The shaping and testing of two 20” optical telescope mirrors

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About this talk

- Basic mirror shaping processes
- Grinding and polishing machine
- Grinding and polishing tools
- Mirror testing techniques
- Digital data reduction

Large Mirror Making

- For many years the standard amateur mirror was 6 inches in diameter with a focal length of 48 inches.
- This is a very modest mirror by today's standards when 20 inch (0.5m) mirrors are commonplace and advanced amateurs are creating 40-inch mirrors and planning larger.
- There is the current AltAzInitiative where telescope mirrors up to 2m are being considered for transportable applications.

The Dobsonian Mount

- The Dobsonian mounting makes possible the construction of large transportable telescopes.
- Large mirrors often need to be fast (small F/D ratio) to be practical.
- Such mirrors are more difficult to figure.


Two 20" Dobsonians at ScopeX 2011
Photo by Pierre Lourens

The mirrors

- Two 20” (508mm) Pyrex mirror blanks imported from Newport Glass Works.
- Factory diamond tool pre-ground to F4.5 and fine annealed.
- 48mm thick – classed as “thin” mirrors.
- Weight of 20 kg each.
- Had to be further shaped by grinding, polishing and eventually figured to a good paraboloid.

Shaping the mirrors

- Rough grinding to get tile tool to fit.
- Fine grinding.
- Smoothing.
- Polishing to a good sphere.
- Figuring (parabolising/correcting).
- All of these steps can be done by hand or machine or both.

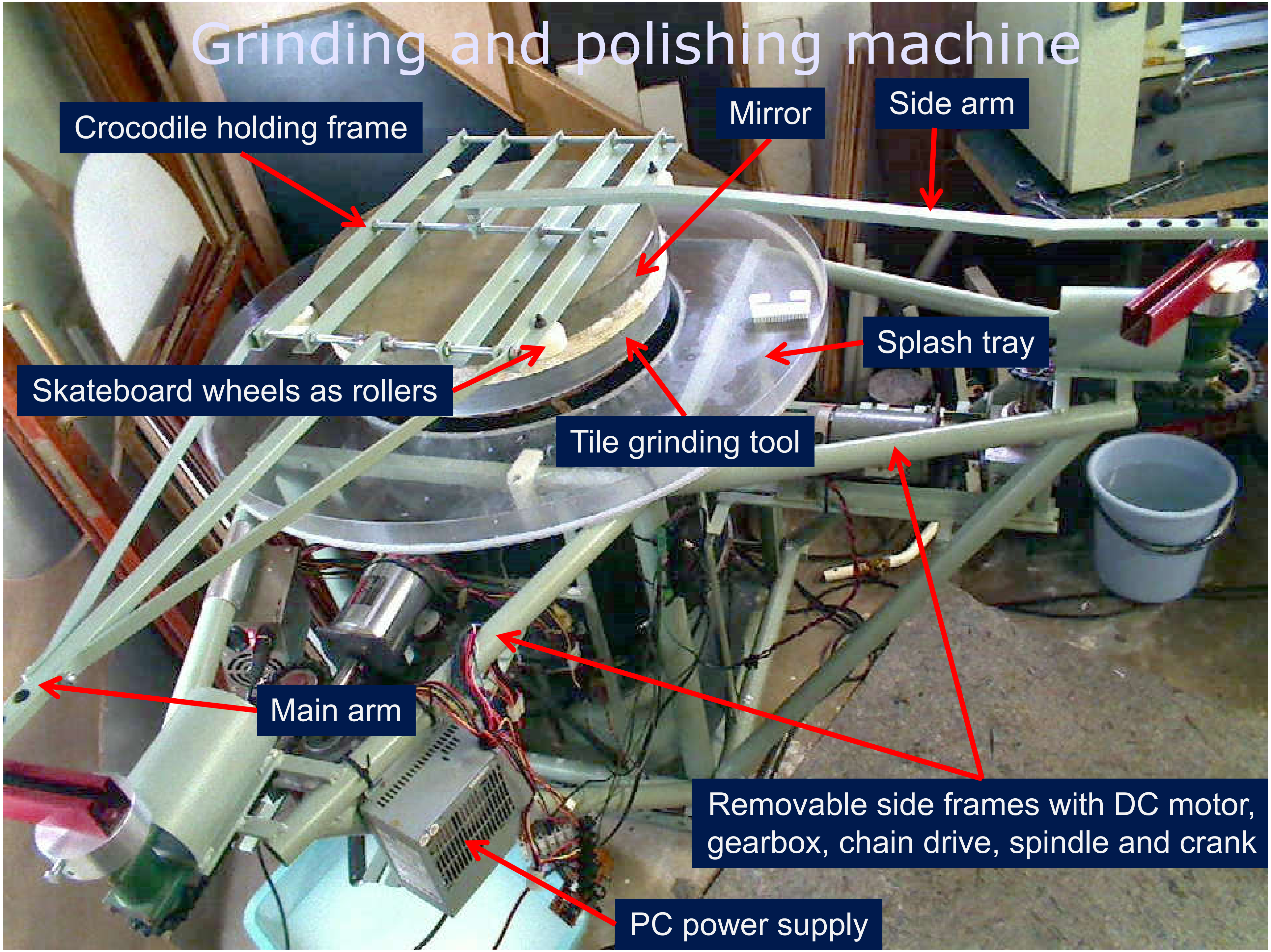
Shaping the mirrors

- First four steps (grinding and polishing to a good sphere) are relatively easy to accomplish.
- Figuring (parabolising/correcting) is a lot more challenging – especially for large fast mirrors.
- Regular testing to establish shape and amount of correction is a key component.
- Special machine was built for doing this work.


Grinding and polishing machine
Recycling a Speed Queen washing machine

Grinding and polishing machine

- Based largely on the principles of a machine described by John Hindle in Amateur Telescope Making volume 3 – Chapter A.2.
- Mirror free floating on top of the tool, inside a holding cradle (crocodile) allowing the mirror to rotate freely without undue pressure and so avoiding any astigmatism.


Grinding and polishing machine
Crocodile holding frame
Mirror
Side arm
Splash tray
Skateboard wheels as rollers
Tile grinding tool
Main arm
Removable side frames with DC motor, gearbox, chain drive, spindle and crank
PC power supply

Grinding and polishing machine

- Machine built to allow modifications, adaptations and experimentation, many of which only evolved during the figuring process.
- Very little sensible information available in the literature or on the web, especially that dealing with machine figuring.
- Typical manual strokes do not always work as desired when applied on the machine.

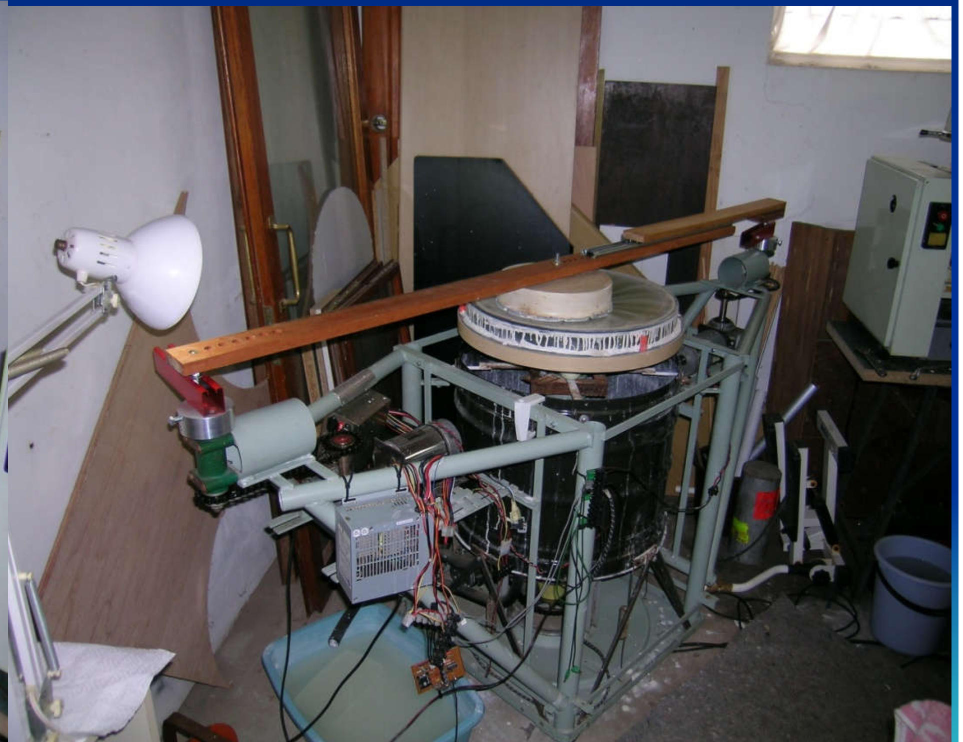
Grinding and polishing machine

- Machine provided opportunity to research some of these issues, especially the use of various sub-diameter laps and in controlling the outer edge of mirror.

Machine modes

Hypocycloidal mode using 10” sub-diameter polishing tool held by telescopic Draper arm – mirror spinning face up.

Telescopic arm being used either in Mirror-O-Matic type hypocycloidal polishing mode or Draper mode.



Machine modes

Wooden adjustable slotted arm in Zeiss mode – 13” sub-diameter tool doing a W-stroke.

Wooden frame holding sub-diameter tool between four rollers in Zeiss mode.

20" tile tool for grinding

Just after casting – porcelain tiles cast in Hydrastone.

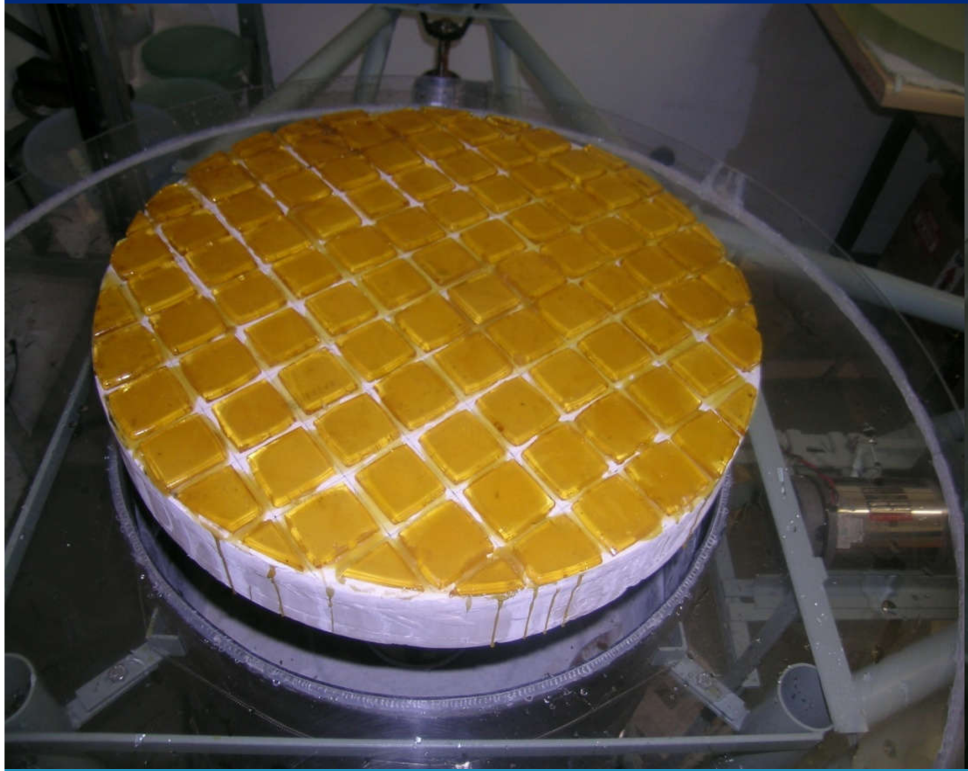
Ground to fit mirror.

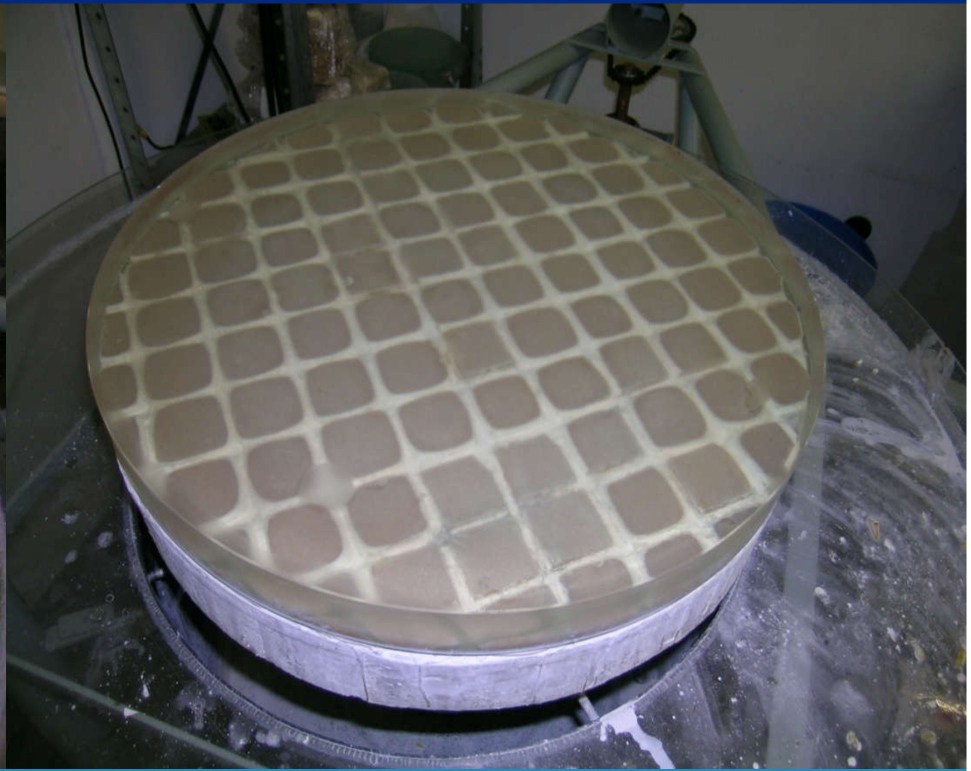
Never waste a piece of glass by using it as a grinding tool!

20” pitch lap for polishing

Full size pitch polishing lap before pressing – Hydrastone base.

Full size polishing lap with mirror on top – polishing with Cerium Oxide.

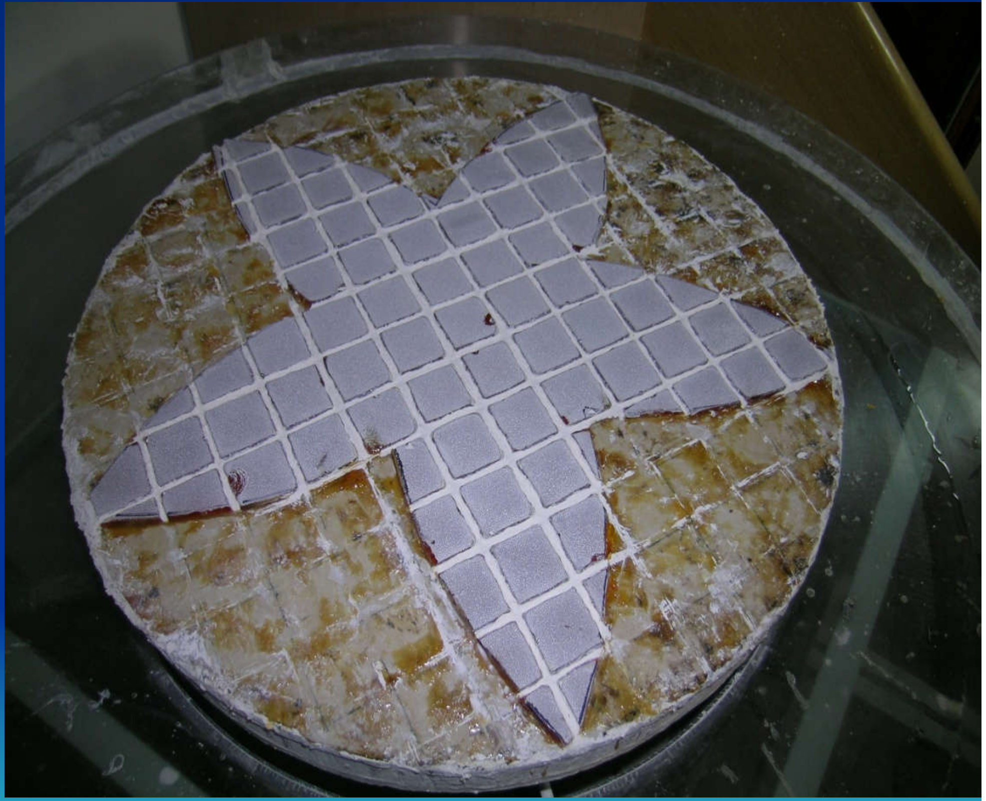




20” pitch laps

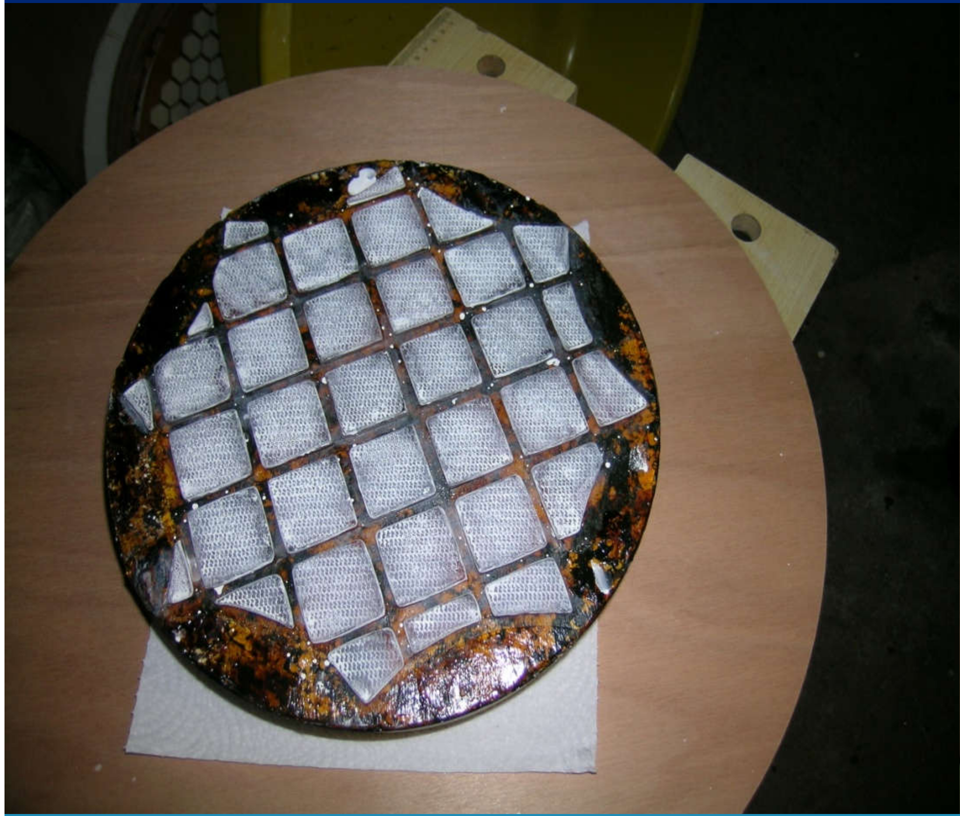
Re-doing a 20” pitch lap because of lousy pitch – messy job!

20” pitch lap cut to 5-star shape for initial parabolising.



Sub-diameter laps for figuring

10″ scalloped pitch lap cast using a silicone rubber mould.



8″ pitch lap with hexagonal facets cast using a 20″ silicone rubber mould.

Moulds for casting pitch laps

Making silicone rubber moulds – routered mould in treated plywood ready for pouring RTV silicone rubber mix.

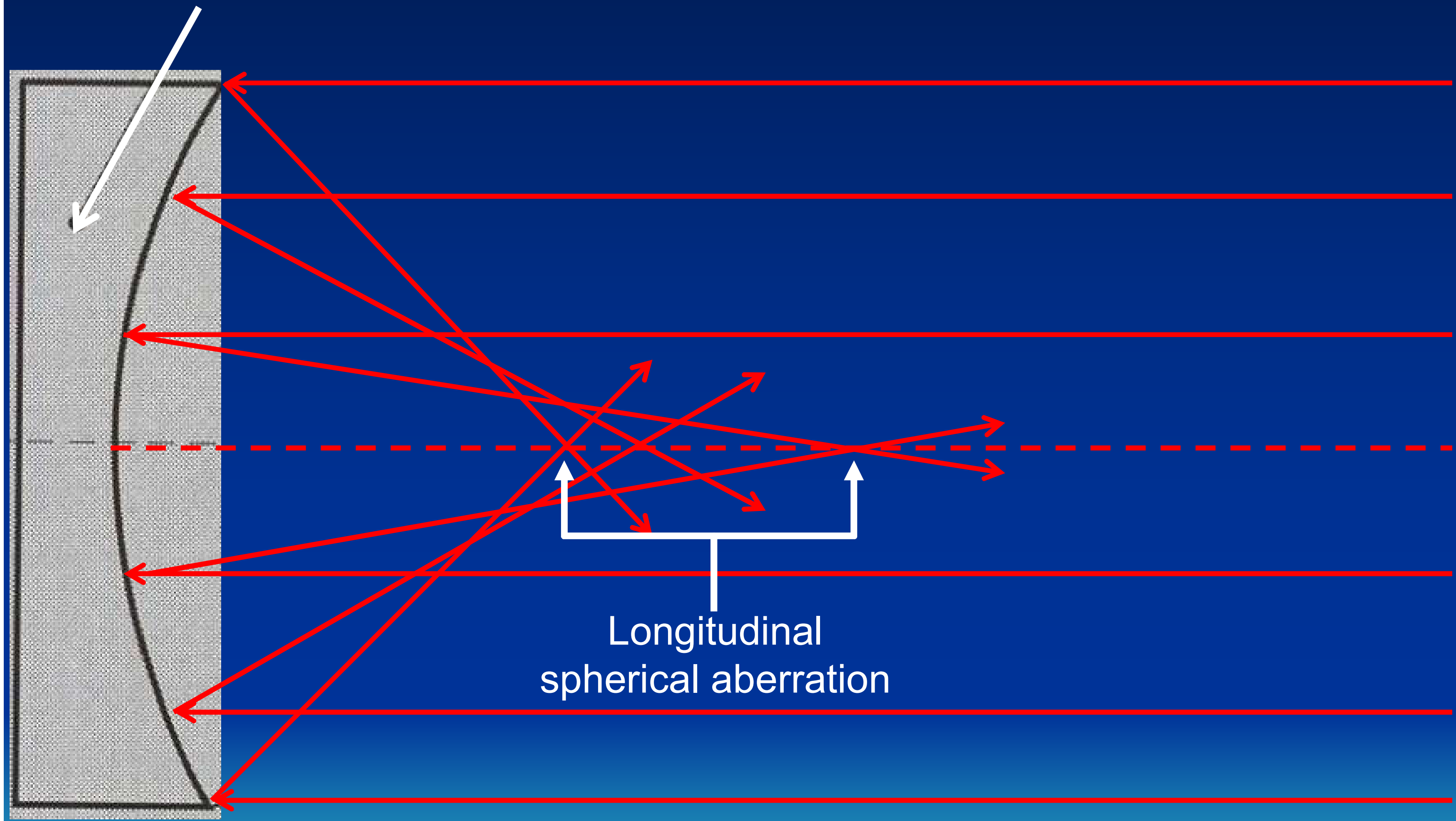
Silicone rubber mould ready for casting laps or loose pitch blocks.

Moulds for casting pitch laps

Large 20”rubber mould made using a hexagonal tile mould.

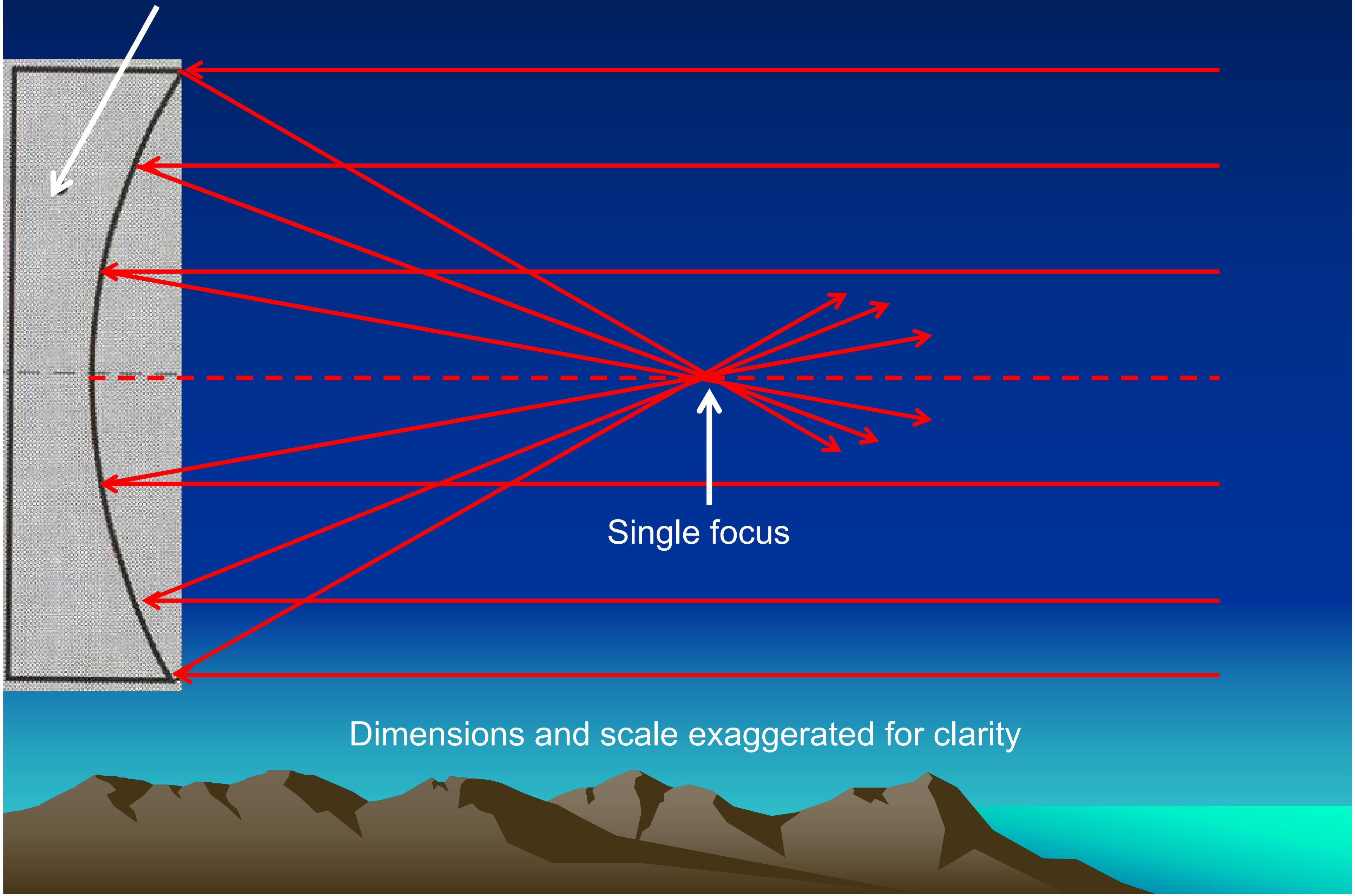
10” mould for an experimental spiral lap for hypocycloidal polishing motions.

Spherical mirror – light source at infinity

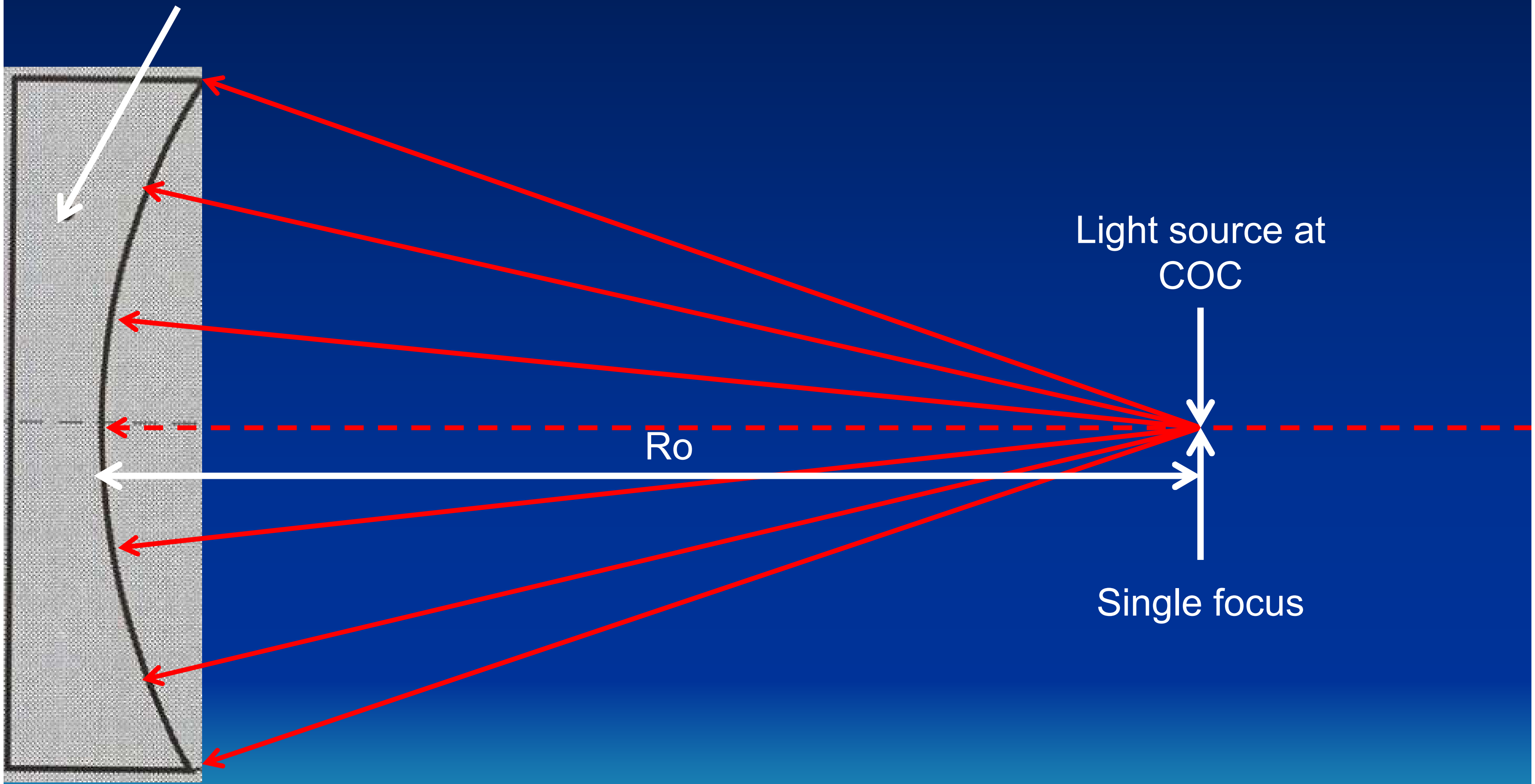


Dimensions and scale exaggerated for clarity

Paraboloidal mirror – light source at infinity

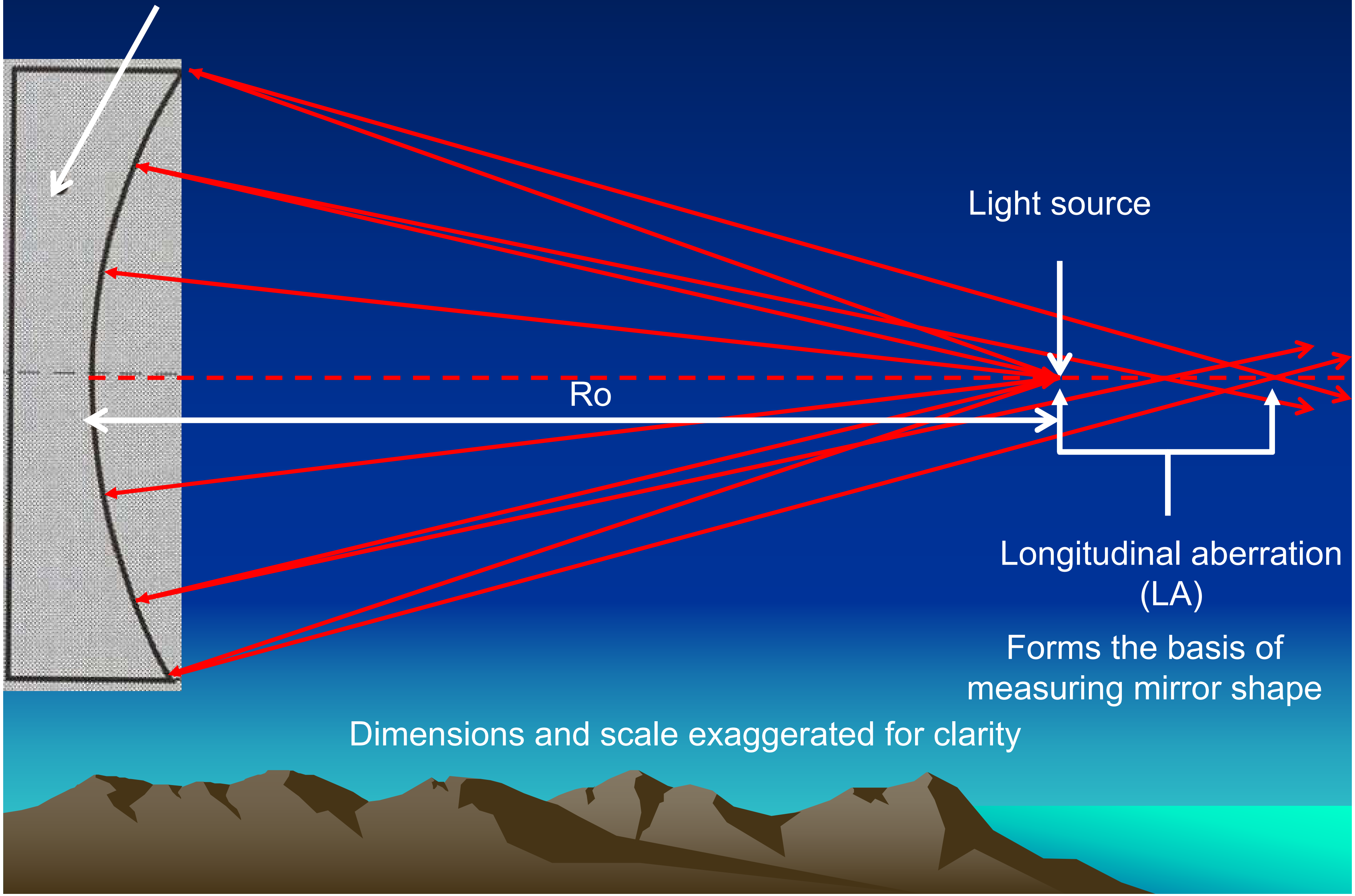


Spherical mirror – light source at COC

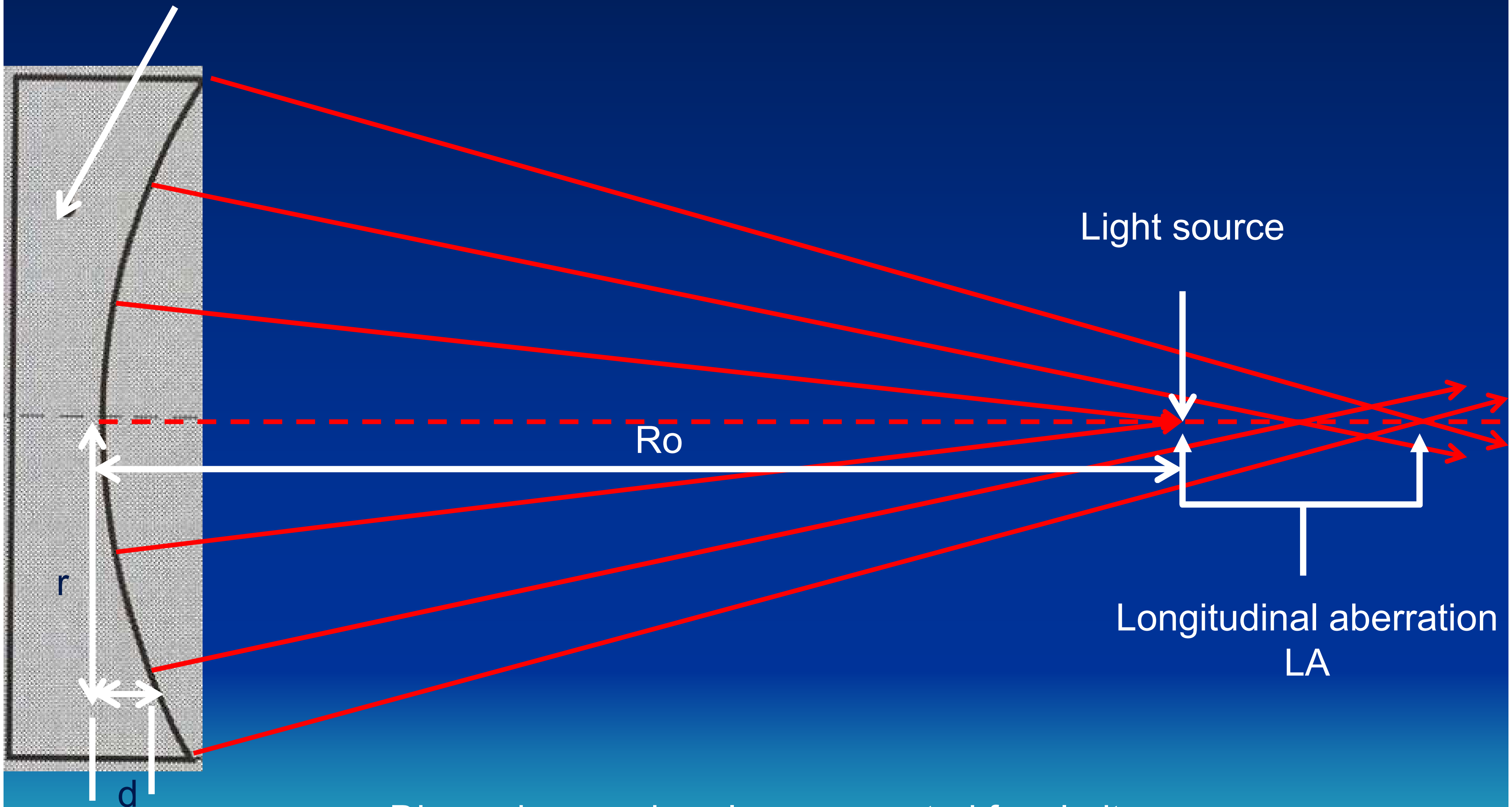


Dimensions and scale exaggerated for clarity

Paraboloidal mirror – light source near COC



Paraboloidal mirror – light source near COC



Dimensions and scale exaggerated for clarity

Longitudinal aberration for paraboloid

$$LA = \frac{r^2}{R_0} + \frac{r^4}{2R_0^3}$$

Fixed source case

$$LA = \frac{r^2}{2R_0}$$

Moving source case

$$d = \frac{r^2}{2R_0}$$

Also shape of mirror

Sagitta of paraboloid (mm)

Focal ratio (F/D)	3	4	4.5	5	6	8	10	12	15
Diameter D (ins)									
6	3.175	2.381	2.117	1.905	1.588	1.191	0.953	0.794	0.635
8	4.233	3.175	2.822	2.540	2.117	1.588	1.270	1.058	0.847
10	5.292	3.969	3.528	3.175	2.646	1.984	1.588	1.323	1.058
12	6.350	4.763	4.233	3.810	3.175	2.381	1.905	1.588	1.270
16	8.467	6.350	5.644	5.080	4.233	3.175	2.540	2.117	1.693
20	10.583	7.938	7.056	6.350	5.292	3.969	3.175	2.646	2.117
25	13.229	9.922	8.819	7.938	6.615	4.961	3.969	3.307	2.646

Also the moving source LA for a fully parabolised mirror

Correction (microns)

Focal ratio (F/D)	3	4	4.5	5	6	8	10	12	15
Diameter D (ins)									
6	5.531	2.330	1.636	1.192	0.690	0.291	0.149	0.086	0.044
8	7.375	3.107	2.181	1.589	0.919	0.388	0.198	0.115	0.059
10	9.219	3.883	2.726	1.987	1.149	0.485	0.248	0.144	0.074
12	11.063	4.660	3.272	2.384	1.379	0.582	0.298	0.172	0.088
16	14.750	6.213	4.362	3.179	1.839	0.776	0.397	0.230	0.118
20	18.438	7.767	5.453	3.974	2.299	0.969	0.496	0.287	0.147
25	23.047	9.708	6.816	4.967	2.873	1.212	0.620	0.359	0.184

Correction (wavelengths)

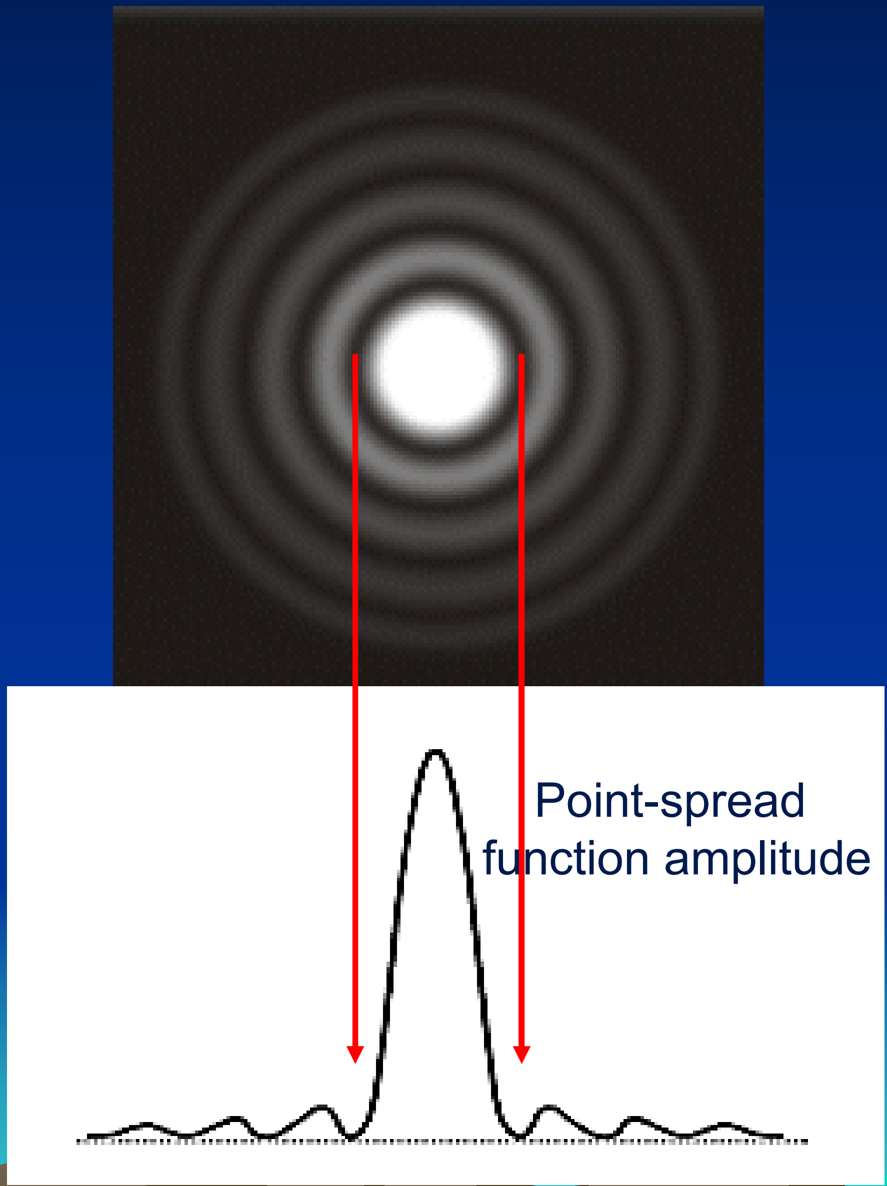
Focal ratio (F/D)	3	4	4.5	5	6	8	10	12	15
Diameter D (ins)									
6	10.06	4.24	2.97	2.17	1.25	0.53	0.27	0.16	0.08
8	13.41	5.65	3.97	2.89	1.67	0.71	0.36	0.21	0.11
10	16.76	7.06	4.96	3.61	2.09	0.88	0.45	0.26	0.13
12	20.11	8.47	5.95	4.33	2.51	1.06	0.54	0.31	0.16
16	26.82	11.30	7.93	5.78	3.34	1.41	0.72	0.42	0.21
20	33.52	14.12	9.91	7.22	4.18	1.76	0.90	0.52	0.27
25	41.90	17.65	12.39	9.03	5.22	2.20	1.13	0.65	0.33

Wavelengths at 550 nm

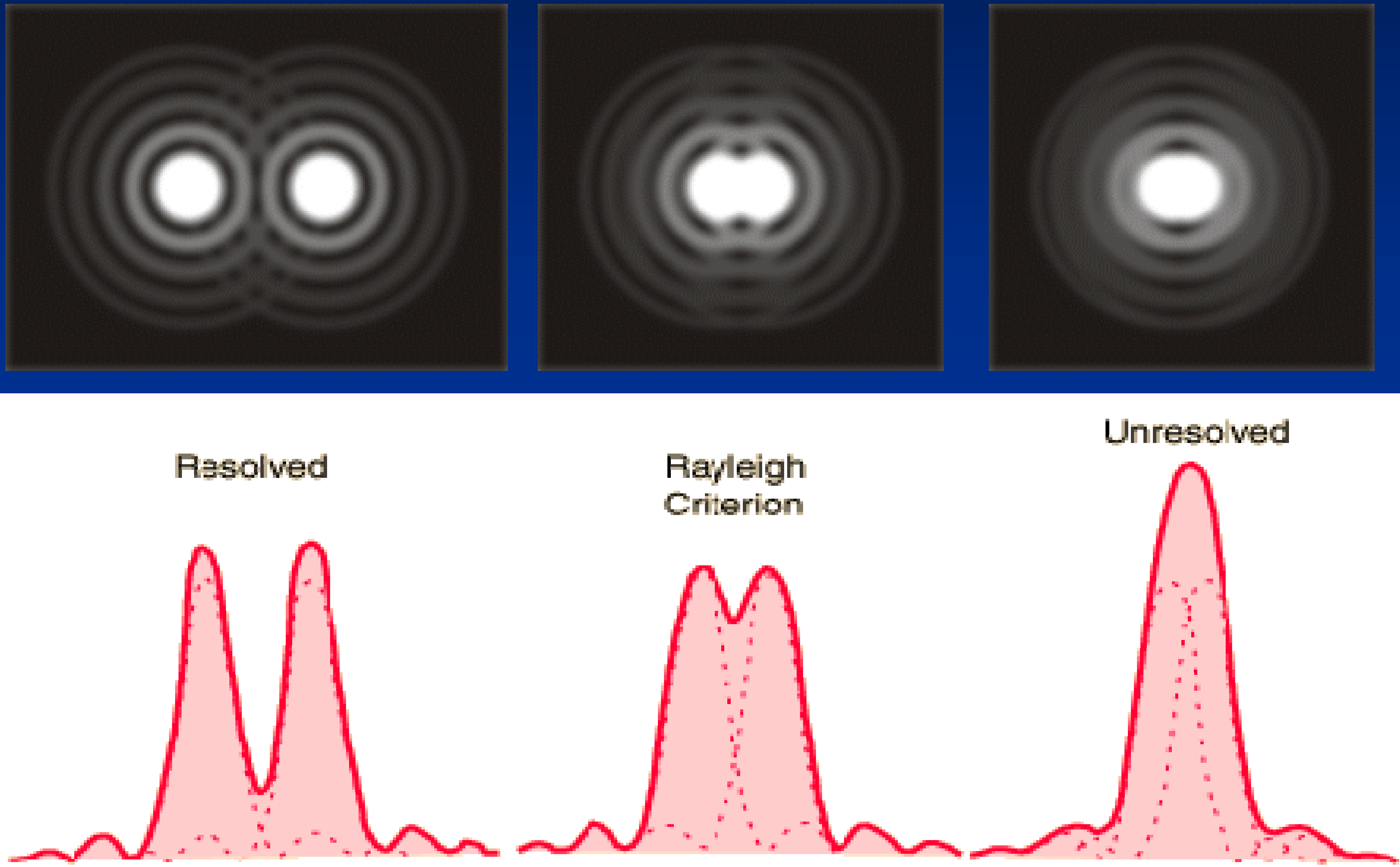
Resolving limit

- All telescopes have a theoretical resolving limit that depends on their aperture.
- At the focus the image of a star appears as a small bright disk surrounded by concentric rings of diminishing brightness.
- Called the Airy disk or diffraction spot.

The Airy disk



The Airy disk



Airy disk radius

The linear radius of the first dark ring is given by:

$$\rho = 1.22\lambda\left(\frac{F}{D}\right)$$

Function of F/D ratio not aperture

F/D ratio	3.0	4.0	4.5	5.0	6.0	8.0	10.0	12.0	15.0
mm	0.0020	0.0027	0.0030	0.0034	0.0040	0.0054	0.0067	0.0081	0.0101
nm	2013	2684	3020	3355	4026	5368	6710	8052	10065

Wavelength = 550 nm

Resolving power

The corresponding angle is given by:

$$\rho_{rad} = \frac{1.22\lambda}{D}$$ radians or $$\rho'' \cong \frac{140}{D}$$ arc seconds

Diameter D (ins)	Arc seconds
6	0.91
8	0.68
10	0.54
12	0.45
16	0.34
20	0.27
25	0.22

Function of aperture

Wavelength = 550 nm

How much correction error?

Peak to Valley difference (correction error) (wavelengths)	RMS difference (wavelengths)	Strehl ratio	Energy in Airy disc (percent)	Energy in surrounding diffraction rings (percent)
0	0	1	84	16
1/16	1/54	0.99	83	17
1/8	1/27	0.95	80	20
1/4	1/14	0.8	68	32
1/2	1/7	0.4	40	60
1	1/3	0.1	10	90

Adapted from: Karine and Jean-Marc Lecleire

Perfect optics → 0

Françon limit → 1/16

Rayleigh criterion → 1/8

Light bucket! → 1

Many commercial mirrors → 0.8

Objective → 0.95

Testing

Variety of tests available to establish mirror shape and deviations:

- Foucault test
- Ronchi test
- Gaviola Caustic test
- Various interferometry tests
- Various null tests
- Star test
- SCOTS

Combination of these two (Foucault test, Ronchi test)

Very promising future (SCOTS)

Foucault test

- Oldest and easiest is the Foucault knife-edge shadow test.
- Described by Leon Foucault in 1858.
- Many variations on the theme used today (e.g. slitless tester).
- Modern technology can extend the usefulness and accuracy (webcam and software).

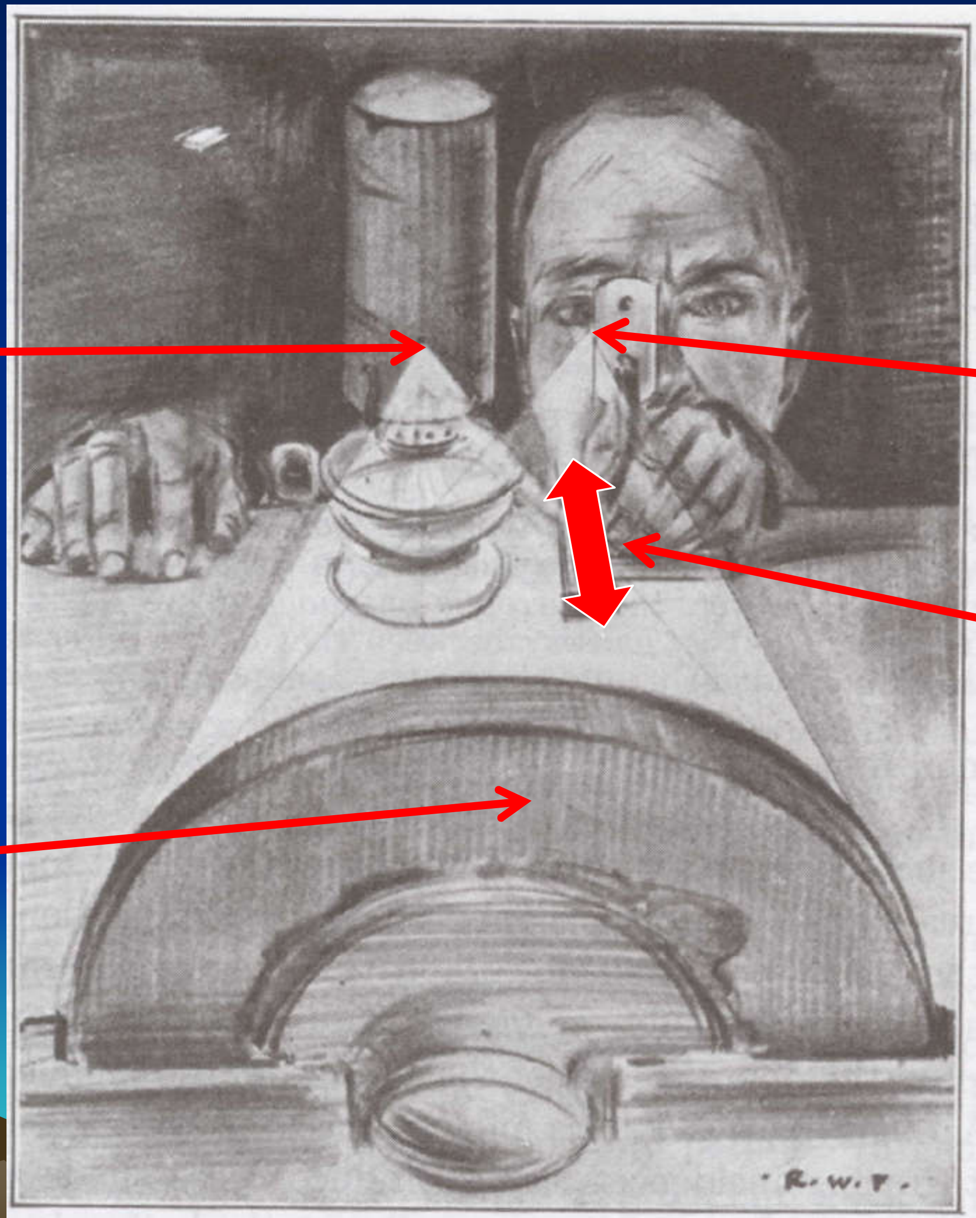
Making the knife-edge shadow test

Pinhole light source

Knife edge

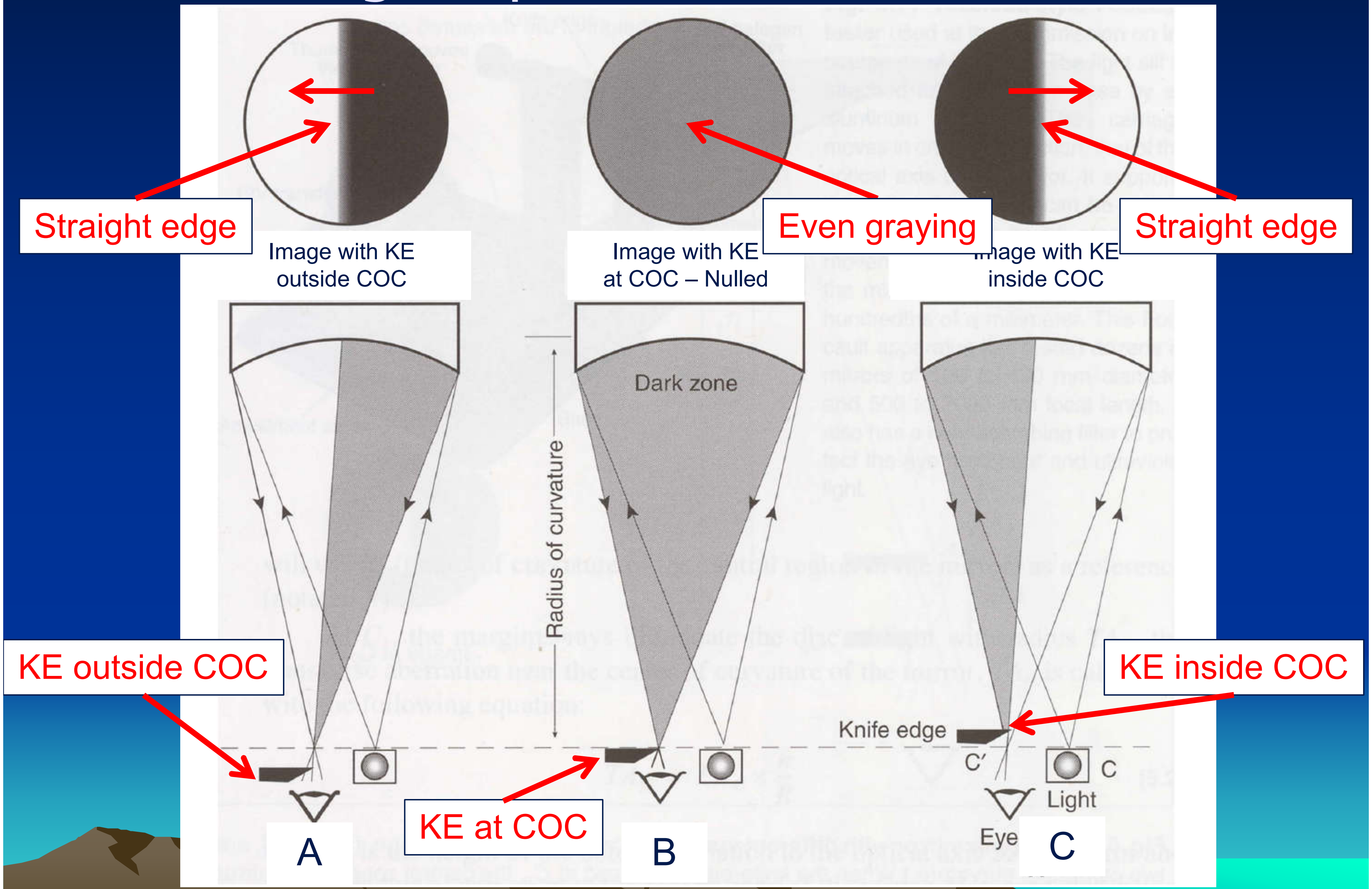
Sliding stage to move K-E and measure position

Mirror



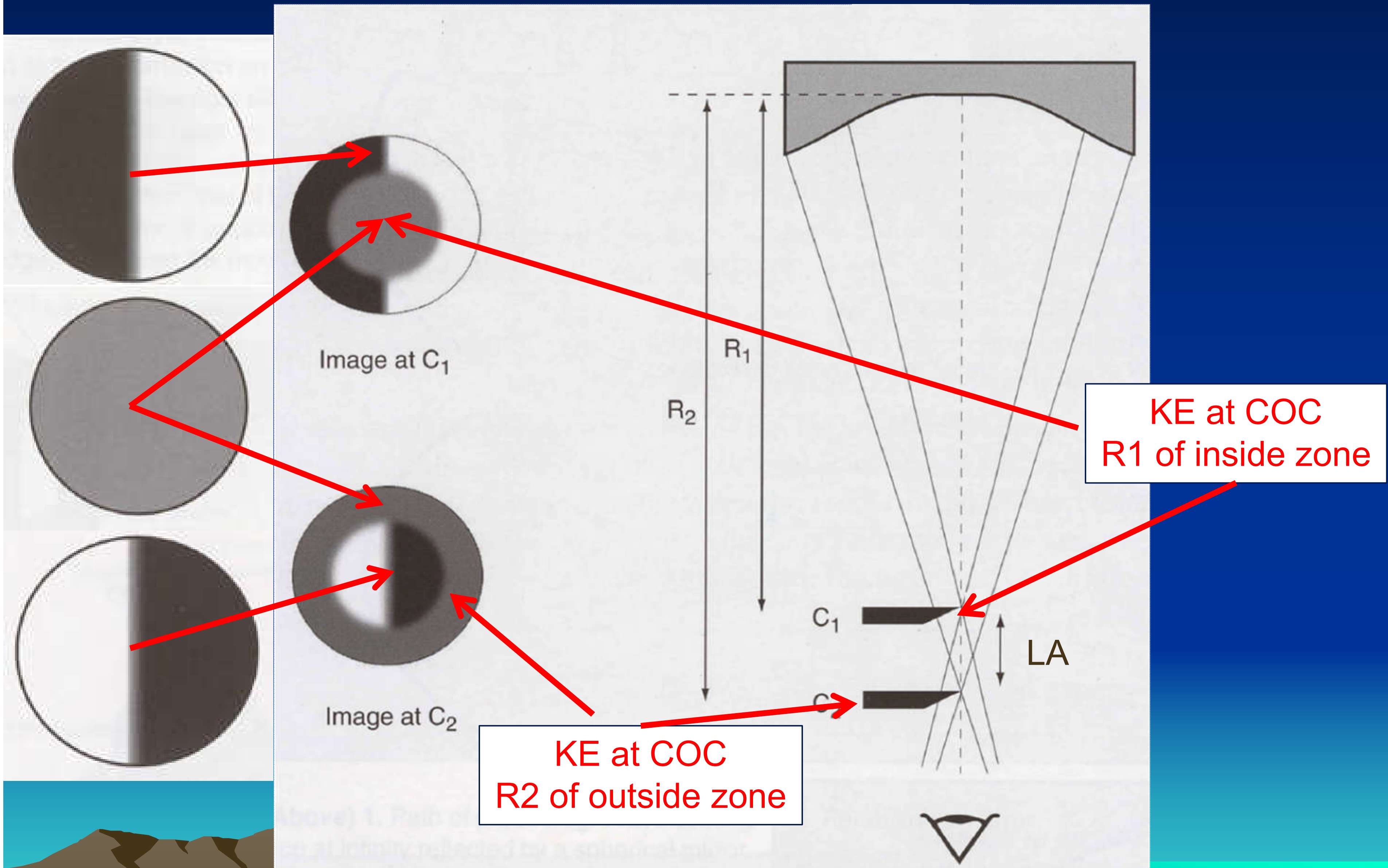
Picture: ATM 1 p 11 - Ingalls

Testing a spherical mirror at ROC



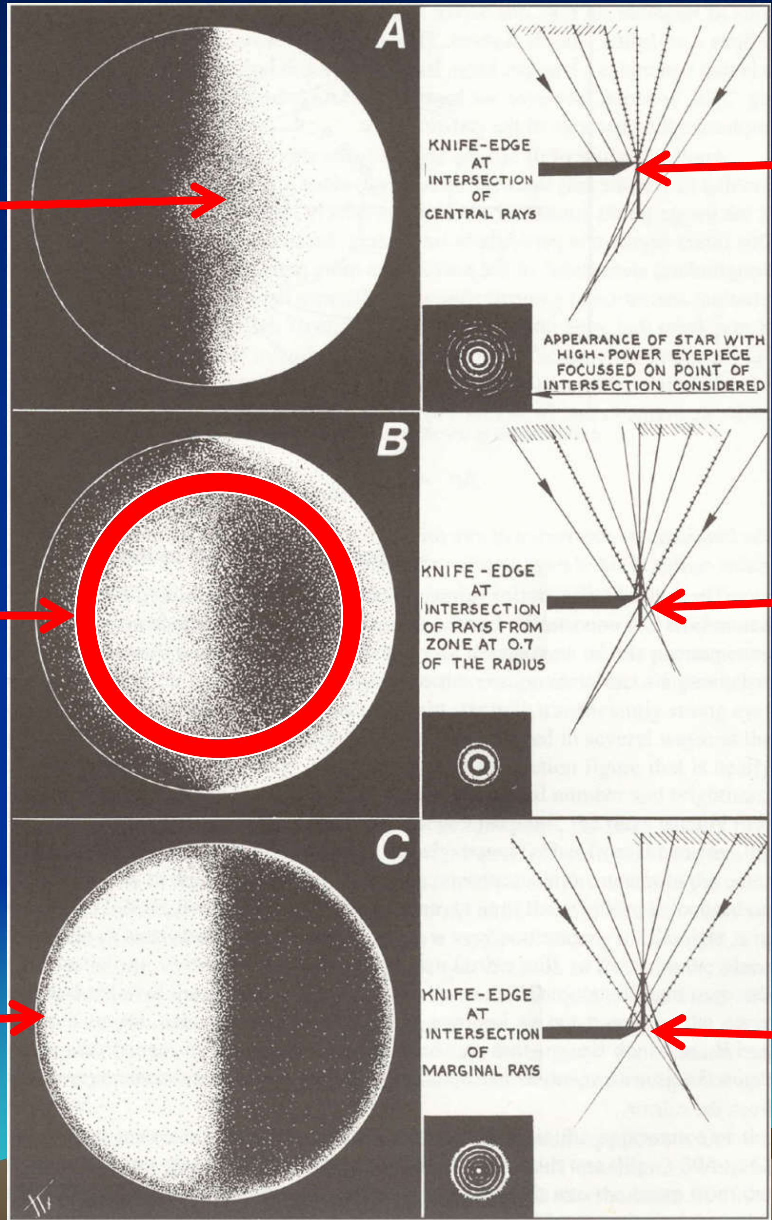
Adapted from: Karine and Jean-Marc Lecleire

Testing an aspheric mirror



Adapted from: Karine and Jean-Marc Lecleire

Testing a paraboloidal mirror



Inside zone nulled

KE at COC of inside zone

Intermediate zone nulled

KE at COC of some intermediate zone

Outside zone nulled

KE at COC of outside zone

Adapted from: Jean Texereau

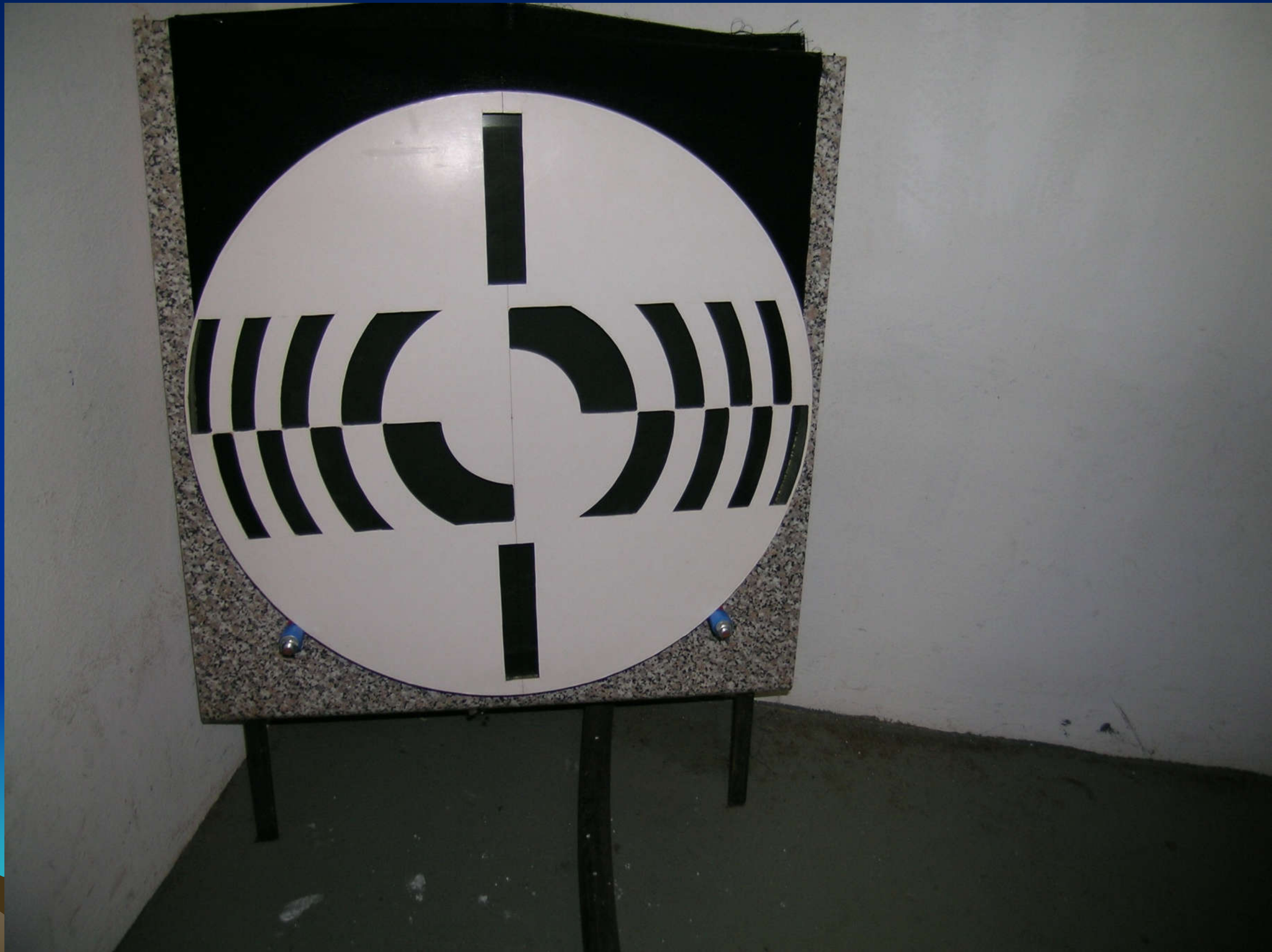
Measuring with the Foucault Test

- That's what you see but need to measure.
- Longitudinal position of knife-edge vs radial position of nulls or crest on mirror (or the other way round).
- Require sufficient number of positions to properly characterize surface.
- Measured and calculated results are plotted to establish amount of aberration and shape of figure.
- Corrections are then applied where necessary until figure meets desired criteria.

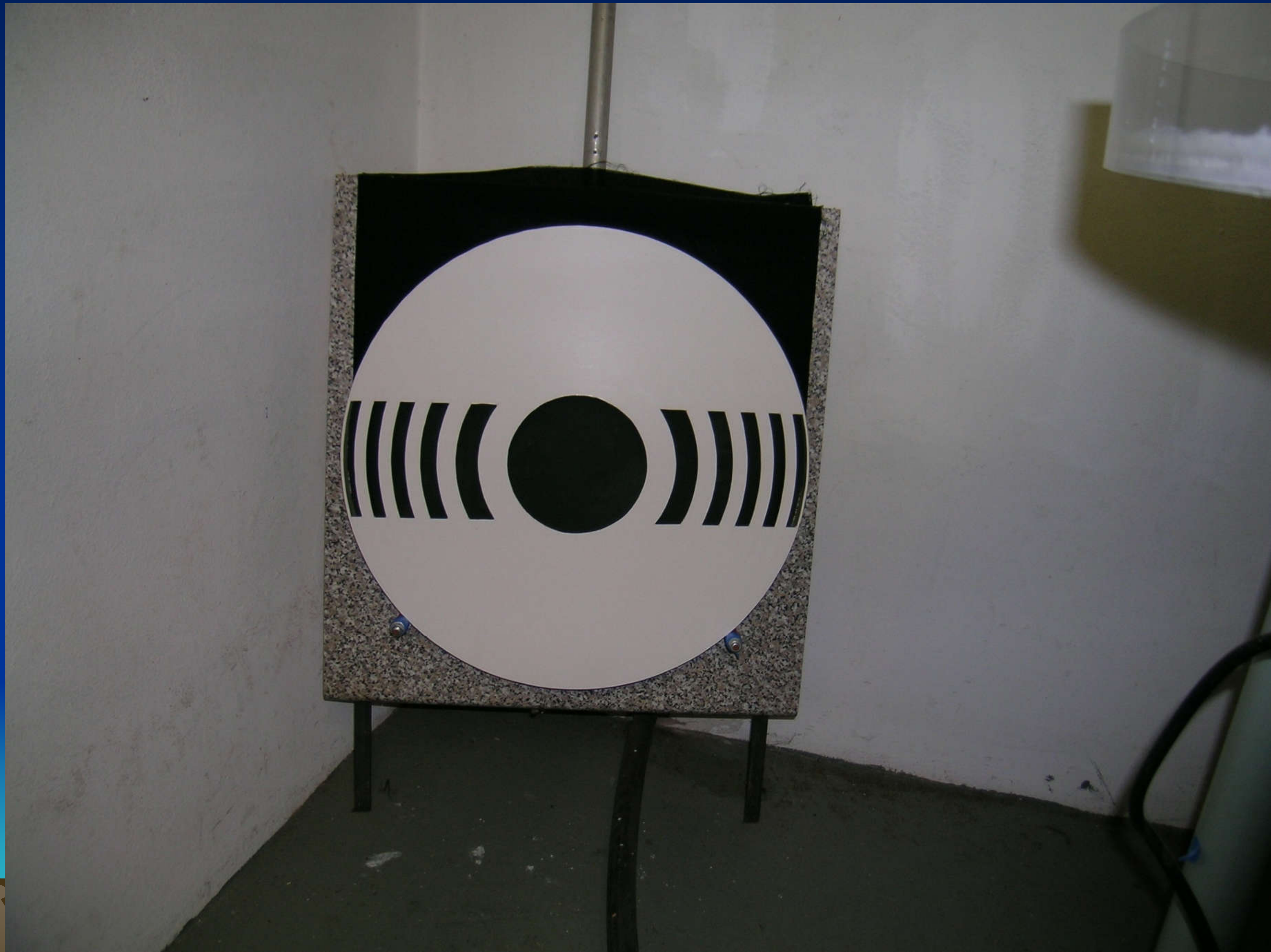
The Foucault Test – with masks

- Traditional methods use masks of various kinds.
- Mask slot pair position is independent variable.
- Longitudinal knife edge position is dependent variable which needs to be measured.
- Can be done by eye or nowadays using webcam assistance.
- Need to judge equal graying of zone pairs (subjective and plagued by diffraction).
- Several readings per position are averaged.

8-zone mask

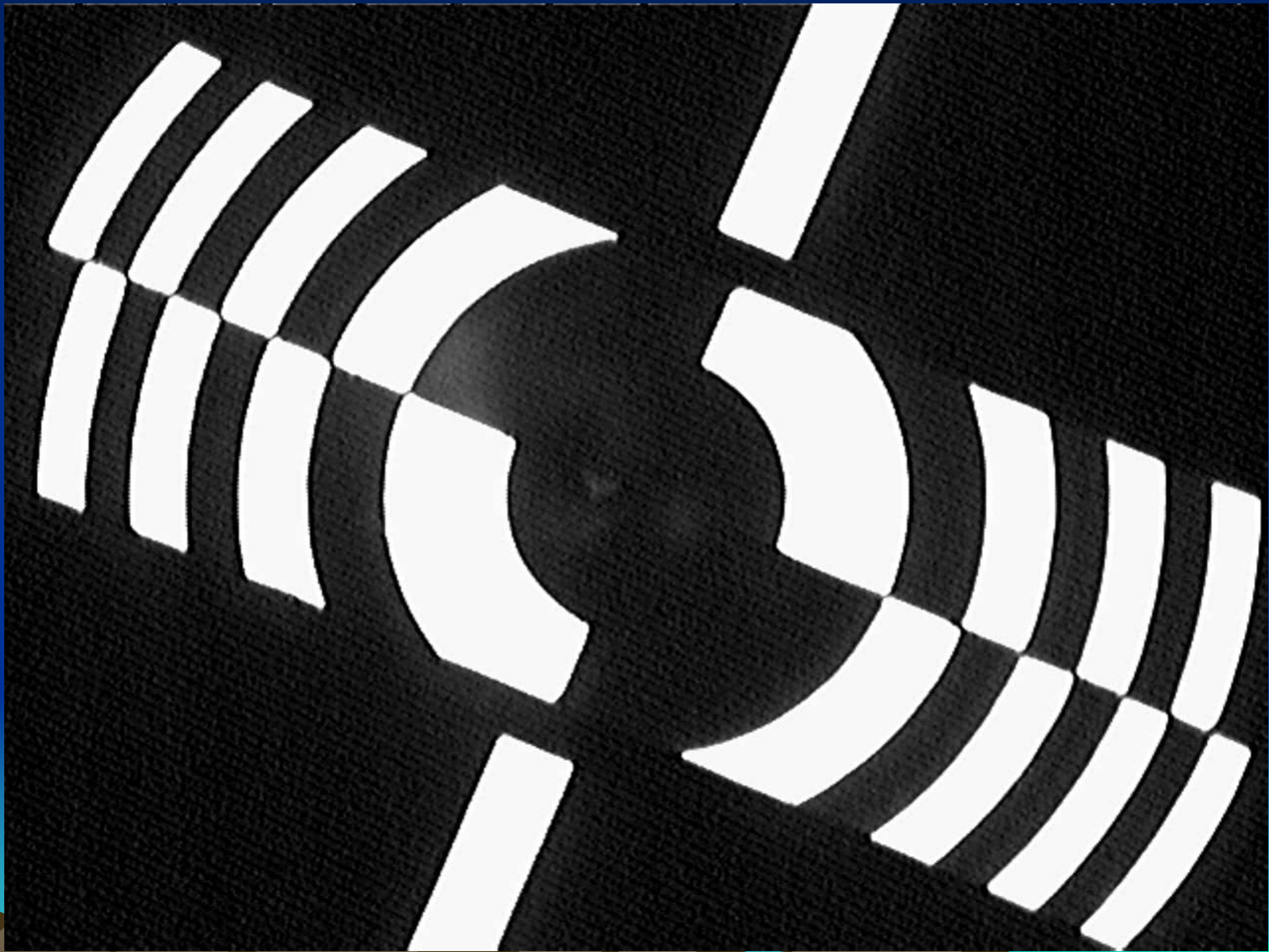


11-zone mask – odd zones

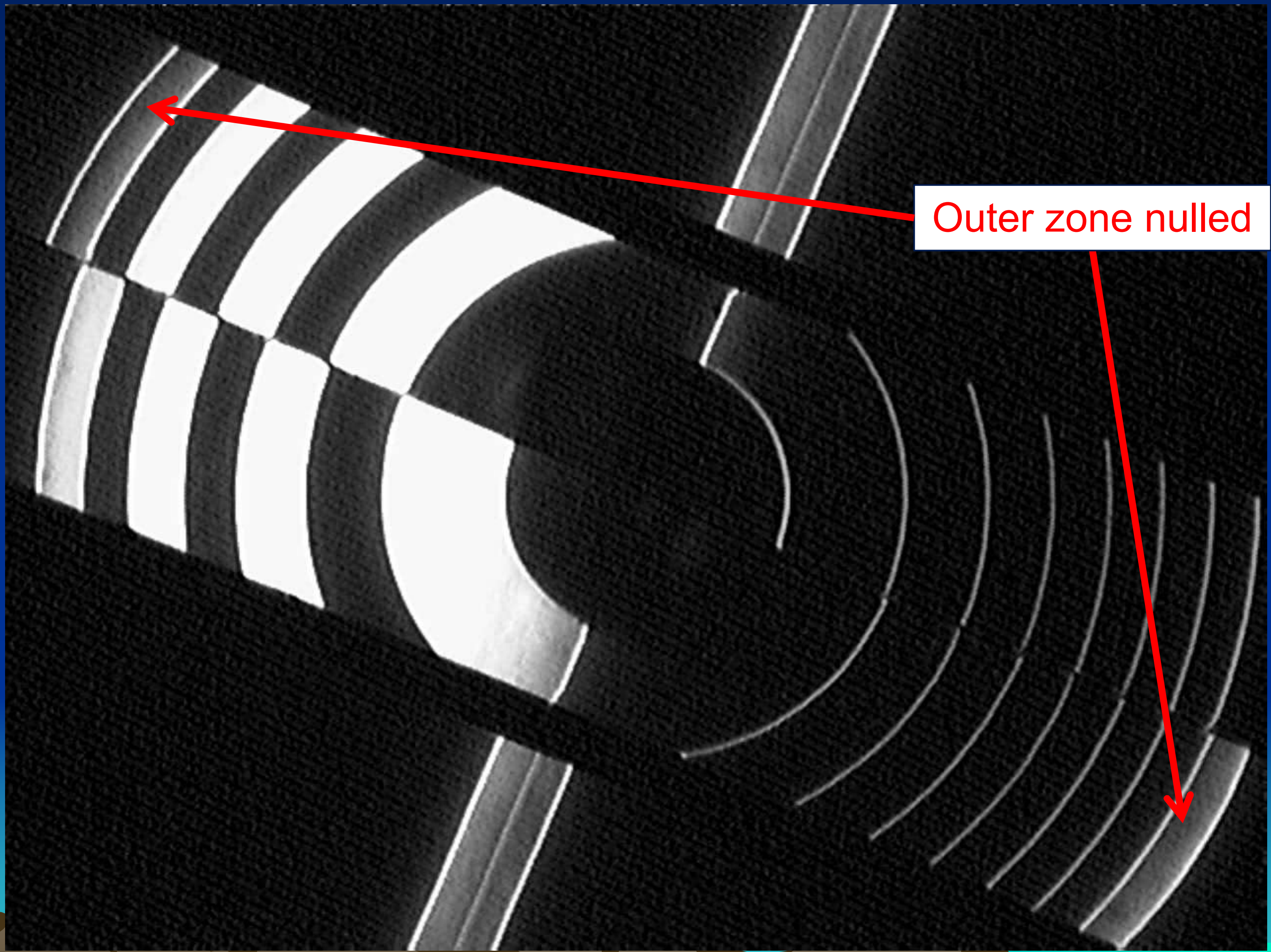


11-zone mask – even zones

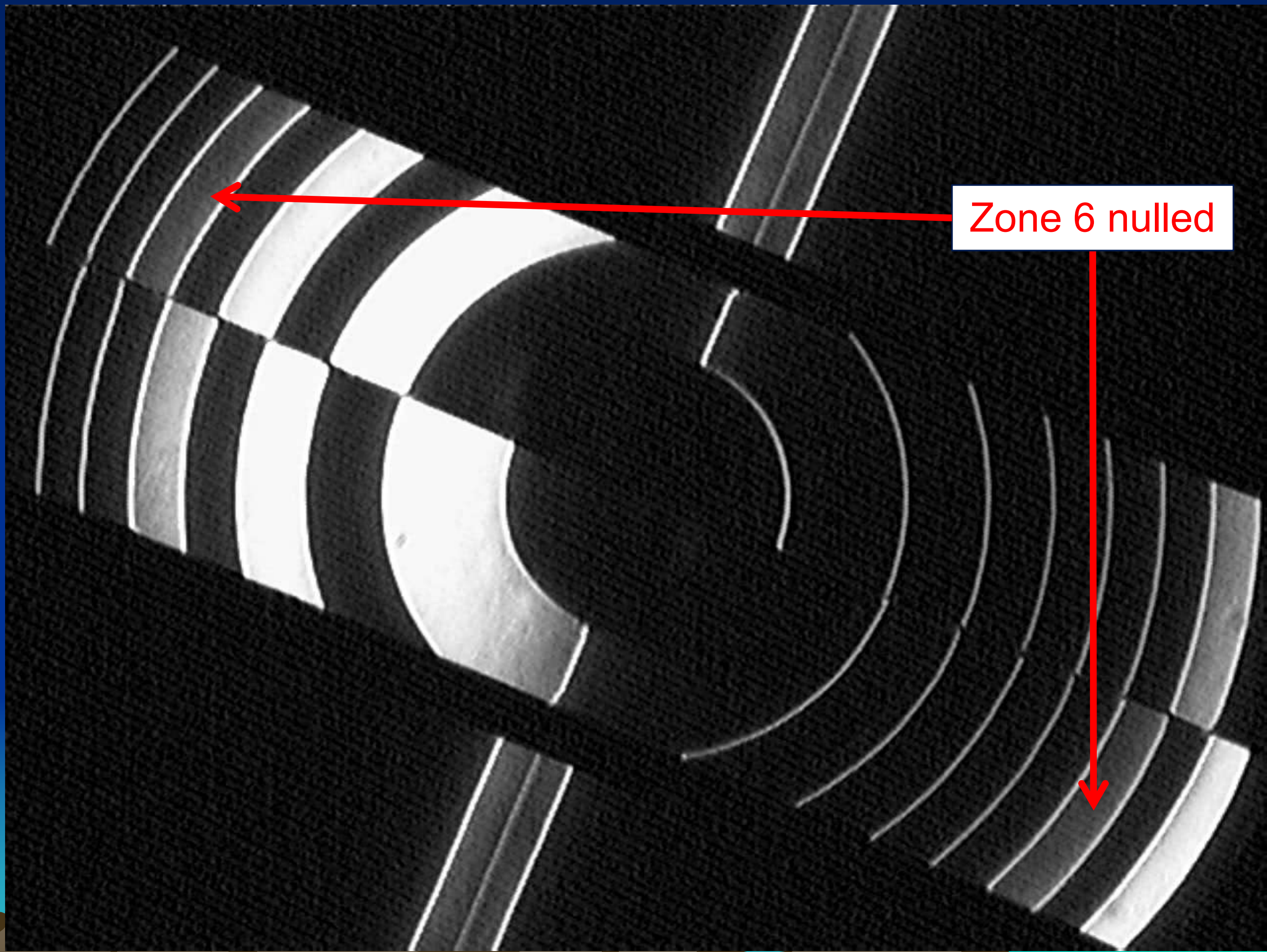
Test example



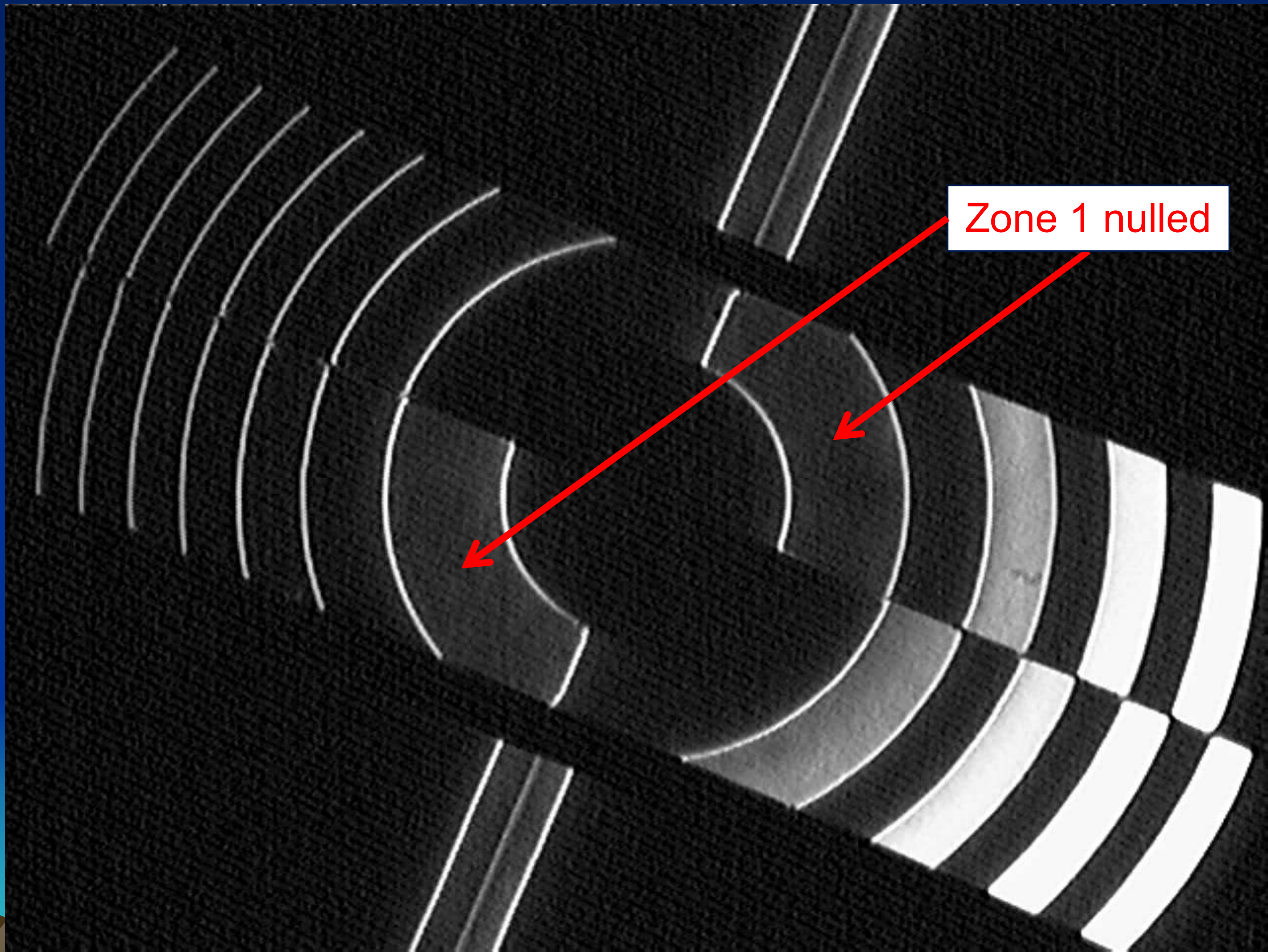
Test example



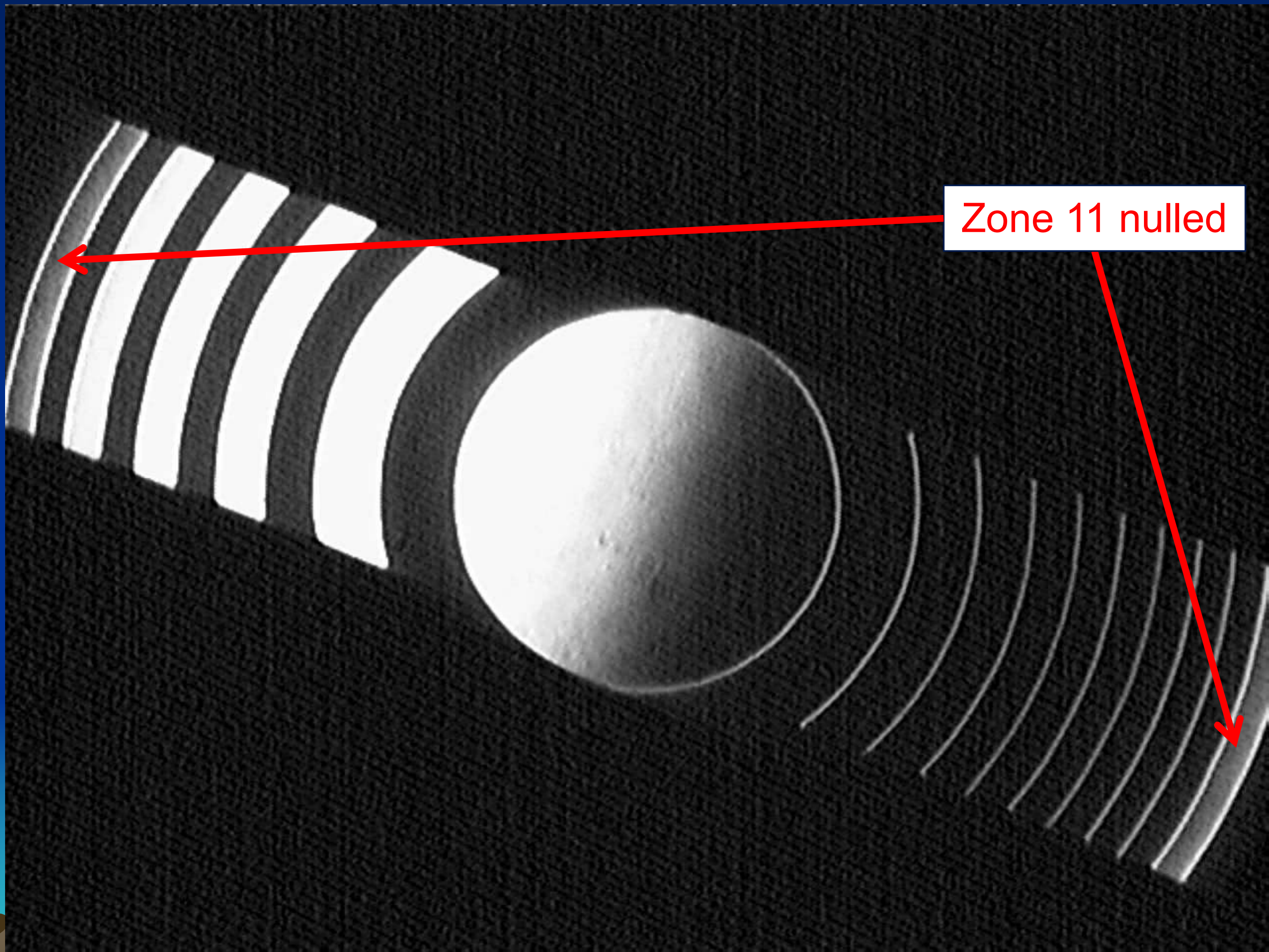
Test example



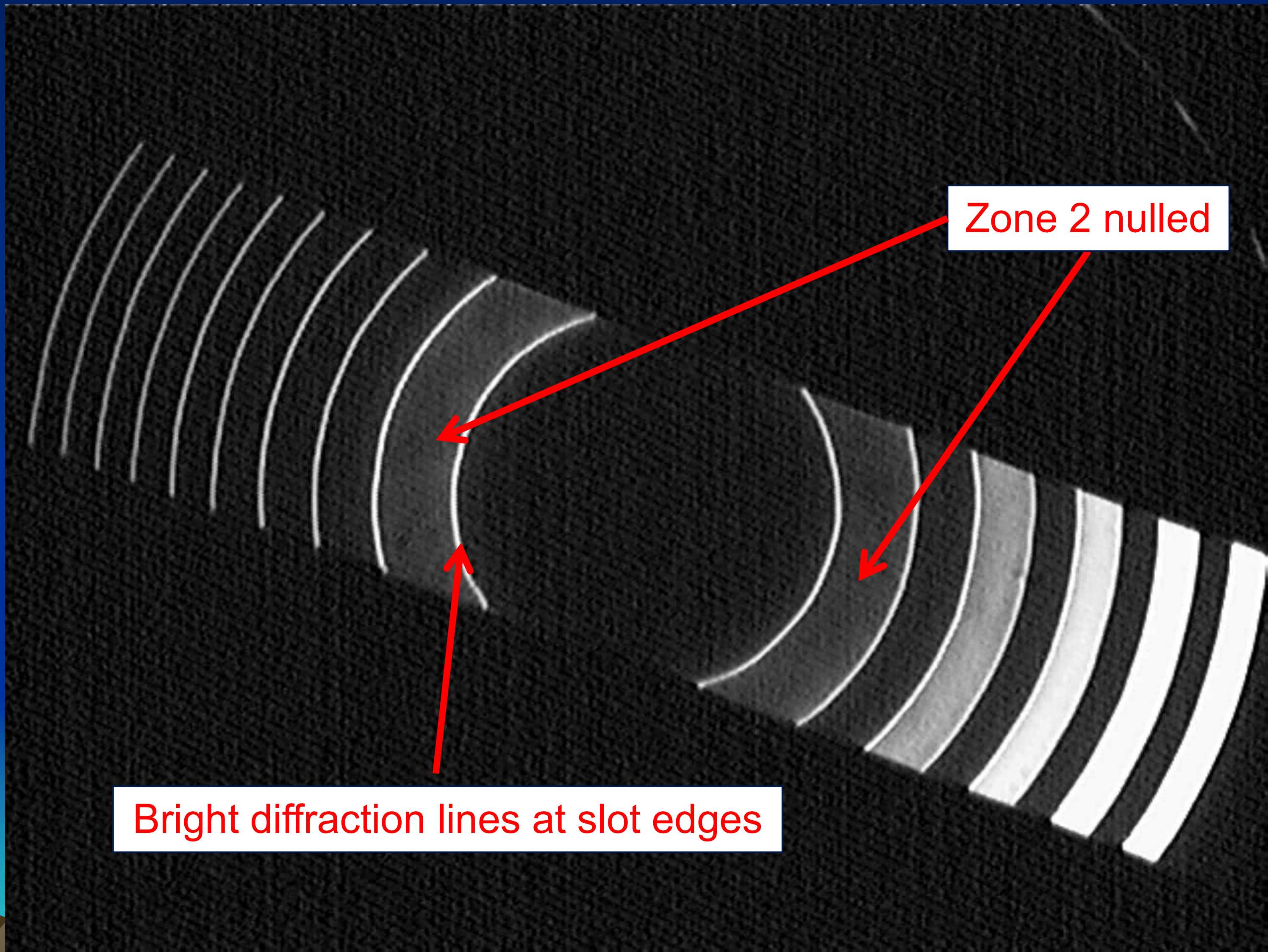
Test example



Test example



Test example



The Foucault Test – No Masks Required

- More modern approach that overcomes limitations of using masks.
- Almost unlimited number of test points across mirror possible – also close to edge.
- More objective, convenient, reliable and repeatable measurements obtained.
- Well-suited to testing large fast mirrors.

The Foucault Test – No Masks Required

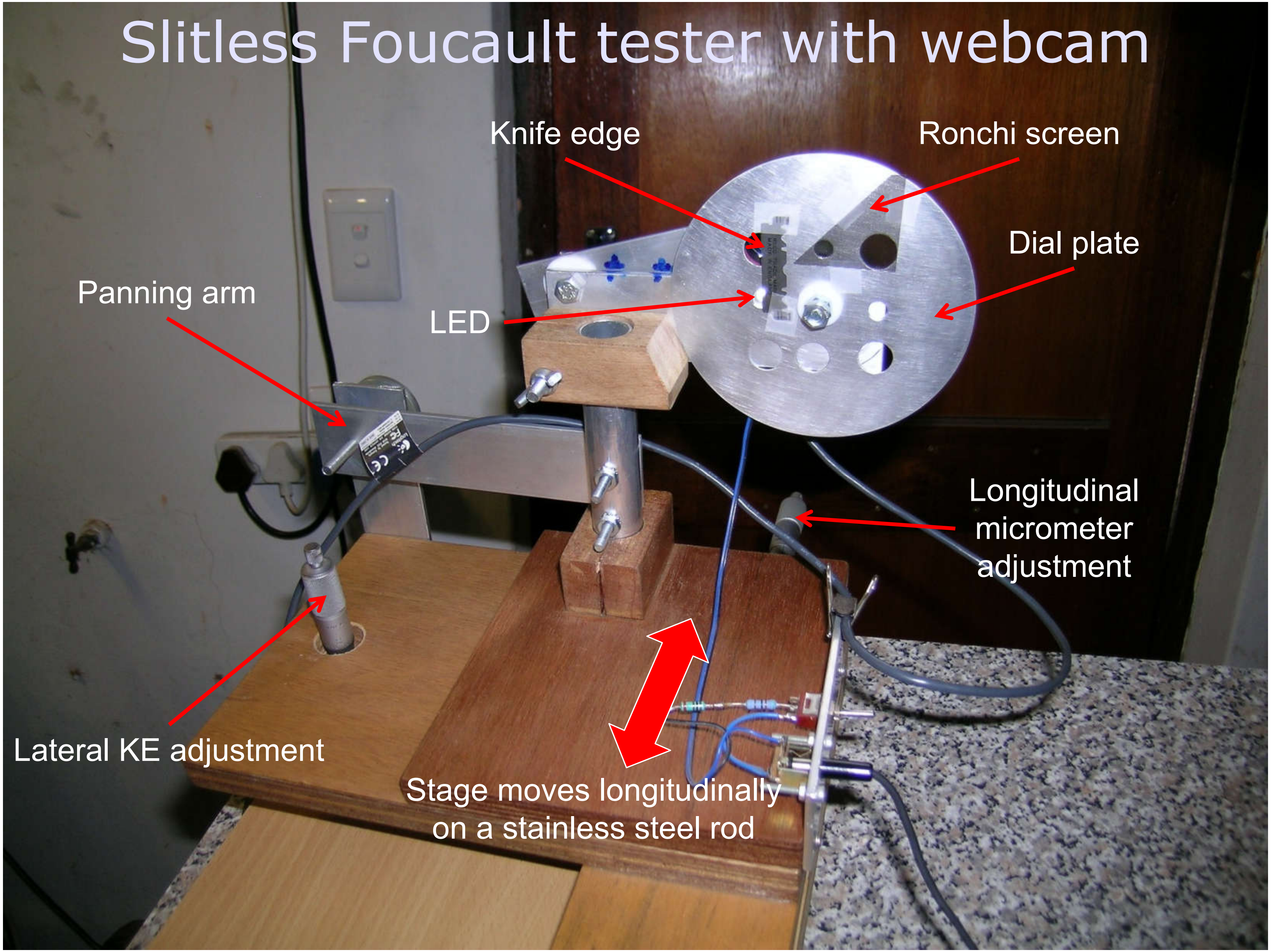
- Harold Suiter’s method (ATMJ 2 chap 13) – “Digital knife-edge test reduction”.
- Video camera and frame grabber to capture series of images.
- Adobe Photoshop to manipulate pictures.
- Split and splice of pictures to determine null crossings.
- Spreadsheet to reduce and analyse the raw data and display the results.

The Foucault Test – No Masks Required

- Modified webcam to capture series of images.
- Made various improvements to slitless tester.
- Initially used GIMP to split and splice images to determine null crossings (time consuming and still some subjectivity).

The Foucault Test – No Masks Required

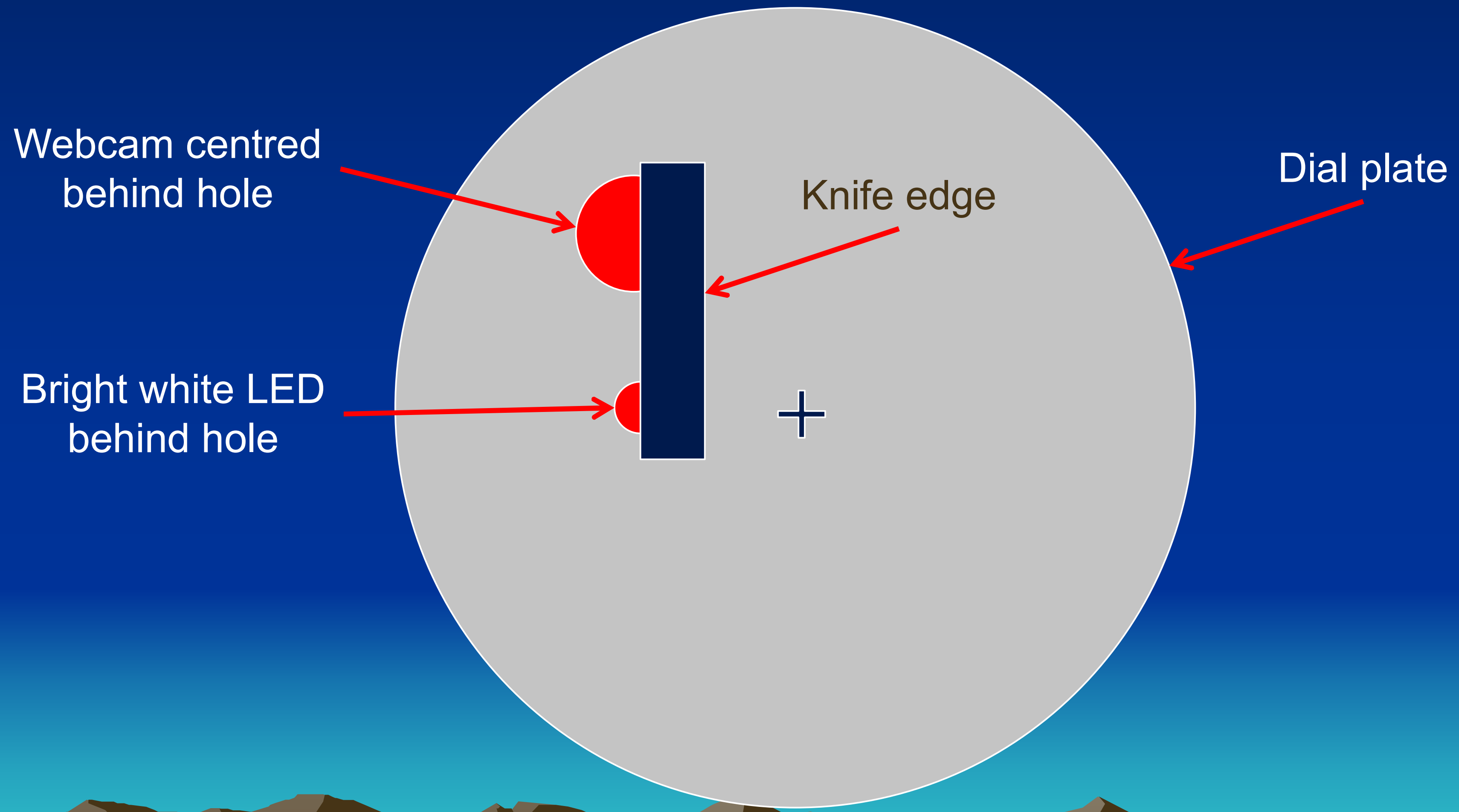
- Subsequently developed software (MirrorProfile) to take image pixel intensity profiles (quick, convenient and more objective and accurate).
- Improvement on Harold Suiter's method.
- Digital analysis of images provides other hidden information not visible to the human eye.


Slitless Foucault tester with webcam
Knife edge
Ronchi screen
Dial plate
Panning arm
LED
Longitudinal micrometer adjustment
Lateral KE adjustment
Stage moves longitudinally on a stainless steel rod

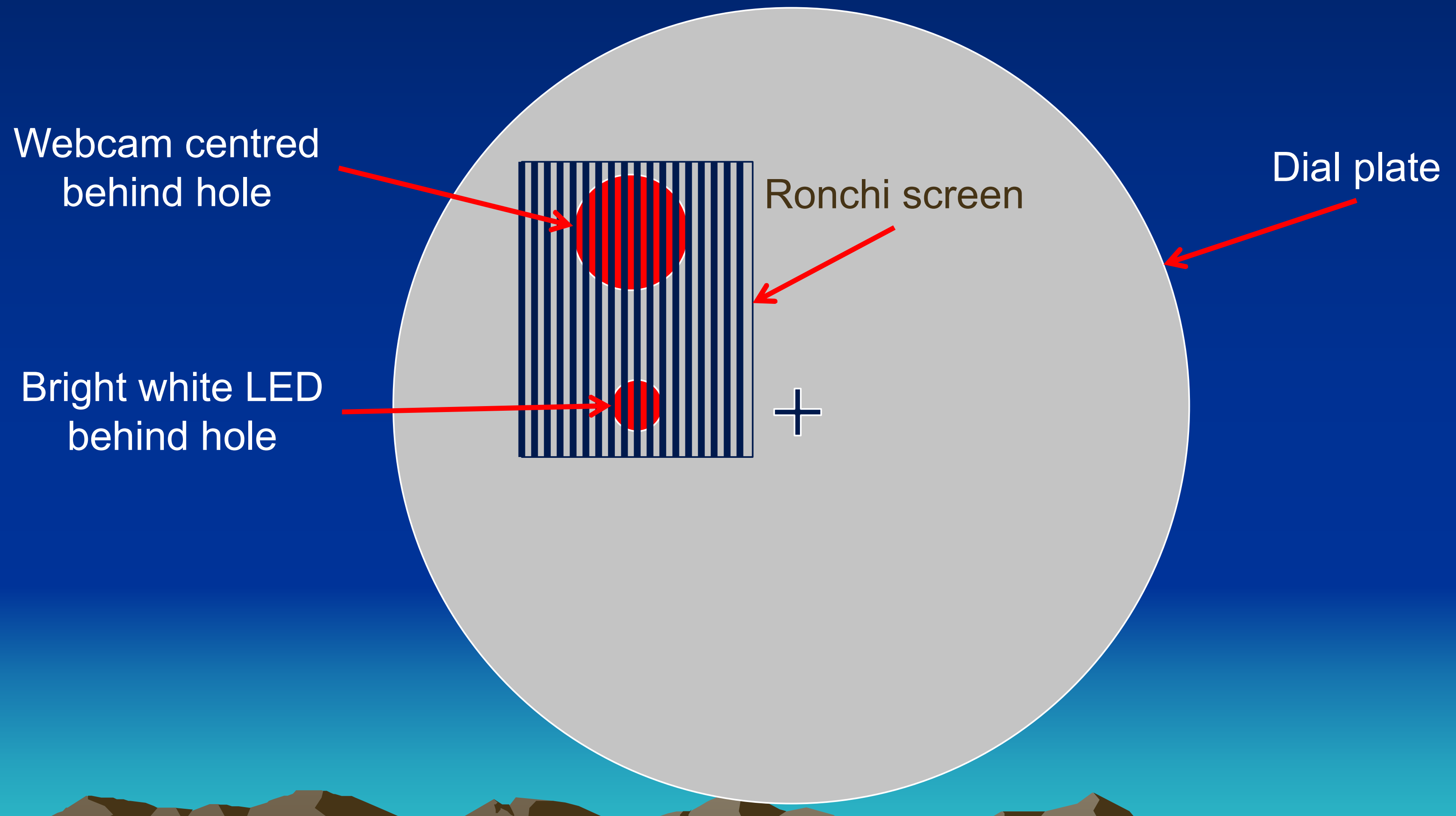
Slitless Foucault tester with webcam

Rear showing modified webcam behind
knife-edge.

Tester dial plate with KE



Tester dial plate with Ronchi screen

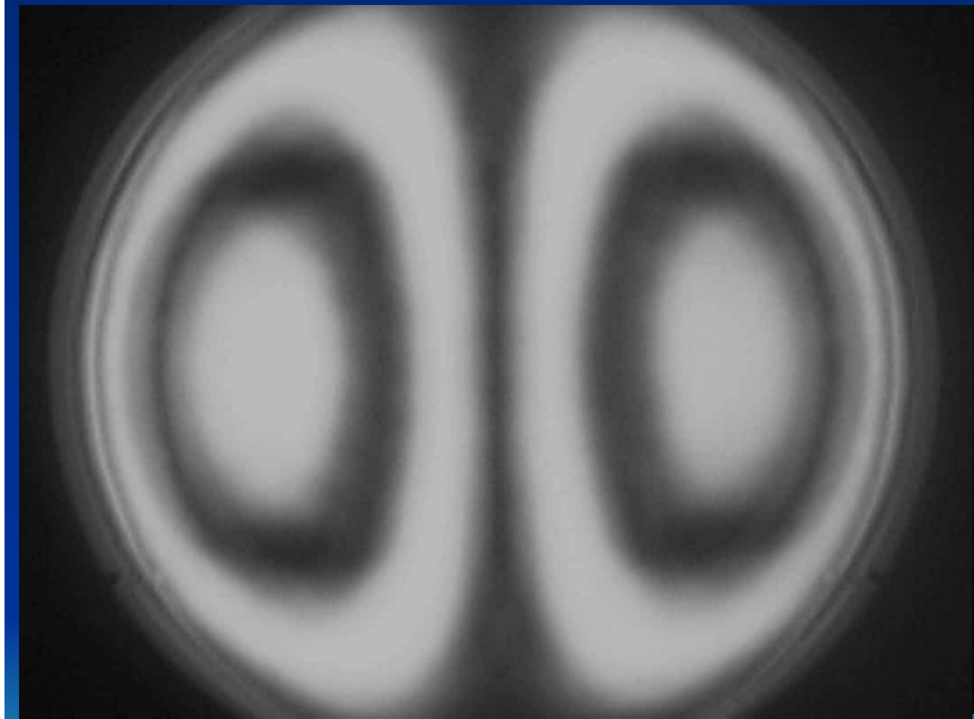


Testing mirror in telescope

Tailgate and flotation system

LA alignment with Ronchi screen

Nulling the outer zone



Nulling the inner zone

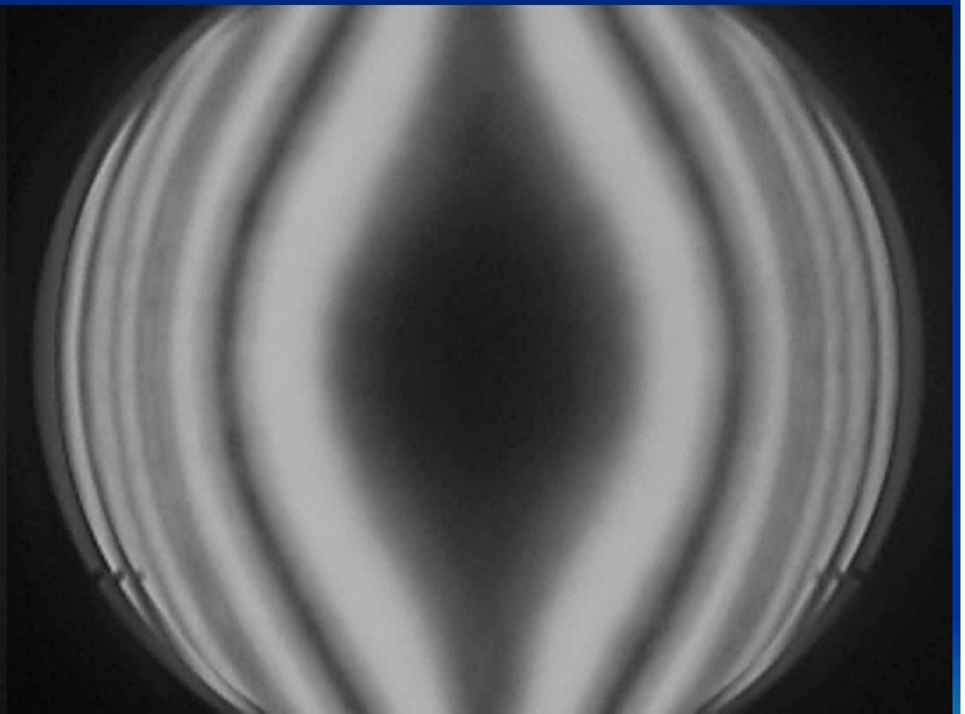
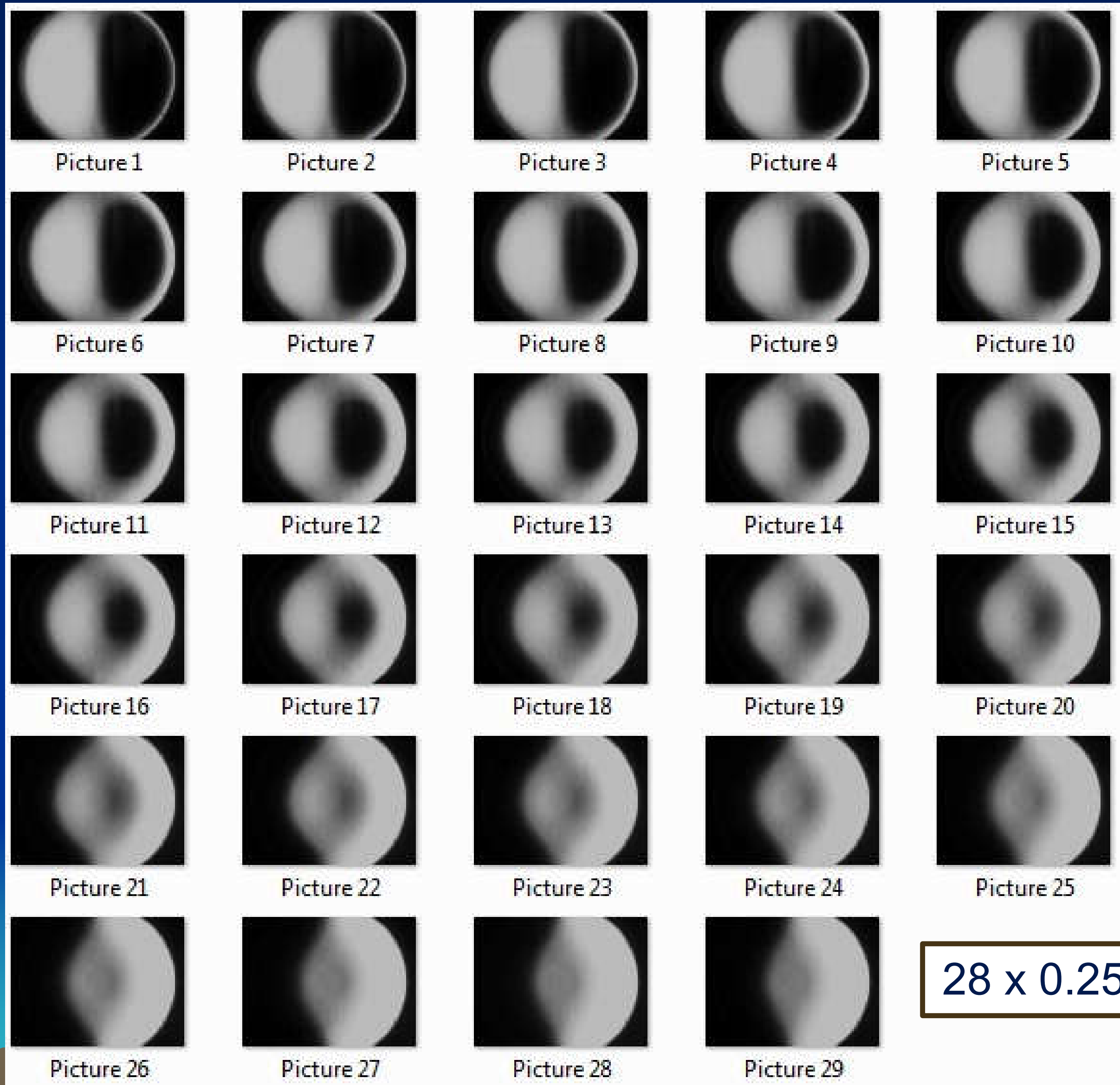


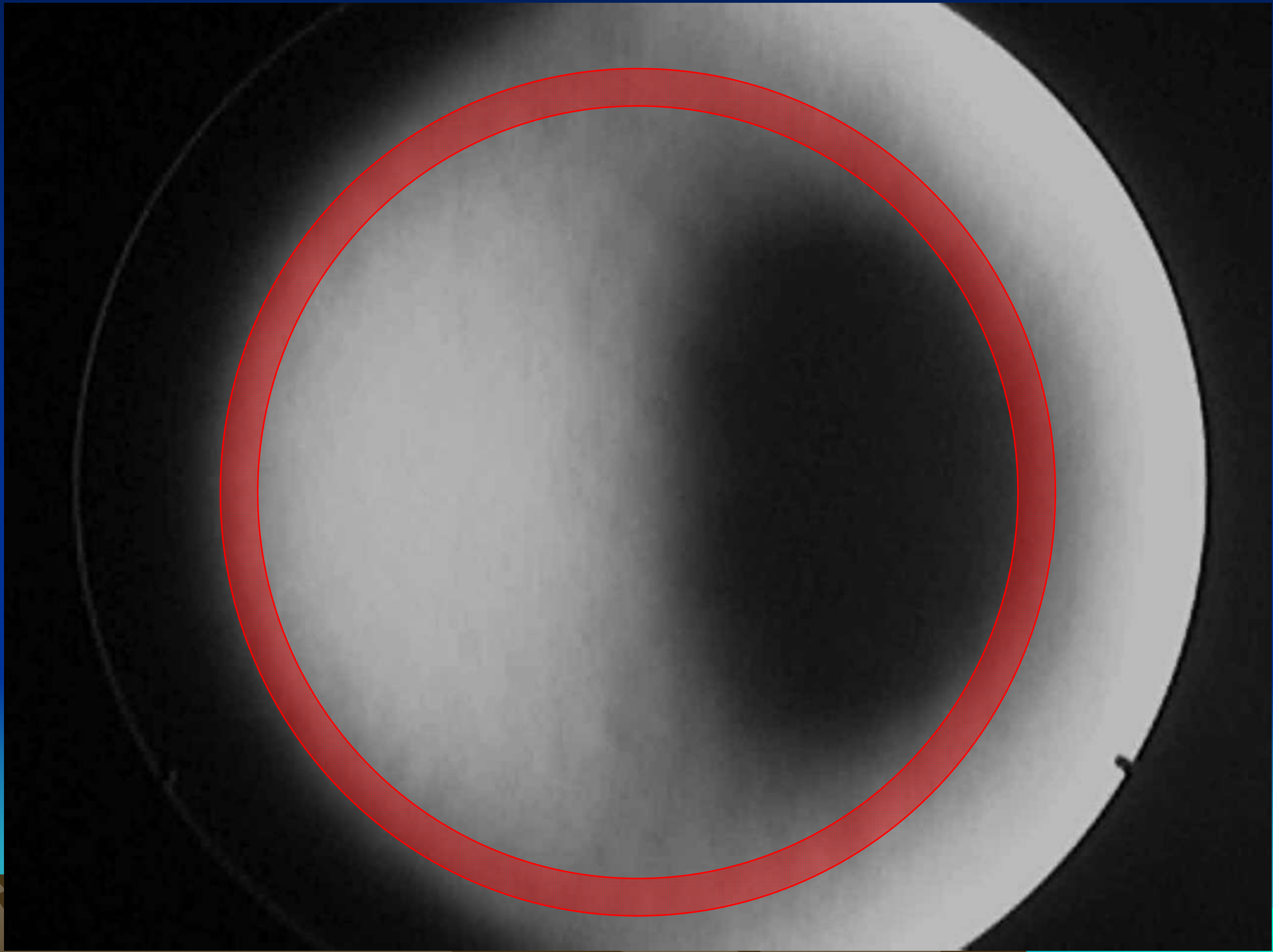
Image set for 20” F4.5 mirror



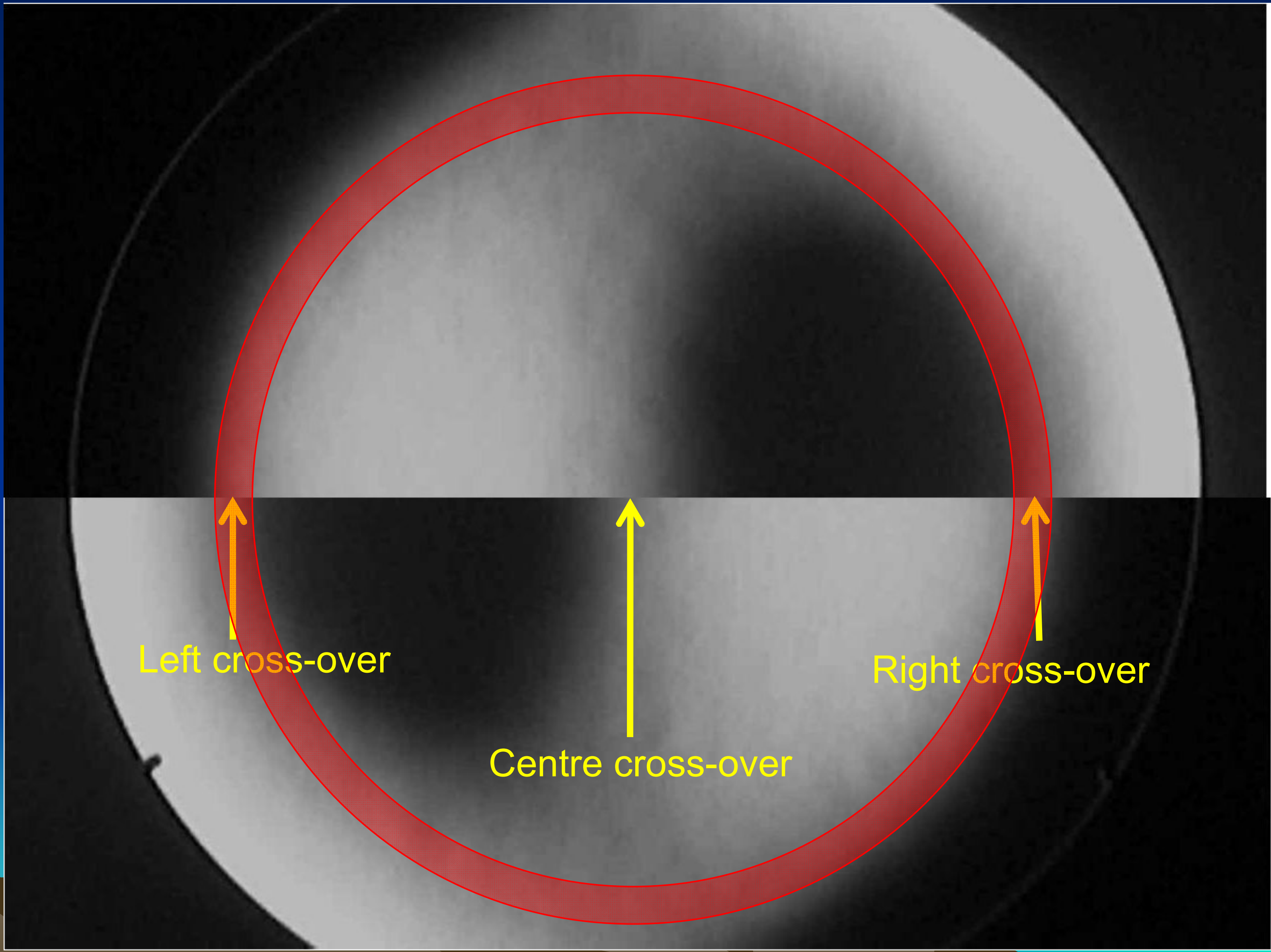
28 x 0.25 = 7 mm

Images taken at 0.010” (10 thou or 0.25 mm) intervals along longitudinal axis – takes less than 10 minutes for set of images

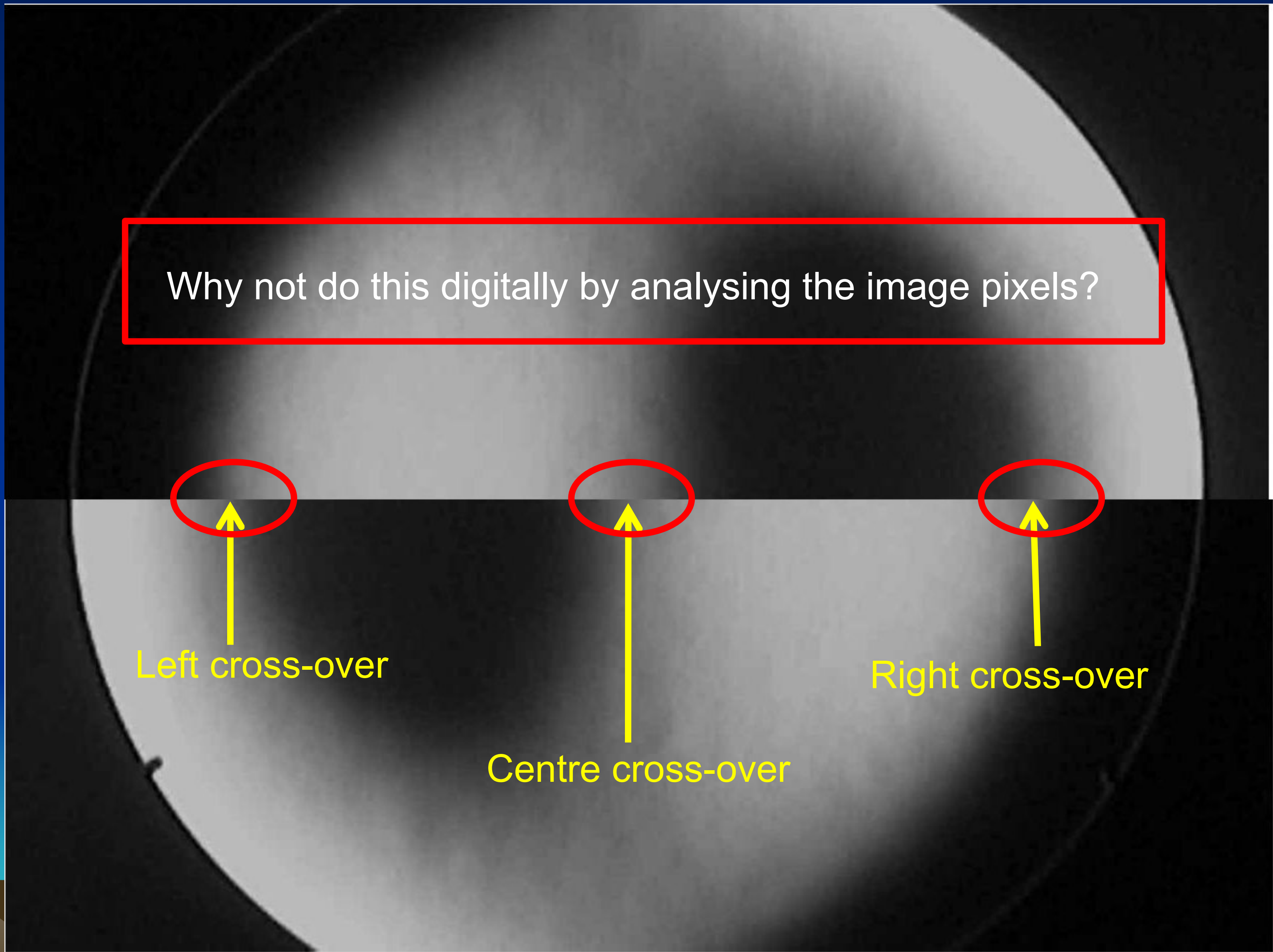
Typical Image



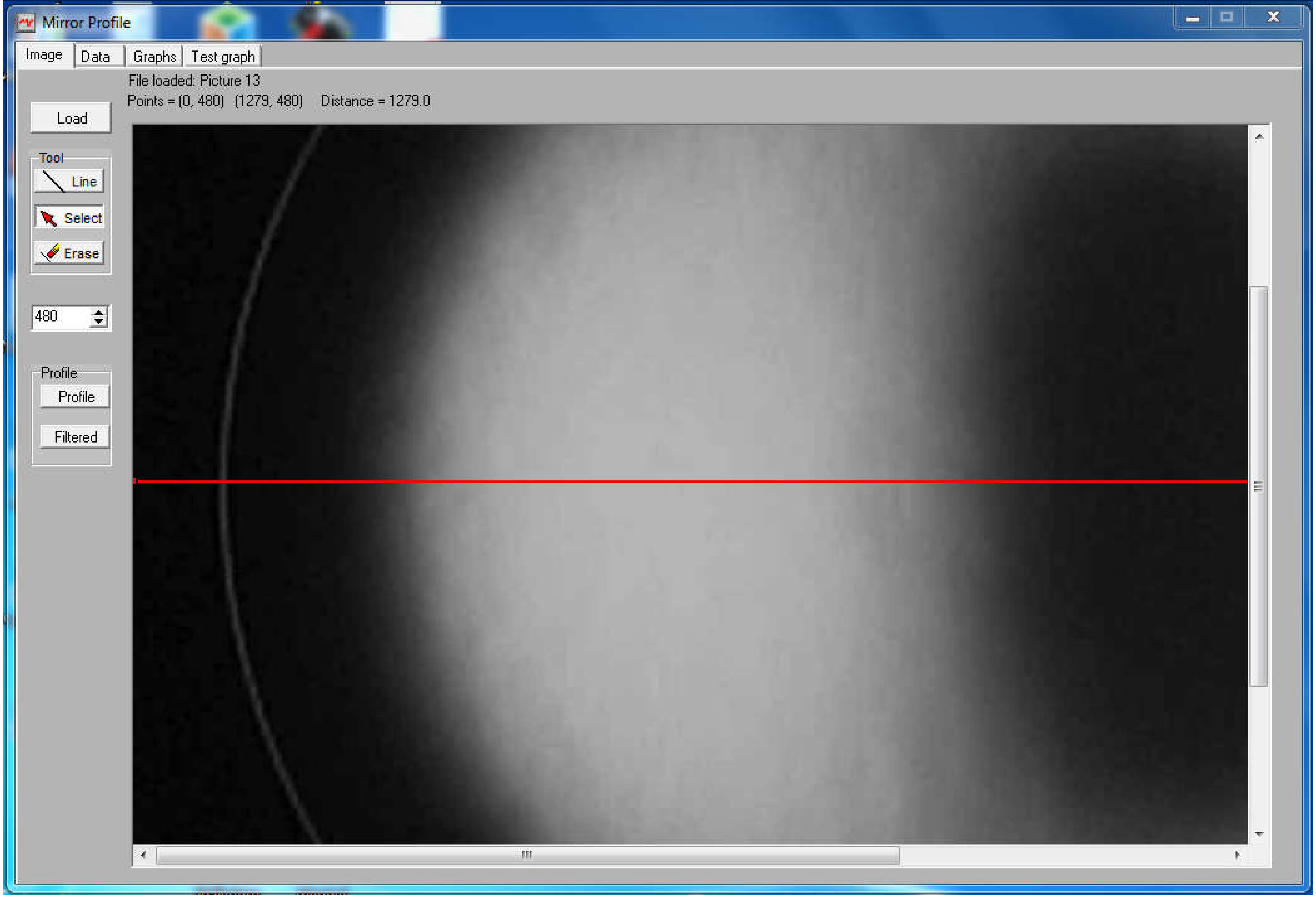
Split and splice



Splitting the Foucaultgram



Pixel profile through image centre



Pixel profile through image centre

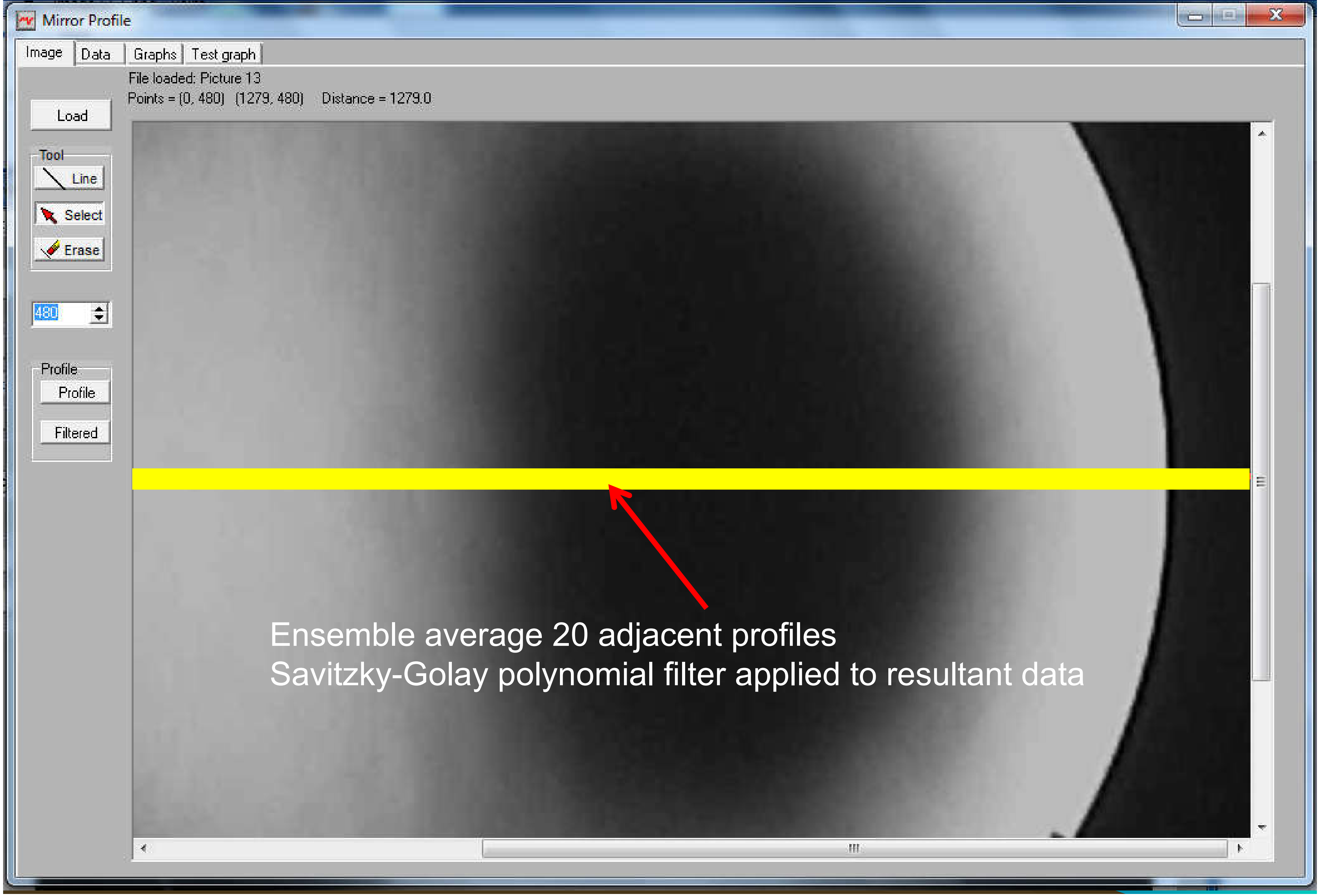


Image profile showing zone nulls

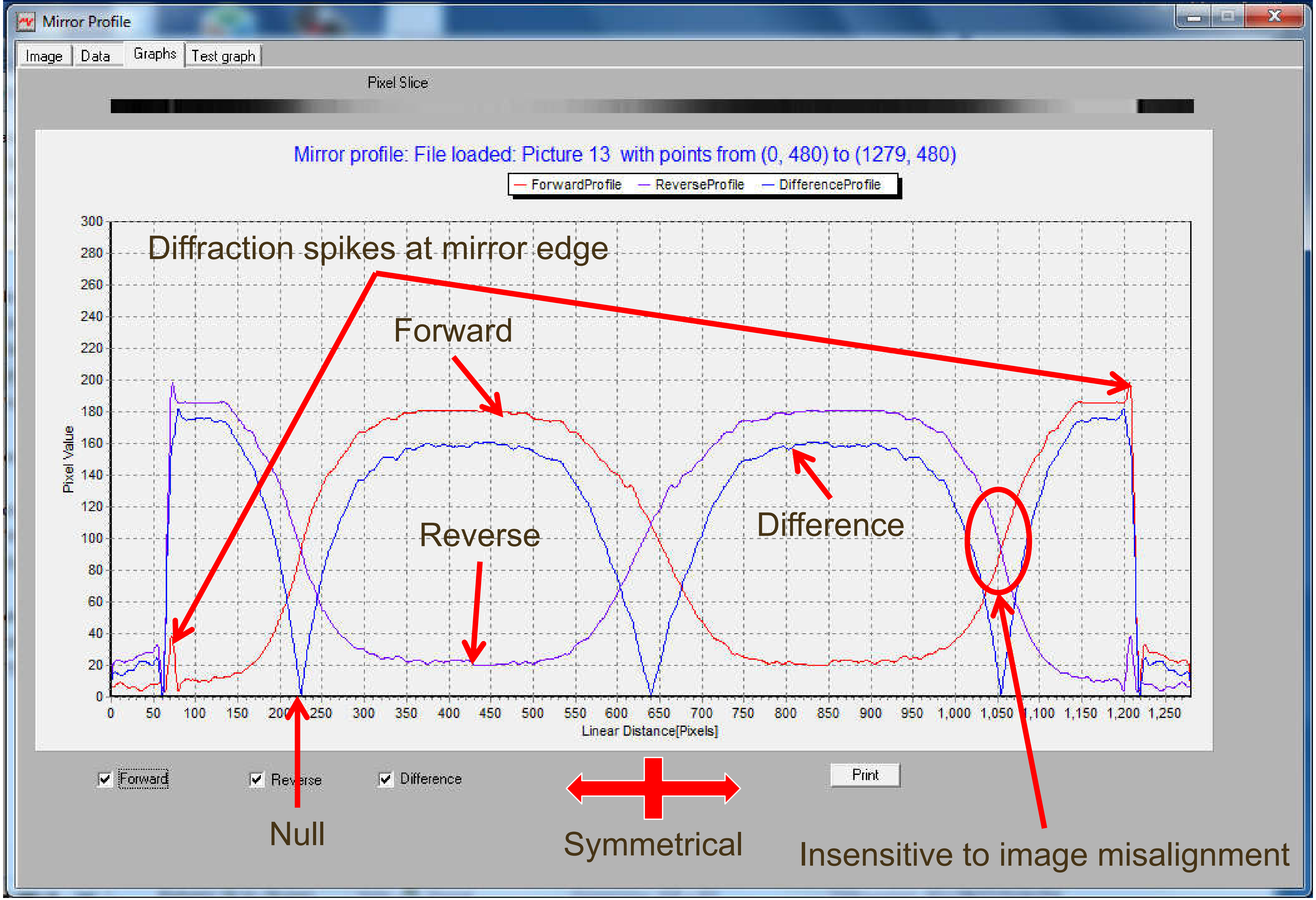
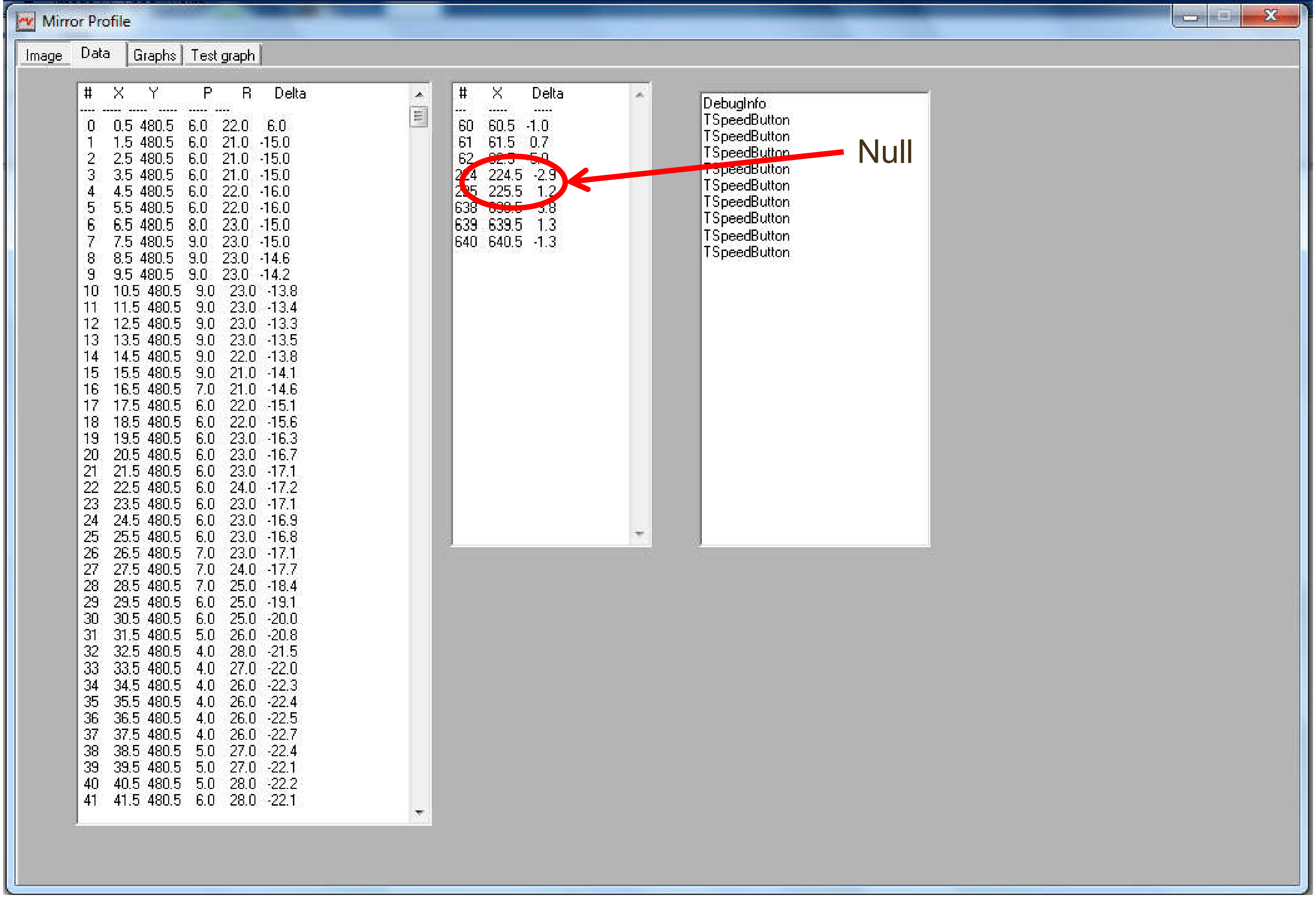


Image profile data



#	X	Y	P	R	Delta
0	0.5	480.5	6.0	22.0	6.0
1	1.5	480.5	6.0	21.0	-15.0
2	2.5	480.5	6.0	21.0	-15.0
3	3.5	480.5	6.0	21.0	-15.0
4	4.5	480.5	6.0	22.0	-16.0
5	5.5	480.5	6.0	22.0	-16.0
6	6.5	480.5	8.0	23.0	-15.0
7	7.5	480.5	9.0	23.0	-15.0
8	8.5	480.5	9.0	23.0	-14.6
9	9.5	480.5	9.0	23.0	-14.2
10	10.5	480.5	9.0	23.0	-13.8
11	11.5	480.5	9.0	23.0	-13.4
12	12.5	480.5	9.0	23.0	-13.3
13	13.5	480.5	9.0	23.0	-13.5
14	14.5	480.5	9.0	22.0	-13.8
15	15.5	480.5	9.0	21.0	-14.1
16	16.5	480.5	7.0	21.0	-14.6
17	17.5	480.5	6.0	22.0	-15.1
18	18.5	480.5	6.0	22.0	-15.6
19	19.5	480.5	6.0	23.0	-16.3
20	20.5	480.5	6.0	23.0	-16.7
21	21.5	480.5	6.0	23.0	-17.1
22	22.5	480.5	6.0	24.0	-17.2
23	23.5	480.5	6.0	23.0	-17.1
24	24.5	480.5	6.0	23.0	-16.9
25	25.5	480.5	6.0	23.0	-16.8
26	26.5	480.5	7.0	23.0	-17.1
27	27.5	480.5	7.0	24.0	-17.7
28	28.5	480.5	7.0	25.0	-18.4
29	29.5	480.5	6.0	25.0	-19.1
30	30.5	480.5	6.0	25.0	-20.0
31	31.5	480.5	5.0	26.0	-20.8
32	32.5	480.5	4.0	28.0	-21.5
33	33.5	480.5	4.0	27.0	-22.0
34	34.5	480.5	4.0	26.0	-22.3
35	35.5	480.5	4.0	26.0	-22.4
36	36.5	480.5	4.0	26.0	-22.5
37	37.5	480.5	4.0	26.0	-22.7
38	38.5	480.5	5.0	27.0	-22.4
39	39.5	480.5	5.0	27.0	-22.1
40	40.5	480.5	5.0	28.0	-22.2
41	41.5	480.5	6.0	28.0	-22.1

#	X	Delta
60	60.5	-1.0
61	61.5	0.7
62	62.5	5.0
224	224.5	-2.9
225	225.5	1.2
638	638.5	3.8
639	639.5	1.3
640	640.5	-1.3

DebugInfo
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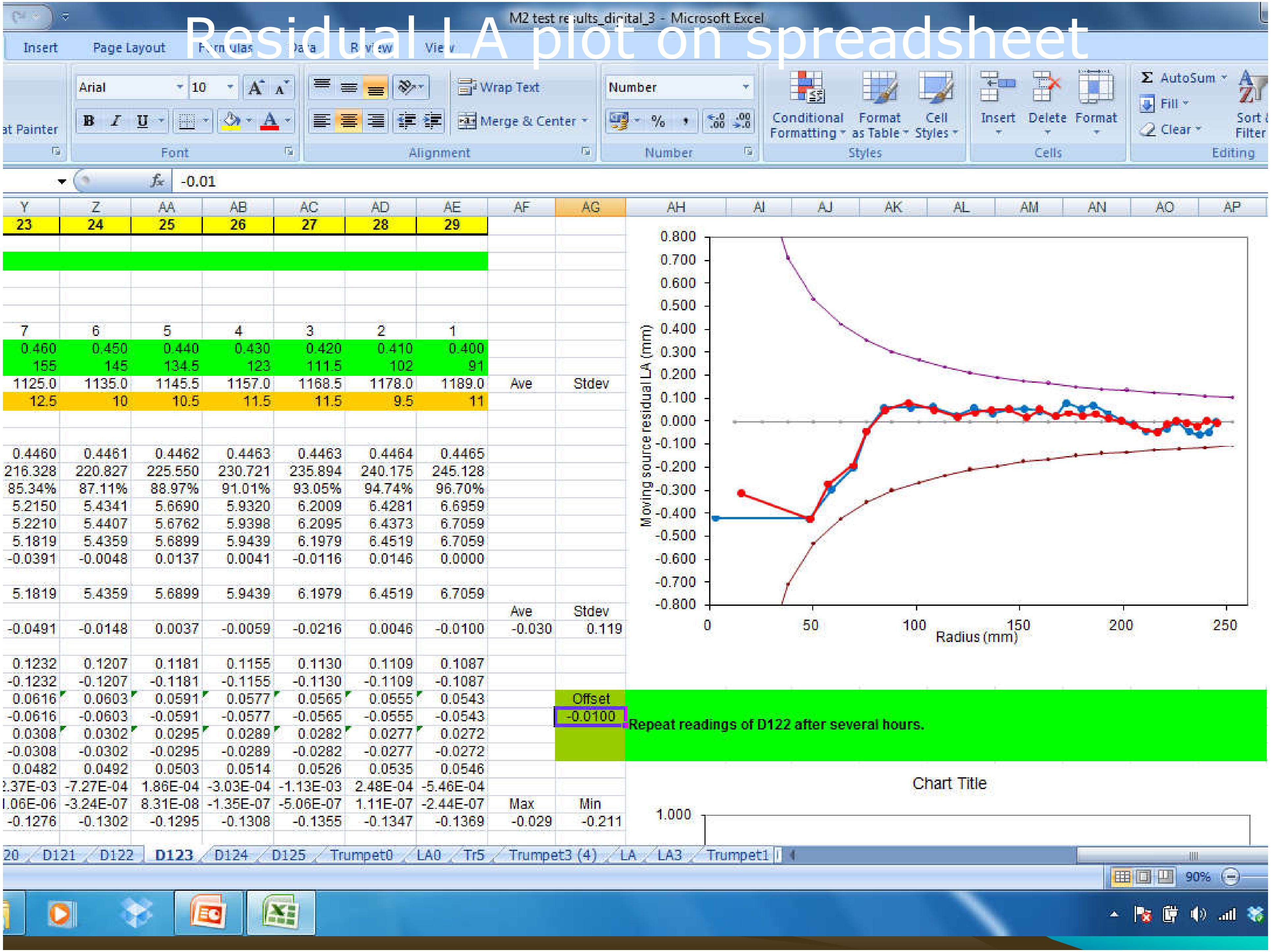
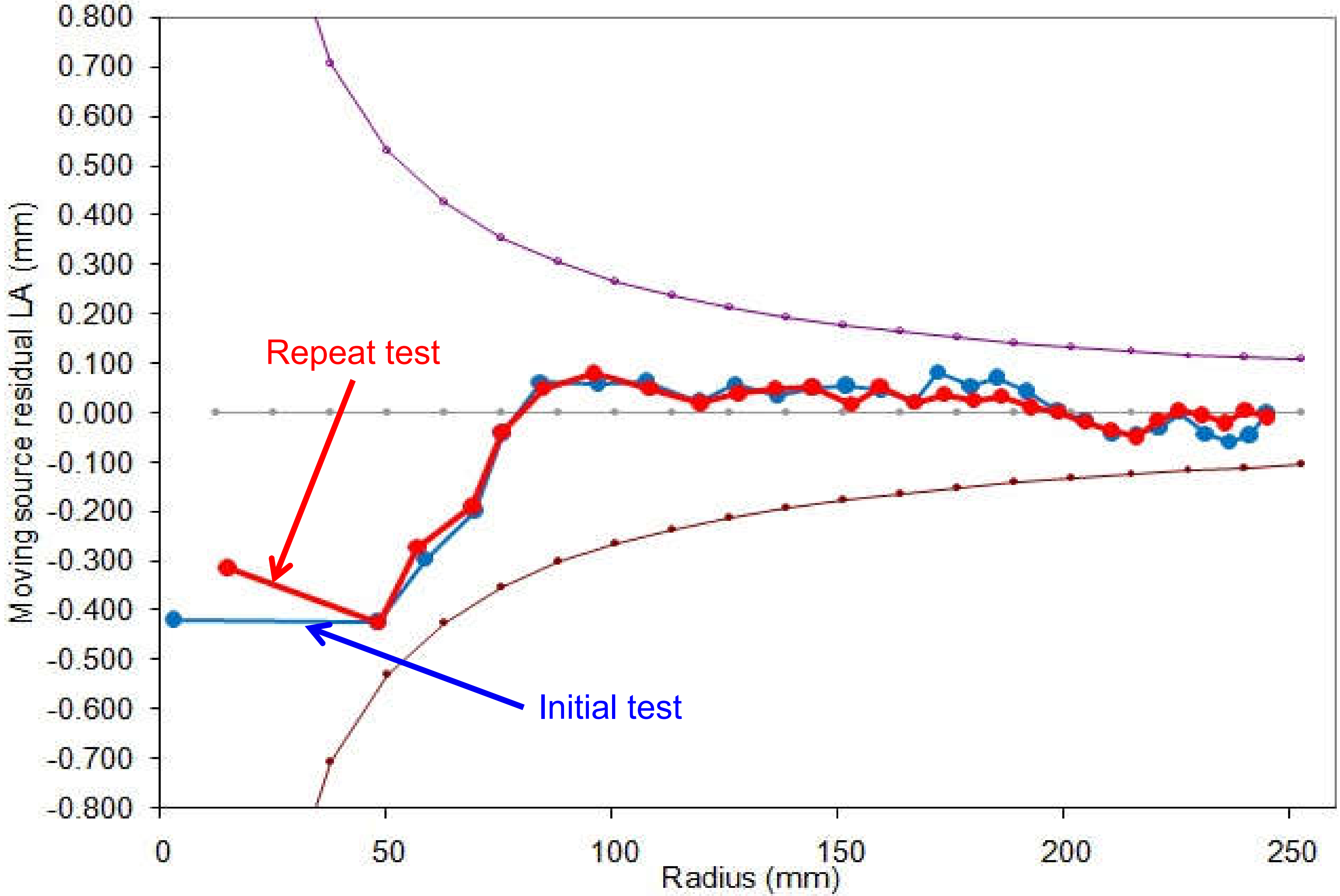
Residual LA plot on spreadsheet

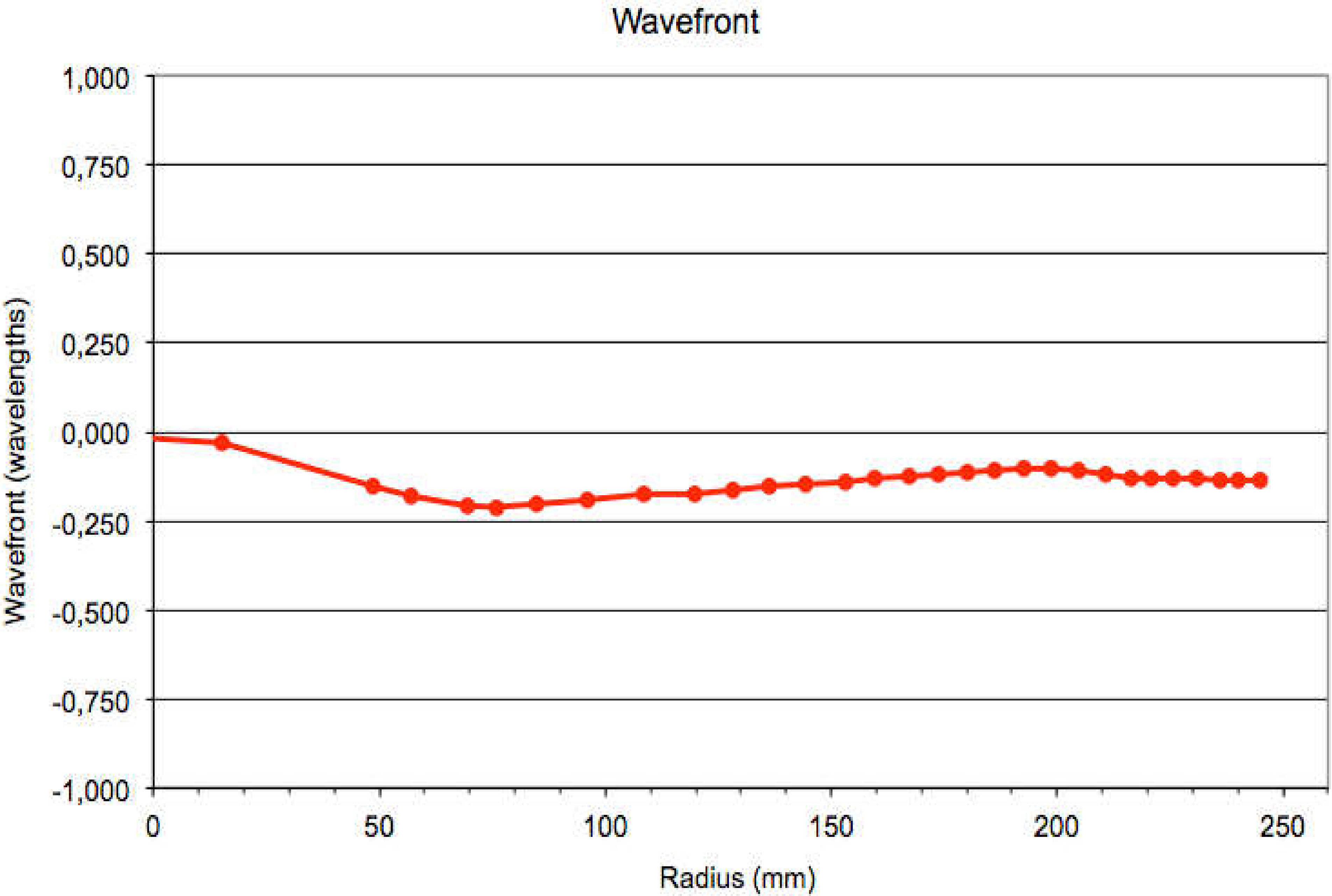


Y	Z	AA	AB	AC	AD	AE	AF	AG
23	24	25	26	27	28	29		
7	6	5	4	3	2	1		
0.460	0.450	0.440	0.430	0.420	0.410	0.400		
155	145	134.5	123	111.5	102	91		
1125.0	1135.0	1145.5	1157.0	1168.5	1178.0	1189.0	Ave	Stdev
12.5	10	10.5	11.5	11.5	9.5	11		
0.4460	0.4461	0.4462	0.4463	0.4463	0.4464	0.4465		
216.328	220.827	225.550	230.721	235.894	240.175	245.128		
85.34%	87.11%	88.97%	91.01%	93.05%	94.74%	96.70%		
5.2150	5.4341	5.6690	5.9320	6.2009	6.4281	6.6959		
5.2210	5.4407	5.6762	5.9398	6.2095	6.4373	6.7059		
5.1819	5.4359	5.6899	5.9439	6.1979	6.4519	6.7059		
-0.0391	-0.0048	0.0137	0.0041	-0.0116	0.0146	0.0000		
5.1819	5.4359	5.6899	5.9439	6.1979	6.4519	6.7059		
							Ave	Stdev
-0.0491	-0.0148	0.0037	-0.0059	-0.0216	0.0046	-0.0100	-0.030	0.119
0.1232	0.1207	0.1181	0.1155	0.1130	0.1109	0.1087		
-0.1232	-0.1207	-0.1181	-0.1155	-0.1130	-0.1109	-0.1087		
0.0616	0.0603	0.0591	0.0577	0.0565	0.0555	0.0543		Offset
-0.0616	-0.0603	-0.0591	-0.0577	-0.0565	-0.0555	-0.0543		-0.0100
0.0308	0.0302	0.0295	0.0289	0.0282	0.0277	0.0272		
-0.0308	-0.0302	-0.0295	-0.0289	-0.0282	-0.0277	-0.0272		
0.0482	0.0492	0.0503	0.0514	0.0526	0.0535	0.0546		
.37E-03	-7.27E-04	1.86E-04	-3.03E-04	-1.13E-03	2.48E-04	-5.46E-04		
.06E-06	-3.24E-07	8.31E-08	-1.35E-07	-5.06E-07	1.11E-07	-2.44E-07	Max	Min
-0.1276	-0.1302	-0.1295	-0.1308	-0.1355	-0.1347	-0.1369	-0.029	-0.211

Moving source residual LA



Wavefront analysis

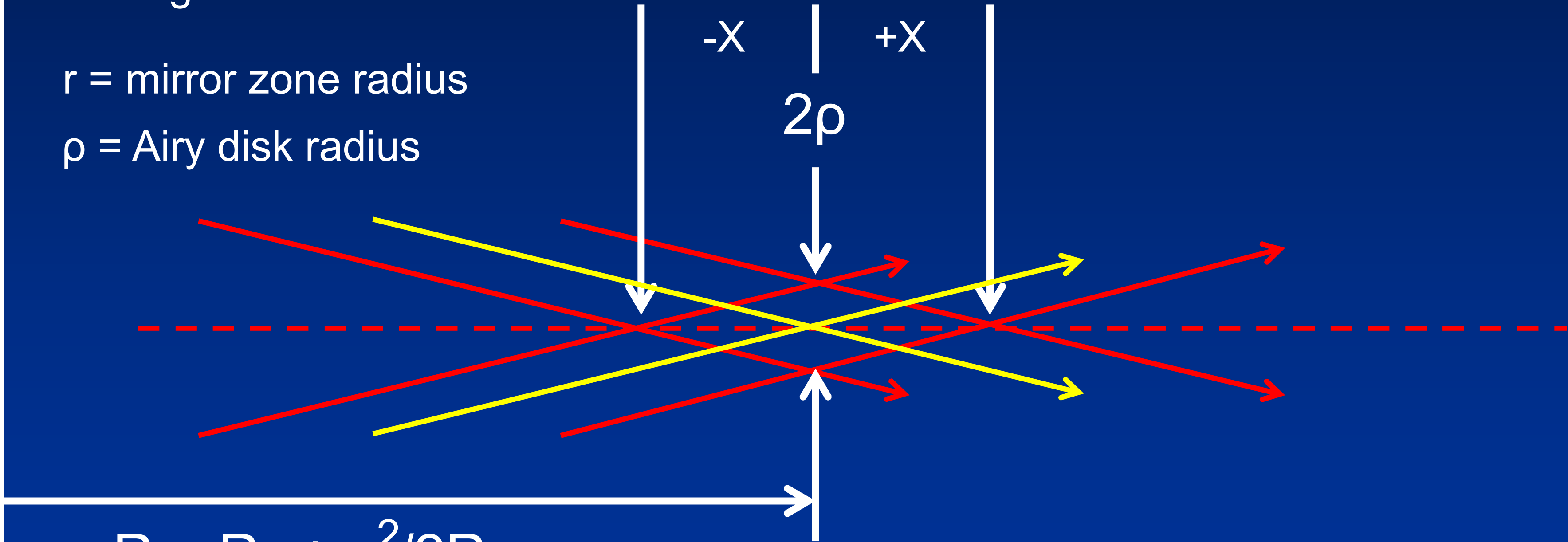


Tolerance mask

Moving source case

r = mirror zone radius

ρ = Airy disk radius



$R = R_o + r^2/2R_o$

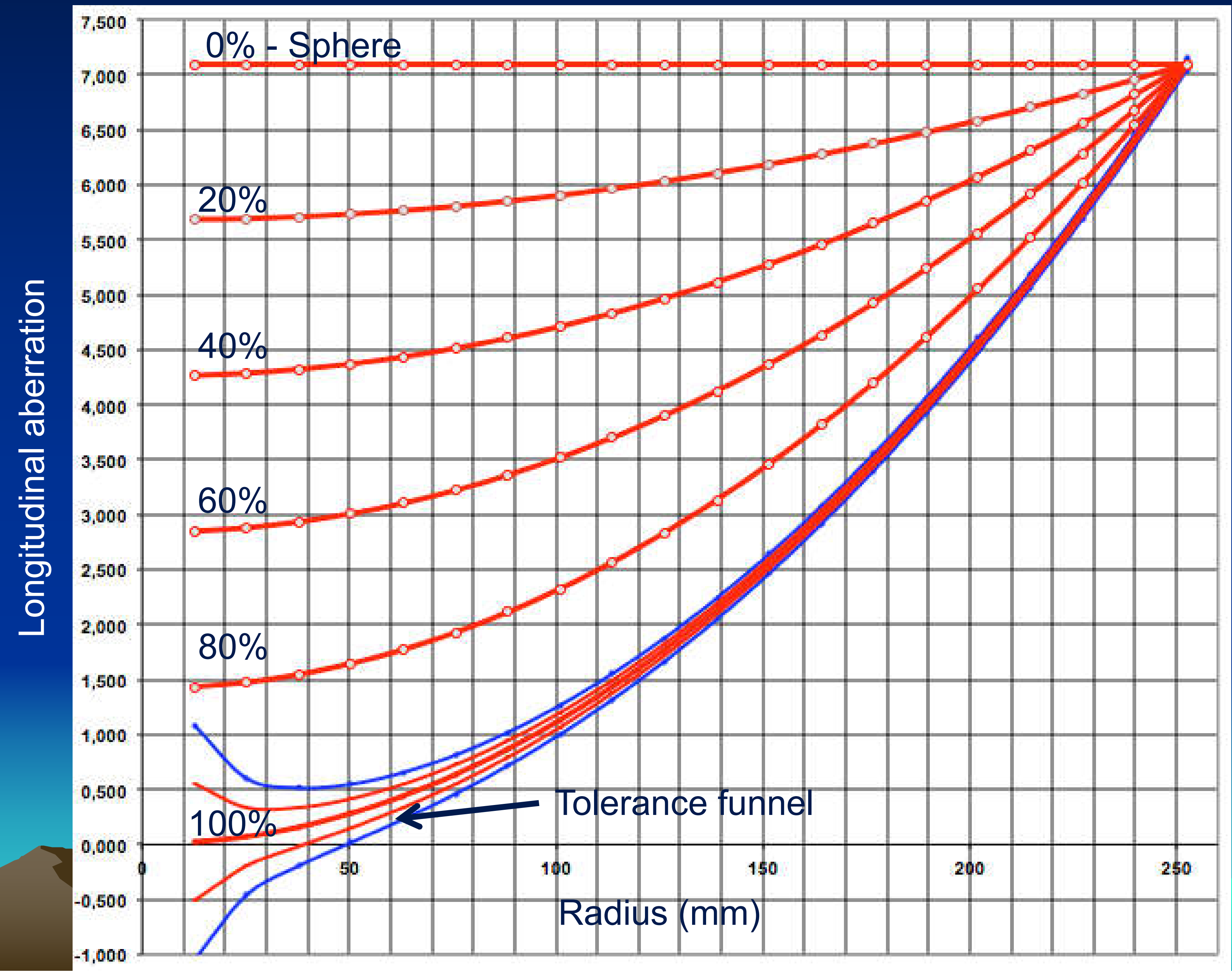
$X/\rho \approx R/r$

$X = \rho R/r$ "Easy" tolerance

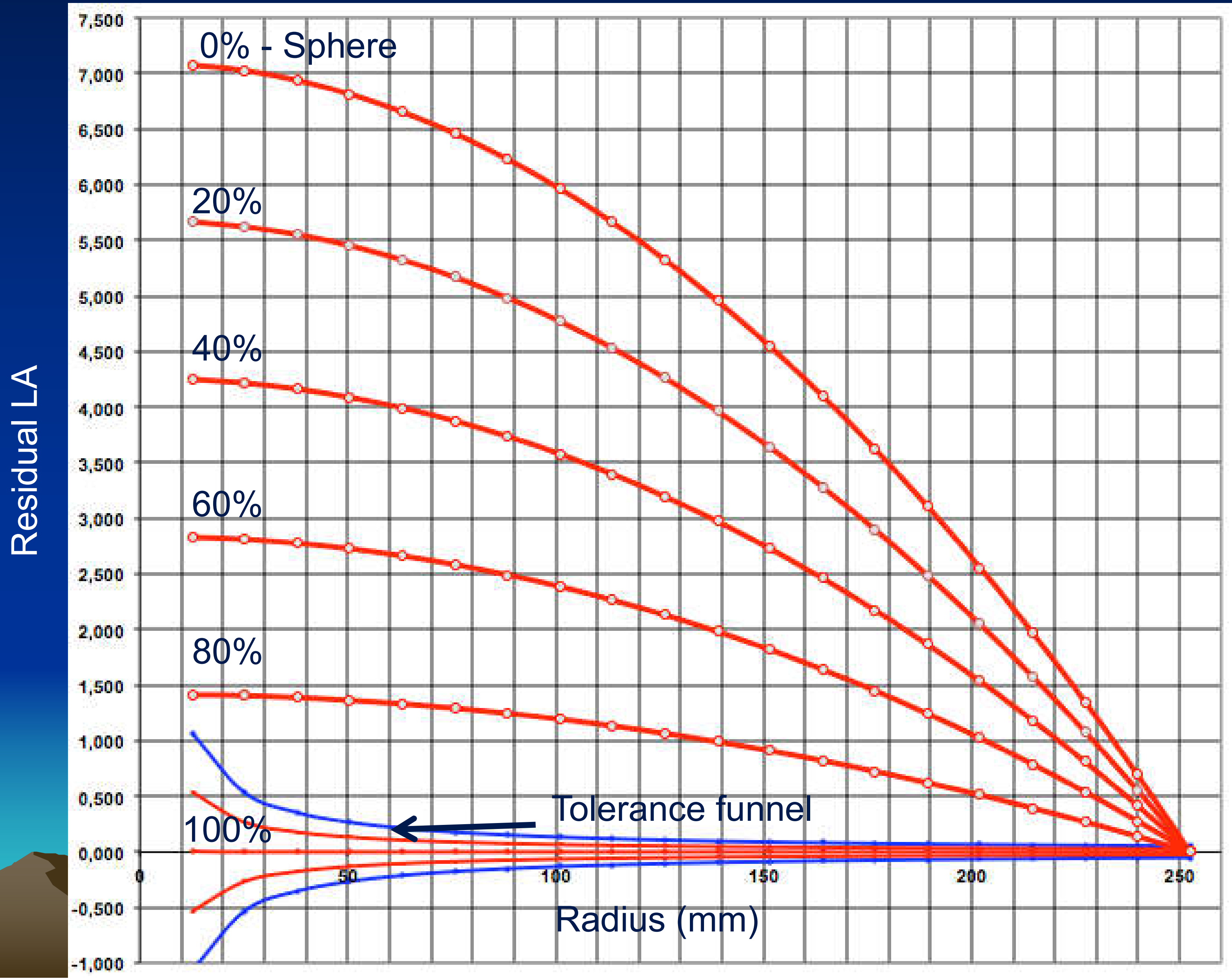
$X = \rho R/2r$ Demanding tolerance

Originally proposed by Adrien Milles-Lacroix (M-L mask)

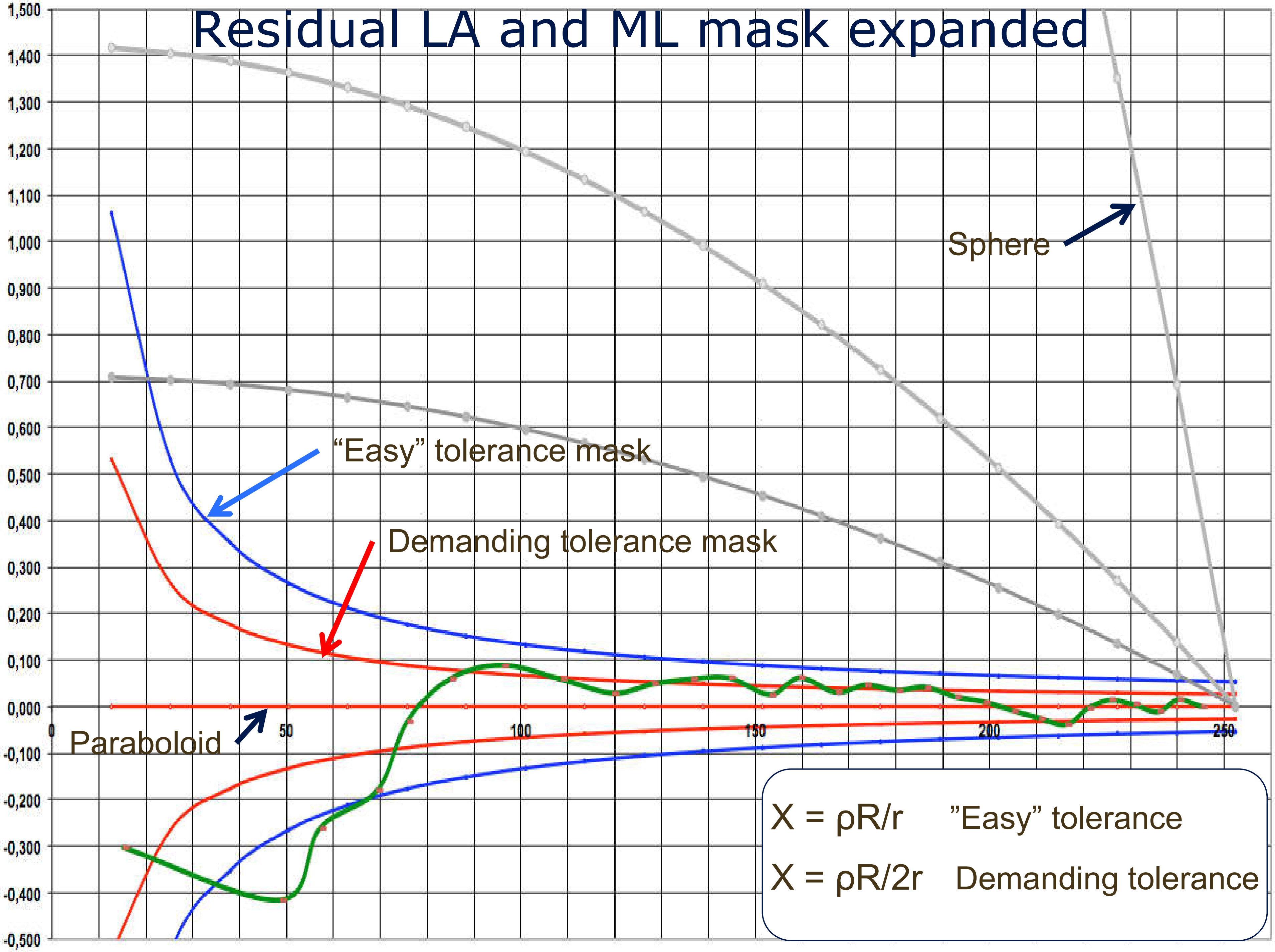
LA and ML mask



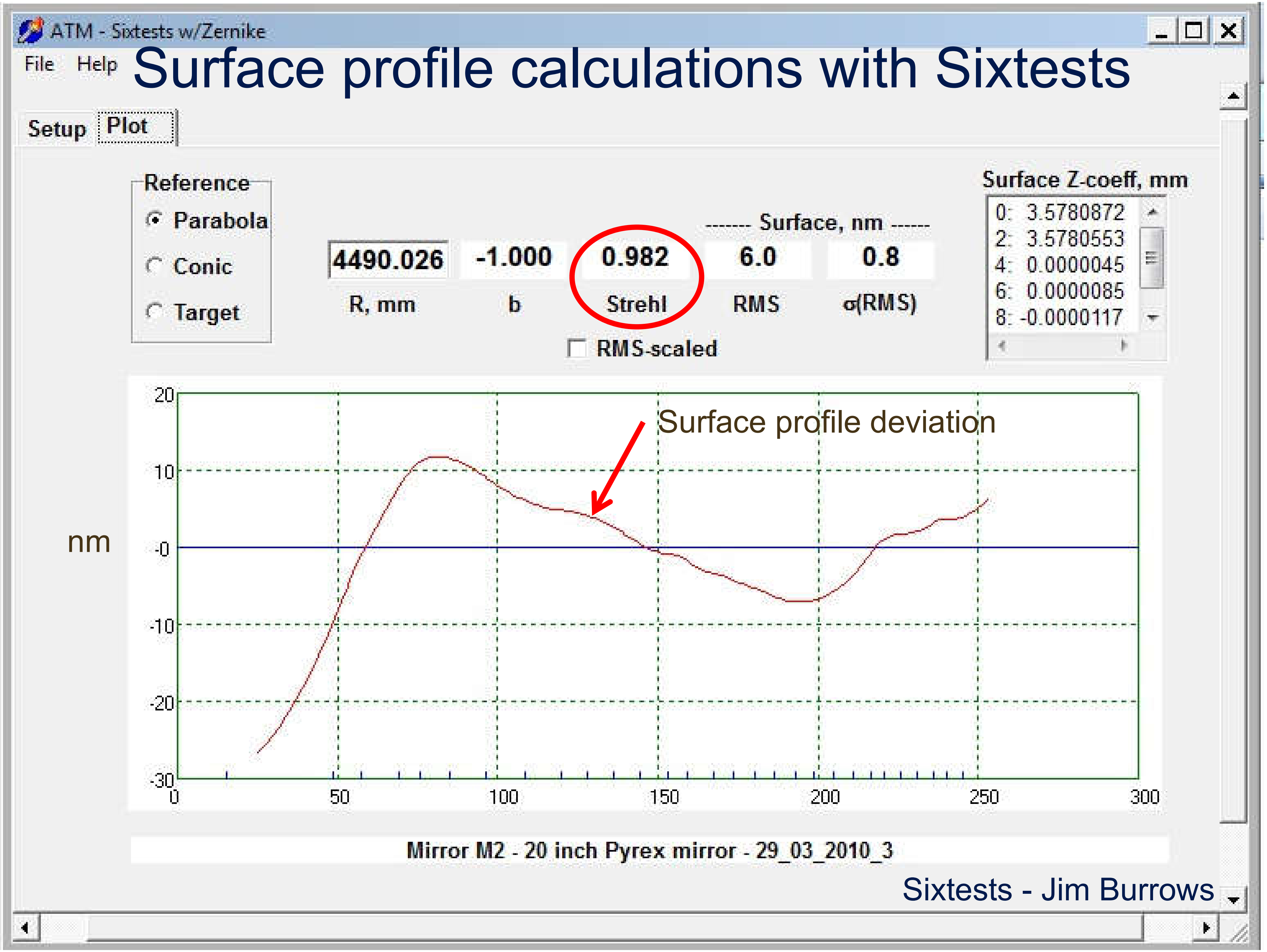
Residual LA and ML mask



Residual LA and ML mask expanded

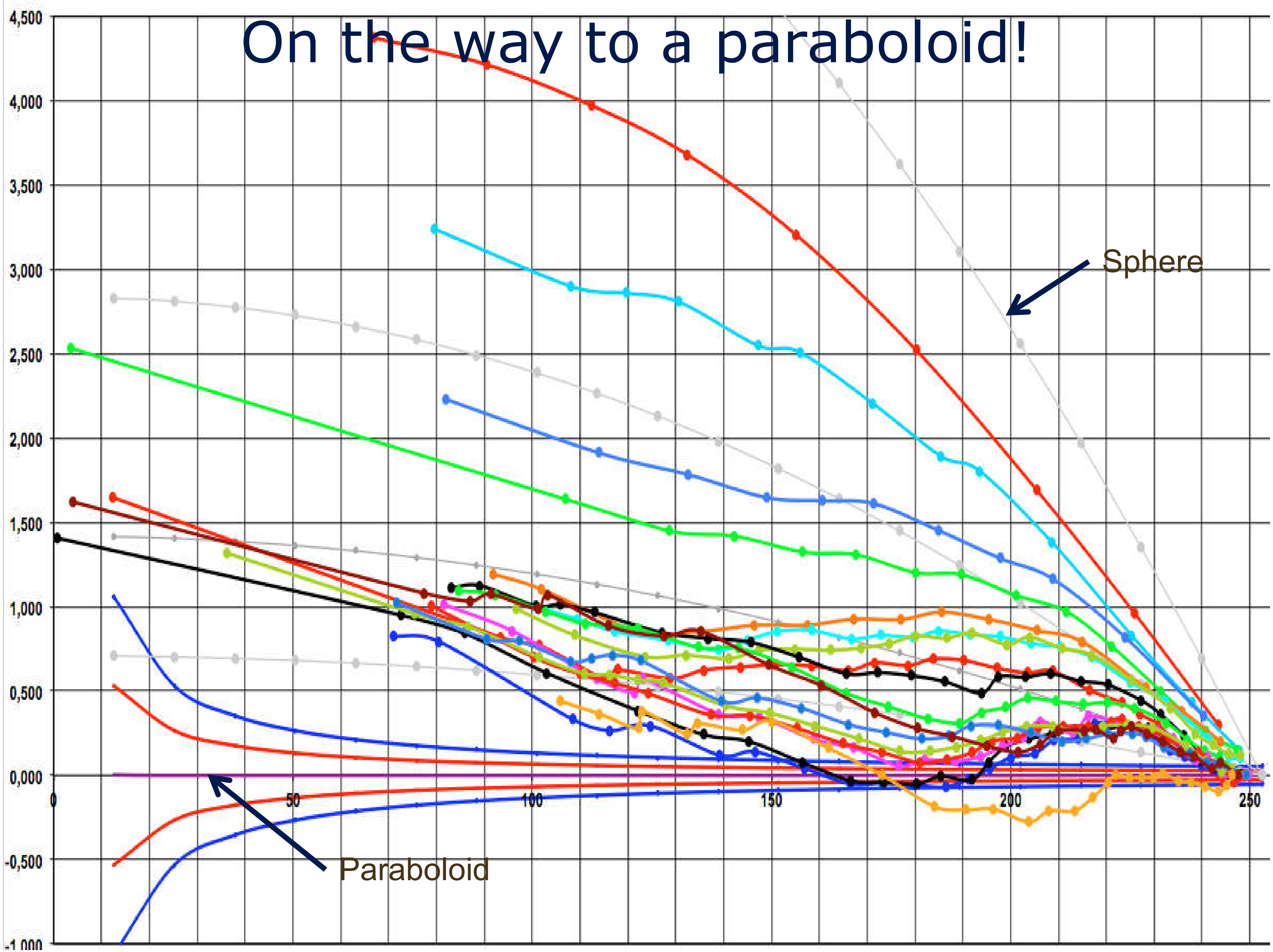


Surface profile calculations with Sixtests

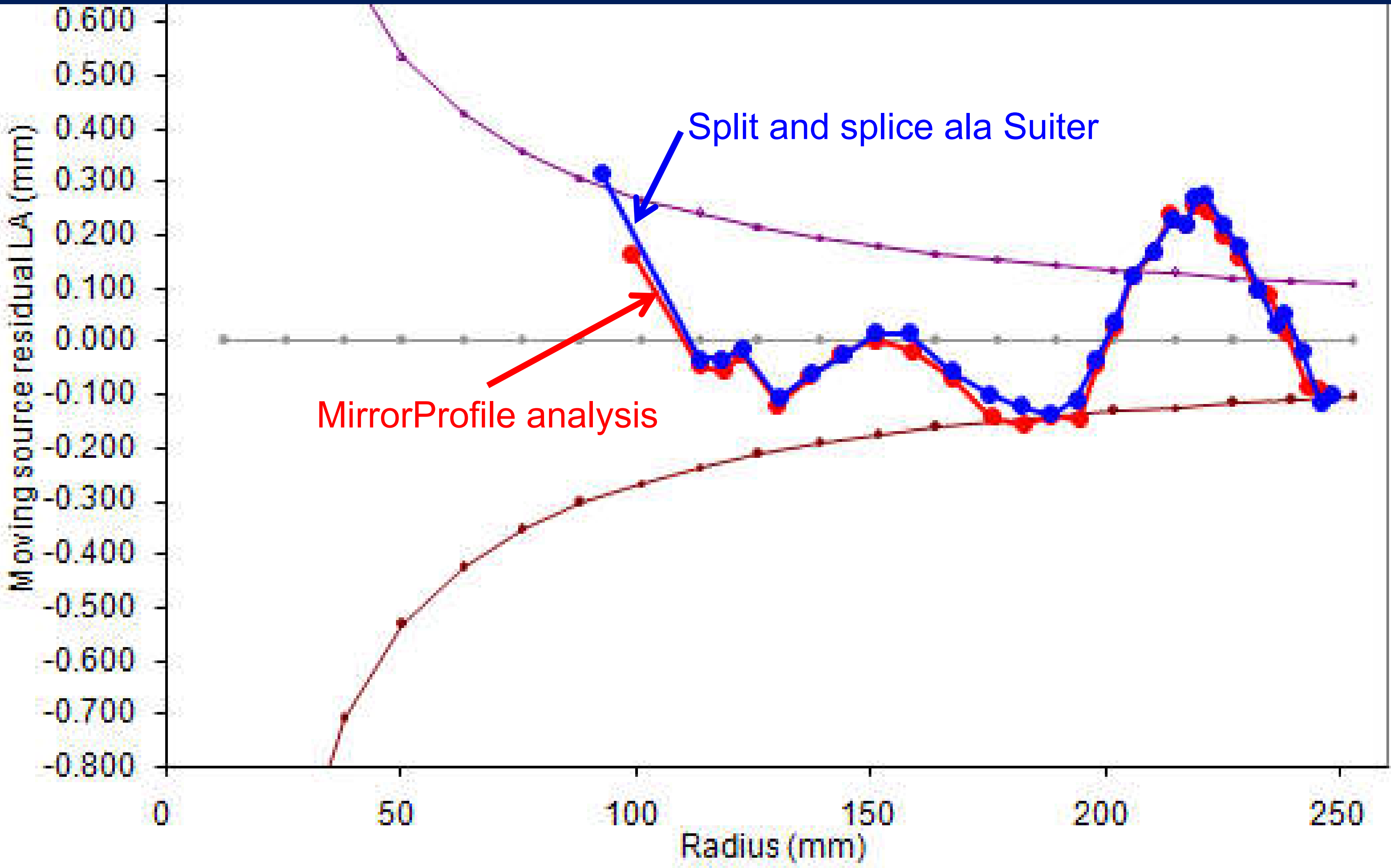


Sixtests - Jim Burrows

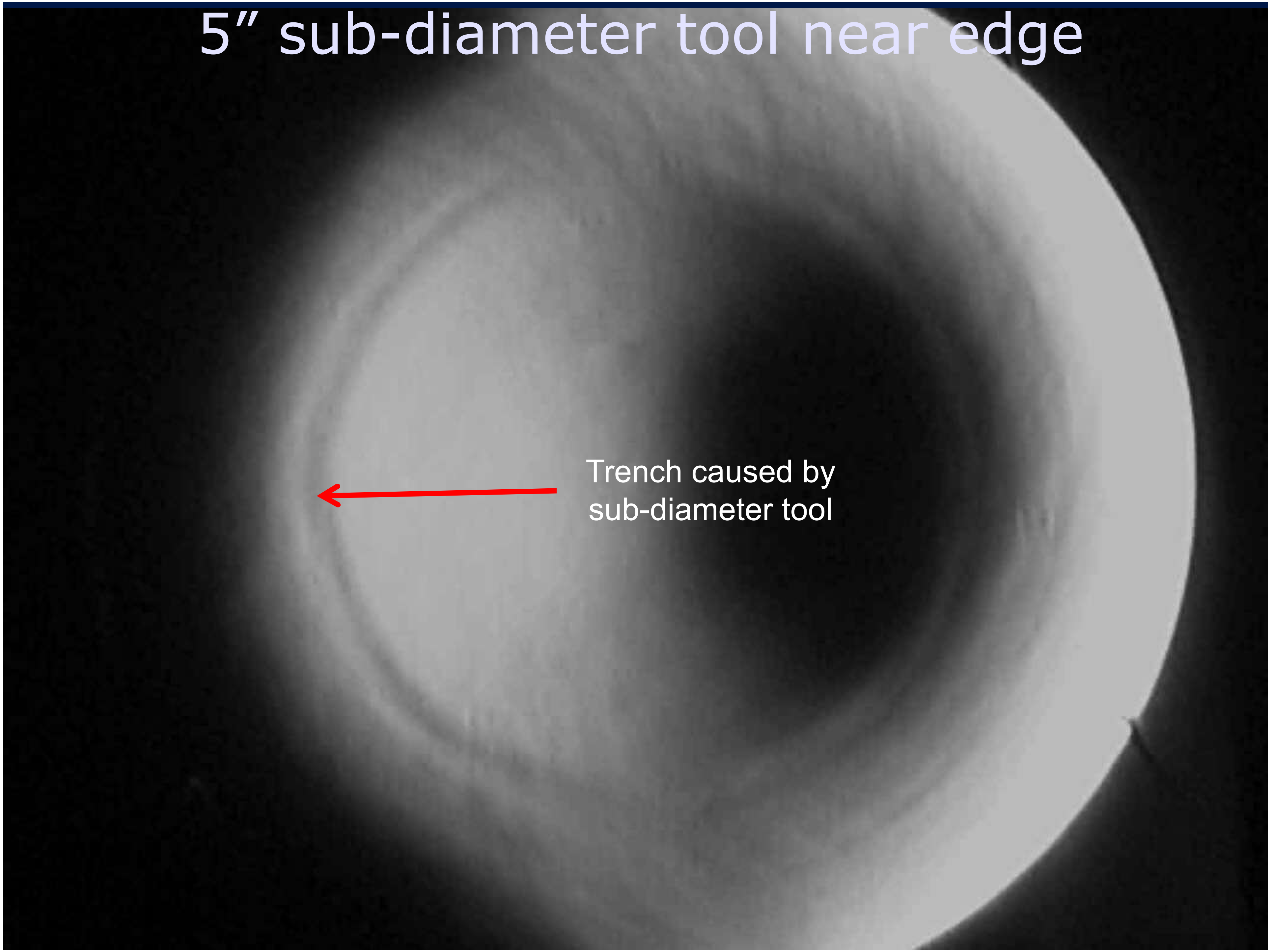
On the way to a paraboloid!



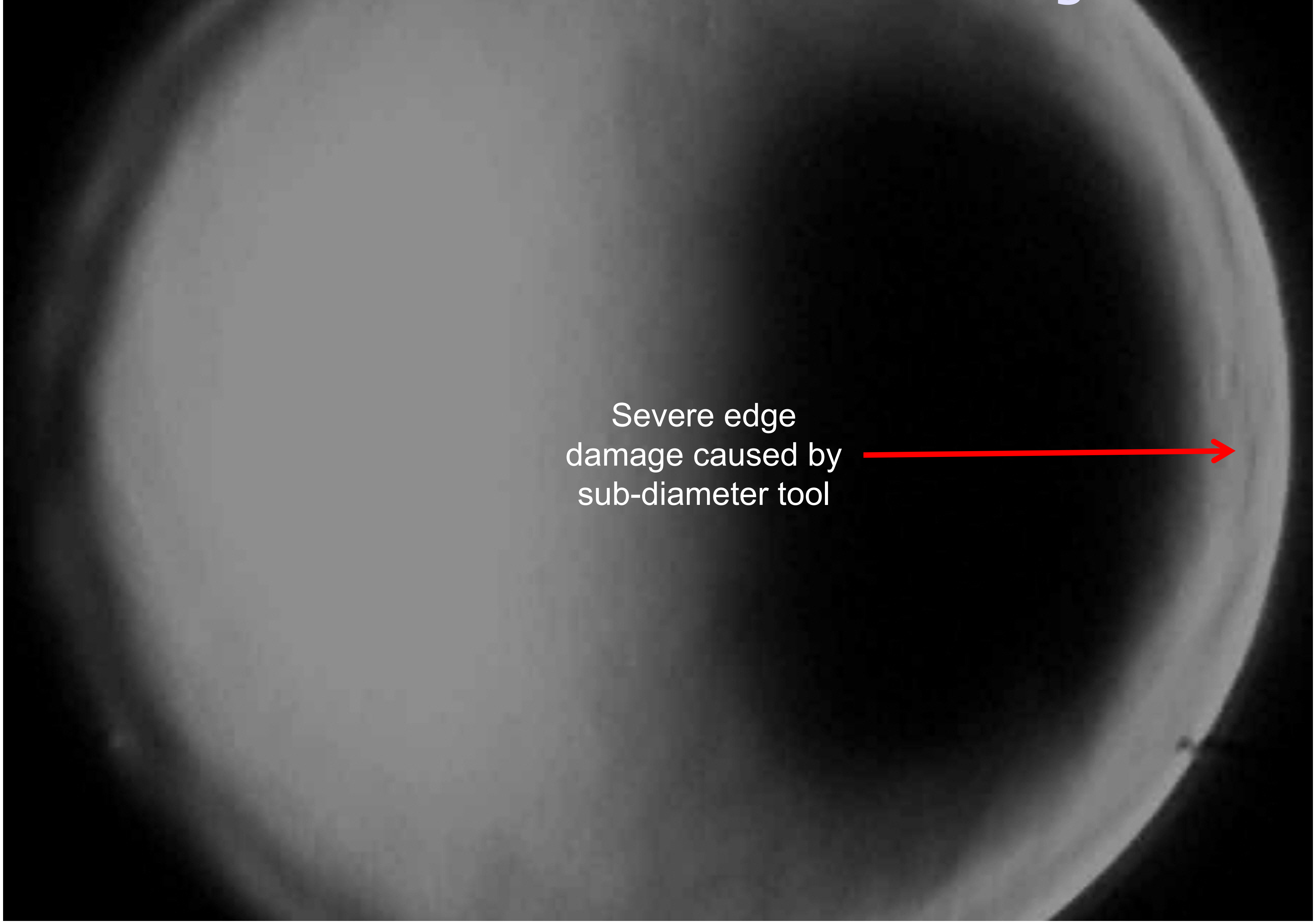
Comparison of two methods



5” sub-diameter tool near edge



5″ sub-diameter tool near edge



Thank you!

If you have any questions or want more info you are welcome to:

- Confront me during the course of the symposium
- Contact me on jgfswanepoel@gmail.com