 90: Done
Confocal 180: Done
Confocal 270: Done

Figure 3: Test data provided by vendor of λ/40 surface (62,121 points, PV = 13 nm).



PV 31.430 nm
rms 1.283 nm
Power -0.006 wave
Size X 61.8 mm
Size Y 61.8 mm
Points 678169

PV 8.169 nm
rms 1.477 nm

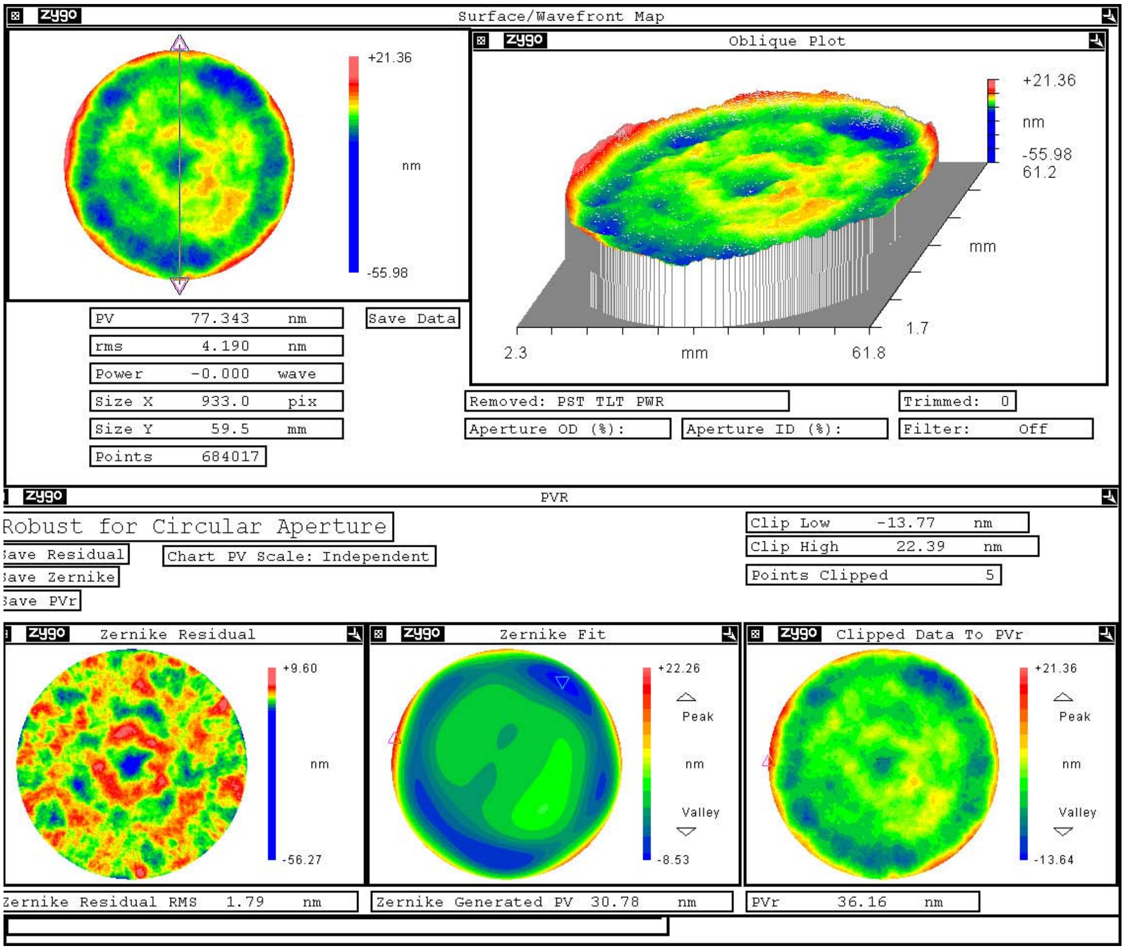
Removed: PST TLT PWR
Trimmed: 0
Aperture OD (%): 98
Aperture ID (%): 0
Filter: Off

Robust for Circular Aperture
Chart PV Scale: Independent
Clip Low -6.42 nm
Clip High 3.43 nm
Points Clipped 1793

Zernike Residual RMS 0.81 nm
Zernike Generated PV 7.41 nm
PVr 9.85 nm

Figure 4: PVr value for λ/40 surface

Measurement Method	Result	Number of Points
Direct – Low Resolution	13 nm	62,121
Direct – High Resolution	32 nm	678,169
PVr	10 nm	677,532



PV 77.343 nm
rms 4.190 nm
Power -0.000 wave
Size X 933.0 pix
Size Y 59.5 mm
Points 684017
Removed: PST TLT PWR
Trimmed: 0
Aperture OD (%):
Aperture ID (%):
Filter: Off

Robust for Circular Aperture
Chart PV Scale: Independent
Clip Low -13.77 nm
Clip High 22.39 nm
Points Clipped 5

Zernike Residual RMS 1.79 nm
Zernike Generated PV 30.78 nm
PVr 36.16 nm

Figure 5: Surface Data for an Aplanat

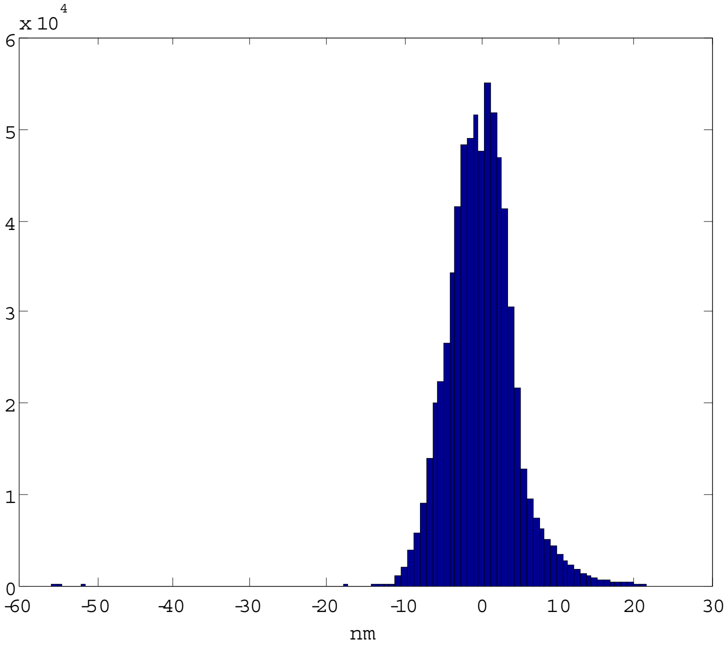


Figure 6: Histogram for the data of Figure 5.

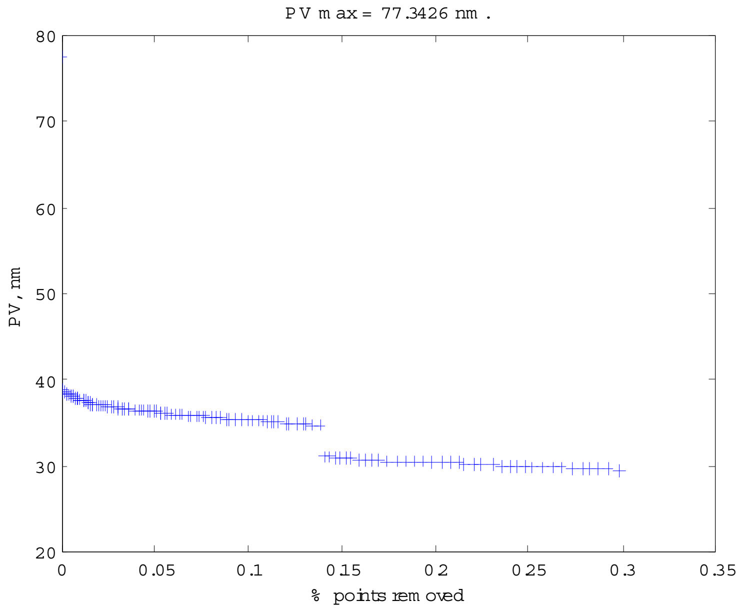


Figure 7: Data of Figure 5 truncated in equal height increments

References

1. Laser Focus World, August 2003; also available from the ARO web site
2. See Evans, C. "Robust Estimation of PV for Optical Surface Specification and Testing" Optical Fabrication and testing Workshop (OSA), paper OWA4, October 2008; Evans, C. "PVr: a robust amplitude parameter for surface and wavefront specification" ASC-OP1 Standard Committee, January 20, 2008;
3. There are reports of users defocusing an interferometer to get what they believe to be the "true" PV of the surface under test. This is not recommended.
4. Optical surfaces are not expected to be a good fit to a Gaussian, although they may not deviate by too much. Assuming a Gaussian, a real surface height 3 times the rms of the surface is not unexpected.

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