Measuring surface slope errors on precision aspheres

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When is it important for an optical designer to control slope errors? (what types of optical systems?)

- Laser radar transmitters that project laser beams into far field rely on a tight point spread function
- High Energy Laser Systems that focus the energy into as small a spot as possible at the highest possible fluence
- UV systems where mid-spatial frequency errors (ripple) degrade image quality
- Grazing incidence optics

How should you specify surface slope error?

ISO 10110 is silent about how to quantify or measure surface slope errors

ISO 10110 Part 5 has 25 pages on surface form tolerances and part 12 has 10 pages on defining aspheric surfaces, but neither mentions how to define a surface slope tolerance

What units should be used to specify slope error?

- Waves per cm?
- Waves per inch?
- Radians? Milliradians? Microradians?
- Degrees?

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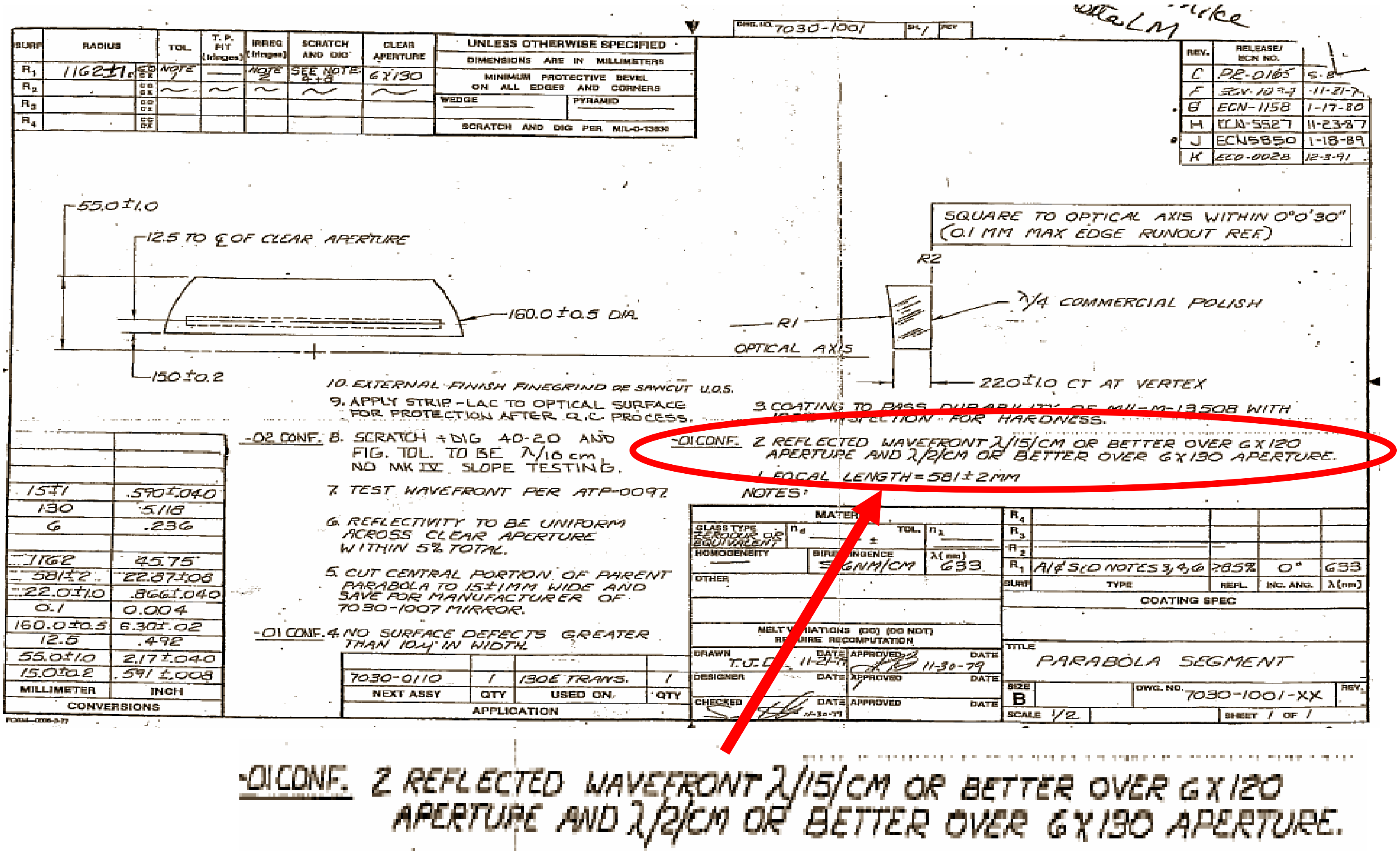
Example 1 - Laser dimensional gauging instrument



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Examples #2
Satellite instrument mirrors
85 x 75 mm off-axis aspheric (oblate spheroid) mirror

3.3.3 Surface Figure: Surface 1 shall have a surface figure error of ≤ 0.1λ rms over the entire clear aperture measured at or converted to 632.8nm. Surface slope errors shall be ≤ 5 E –5 radians over the entire clear aperture.

180 mm diameter parabolic mirror

3.3.3 Surface Figure: Surface 1 of [redacted]) shall have a surface figure error of ≤ 0.05λ rms measured at or converted to 632.8nm over the entire clear aperture as noted on **Sheet 3.** [redacted] ([redacted], and [redacted]) shall have a surface figure error of ≤ 0.05λ rms measured at or converted to 632.8nm over the entire clear aperture as noted on **Sheets 4**. Surface slope errors for all mirrors shall be ≤ 5 E –5 radians over the entire clear aperture.

No indication of the spatial frequencies of interest

Example #3 - COSTAR optical prescription

Table IV. Anamorphic asphere requirements

Acronym	d01	d06	d02	d07
AHRS	1.173965 E-3 ±.25%	1.0330 - 1.0340	3.2470 E-7 ±1.0%	1.0395 - 1.0415
AFOS	1.660584 E-3 ±.25%	1.1310 - 1.1330	9.7435 E-7 ±1.0%	1.2330 - 1.2360
AFOC	1.709724 E-3 ±.25%	1.00265 - 1.00285	9.7845 E-7 ±1.0%	1.004 - 1.006

Acronym	Surface Figure	Surface Roughness RMS
AHRS	λ/100 RMS	< 10 Å
AFOS	λ/100 RMS	< 10 Å
AFOC	λ/100 RMS	< 10 Å

14-18 mm aperture

Notes:

$Z = d01\ (d06\ X^2 + Y^2) + d02\ (d07\ X^2 + Y^2)^2$ ACCOS V Format

All optics are concave

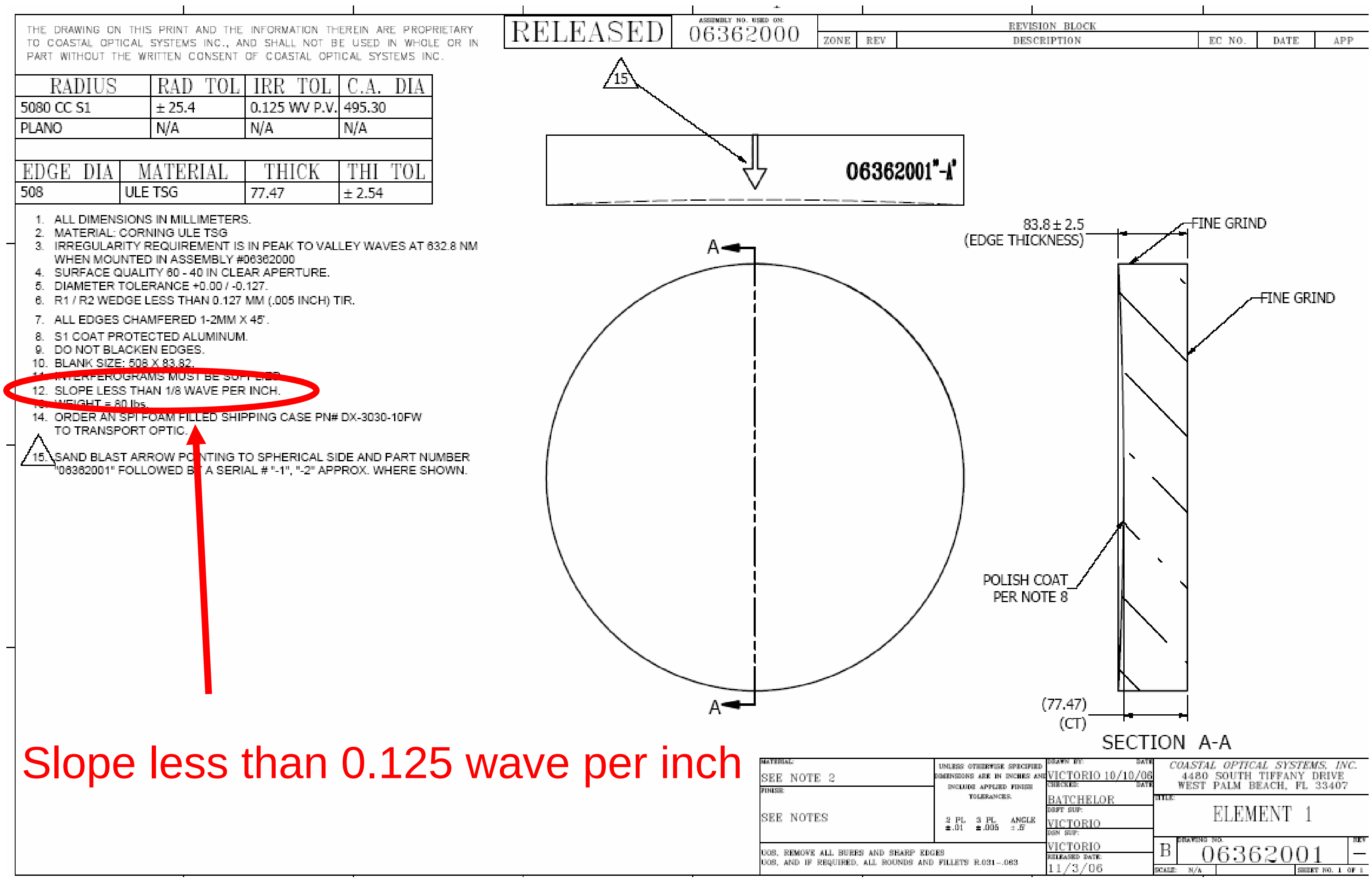
λ = .6328 mm

All surface errors are RMS waves

Surface Error Bandwidths

Surface Errors	Spatial Frequencies
Surface Figure	> 1 mm
Surface Roughness	< 1 mm

Example #4 - 0.5 meter (20 inch) diameter mirror



Slope less than 0.125 wave per inch

Example #5 - NIF Small Optics
Drawings control form, figure, rms slope, sampling and filtering[1]

Lambda/8 peak to valley

Lambda/40 rms

Lambda/30/cm RMS gradient

With these values evaluated for spatial periods greater than 2 mm only.

All interferometry must have a minimum of 200 pixels across the aperture

"Surface Figure and Roughness tolerances for NIF optics and the interpretation of the gradient, P-V wavefront and RMS specification", Lawson, Aikens, English, Whistler, House and Nichols, UCRL-JC-134534 presented in Denver, CO,July 1999

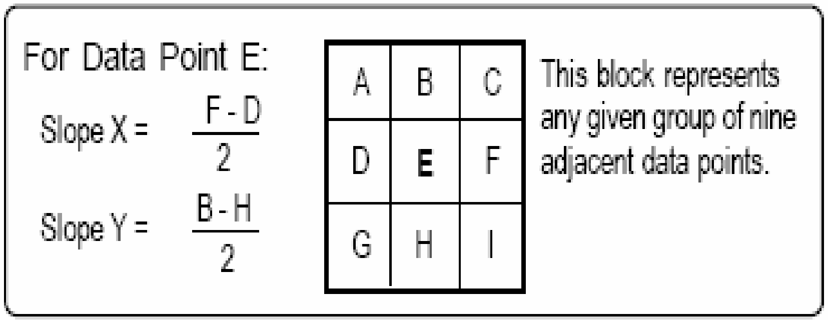
NIF small optics drawings also explicitly specify the filtering that should be used when using interferometers to evaluate surfaces

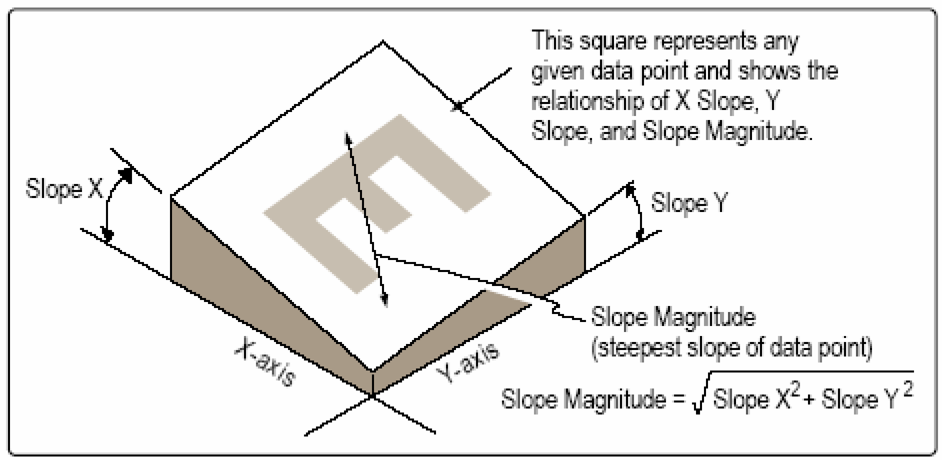
The wavefront error for individual optics is derived from the error budget permitted for the laser beam using system models. Specification for surface form as well as transmitted and reflected wavefront errors are applied. In particular, the RMS gradient of the wavefront error (RMS Gradient) is specified because it has the best correlation with the focusability of the beam. Because of the relationship between the spatial frequency of a given error and its effect on laser system performance, spatial filtering is applied (>2 mm). This approach is outside the framework of ISO 10110. Clarifications are provided where necessary. In addition, the surface form and wavefront specifications apply after coating in the use environment.

What metrology tools are used to measure surface slope of optics?

Instrument	Comments	Examples of commercial instruments
Contact profilometers	Profilometers typically measure surface topography (sag) and do not report slope	Taylor Hobson, Mititoyo and others
Shack Hartmann sensors	Wavefront sensors determine wavefront error through slope measurement	Wavefront Sciences and others
Phase measuring microscopes	Measure phase like a Fizeau interferometer, do not measure slope directly	Zygo New View 5000, ADE Phase Shift and others
Polarized topology optical scanning profilometers	Measure slope directly	Chapman Instruments
Fizeau Interferometers	Calculate slope from phase data	Zygo, ADE, 4D and others

How does an interferometer calculate slope?





From MetroPro Reference Guide OMP-0347J (figures used with permission)

Why is slope difficult to measure on aspheres?

Pupil focus problems on non-null cavities

Surface defects influence measurements on high-resolution interferometers

Environmental effects from long cavity lengths

Tilted apertures & surfaces under test

Slope measurements (like figure measurements) are strongly dependent on spatial sampling & filtering

Influence of pupil focus on non-null cavities

- f/3.3 focal ratio
- 3 phase averages
- No trim
- No filters
- 42 mm diameter

See Lowman and Greivenkamp "Modeling an interferometer for non-null testing of aspheres" SPIE 2536, p. 139 for mathematical model of the influence of aberrations of the pupil and definition of the pupil on test results

Extreme edge of surface has (real) zone of high slope (roll-off)

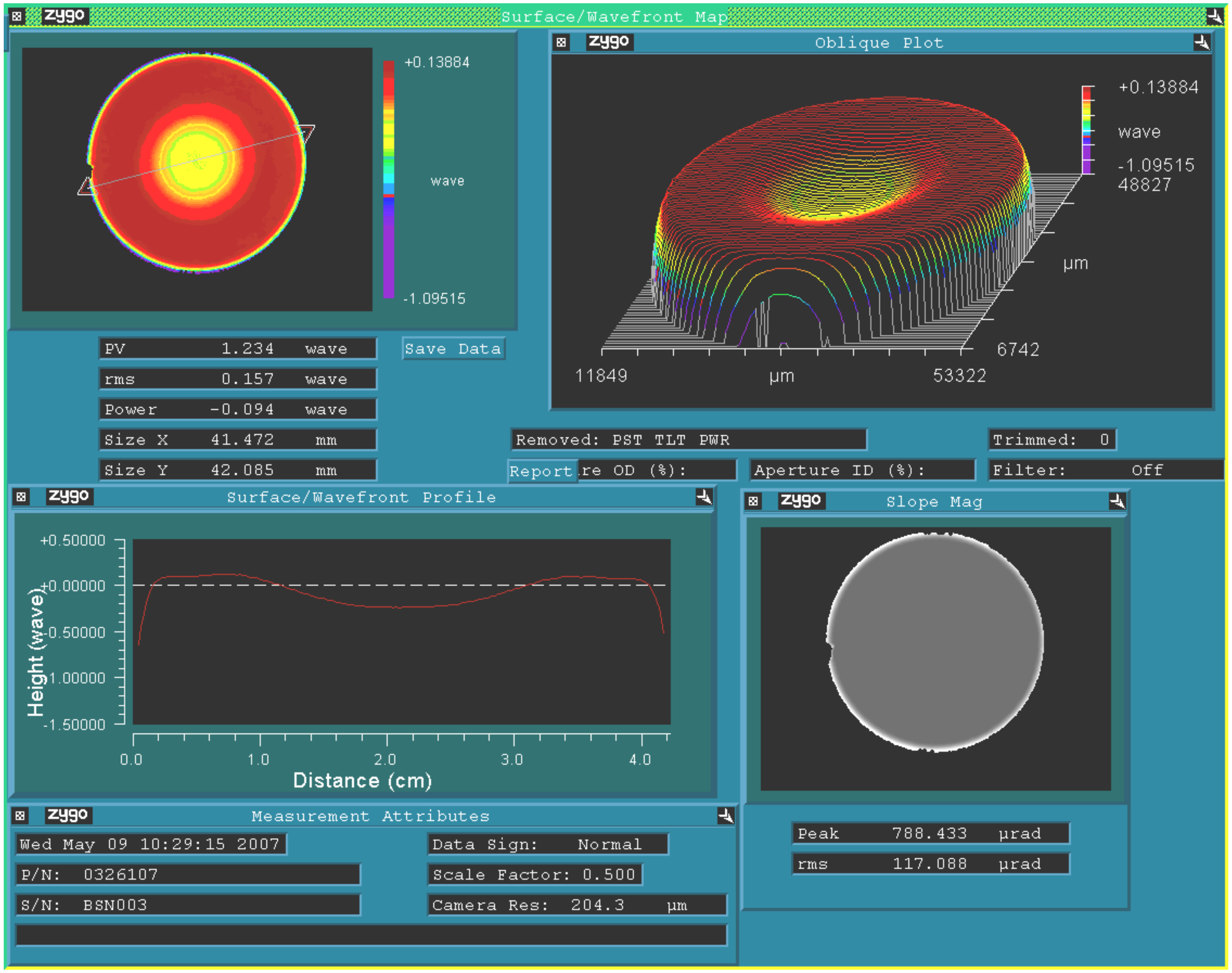
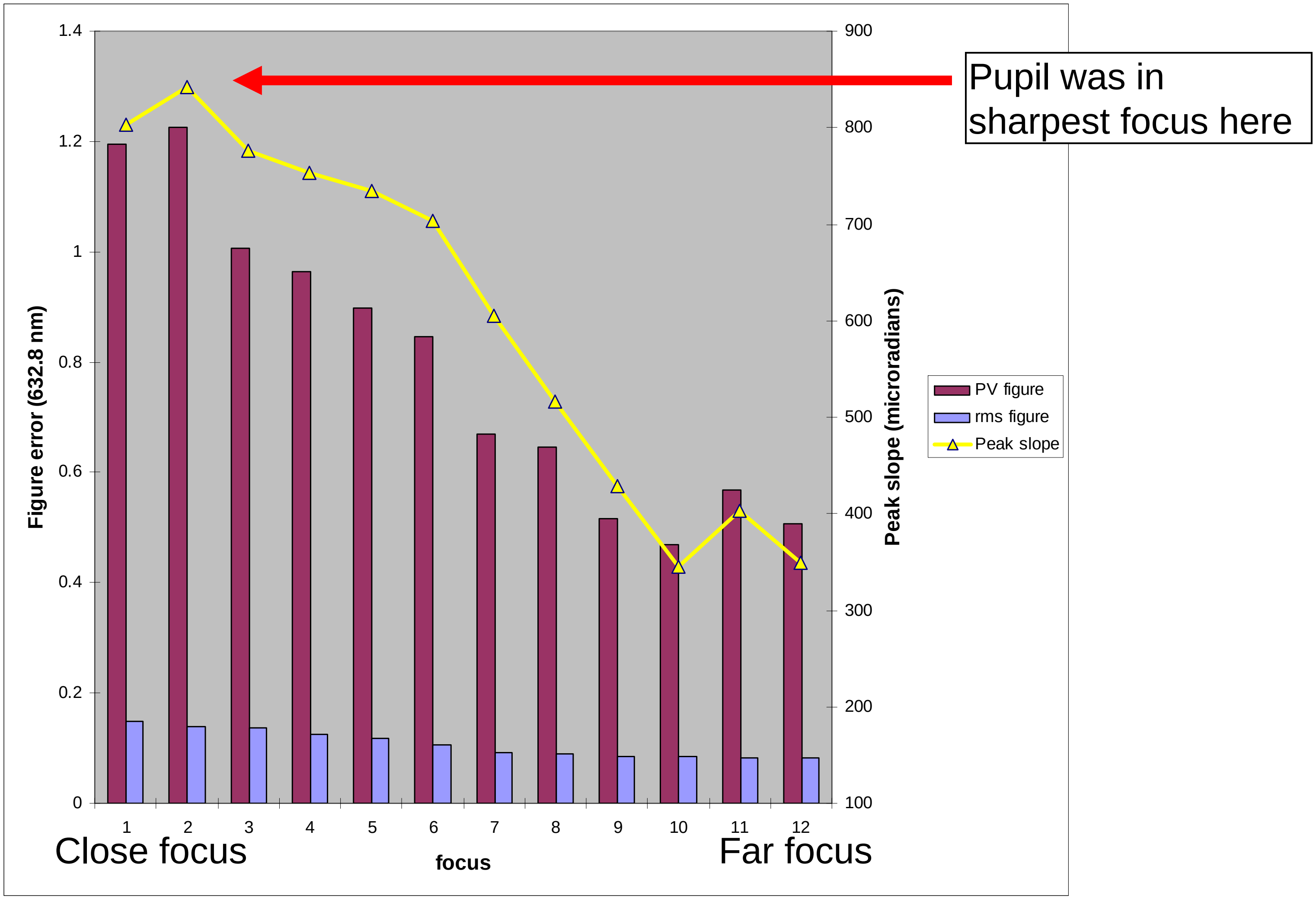
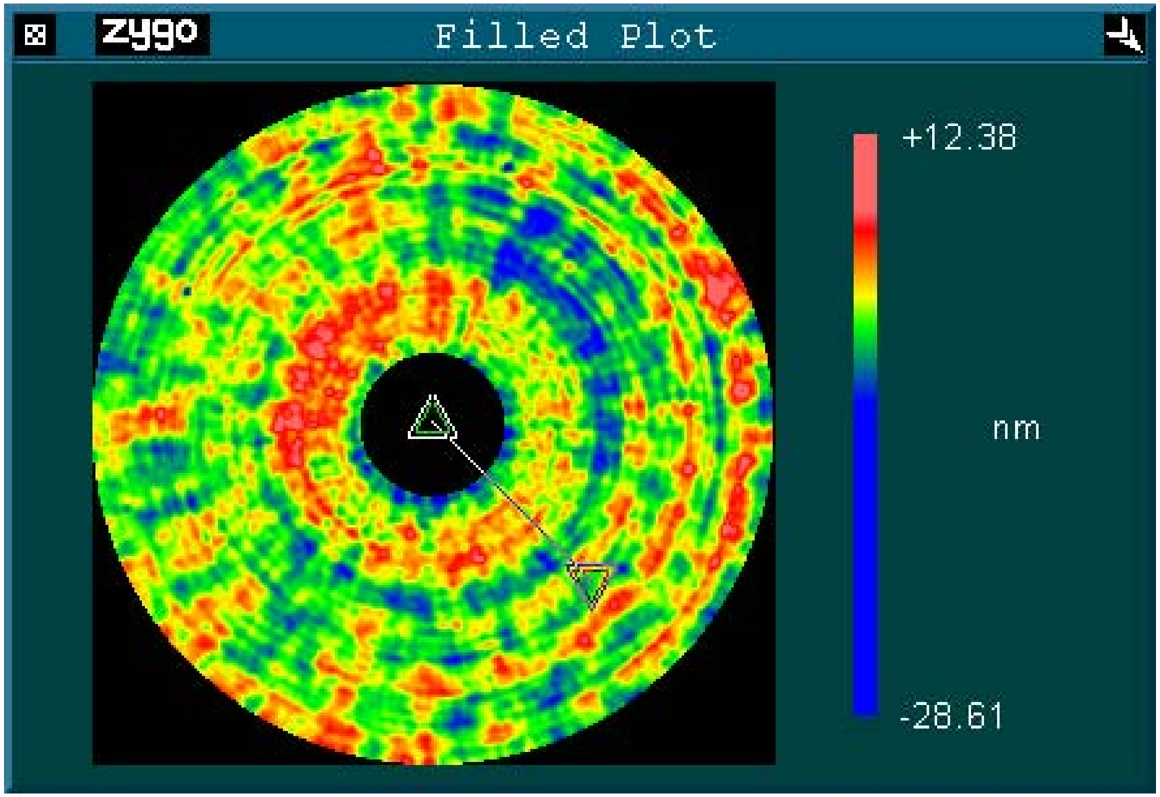


Figure Error and Peak Slope error as a function of pupil focus



Surface Defects influence slope on high resolution interferometers

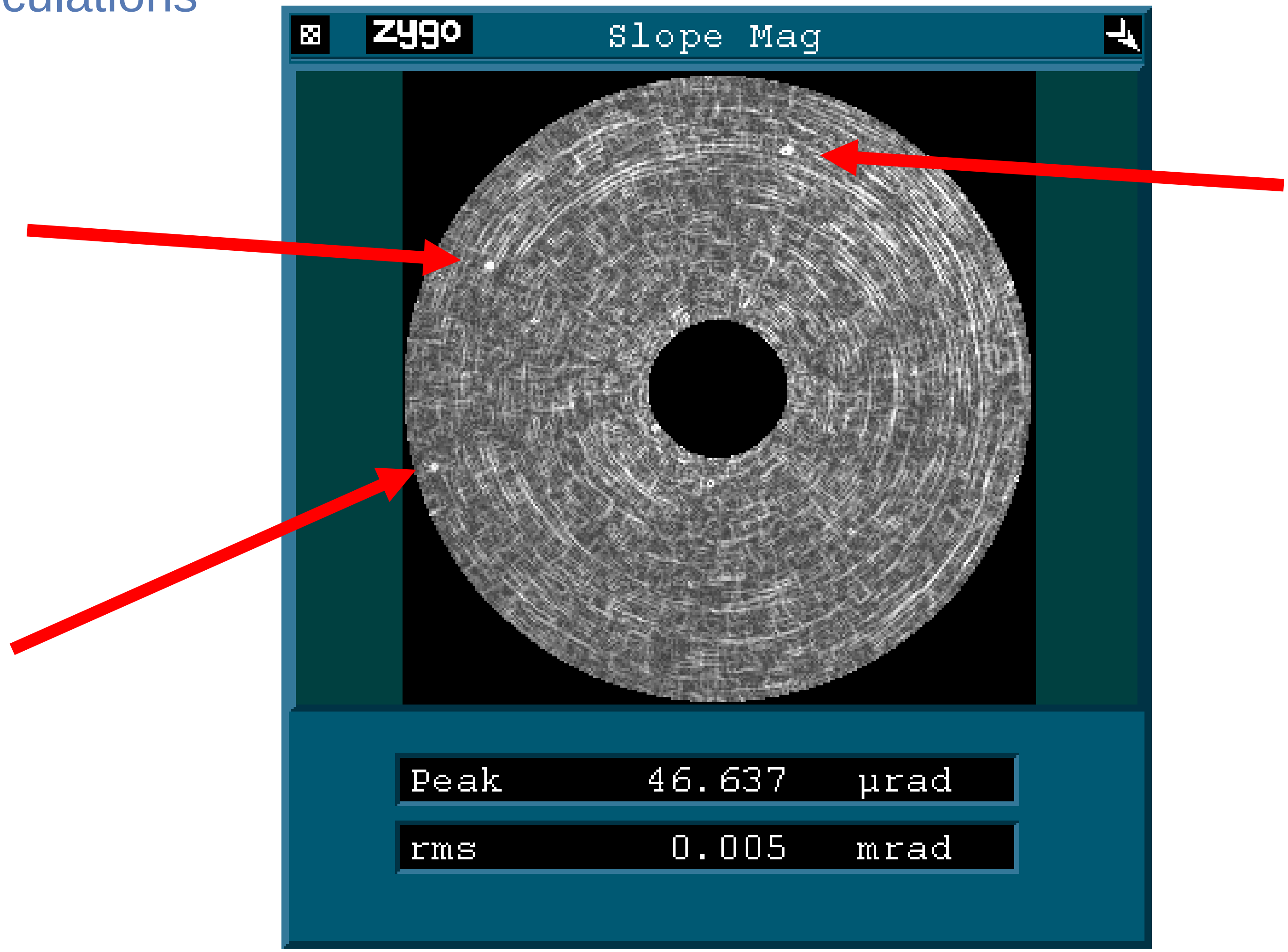


95 mm diameter convex parabolic mirror

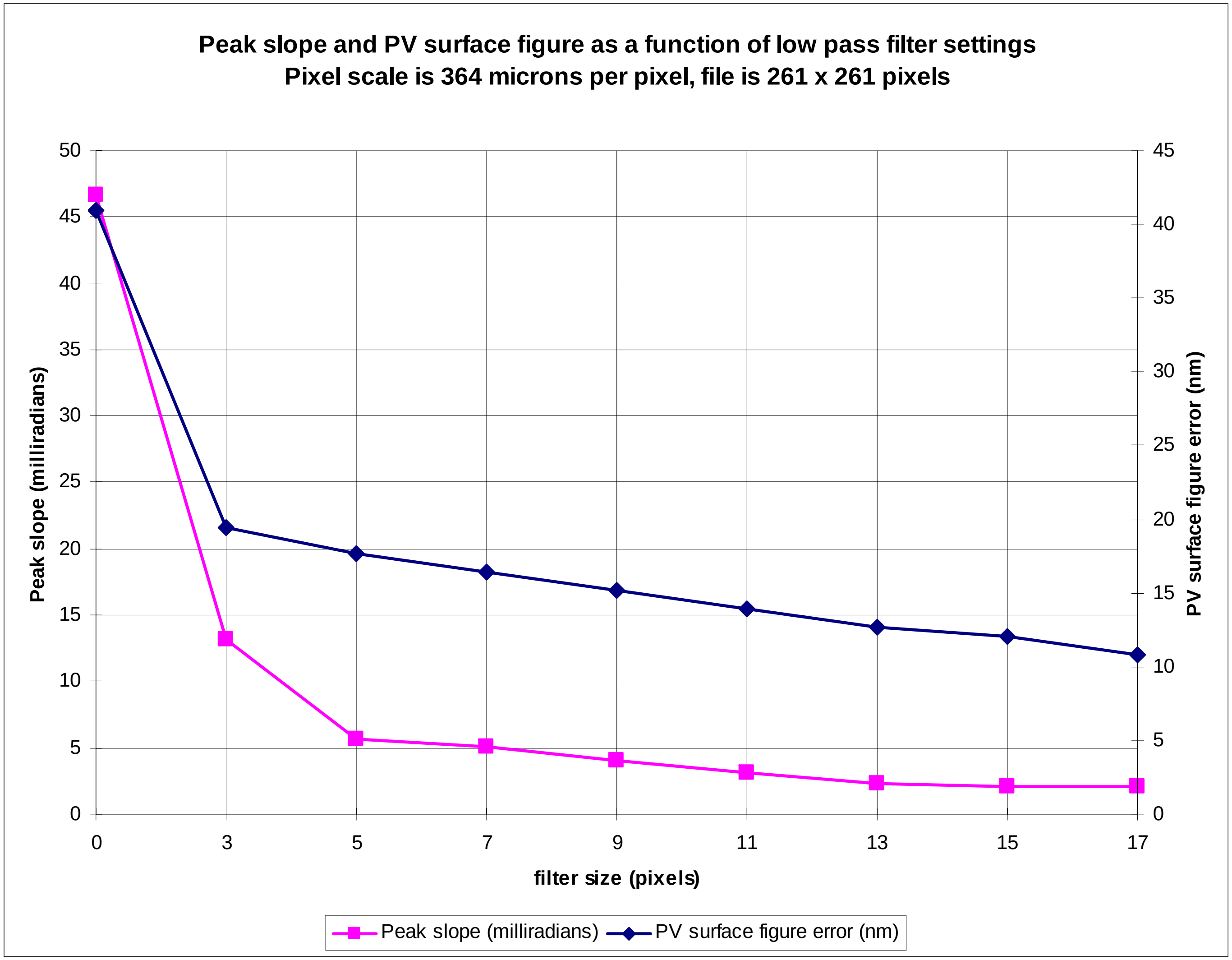
Measured on SSI-A with 1k x 1k camera

0.0647 wave peak to valley, 0.006 wave rms

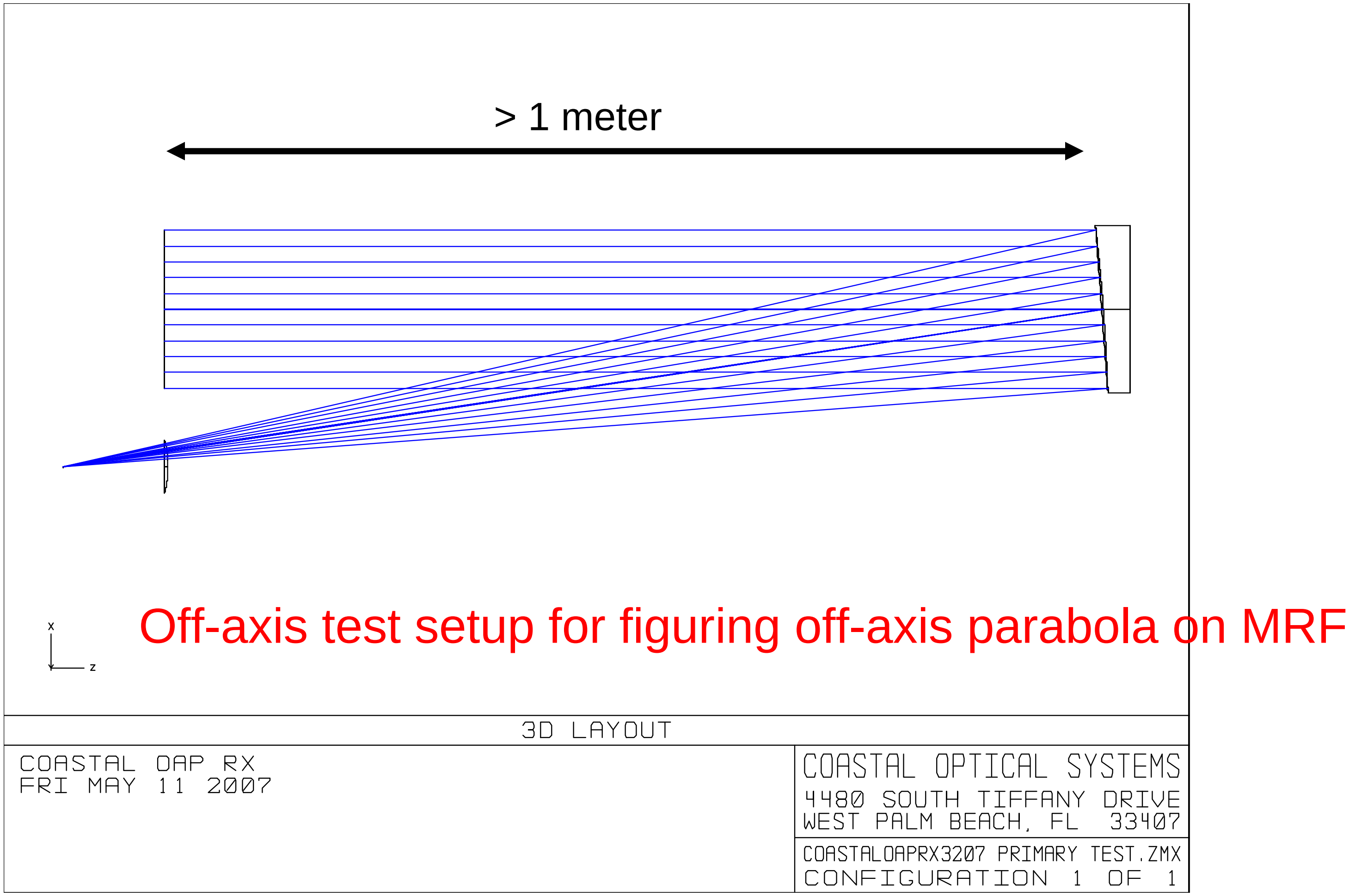
Surface defects or contamination on surface under test influence slope calculations



Using filtering to get any answer you want



Long cavities and tilted stops cause false focusing and field curvature



For further explanation, see Schillke, "Critical Aspects on testing aspheres in interferometric setups"

Example of insufficient spatial sampling – convex parabolic mirror

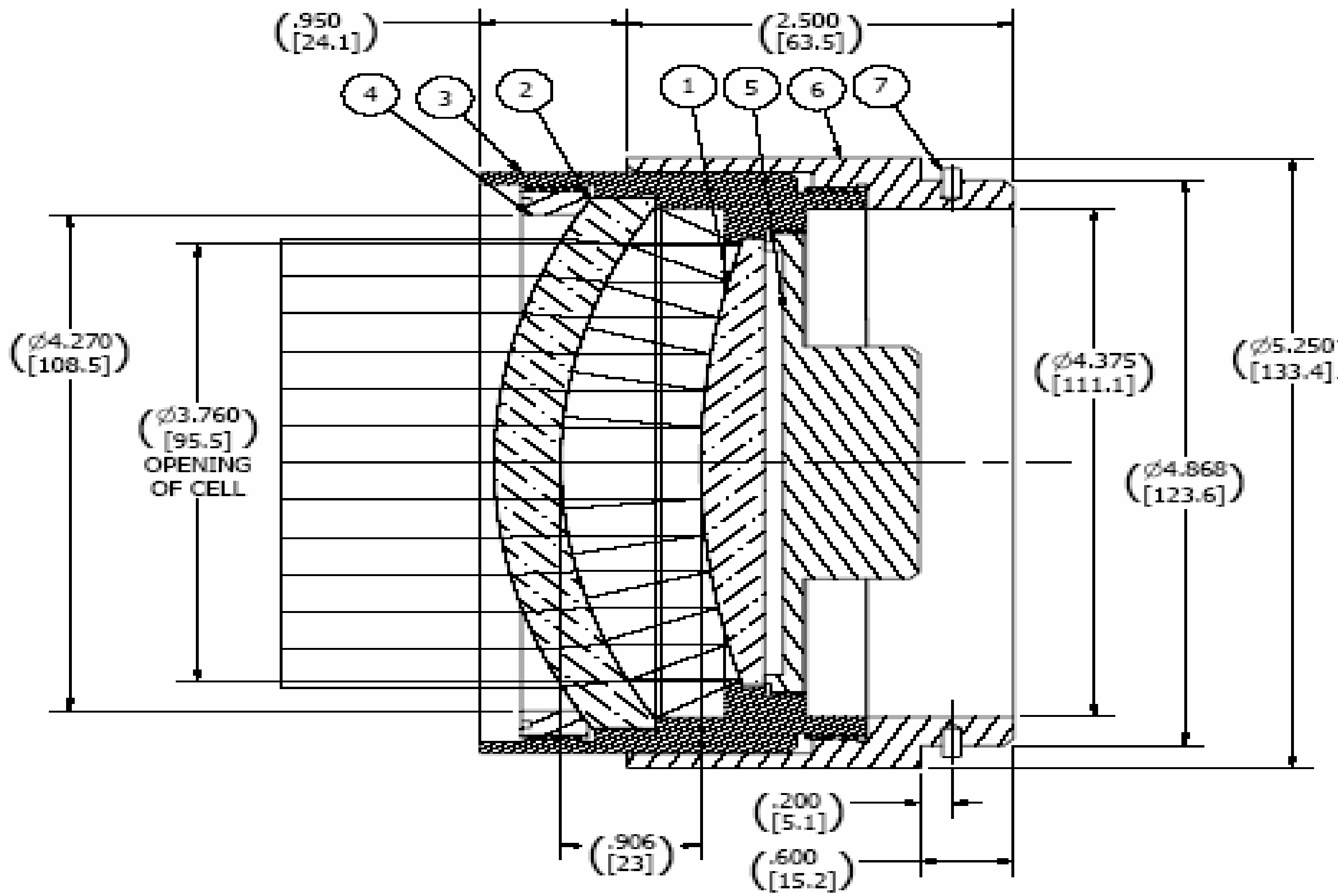
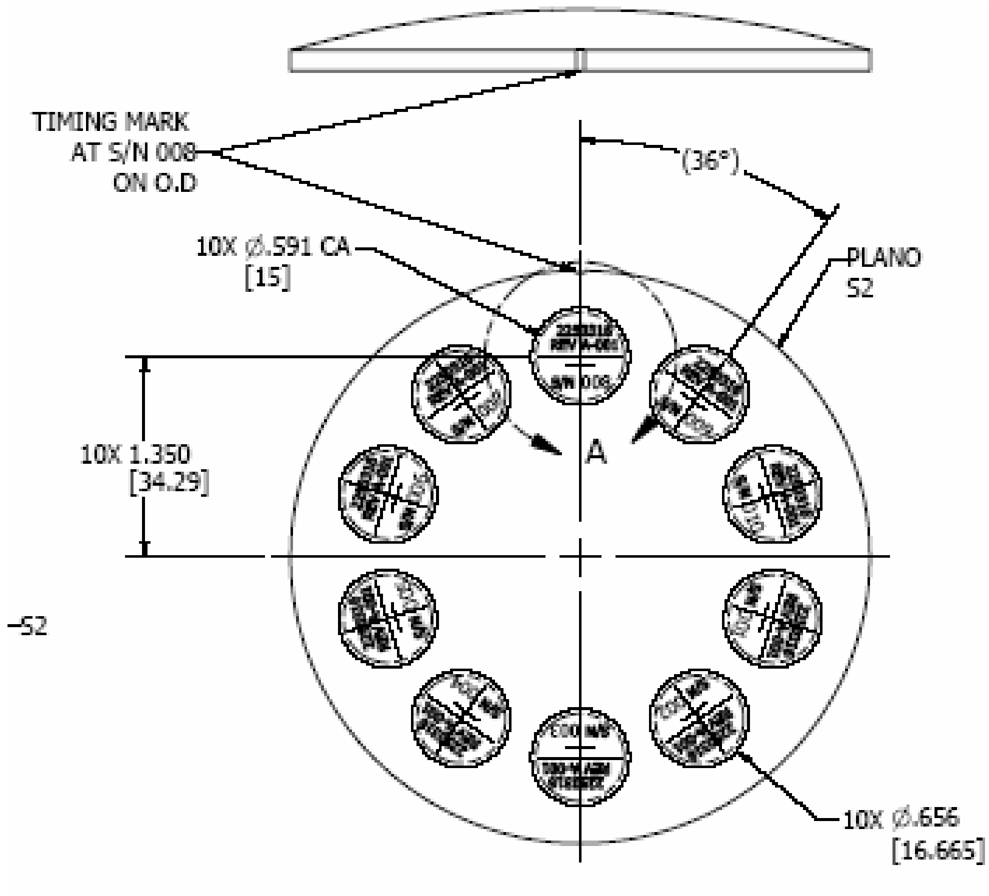
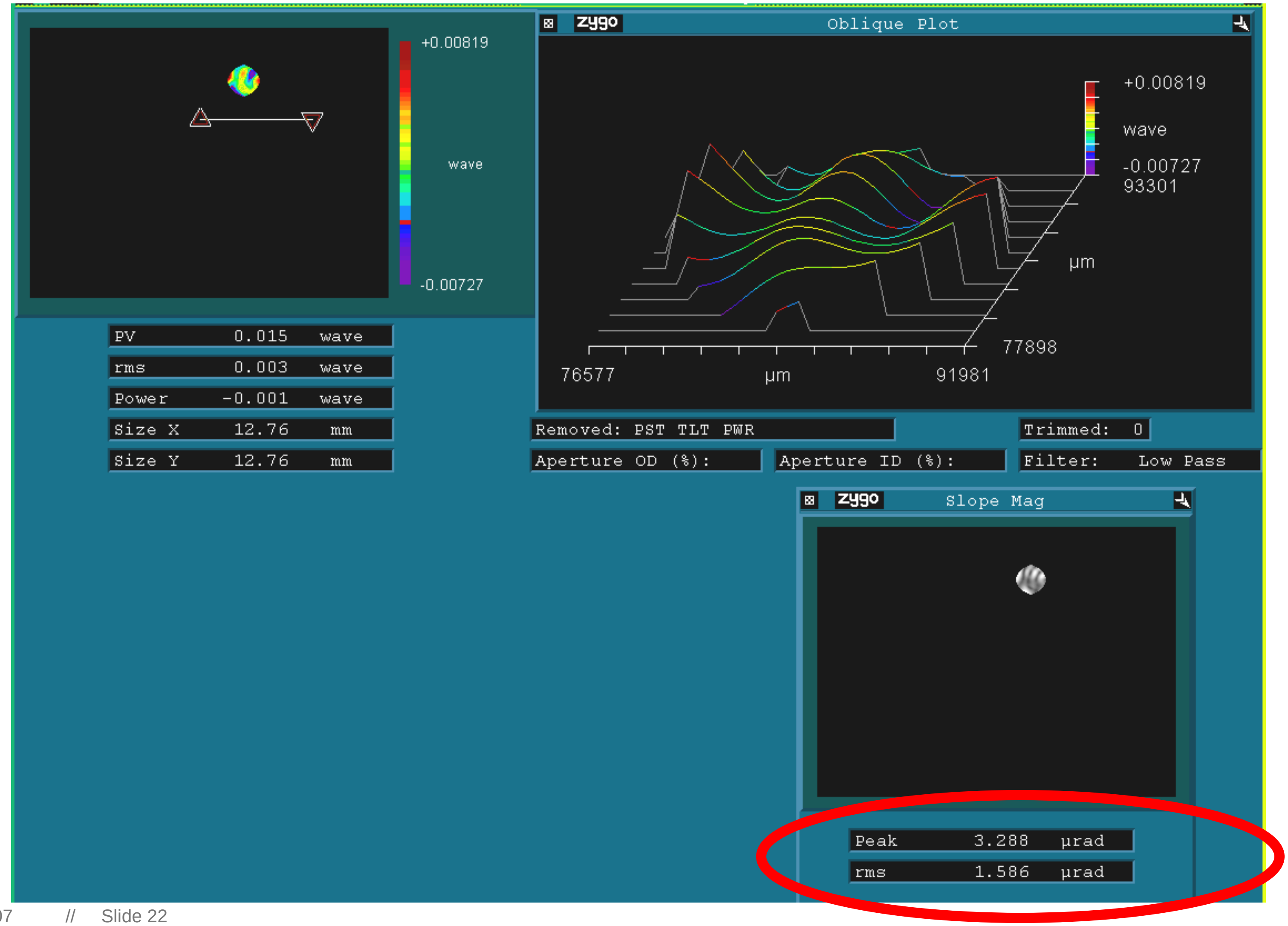


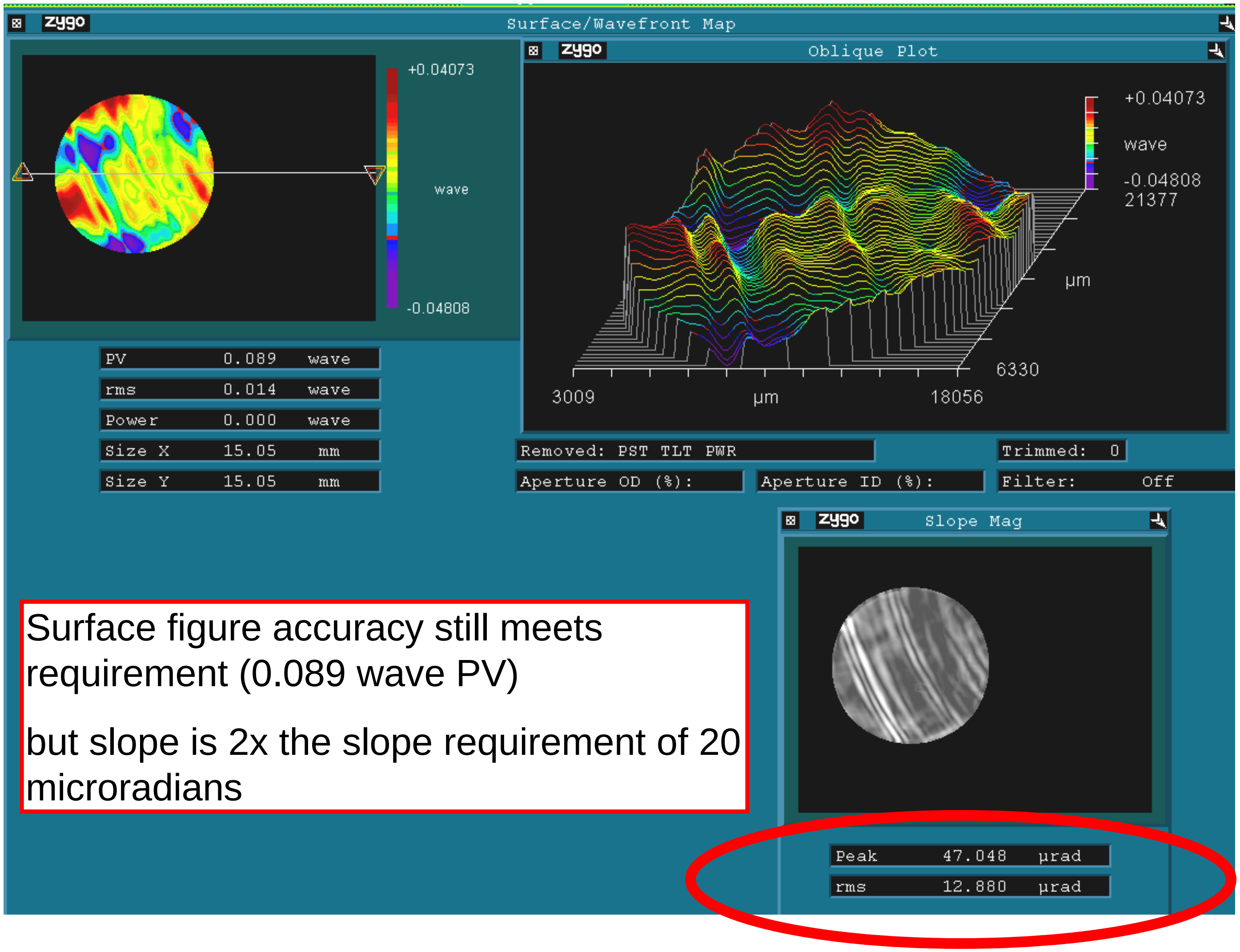
Figure and slope was tested moving cursors around parent



Sub-apertures were tested by moving software mask around the parent to the different locations



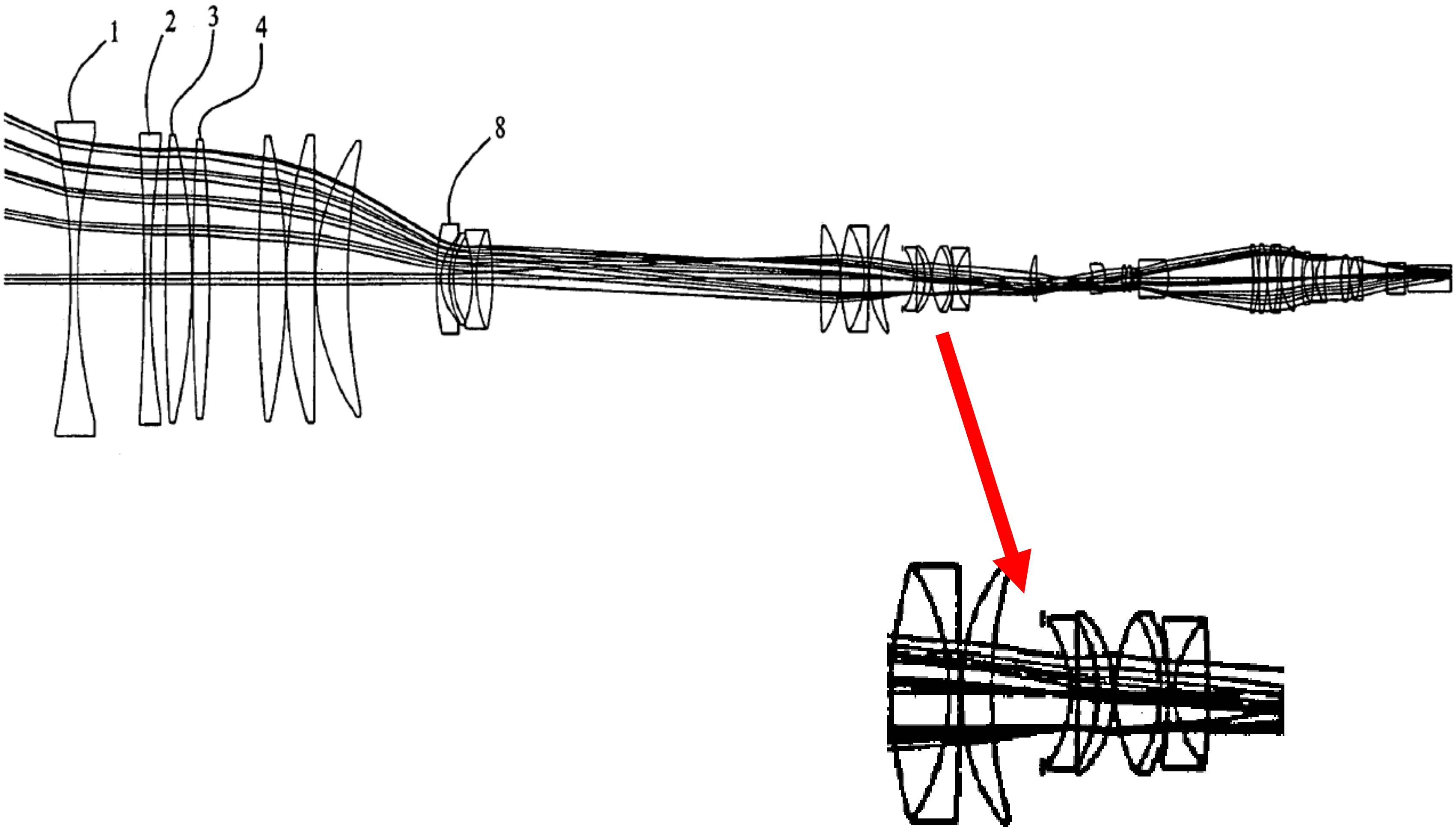
When tested individually, the off-axis segments showed slope error



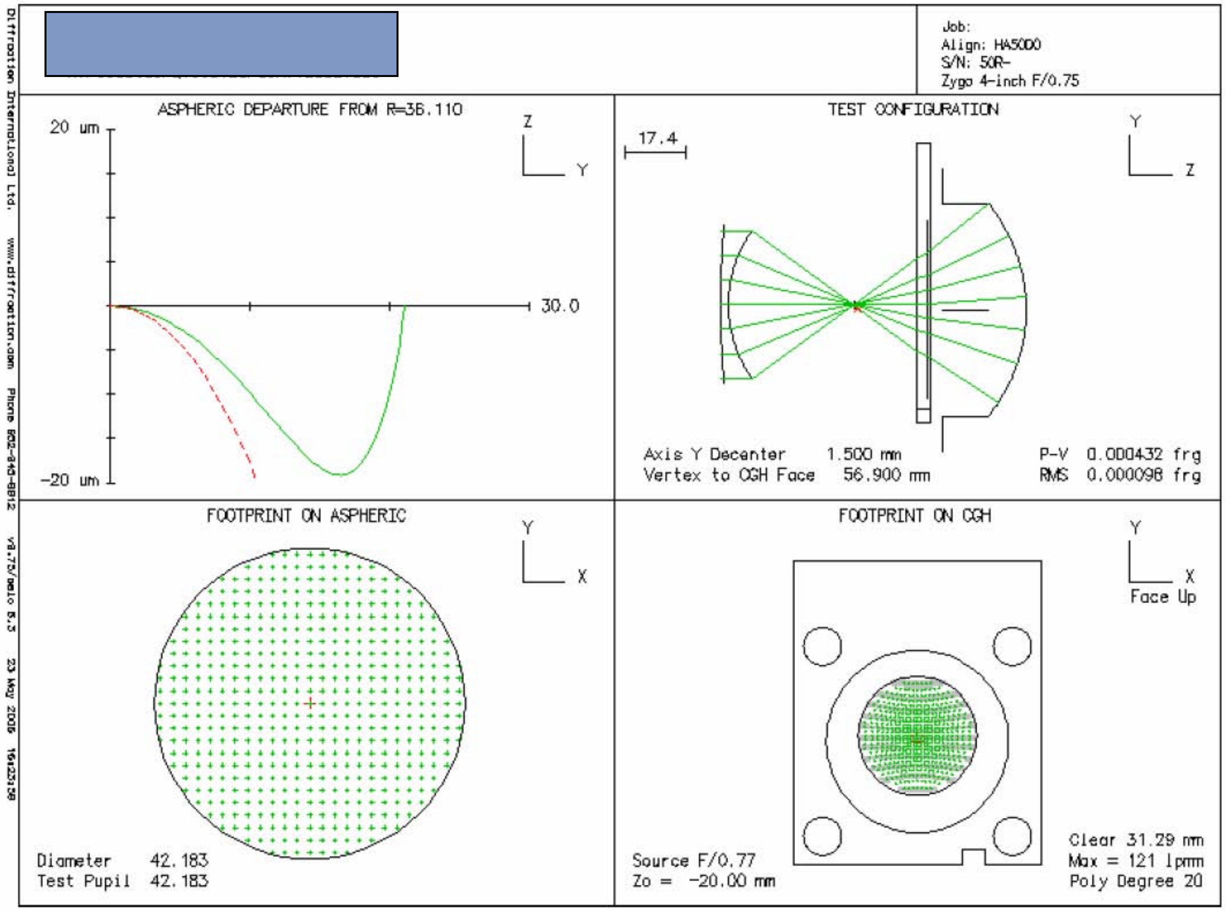
Surface figure accuracy still meets requirement (0.089 wave PV)

but slope is 2x the slope requirement of 20 microradians

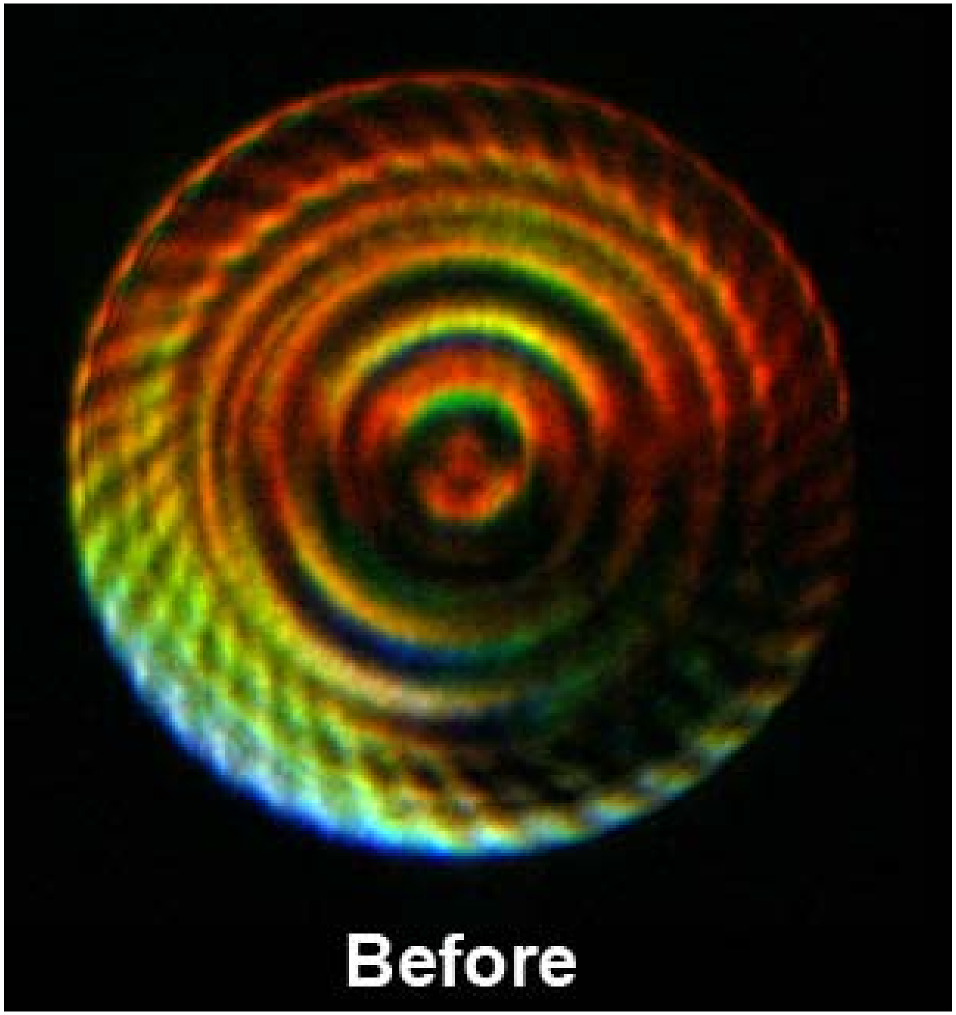
Large zoom system example



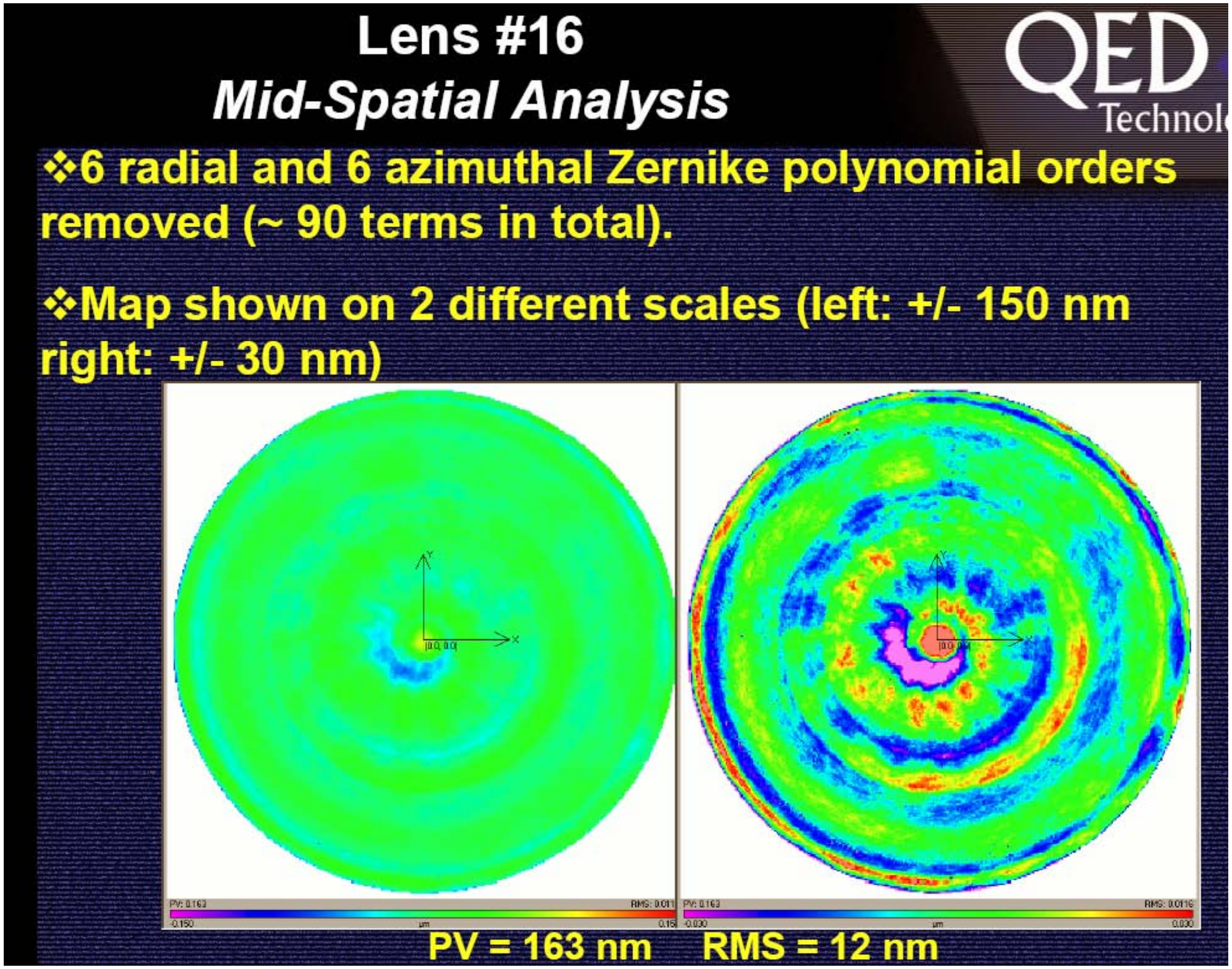
Higher order asphere R(best fit) = 36.11mm, 42 mm dia.



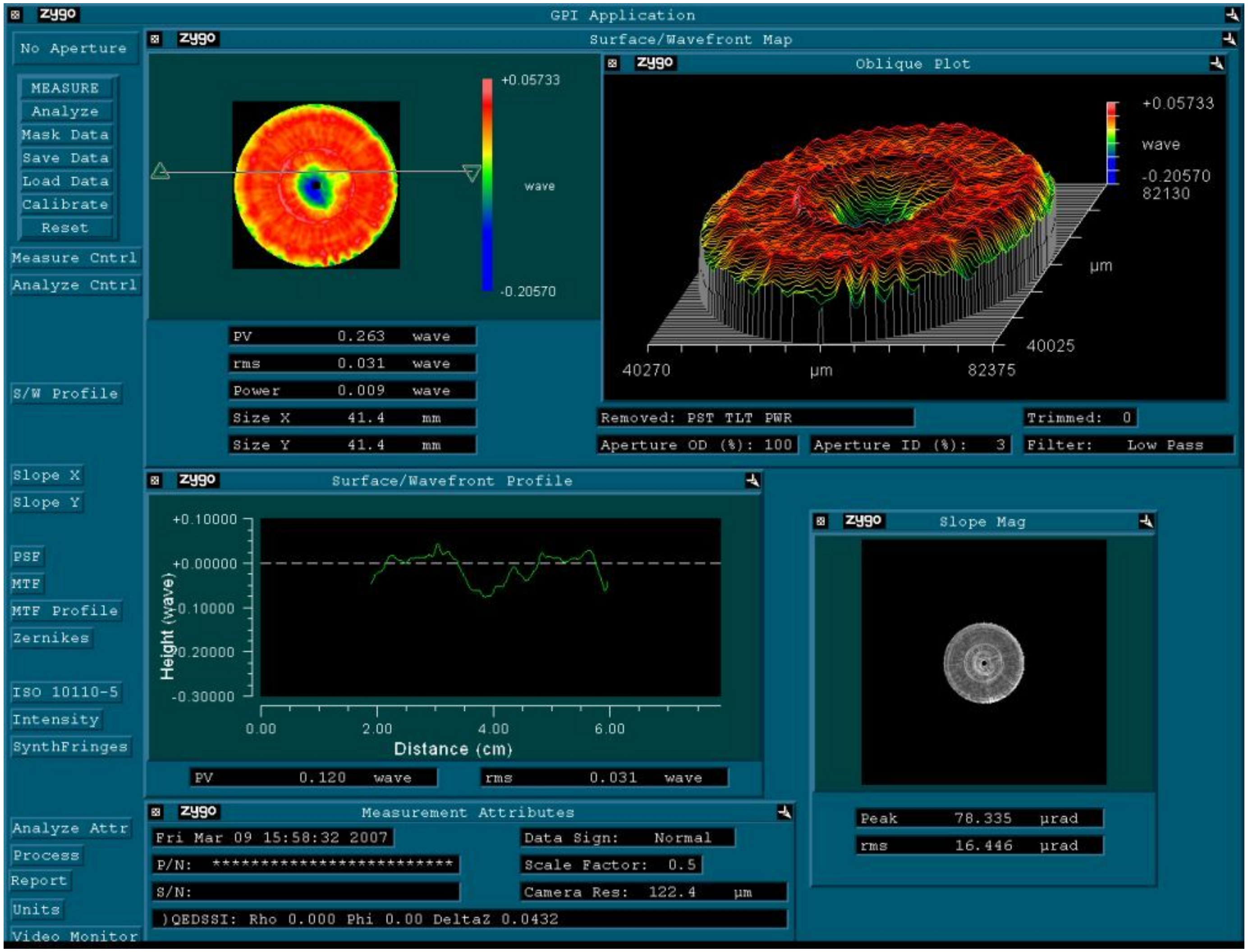
Knife-edge test through as-built system



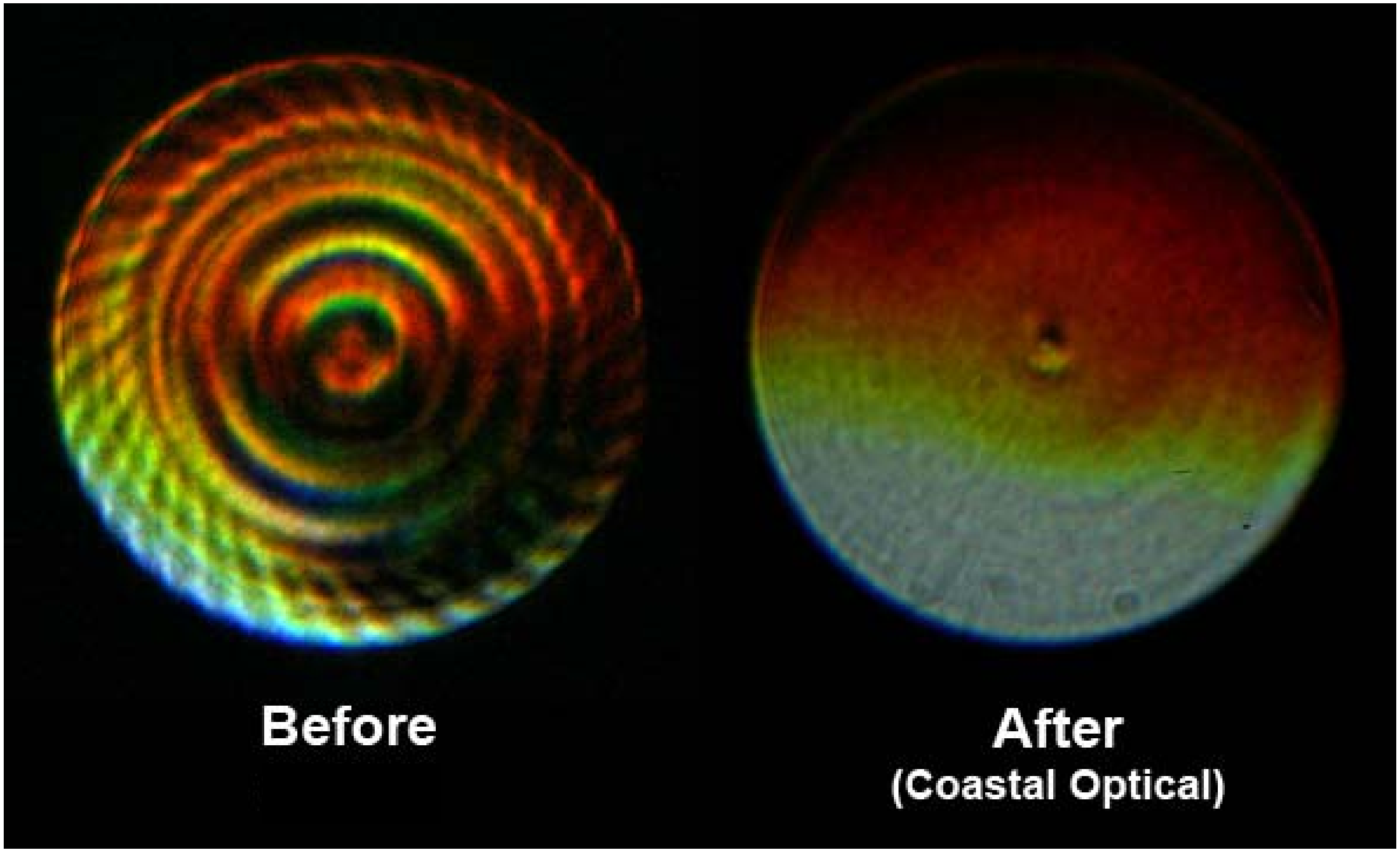
Testing on SSI showed zonal errors under lower order aberrations



Replacement aspheres polished with MRF and tested with SSI-A



Before and after system knife edge (Foucault) test



Concluding thoughts and guidelines

The optical designer should define what spatial frequencies must be captured when specifying slope requirements.

The metrologist can then make sure that they have sufficient interferometric pixel sampling to cover the spatial frequencies of interest

You can not scale slope measurement. If a part measures 0.25 wave per cm, that does not mean you can say the part is 0.635 wave per inch.

If trying to get accurate slope measurements:

Zoom up the pupil image to use the most pixels in the aperture

Always use 4” to 33mm aperture converter for small pupils

Use care when focusing the pupil

For aspheres, you should have 200+ pixels across the aperture because there may be mid-spatial frequency errors

Powerful analysis tools like sampling and filtering options will often distort the slope results. *Filter with caution*.

References

"*Surface Figure and Roughness Tolerances for NIF optics and the Interpretation of the Gradient, P-V Wavefront and RMS Specfications*", Lawson, Aikens, English, Whistler, House and Nichols, LLNL UCRL-JC-134534 presented at Denver, CO July 18, 1999.

"*Slope Error Tolerances for Optical Surfaces"*, John R. Rogers, Optifab 2007.

"*Critical aspects on testing aspheres in interferometric setups*", Frank Shillke, Carl Zeiss EUROPTO Conference on Optical Fabrication and Testing, Berlin, Germany, May 1999.

"*Modeling an interferometer for non-null testing of aspheres*", Andrew Lowman and John Greivenkamp, SPIE Vol. 2536, p. 139-147.

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