

Bath Interferometry

Arjan te Marvelde, December 2015

At some point during the making of a telescope mirror one needs to evaluate the quality of its surface and curve. This is especially important when the mirror obtains its eventual correction, during the parabolization phase. Traditionally, ATMs use a number of relatively simple methods, in particular the Ronchi and Foucault test. The problem with these test methods is that they inherently contain a level of subjectivity. As also concluded in the report by Jan van Gastel¹ these tests have a limited quantitative accuracy and should really only be used for qualitative analysis.

When reaching the final stage of the correction phase, better methods should be used instead. This article describes such method, which is well within reach of ATMs: the *Bath interferometer*.

Sensitivity of Foucault and Ronchi tests is maximal when used as a null-test, i.e. in the Radius of Curvature of a spherical mirror, the Focal point of a parabolic mirror or at Conjugate foci of an elliptical mirror. In case of a null test, the converging light has spherical wavefronts, in all other cases the wavefronts will have different shape and do not focus in a single point. In a null test, Ronchi shows straight lines and Foucault shows homogeneous darkening of the mirror. Null tests can be created in the lab by using additional optical elements, for example by autocollimation with a large flat mirror or the introduction of a Ross lens. The main disadvantage is that the additional elements bring also additional sources of error.

The principle of an interferometer is the comparison of a lightbeam reflected by the mirror under test (the *measurement beam* or *test beam*) with a *reference beam* having known characteristics. The comparison is done by letting both beams interfere and by registration of the resulting interference pattern. The way the interference pattern looks is caused by the differences between both beams. From this *fringe pattern* and the known characteristics of the reference beam the actual surface shape of the mirror under test can be deduced. This is done by means of a mathematical algorithm in a computer program. There may still be sources of error in this method, but the observer subjectivity is limited to a minimum.

This article describes how a Bath interferometer works, how you can build one and finally how to use it.

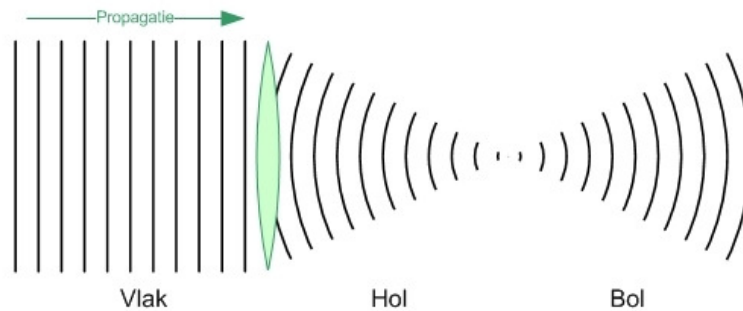
1 The Bath Interferometer

1.1 General mechanism

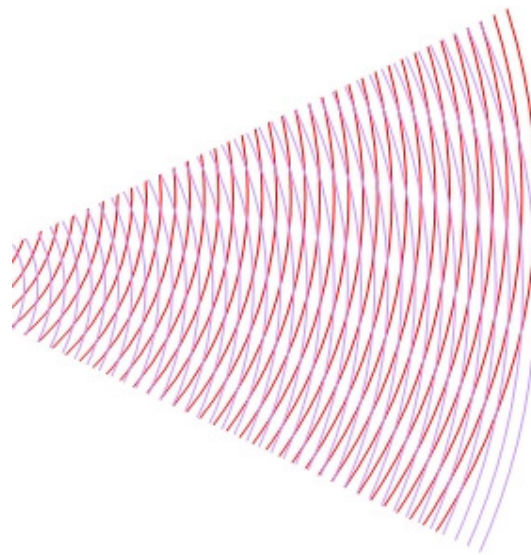
As stated before, the mechanism of an interferometer is based on interference between a measurement beam and a reference beam. For these beams a single *coherent light* source is used, a LASER. One characteristic of coherent light is that *the colour is well defined*, which means that the wavelength has a specific value, and the bandwidth around this value is very narrow. This means that the electromagnetic waves that make up the light go up and down with the same time behaviour. Another characteristic of coherent light is that, for a certain location the peaks of these waves all pass in the same moment, in other words that the waves have *the same phase* (spatial and temporal coherence).

So, coherent light has well defined wave fronts with a well defined wave length, characteristics that can be used to make precise measurements of for example distances.

¹ http://members.ziggo.nl/jhm.vangastel/Astronomy/De_Foucaulttest.pdf



The wave front of light in a laser beam is approximately flat, meaning that all light propagates in the same direction. When this beam passes a lens, the light is refracted and the direction is changed. Using a positive lens as in the picture, the light will first converge into focus and then diverge.



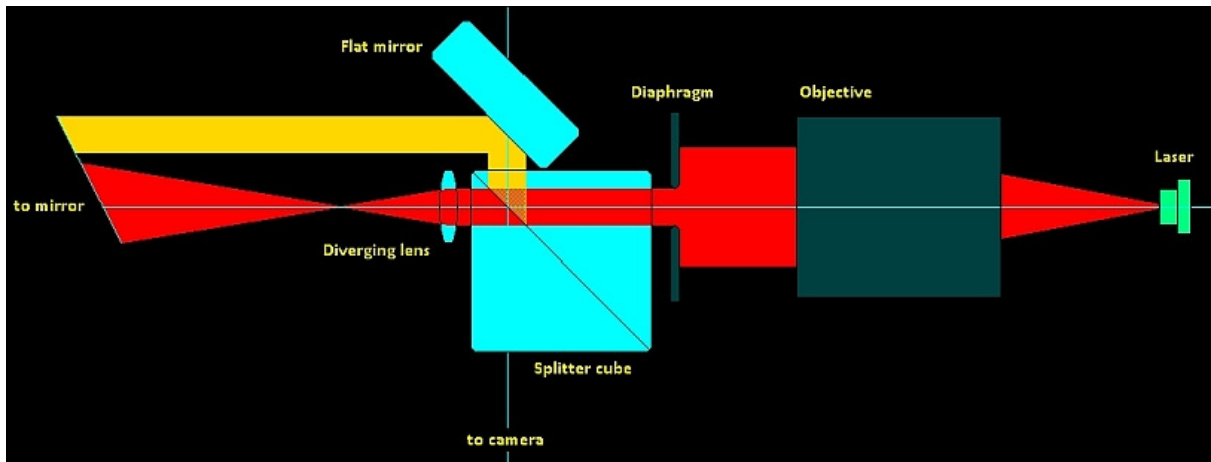
In a *Bath interferometer*, at the location where the fringe pattern is registered the reference beam is *diverging* with *spherical* wavefronts. The test beam is also diverging and close to spherical. Each beam seems to originate from a single point, these points are in close proximity so the wavefronts are almost completely overlapping. The picture shows what happens in such case: wave crests intensify each other at some locations and are cancelled by valleys on other locations. This fringe pattern is stationary, and can be registered with a camera.

Key is that the test beam contains small deviations in the phase (or time of arrival) in a wavefront, i.e. the spherical shape is disturbed or aberrated. These phase disturbances are directly caused by high and low areas on the mirror surface. These high and low areas may be a large scale deviation, like for example due to parabolization, or smaller scale effects like low or high mirror zones. All deviations from a spherical wavefront of the measurement beam will cause deformations of the fringe pattern. From these fringe pattern deformations the mirror surface shape can be exactly deduced by means of a computer program.

1.2 The blueprint of a Bath

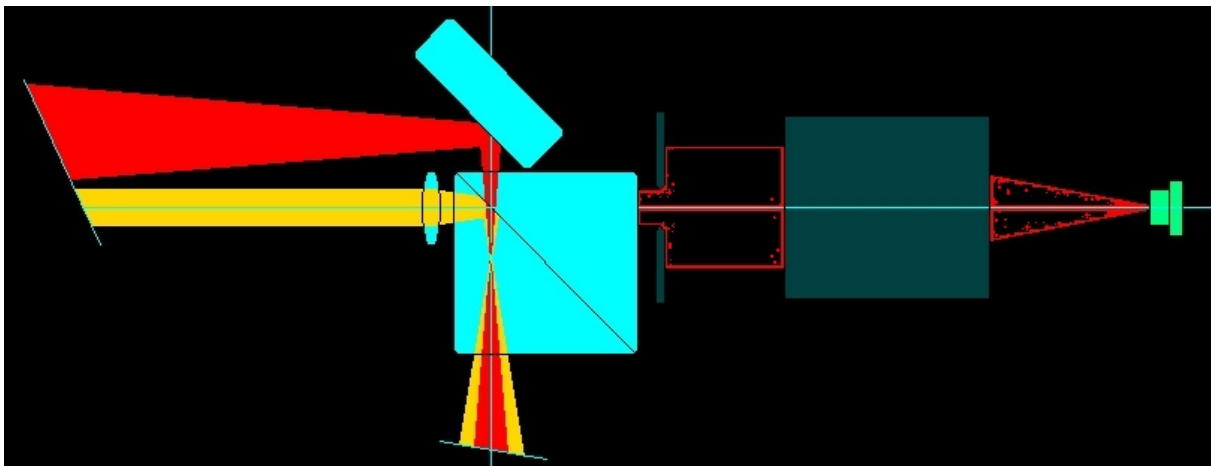
A Bath interferometer contains the following essential elements:

1. *Laser*, serving as the coherent lightsource
2. *Beamsplitter*, to separate test and reference beams
3. *Flat mirror*, to redirect the egress reference beam and ingress test beam
4. *Diverging lens*, to obtain diverging wavefronts



The layout of a typical Bath configuration (right-angle variant) is shown above schematically. The four basic elements can be recognized, Laser, Splitter cube, Flat mirror and Diverging lens. As a light source a cheap laserpointer can be used, which already contains a collimation lens. The diagram shows a bare laser diode with an objective as external (aspheric) collimation lens. This widens the beam beyond the 1-2mm you get from a laserpointer, resulting in a wider divergence and the possibility to test faster mirrors.

The diagram draws the test beam in red, and the reference beam in yellow. For clarity it also only shows the egress beams, which both end up at the mirror under test. The reference beam uses only a small area of the mirror, and hence large scale surface errors can be ignored. Other errors will also cancel out due to the averaging effect of multiple measurements.



The path of the return beams is shown in the second diagram. As can be seen the reverse path is switched between beams, now the reference beam passes through the diverging lens, but in opposite direction. The ultimate focal points of both beams need to be approximately co-

located, in the diagram this takes place in the splitter cube (the location of this spot is in fact determined by the focal length of the diverging lens). Both beams follow the shared path to a camera, where the interference pattern is captured.

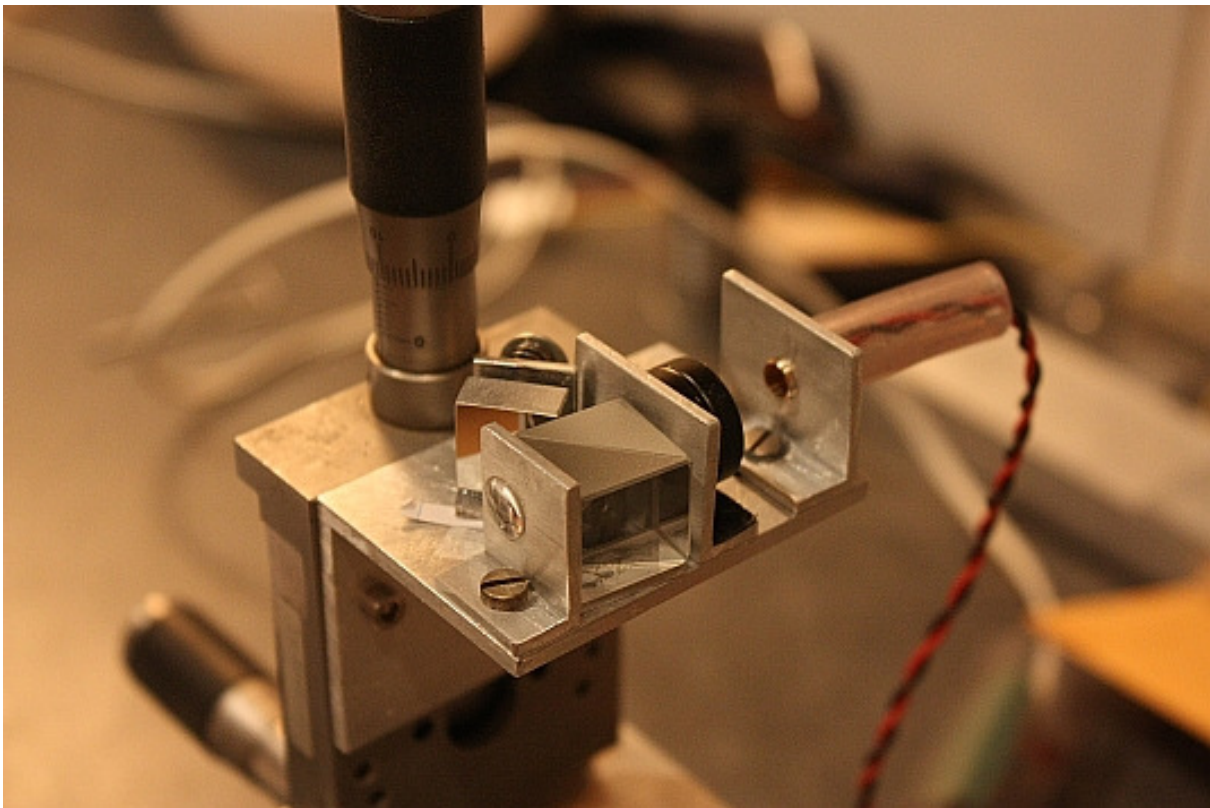
Since the mirror under test only reflects part of the test beam, the returned cone normally fits inside the wider cone of the reference beam. In practice, when looking into the cube from the camera position, the test beam reflected by the mirror can be seen within a larger circle of the diverging reference beam. On the mirror appears a line pattern, these lines are the fringes that need to be captured.

As can be seen in the diagrams, the test and reference beams follow the same path, but in reverse direction. For this reason the Bath interferometer is of a type called "Common Path Interferometer". A big advantage of a CPI is that this type is relatively insensitive to vibrations, air currents and other defects. Some of the results of these defects are largely cancelled out, because the beams experience them in opposite direction. Also the LASER can be of fairly low coherence, because the path lengths are essentially of equal length.

These characteristics make the Bath ideally suited for amateur use!

1.3 Building a Bath

Construction of the optical measurement head is fairly straightforward, more challenging is the XYZ translation stage. Translators can also be purchased, but are usually quite costly.



The image above shows an example of a Bath construction, in which all elements can be recognized. The lens is 6mm diameter biconvex with $f=10\text{mm}$, the beamsplitter is a 15mm cube, the flat front surface mirror is 12mm wide and finally there is an $f=18\text{mm}$ aspheric laser collimator and a laser diode.

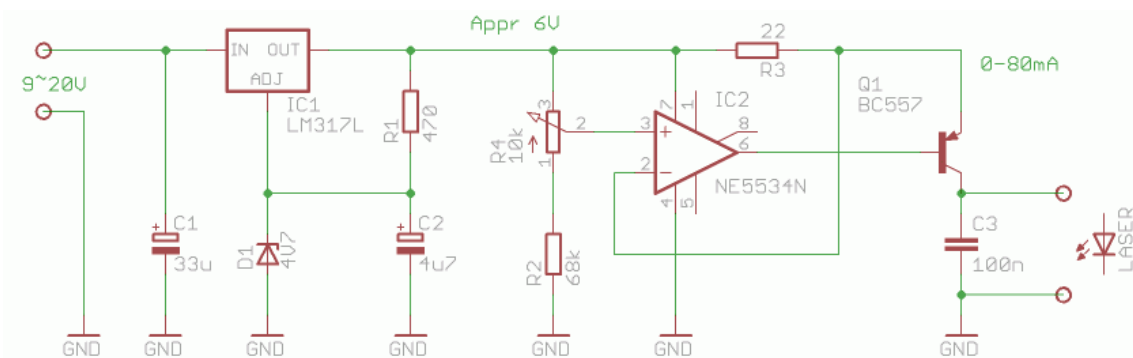
The laser diode could range from a simple 650nm 1\$ each from Deal-Extreme, to a long coherence length HL6501MG from Hitachi. All components have been mounted on a piece of aluminium L profile, with screws to enable adjustments. The translators have been obtained from E-Bay and the optics are low cost from SurplusShed.



Important points of attention:

- The splitter must be adjustable in azimuth. In the example it is epoxied to an aluminium plate, which in turn hosts a central M3 screw.
- The flat mirror must be adjustable in azimuth and elevation. In the example the mirror is glued to an alu profile with a dot of silicone caulk that serves as flexure (elevation). The profile also contains a central screw like the splitter (azimuth).
- Laser, collimator and diverger have been mounted on aluminium L profiles on the proper height. Shims can be used to fine-adjust height
- The beams need to have low separation, so the diverger is on the edge of its cell.
- The camera objective needs to almost touch the splitter cube.
- Laser light is preferably dimmable, e.g. by means of a variable current source.

A simple current source can be made with an LM317 and an adjustable resistor. An example of a more complicated but also more stable circuit is given below:

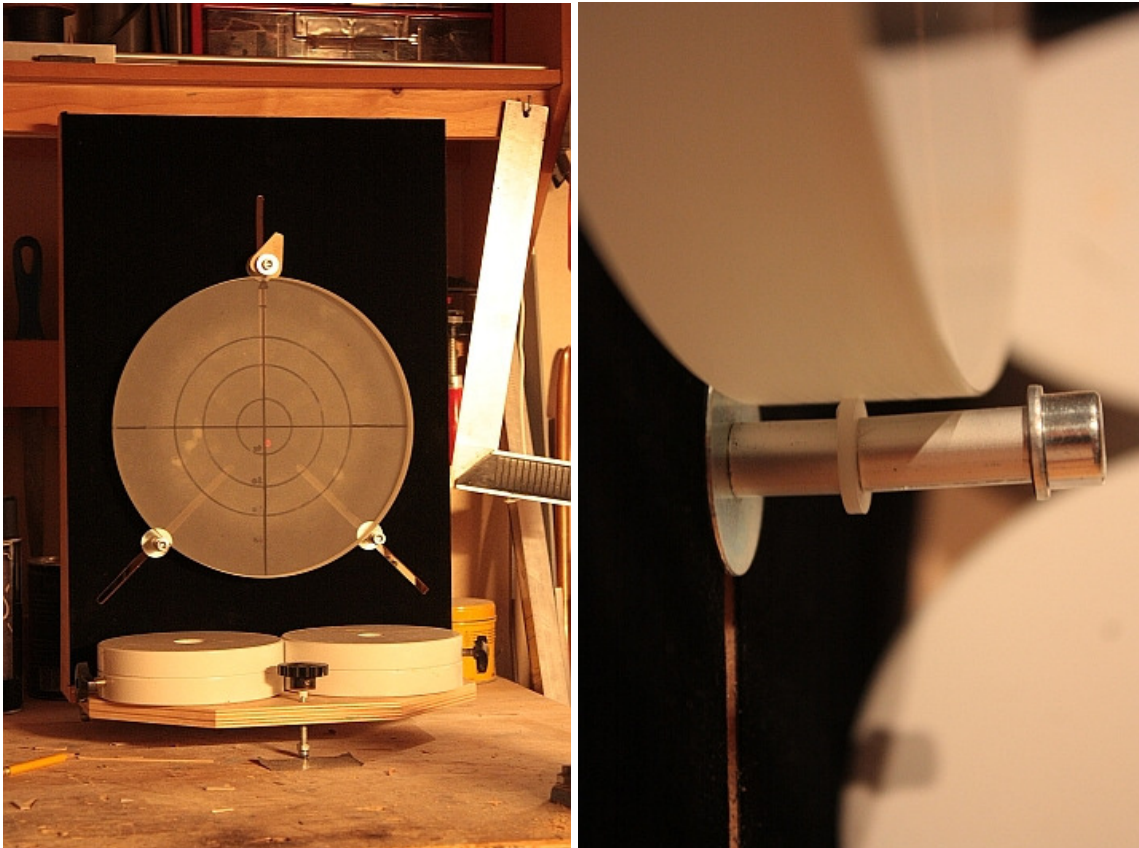


It consists of a regulated voltage source followed by an adjustable current source. A better choice of OpAmp would be a rail-to-rail single supply variant, but this one also works...

2 Using the Bath

2.1 Capturing Interferograms

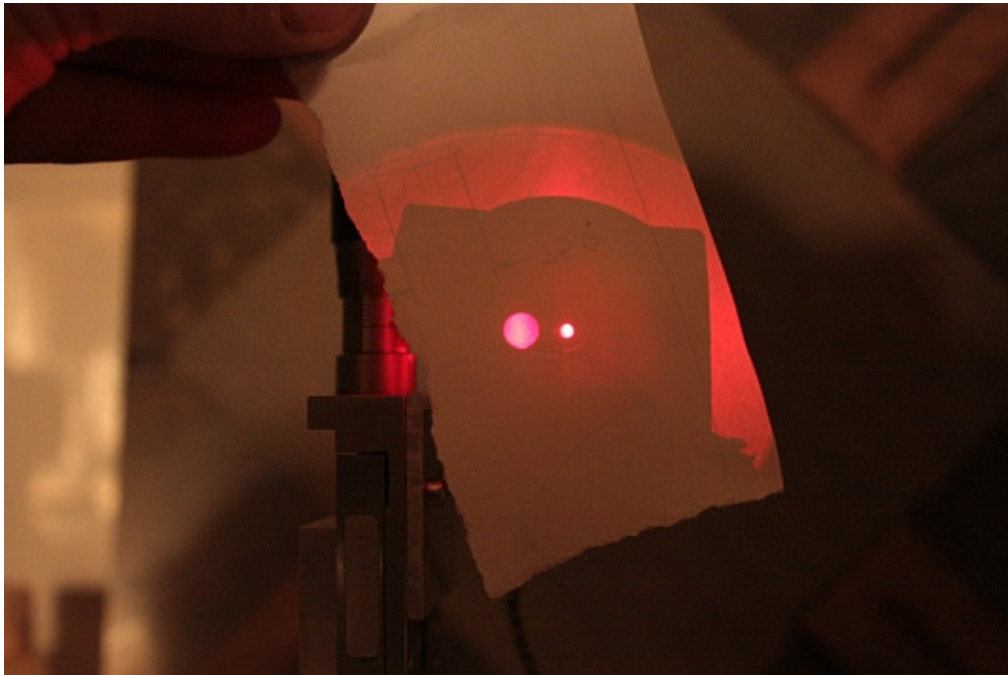
Initial set up and alignment of the measurement configuration will cost some time at first, but successive sessions are a lot quicker. It is important to mount the mirror as vibration free as possible. To this purpose a sturdy test stand is required, which is made heavy with additional weights and mechanical isolation from its environment. In the images below a set of counter weights is used, which can be amended with some dissipating material under the legs. Once aligned it is best to leave the stand at its location, or otherwise mark where it was to speed up follow-up measurements.



The mirror is supported on $\pm 45^\circ$ points, as shown on Nylon rings that are under the center of gravity of the mirror. The three large metal washers behind the mirror serve as precise axial position definition, for each measurement the mirror is pushed against it.

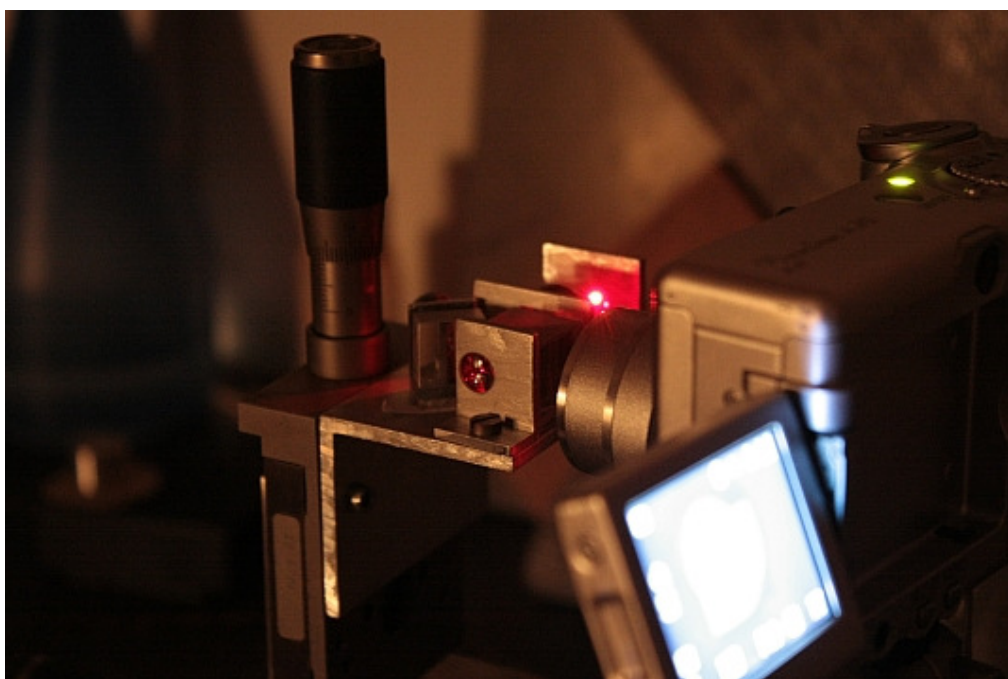
Then interferometer and mirror need to be mutually aligned. It is assumed that at this point the interferometer itself is already aligned, i.e. both beams are parallel. The vertex of the mirror should be at the same height as the laser, and the splitter cube should be near the mirror RoC. The reference beam should hit the mirror near its center.

Then, in low ambient light conditions the reflected reference beam can be traced back and should end in the diverger lens (conform the diagrams shown earlier). To achieve this, first re-position and re-orientate the mirror stand for the course direction, and then move around the Bath for fine adjustment.

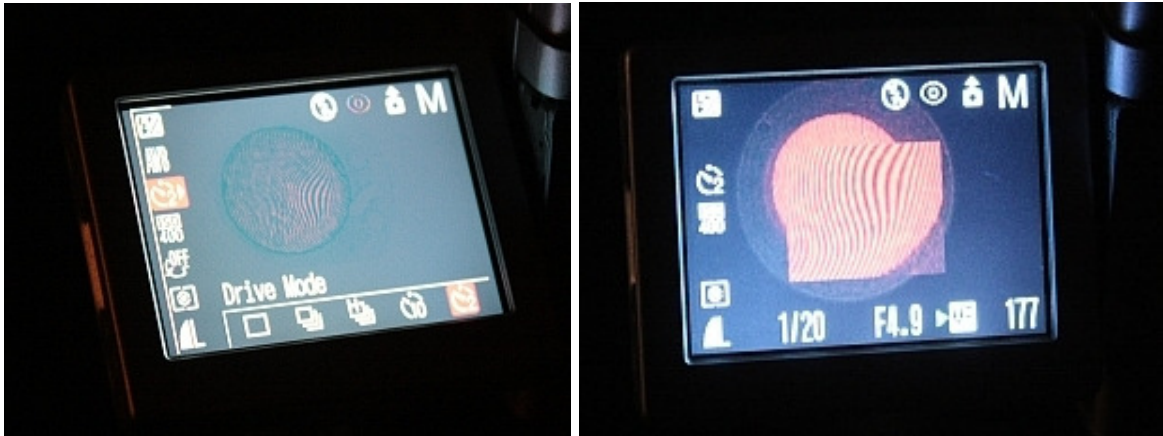


The final positioning to be adjusted is the axial location of the tester. This can be moved around while looking into the cube. The reference beam light circle should approximately center around the mirror, which at some point lights up with the reflected test beam. Fine adjustment of XYZ controls will normally bring up fringes. When the fringes look good, I usually mark the location and orientation of the tester like done for the mirror stand, so set up for successive measurements is only a matter of seconds.

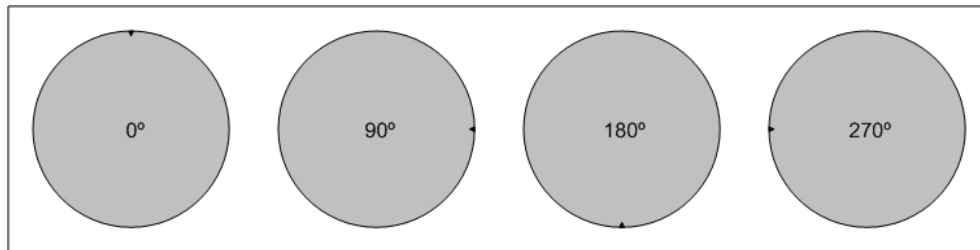
The fringe pattern that can be seen contains an 'eye', corresponding with the foci of the two diverging beams. The fringes curve around the eye, and width/number of fringes is adjusted by the axial (Z) setting, i.e. the distance between mirror and Bath. The eye needs to be shifted away from the mirror image, by adjusting lateral (X, Y) settings. Make sure to get a few tens of fringes before starting the series capture and refrain from having closed loops.



After everything is initialized, the camera can be set up.

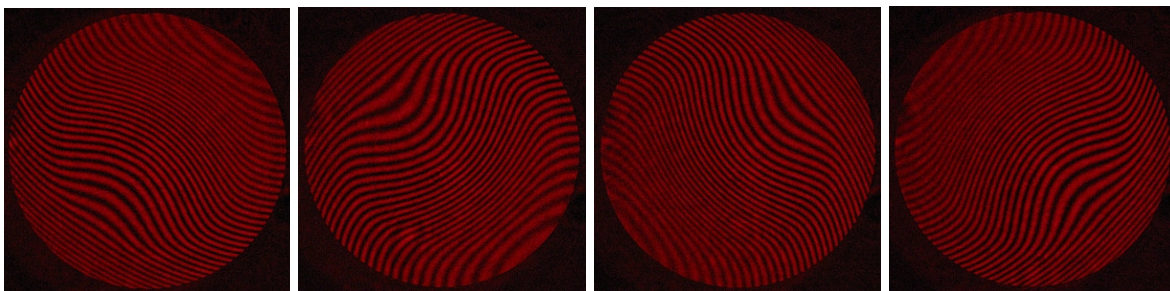


In this example a Canon A95 Powershot is used. The relevant settings in this case are: fixed exposure time, manual focus and exposure delay timer of 2 seconds. The latter is needed to let the camera finish vibrations before capture. The exposure time is determined empirically, and targeted at best contrast, possibly combined with adjustment of iode current. Good focus is mandatory, camera must be focused on mirror (i.e. approximately its radius of curvature).



To cancel out errors induced by the test setup, primarily astigmatism due to beam separation and also astigmatism and trefoil due to the test stand, interferograms are made for several mirror orientations. Best is to use either four (as above) or eight different orientations. The wavefront analysis can be derotated and averaged to eliminate these systematic errors.

For each orientation a set of exposures is made, which will also be averaged to cancel noise and other stochastic sources of error. By adjusting the X and Y position the orientation and number of fringes can be changed (see below). It is best to vary this for all exposures for a certain orientation.



Summarizing the workflow, in the example above 4 exposures are taken for each of 4 mirror orientations, 16 interferograms in total. For each orientation, 4 wavefronts are calculated, averaged and stored. Then the stored averages are each derotated and averaged again. This provides the resulting analysis, with lowered noise and cancelled astigmatism.

2.2 Systematic errors

A word about systematic errors, there are two important sources:

- astigmatism due to beam separation
- deformation due to the test stand

The first error can be understood when considering that the reference beam and the test beam inherently make an angle because their origin is the flat mirror and the diverger lens respectively. The separation is only a few mm, but still enough to introduce apparent astigmatism in the analysis.

The magnitude of this astigmatism is given by: $OPD = \frac{D^2 d^2}{16R^3}$,

where D is the diameter, R radius of curvature and d the beam separation.

For common mirrors the error is below $\lambda/10$, but this is already too much. The error can be removed mathematically by the analysis software, but it is better to use the rotation/derotation technique as mentioned previously. This technique removes also test stand induced deformation along the way.

3 Analysis with OpenFringe

After capturing the series of interferograms, they need to be processed and analysed so that a judgment can be given about the state of the mirror. When this is used to direct the figuring process, it must be kept in mind that the mirror is already on the tool for a cold press while this analysis is run. Therefore it does not have to cost any additional lead time.

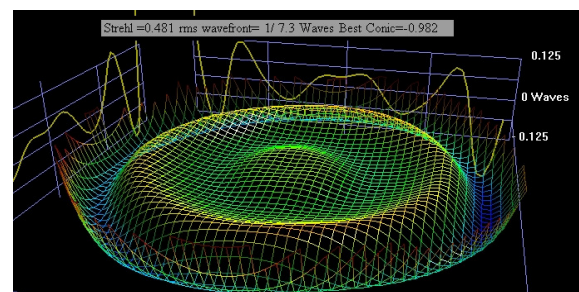
The analysis software being used here is the open source OpenFringe, by Dale Eason. Before doing anything, the mirror and test configuration needs to be entered once. This is done in menu item **Configuration → Mirror/Test Parameters**:

The screenshot shows the 'Mirror Info' dialog box. At the top, a text box contains instructions: 'When entering English Units, clear the mm check box first. Units will be converted to mm on exit or you can check the mm check box before leaving. On re-entry units will be displayed as mm.' Below this, the 'ID' field contains '255F4'. The 'Mirror' section has a checked 'Units in mm' checkbox and fields for 'Diameter: 254.000', 'Roc: 1984.248', 'F Number: 3.906', 'Obstruction: 0', and 'Conic Constant: -1'. The 'Interferogram' section has a 'Wave length nm' field with '658', a checked 'Artificial Null' checkbox with a value of '-2.076', and an unchecked 'Double Pass' checkbox. The 'Fringe tracing' section has two radio buttons: 'One Color Traced' (selected) and 'Light and Dark Fringes Traced', with a 'Spacing in waves' field set to '1'. On the right, the 'Igram image' section has two unchecked checkboxes: 'Flip Left/Right' and 'Flip Vertically'. At the bottom are four buttons: 'OK', 'Cancel', 'Save in a File', and 'Read existing file'.

Enter mirror parameters, some ID text and the LASER wavelength. We will be using an artificial NULL in One Color Tracing.

From here the following process steps are taken:

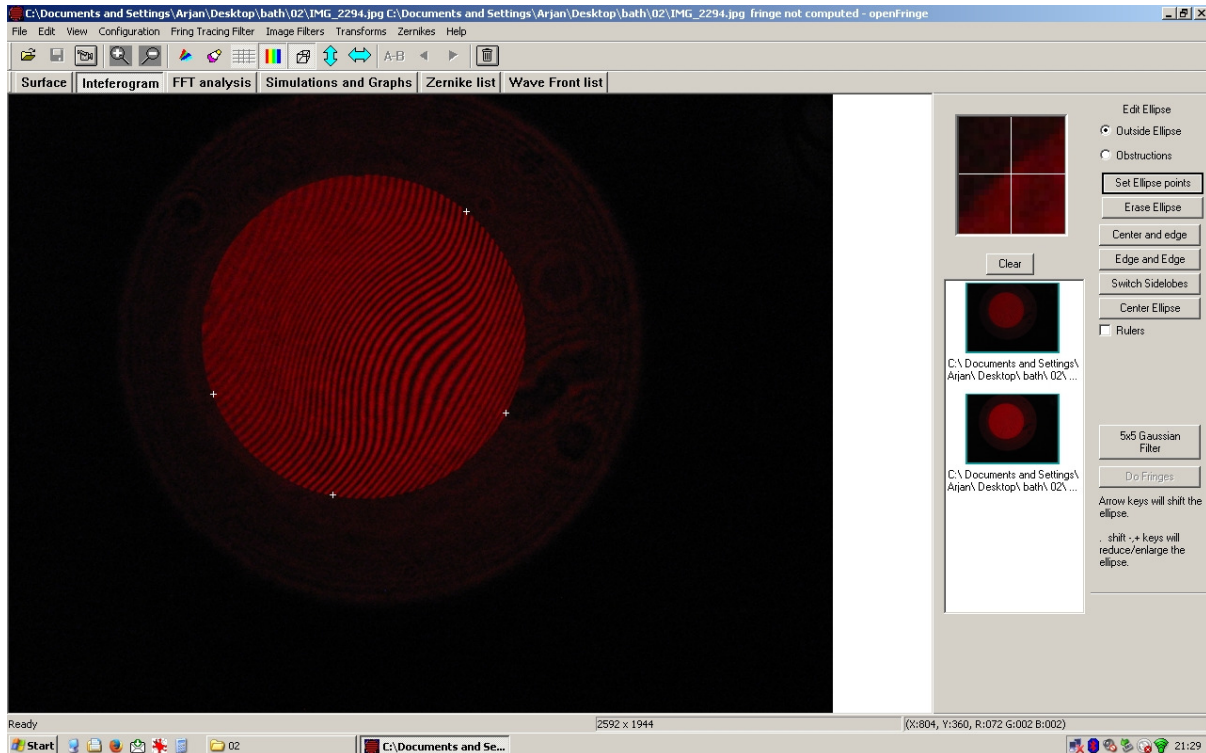
1. Load an interferogram
2. Mark the edge
3. Resize and center
4. Execute Fast Fourier Transform
5. Cover central spike
6. Calculate wavefront
7. Repeat 1-6 for all igrans of an orientation
8. Average wavefronts and store
9. Repeat 1-8 for each orientation
10. Read back the stored averages
11. De-rotate each average to 0°
12. Average derotated wavefronts and store
13. Do post-processing, generate report etc.



3.1 Step 1: Load an interferogram

Open an igram file (jpg) via **File** → **Open**,

3.2 Step 2: Mark the edge



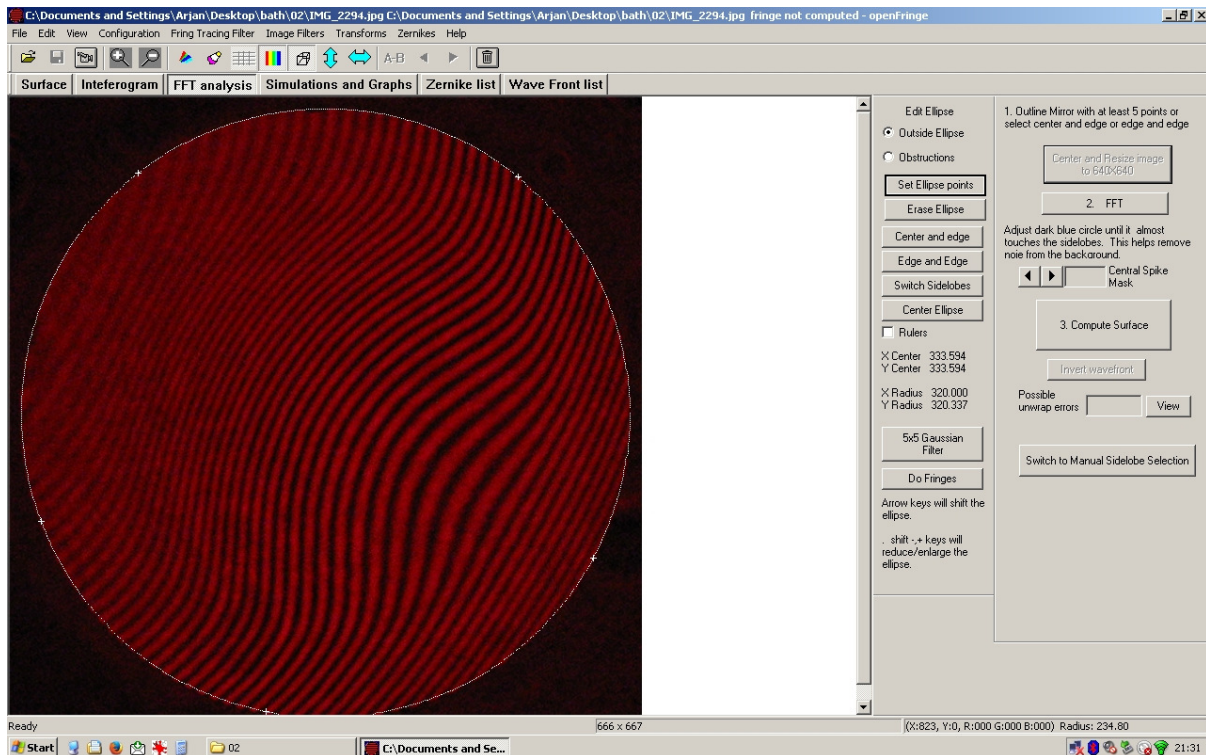
Select the **Interferogram** tab, if not already active.

It is important to mark the edge of the mirror as accurately as possible, to prevent calculation errors. The circumference can be marked in this view by putting 5 crosses on the edge of the mirror. The small window top right gives an enlarged view of the area around the cursor, and can be used to nail down the right spot. Instead of 5 crosses, also 2 crosses on opposite sides can be used with the selection of the "Edge and Edge" button.

When the circle (or ellipse) is resolved, it can still be moved around with the arrow keys, and enlarged or shrunk with Shift and + or Shift and -.

It pays off to experiment a little and find the best way of working. Usually when this view is set up properly, the successive igrams for a certain mirror orientation can re-use it. Not having to redefine the circle speeds up the process considerably.

3.3 Step 3: Center and resize.

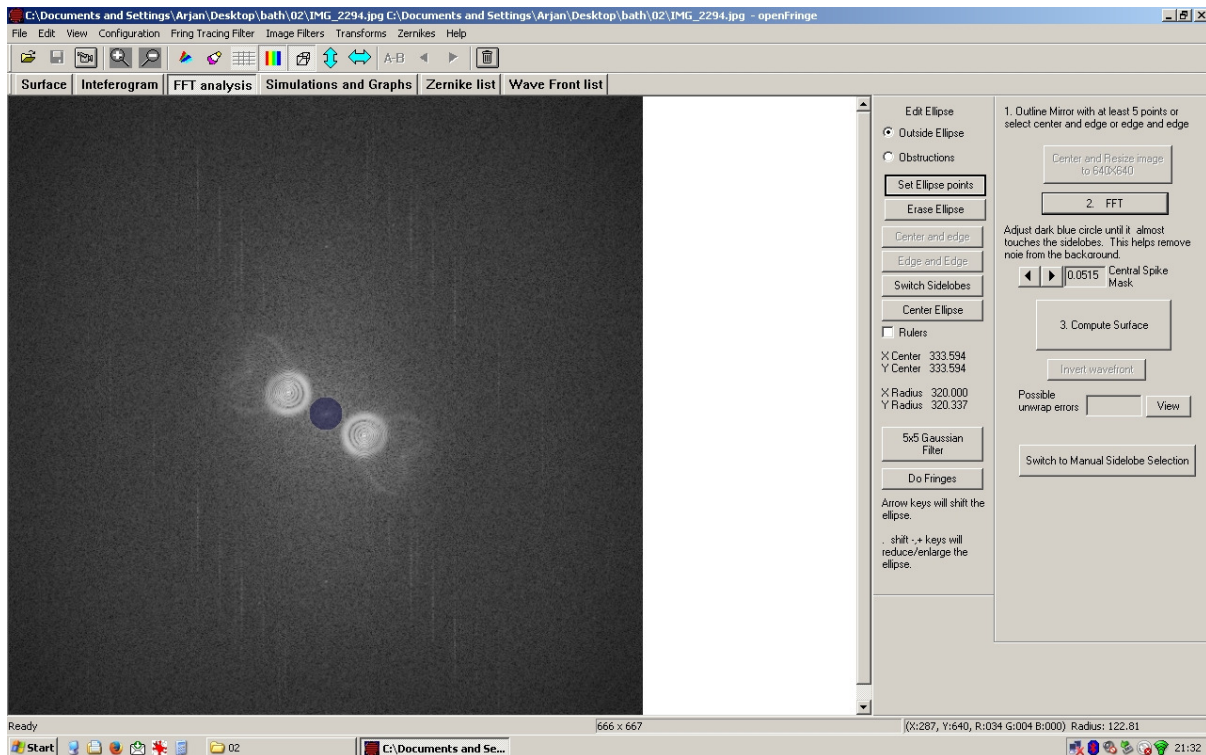


Select the **FFT Analysis** tab.

Click on the "Center and Resize" button.

In this view the mirror area is enlarged so that it nicely fills the FFT domain. Here the circle tweaking buttons still work, and should be used to make a good final fit on the circumference.

3.4 Step 4: Fast Fourier Transform



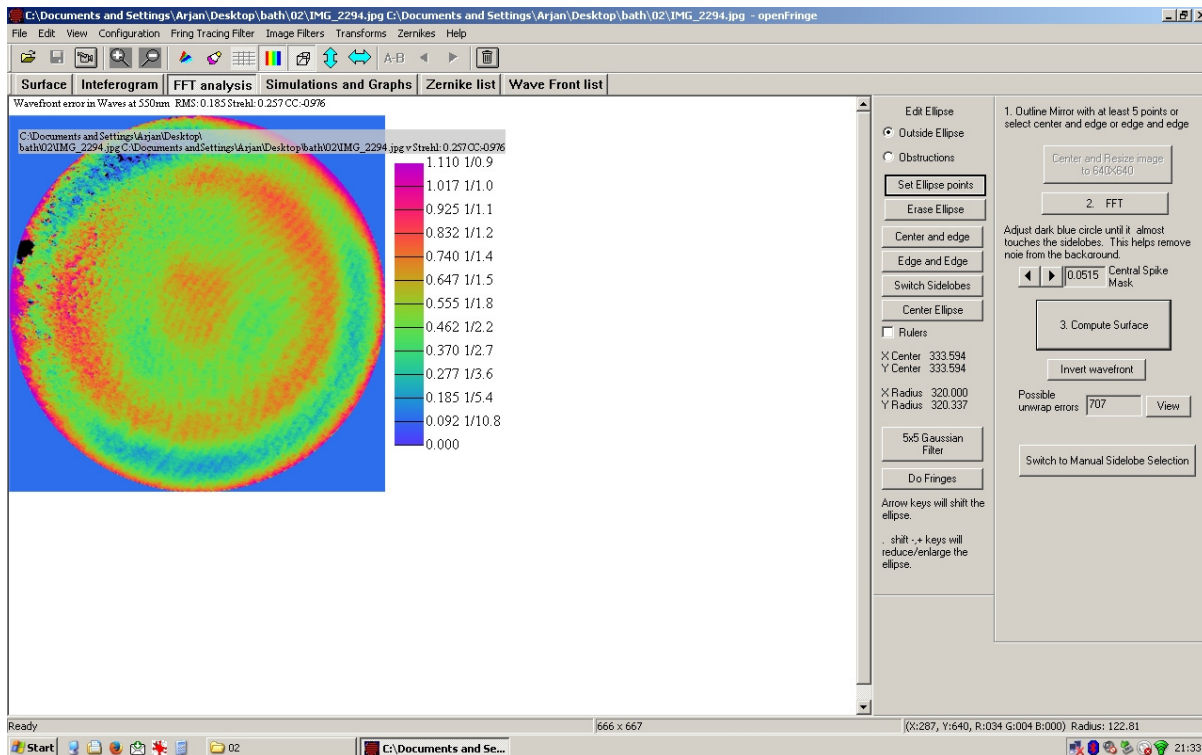
Still in the **FFT Analysis** tab execute the Fast Fourier Transform by clicking the “FFT” button.

The FFT view contains two circular areas and usually two larger and more vague circular areas. These areas are called side lobes.

3.5 Step 5: Spike removal

In between the side lobes, there is a central spike that contains noise, or otherwise unusable information. This spike can be masked off by an adjustable mask, the central grey circle. Using the ◀ ▶ buttons the size can be varied, it should almost touch the side lobes, that contain the useful information.

3.6 Step 6: Calculate wavefront



Finally, still in the **FFT Analysis** tab, generate the wavefront by clicking on the “Compute Surface” button.

The number of possible unwrap errors is given, and this number indicates on how many places the computation possibly went wrong, resulting in phase jumps on the surface analysis. When these errors are spread around it will appear as noise. When the errors are consistent on larger areas the interferogram was not good enough.

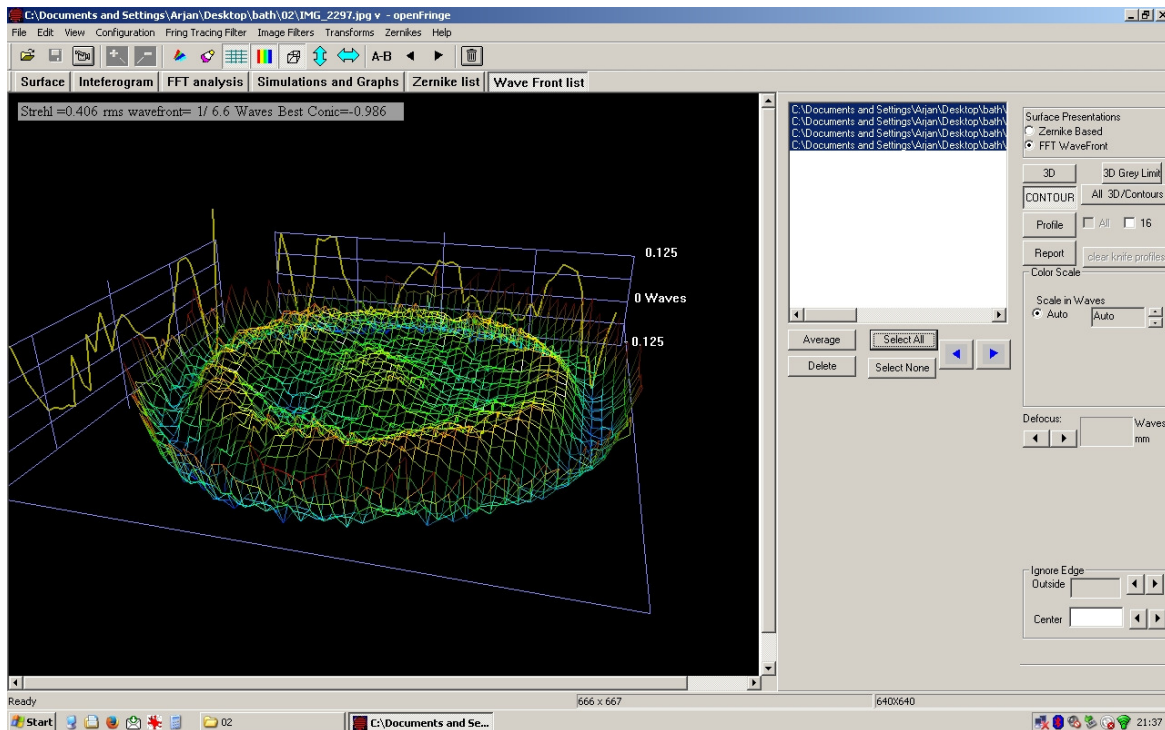
In any case, the number of unwrap errors should be as low as possible. Sometimes you get a few tens, other times a few hundred, which may very well be acceptable. It should certainly not be around thousand or more.

3.7 Step 7: Repeat for the mirror orientation

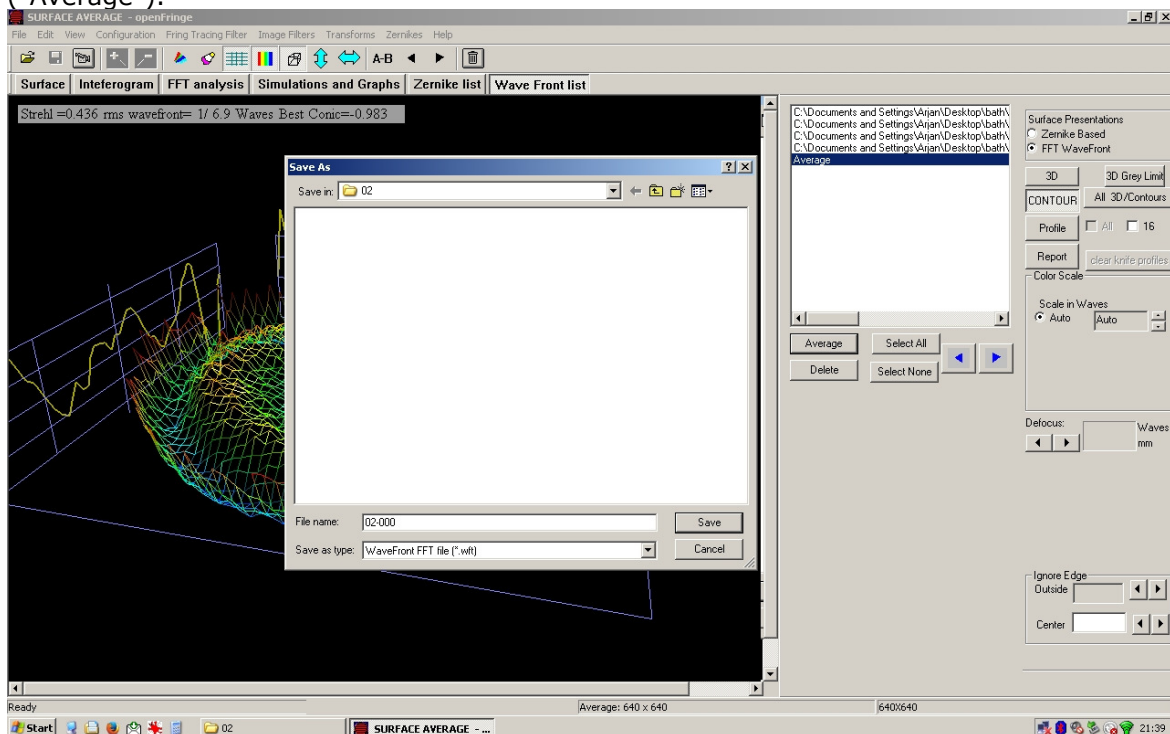
Now the next interferogram is loaded as in Step 1, and the cycle is repeated. As stated, the initial positioning of the ellipse (Step 2) can usually be skipped for subsequent interferograms of the same mirror orientation.

When all interferograms for the orientation have been converted into wavefronts, it's time to move to Step 8.

3.8 Step 8: Average and store



Select the tab **Wave Front list**. Here all wavefronts are selected ("Select All") and averaged ("Average").

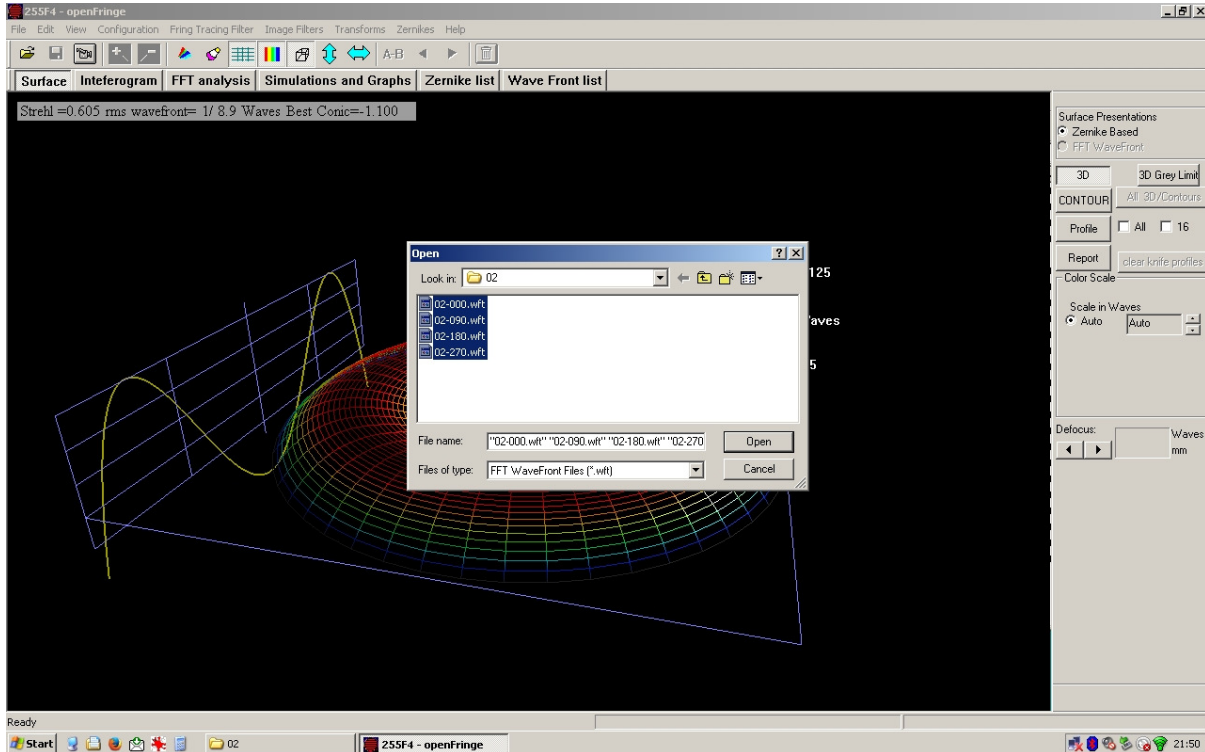


The calculated average is selected and stored for later use via **File → Save FFT Wavefront**. Use a name that represents the mirror orientation for this average. Clear all wavefronts.

3.9 Step 9 Repeat

The cycle described in Step 1 to Step 8 is repeated for each mirror orientation, resulting in an average wavefront file per orientation.

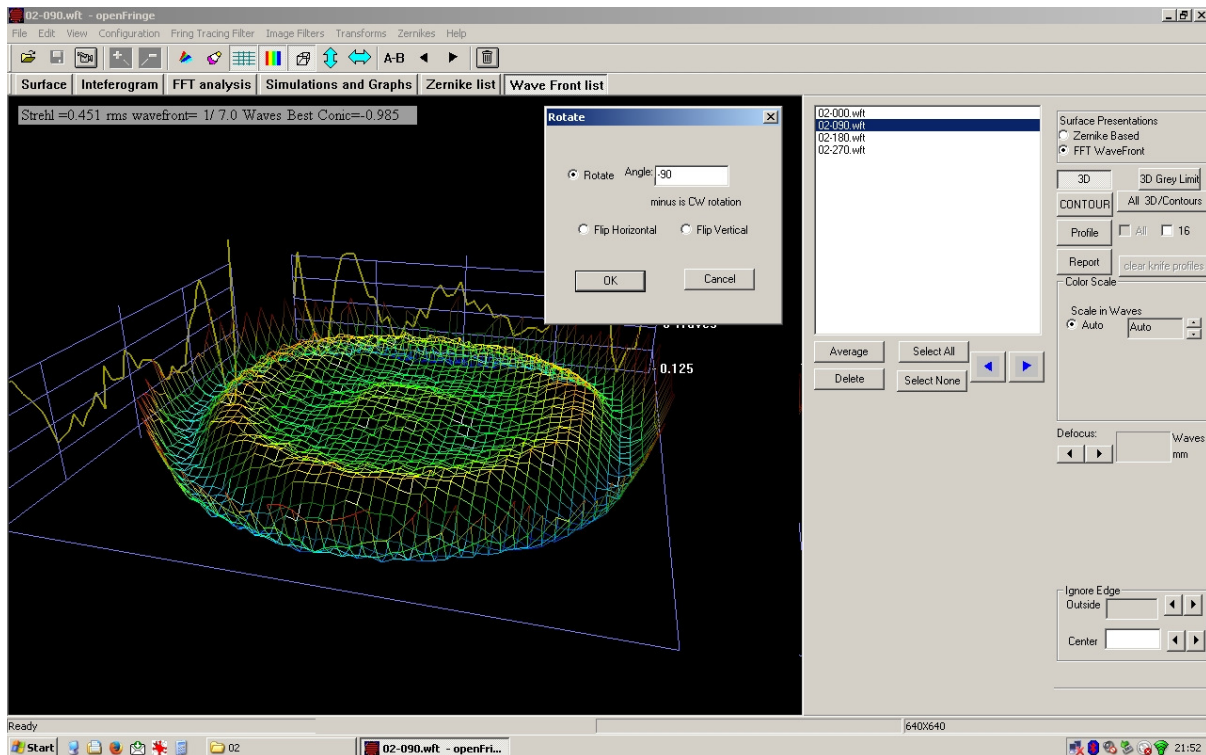
3.10 Step 10: Read all averages



Now the average wavefront (wft) files need to be loaded again via **File → Read FFT Wavefront**.

I like to do this with a freshly started OpenFringe instance, since sometimes it hangs or crashes afterwards.

3.11 Step 11: Derotate the wavefronts

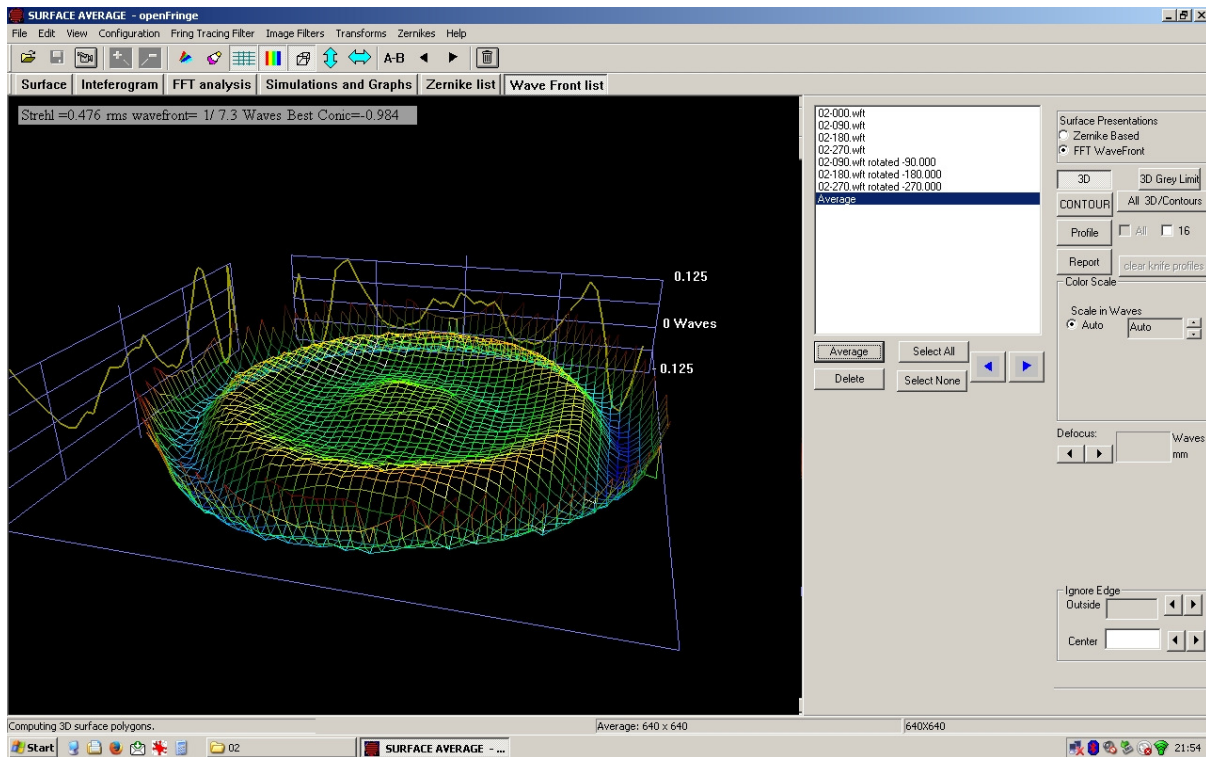


Select the tab **Wave Front list** after reading the averages for each mirror orientation.

Each wavefront now has to be counter rotated, according to the info that was put in the filename. Note that when using an angled Bath, as shown in the example implementation, the mirror rotation is reversed on the camera image. So when the mirror was rotated in clockwise direction, the wavefront analysis must also be counter rotated in this direction.

Now, select a wavefront and rotate this via the **Transforms → Rotate Wavefront** menu option. Enter the angle and click OK. A new wavefront appears in the overview window.

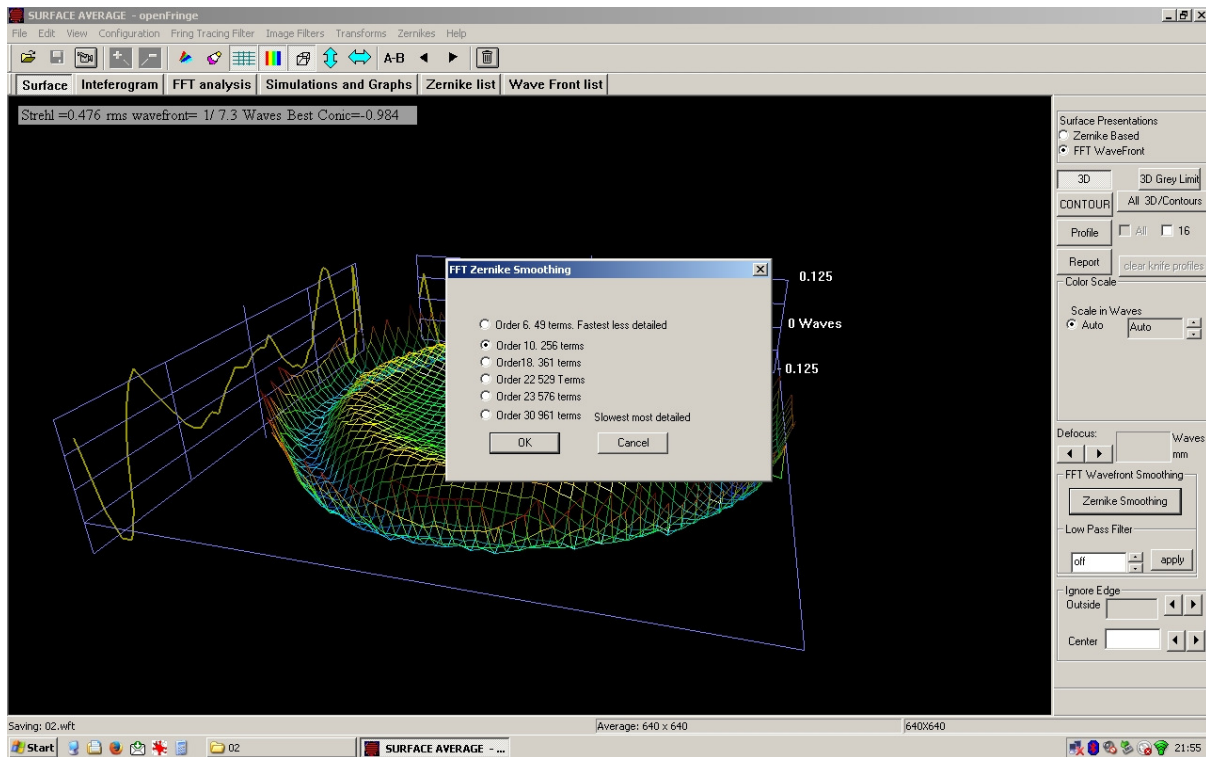
3.12 Step 12: Average and store



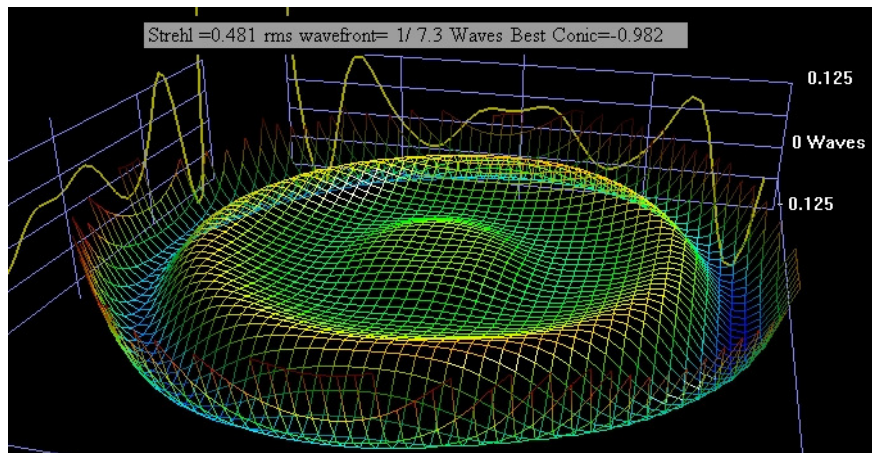
Select all rotated wavefronts as well as the 0° one (ctrl-click) and calculate another average. This final average can be considered as the raw wavefront analysis representing the surface of the mirror. The artifacts that may still be in are mainly noise.

Save this wavefront before further processing it.

3.13 Step 13: Post-processing



Select the **Surface** tab to play a little with the result. It is best to further cancel out noise by removal of high frequency components. This can be done by using a low-pass filter or by applying a Zernike based filter. Recommended values are the default choices.



For further use, the result can be exported as an image. Also at this point, a full report in PDF can be generated.

4 Useful links

Ed Jones on using a Bath: <https://youtu.be/uiDLyiopqIo>

Ed Jones on making a Bath: <https://youtu.be/6KQAjmUC7KE>

Dale Eason on using a Bath: <https://youtu.be/wINnmX15qrw>

Yahoo Interferometry Group: <https://groups.yahoo.com/neo/groups/interferometry/info>

Dave Rowe: [http://starryridge.com/mediawiki-1.9.1/index.php?title=Bath Interferometer](http://starryridge.com/mediawiki-1.9.1/index.php?title=Bath_Interferometer)

Surplus Shed: <http://www.surplussshed.com/>