

Pyramid Wavefront Sensors for the detection of Small Phase discontinuities

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Background and Context

Simulation of Wavefront degrading effects with Spatial Light Modulators

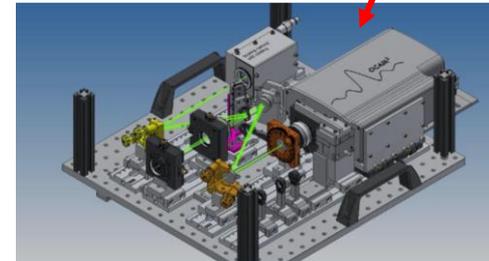
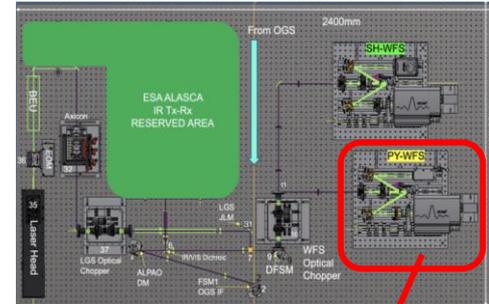
- PhD topic: can you build a device which uses an SLM to calibrate and test an adaptive optics system.
- Atmospheric Turbulence
- Segmentation of the primary mirror
- Petalling / Low Wind effect



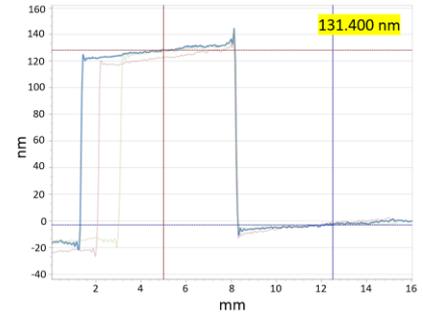
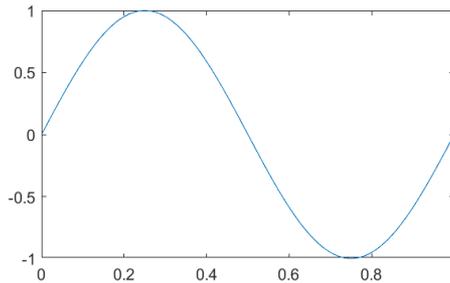
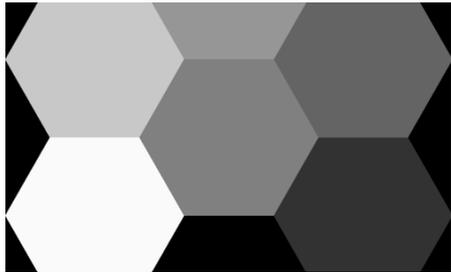
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CaNaPy - LGS-AO experimental facility for visible wavelengths

- Visible LGS-AO concept demonstrator.
- Teide Observatory, Tenerife.
- 589 nm laser for LGS-AO
- SH-WFS and PY-WFS arms for wavefront detection / correction.
- Collaborating with PY-WFS group to calibrate / test PY-WFS before installation on CaNaPy



- Simple idea – Calibrate a PYWFS using an SLM which is simulating a segmented mirror with known phase steps.
- Test the PYWFS on physical phase plates with precisely known phase discontinuities.



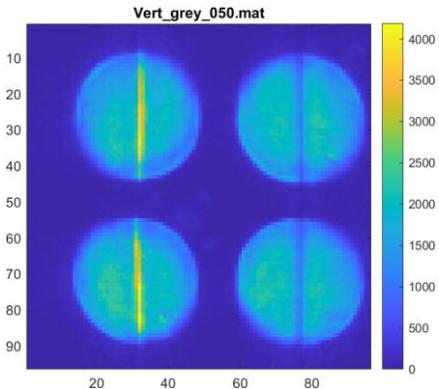
1) Simulate segmented mirrors with the SLM

2) Generate a calibration curve for the PYWFS.

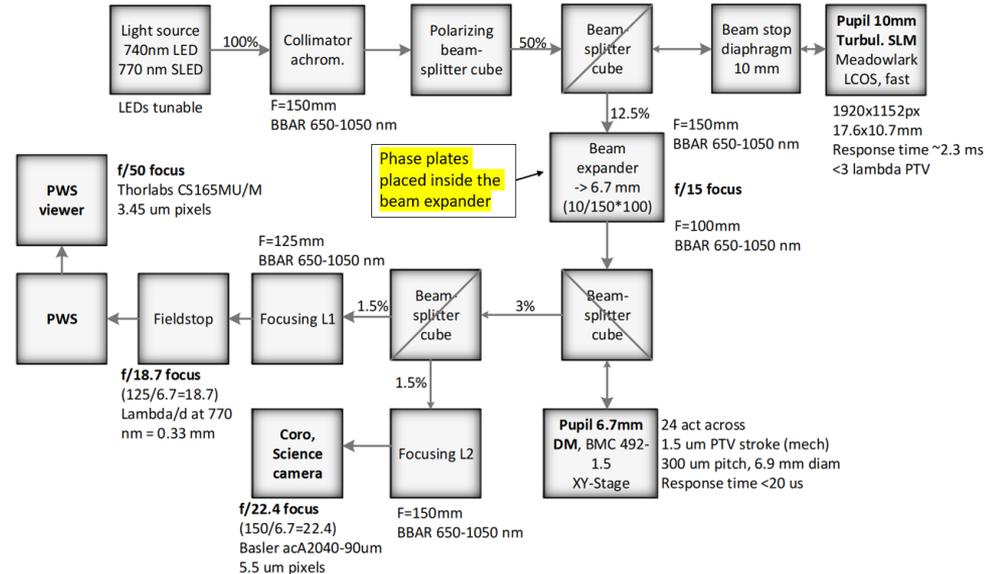
3) Test the calibration curve by measuring physical phase plates with known phase steps

Test bench - GHOST

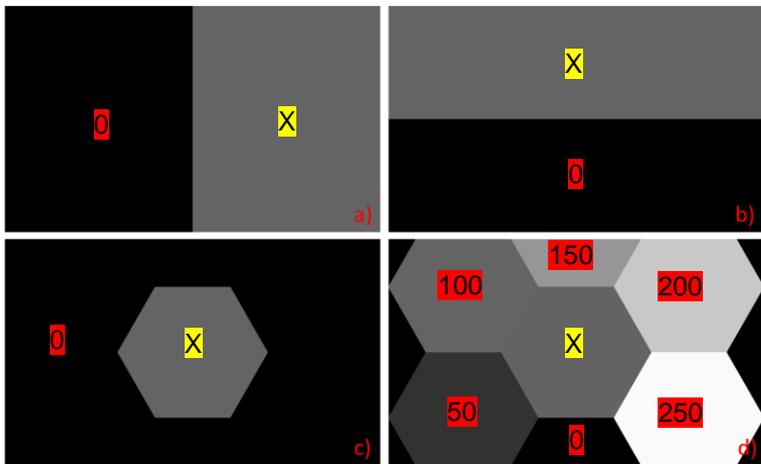
- GHOST - GPU-based High-order adaptive OpticS Testbench.
- 770nm SLED as source.
- Meadowlark LCOS SLM (1920 x 1152 px)
- DM set to flat, not used.
- Modulation radius of $3\lambda/D$



050 denotes a grey level difference of 50 between the two sides.

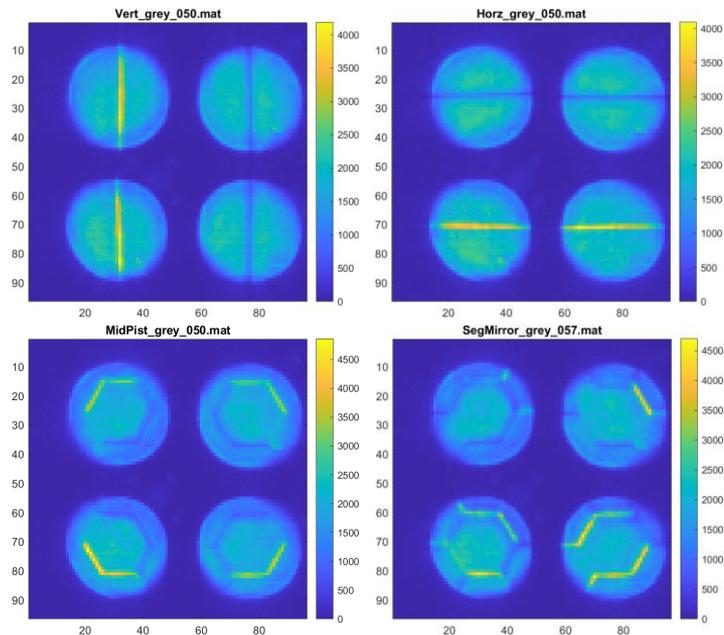


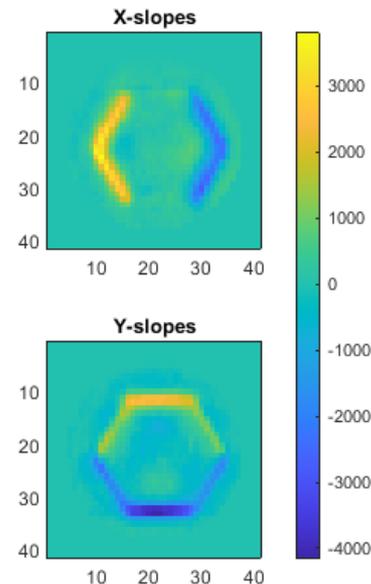
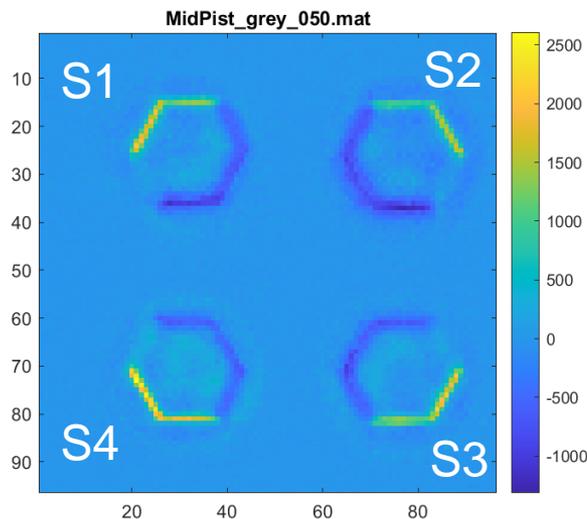
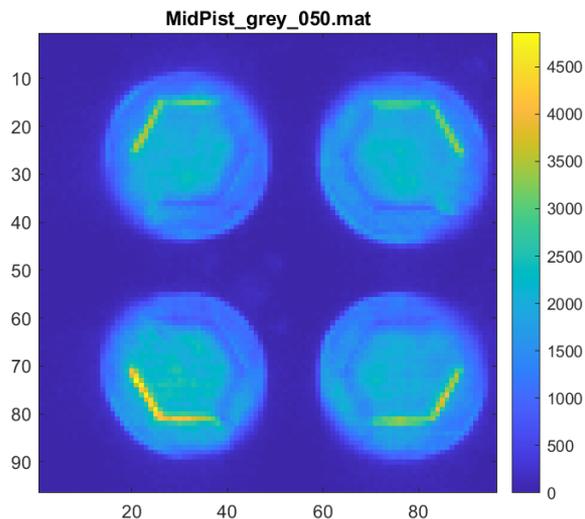
- 4 types of phase screens
- One part of the phase screen varies between grey levels 0-255, rest held at a fixed grey level.



X shows areas of phase screens in which grey level varies from 0 to 255.

Red highlighted numbers show set values.





1) Subtract the flat from the detector image (pixel by pixel subtraction)

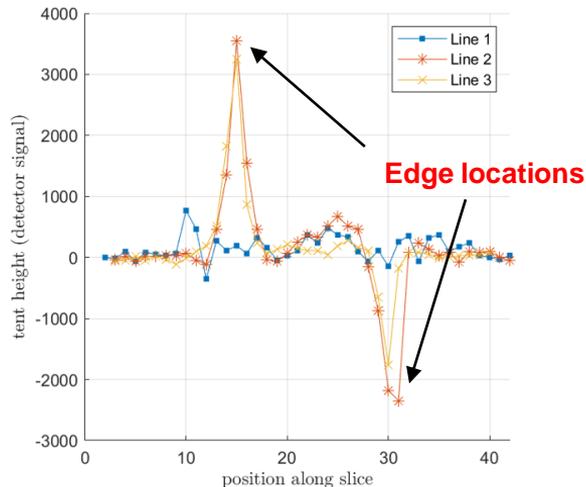
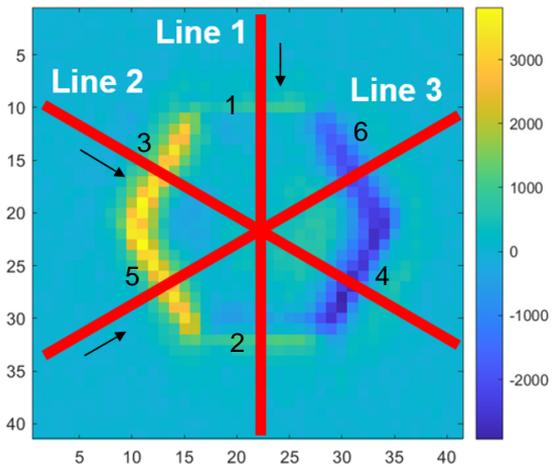
2) Calculate the X and Y slopes from the subapertures

$$S_x = (S_1 + S_2) - (S_3 + S_4)$$

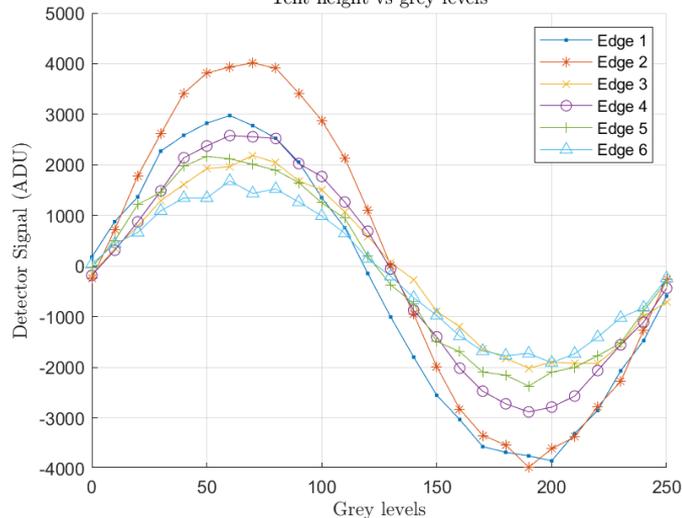
$$S_y = (S_1 + S_4) - (S_2 + S_3)$$

By calculating non-normalized slopes, the resulting sine wave will not be skewed.

X-slope image



Tent height vs grey levels

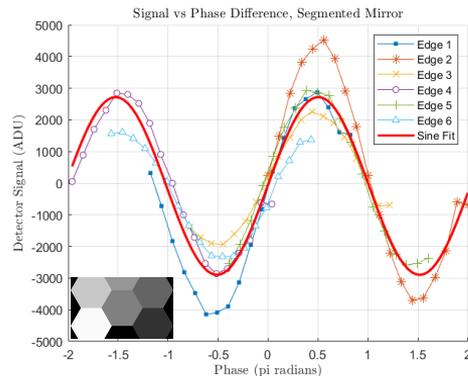
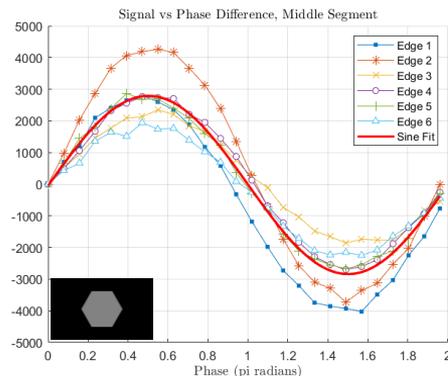
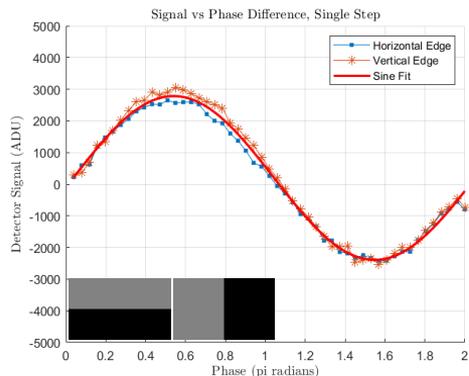


3) Slices through the slopes images, perpendicular to each edge

4) Locate the edges along each slice

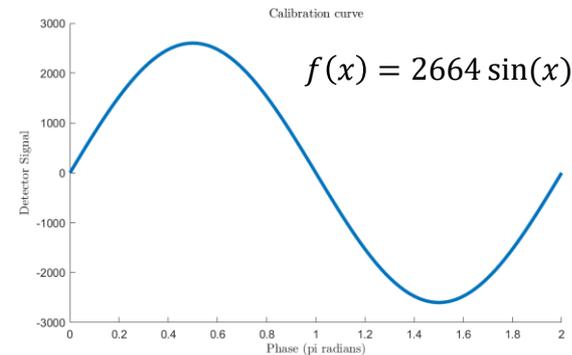
5) Plotting detector signal vs grey level should give a sinusoidal pattern

Resulting Calibration Curve

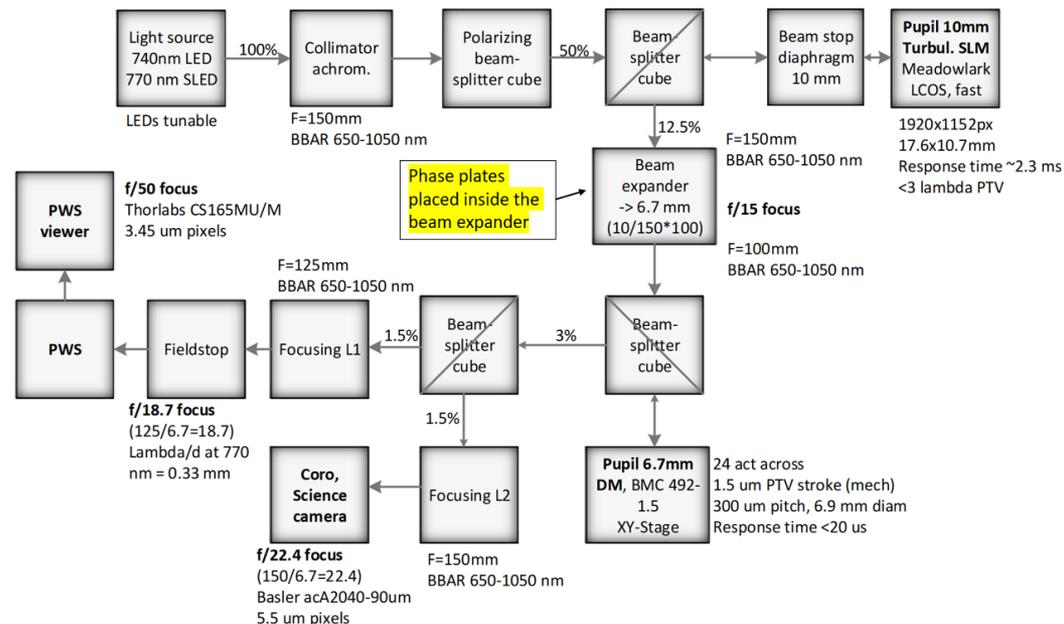


- Calculated a “weighted average” for the amplitude of the calibration curve.
- Amplitudes weighted by RMSE for each individual fit.

$$\bar{a} = \frac{\sum_{i=1}^n a_i w_i}{\sum_{i=1}^n w_i}$$

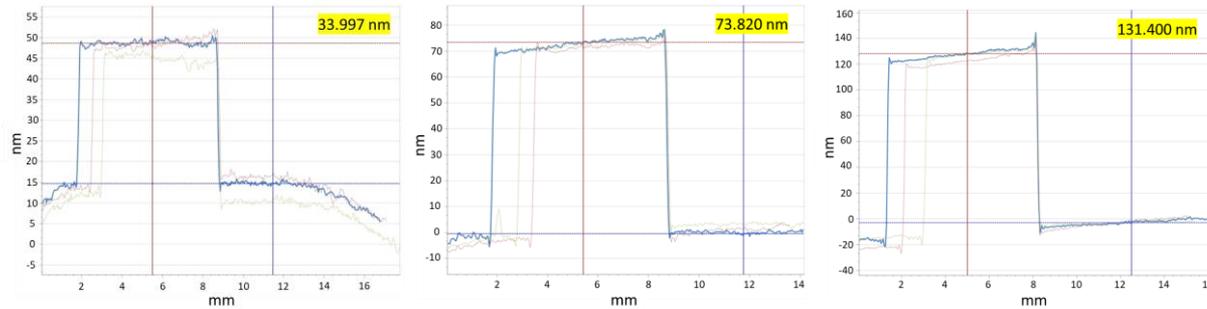


- Could only use GHOST bench without modifying original set-up.
 - Only place phase plates would fit was inside the beam expander section.
 - Unable to place phase plates within a collimated beam.
- Plate plates had a slight wedge shape.
 - Source had to be adjusted to accommodate this
- Introduction of plates introduced an additional defocus to the system
 - Compensated using SLM.
 - Could not eliminate entirely.

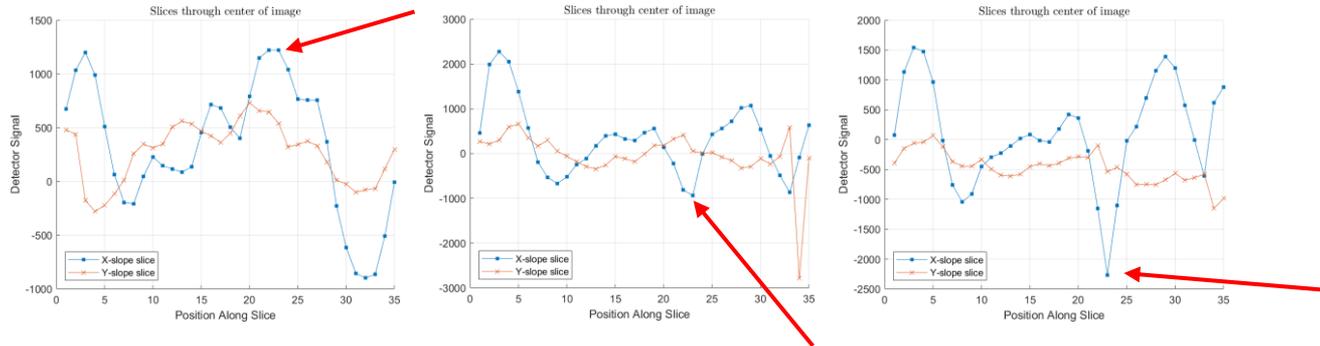


- Phase plates data reduced in the same method as the calibration data.
- Flat subtracted, slopes calculates, slices taken across the images. No normalization.

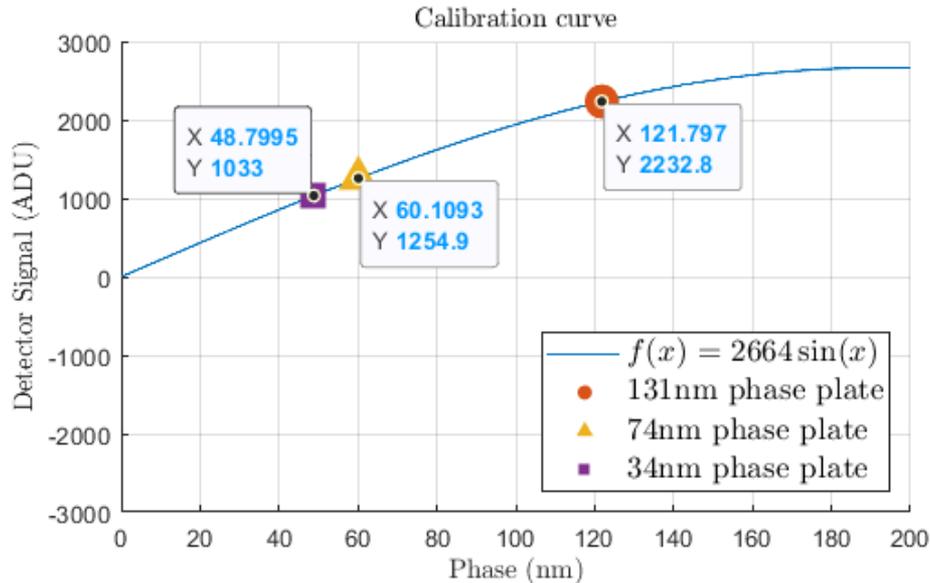
Manufacturer measurements of phase masks



Slices through X and Y slope images for each phase plate



- Height of tent taken as absolute value of tent over the average value for the image.
- Then values interpolated to find position along calibration curve.

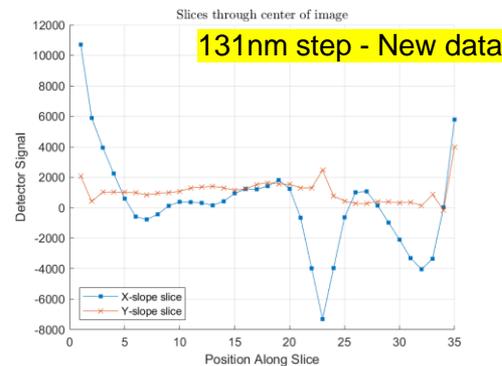
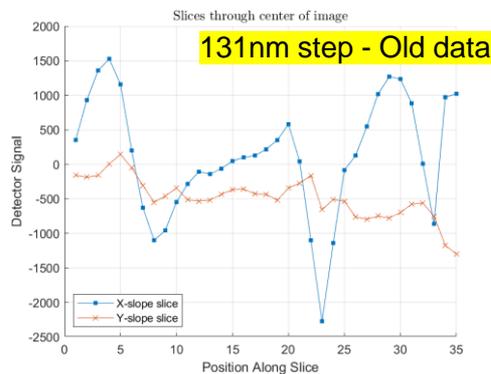


Phase Plate Stepsize (nm)	Tent Value (ADU)	Measured Phase Step (rad)	Phase Step (nm)
131.4	2232.8	0.9938	121.8
73.8	1254.9	0.4905	60.1
33.997	1033.0	0.3982	48.8

Deborah Malone, Petr Janout, Samuel Lévêque, Ronald Holzlöhner, Byron Engler, and Markus Kasper "Detection of discontinuous phase steps with a pyramid wavefront sensor", Proc. SPIE 12185, Adaptive Optics Systems VIII, 121855B (29 August 2022); <https://doi.org/10.1117/12.2632347>

Second Dataset

- Previously limited by wavefront aberrations from additional defocus term and off-axis aberrations introduced by re-alignment of source. Want to eliminate these
 - Introduction of THORLABS mount to tilt phase plates and negate the need for source re-alignment showed an immediate improvement in measurement quality.
- New dataset was taken with a different exposure time - > Required use of normalized calibration curve to compare both sets.



Two data sets taken at different exposure times.

Old data – 4ms exposure

New data – 10ms exposure

Normalising the curve

- What method would work best?

Dealing with flats

- 1) Subtracting a low-order flat

Normalisation

- 1) No normalisation
- 2) Normalising by the sum of the flat subapertures
- 3) Normalising by the sum of the image subapertures

Dealing with tent values in calibration data

- 1) Single peak value across edge
- 2) Average across 2-3 pixels.

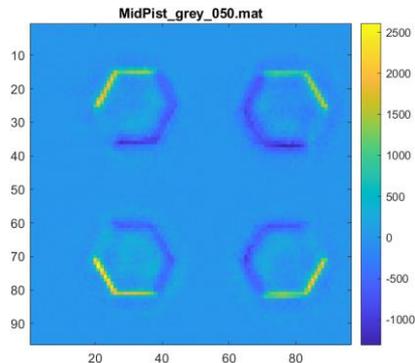
- 6 Different combinations, 2 Un-normalised, 4 Normalised

Subtracting Low-order flats

New method

Pixel-by-pixel subtraction

- If flats include any noise or high-order intensity variations, these will also be subtracted.

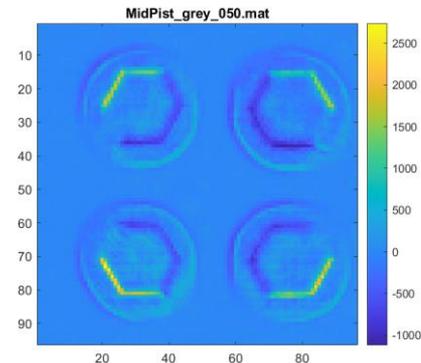


D = Detector image
 F = Flat image
 F_G = Flat with gaussian blur
 I = Resulting image

$$I(x, y) = D(x, y) - F(x, y)$$

Low-order subtraction

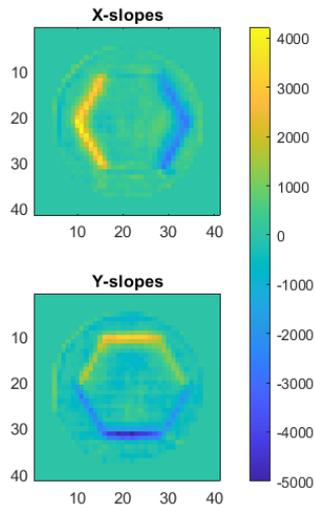
- Flat is blurred (4-pixel Gaussian blur) and subtracted to only remove slowly varying background intensities.



$$I(x, y) = D(x, y) - FG(x, y)$$

Normalization of the Slopes

No normalization

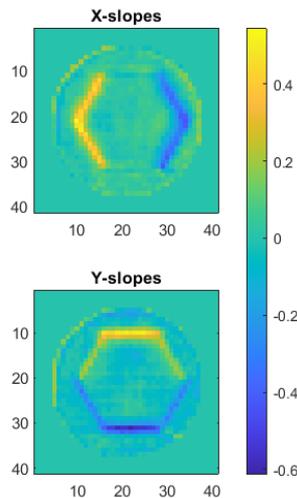


All images have blurred flat subtracted

$$S_x(x, y) = (S_1(x, y) + S_2(x, y)) - (S_4(x, y) + S_3(x, y))$$

$$S_y(x, y) = (S_1(x, y) + S_2(x, y)) - (S_4(x, y) + S_3(x, y))$$

Flat normalization

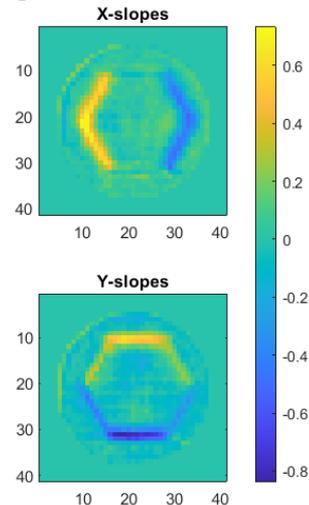


$$I(x, y) = D(x, y) - FG(x, y)$$

$$S_x(x, y) = \frac{(S_1(x, y) + S_2(x, y)) - (S_4(x, y) + S_3(x, y))}{F_{G1}(x, y) + FG_2(x, y) + FG_3(x, y) + FG_4(x, y)}$$

$$S_y(x, y) = \frac{(S_1(x, y) + S_2(x, y)) - (S_4(x, y) + S_3(x, y))}{F_{G1}(x, y) + FG_2(x, y) + FG_3(x, y) + FG_4(x, y)}$$

Image normalization



S_n = Subaperture n of image I
 S_x/S_y = X slope / Y slope
 F_{Gn} = Subaperture n of flat image F_G

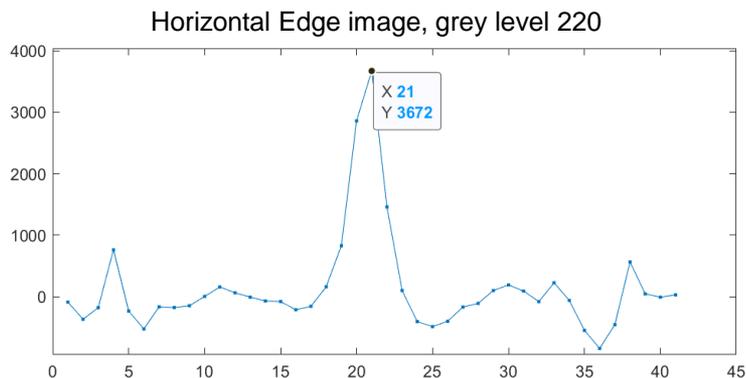
$$S_x(x, y) = \frac{(S_1(x, y) + S_2(x, y)) - (S_4(x, y) + S_3(x, y))}{S_1(x, y) + S_2(x, y) + S_3(x, y) + S_4(x, y)}$$

$$S_y(x, y) = \frac{(S_1(x, y) + S_2(x, y)) - (S_4(x, y) + S_3(x, y))}{S_1(x, y) + S_2(x, y) + S_3(x, y) + S_4(x, y)}$$

Calculating Tent values

Single value across edge

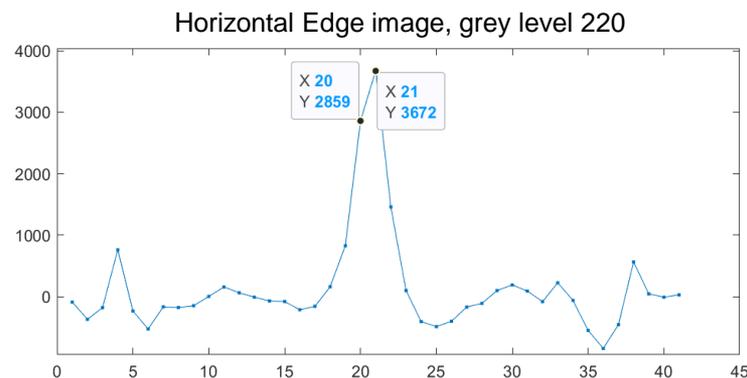
- Picking the single highest value as the value of the tent function



Highest point gives a value of 3672 for a grey level of 220.

Average across edge

- Averaging across 2-3 pixels, results in a lower value for a given phase.

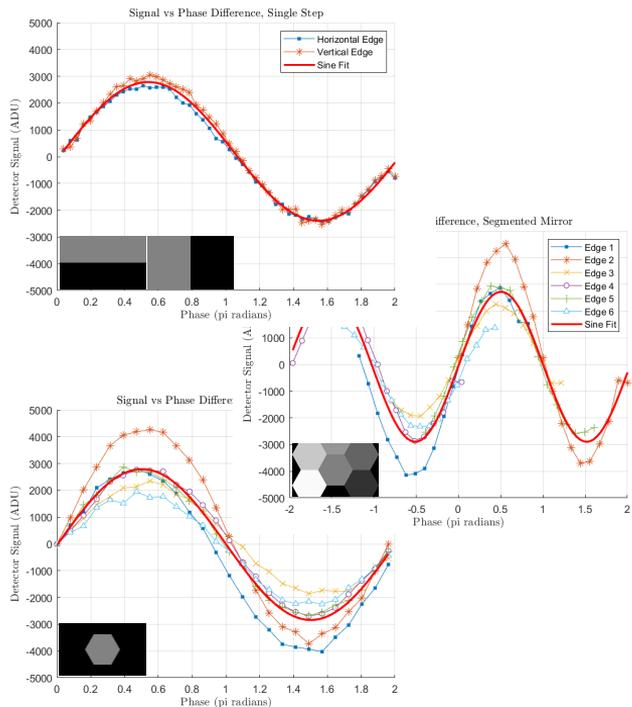


Averaging the two pixels gives a value of 3266 for a grey level of 220.

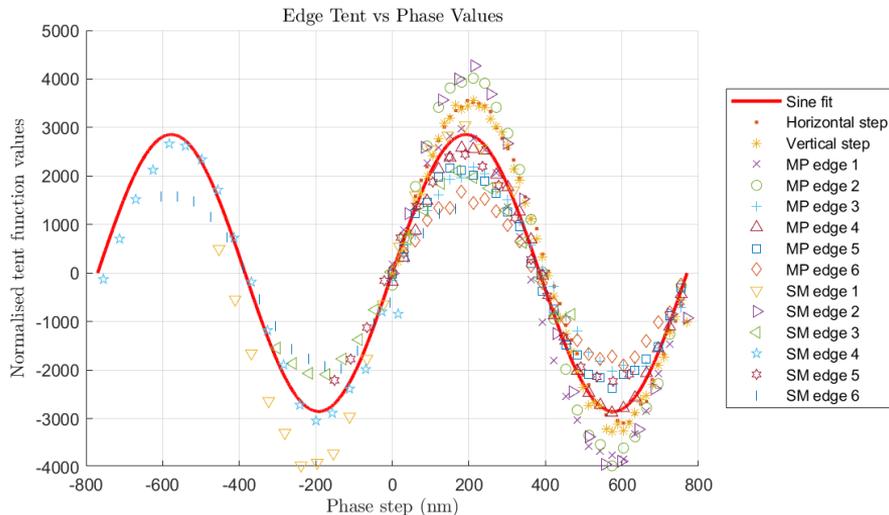
- In a turbulence scenario, edge is blurred, need to average over a few pixels to get the accurate value for the tent function.

Calculating Calibration Curve – New Method

■ Instead of three different fits – all data points fitted together. One fit.



Flat subtracted, no normalization, averaging across the tent function



Before I show the graphs...

■ Flat subtraction

- Now subtracting a blurred flat.

■ Normalisation

- 3 Methods,
 - No normalisation.
 - Normalisation using the flat.
 - Normalisation using the image (common method).

■ Measuring the tent functions

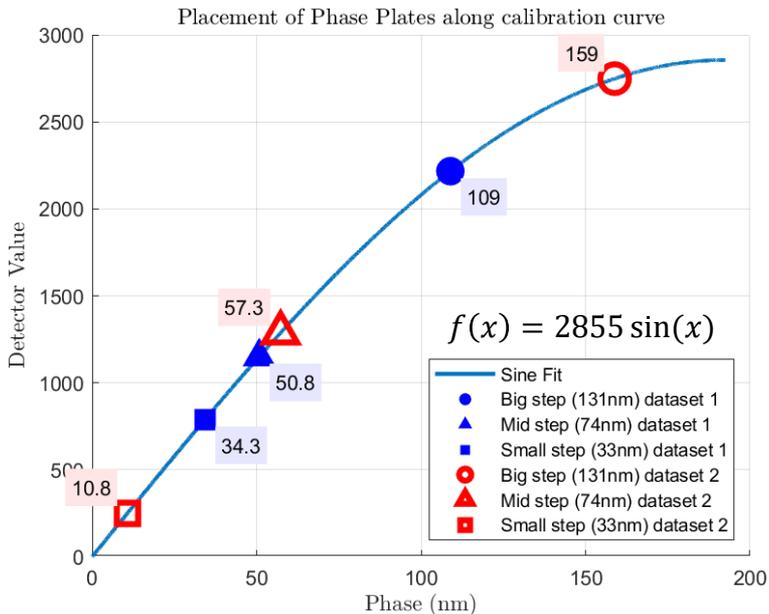
- 2 Methods
 - Single highest value
 - Averaging across 2-3 pixels.

■ Sine fit for all data points from all calibration screens.

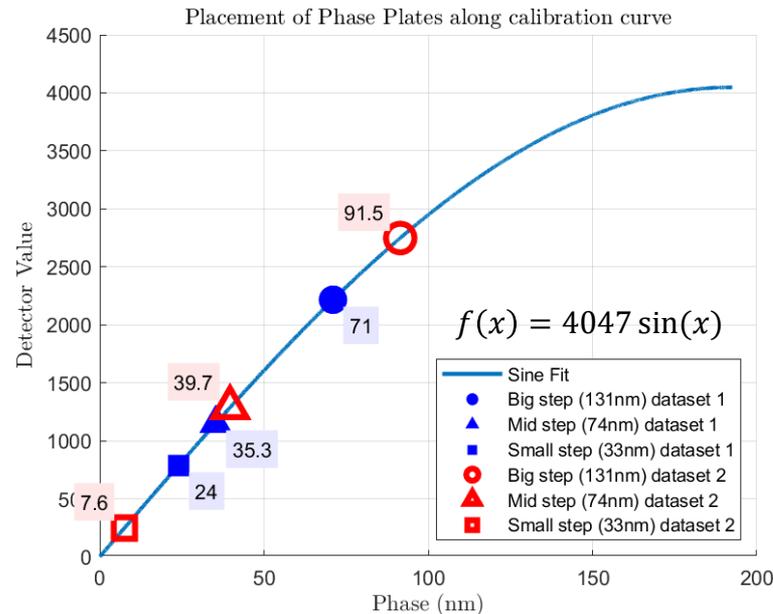
Method 1 – Flat subtracted, No normalisation

- New data taken as 10ms exposure as opposed to 4ms, tried scaling the tent values by 4/10.
- Nearest neighbour interpolation used to find where tent function of physical phase steps sit on the resulting calibration curve

Averaging tent values



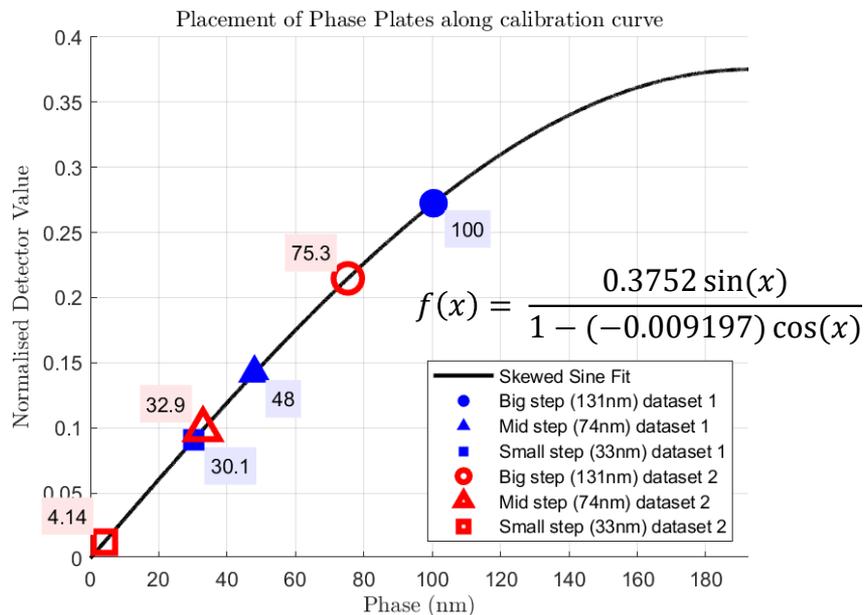
Single tent values



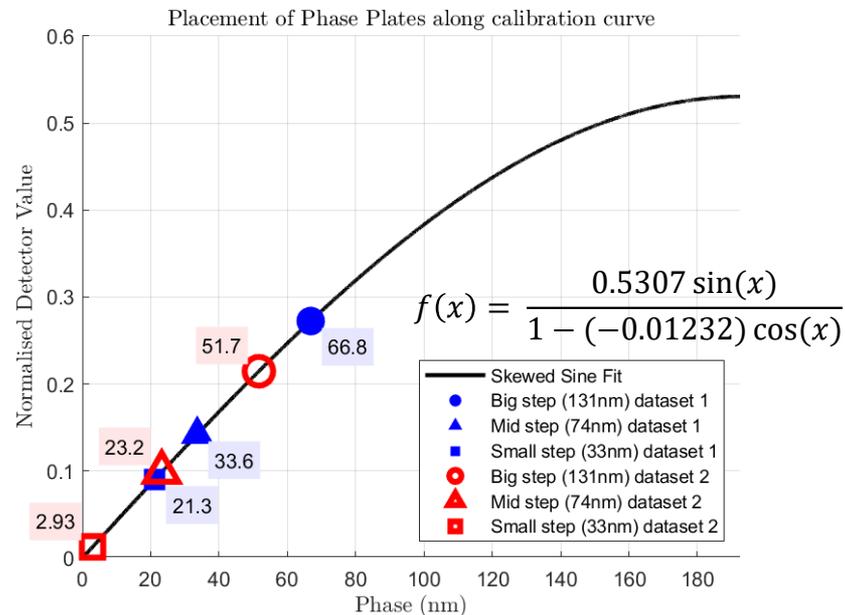
Method 2 – Flat subtracted, Normalised by flat

- Subtracting a low order flat, and then using that same flat to normalise the slopes.

Averaging tent values



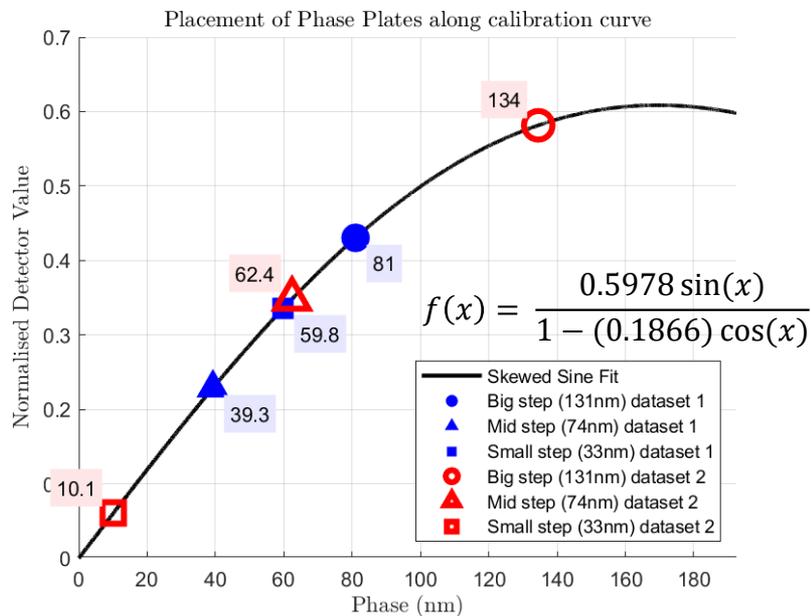
Single tent values



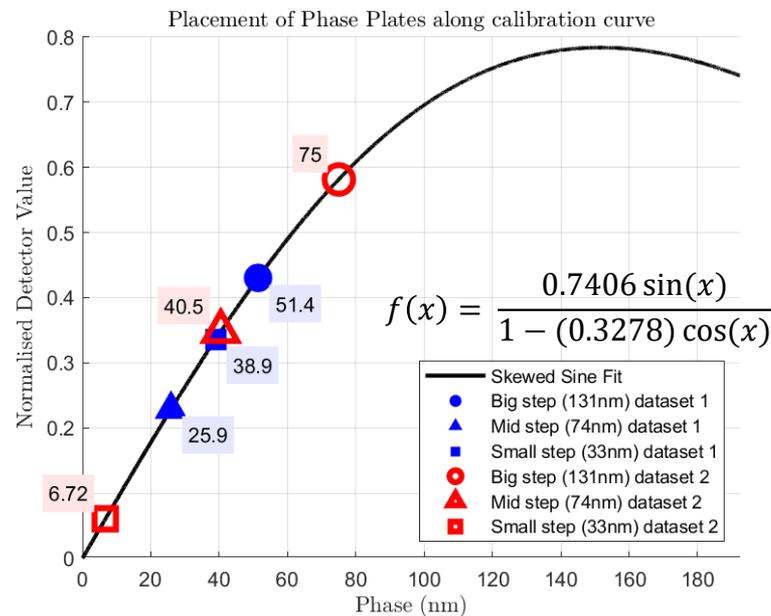
Method 3 – Subtracting flat, normalising by image subapertures

- Subtracting a low order flat, and then using the sum of the resulting subapertures to normalise the result

Averaging tent values



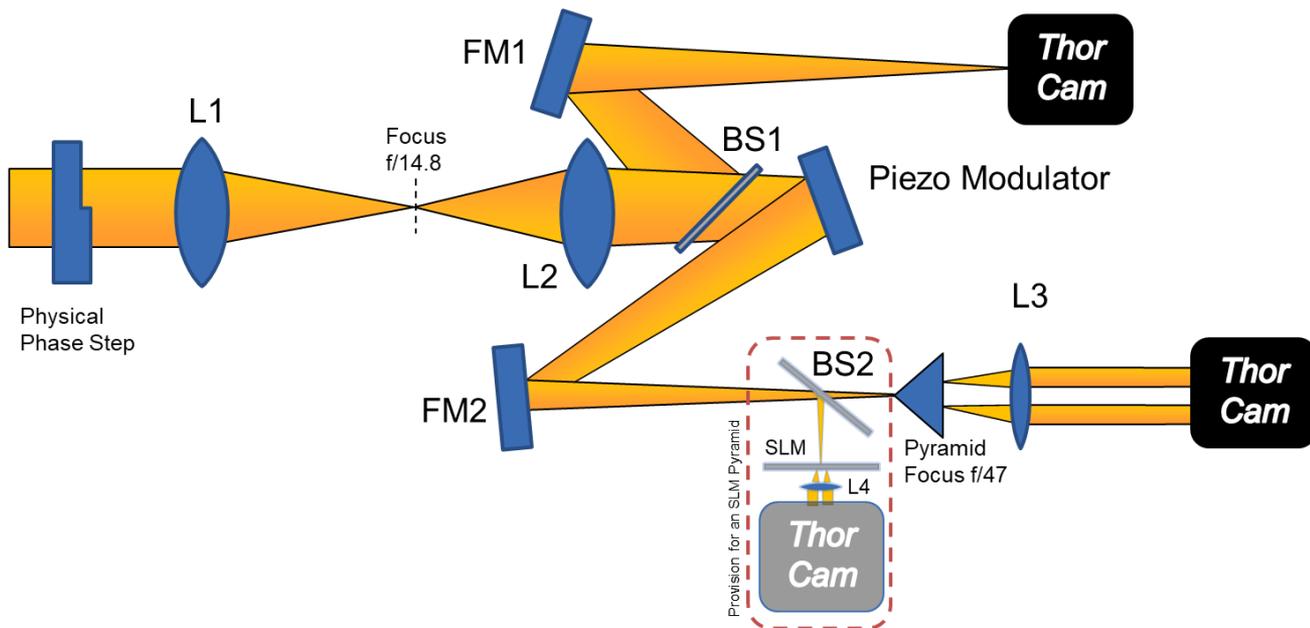
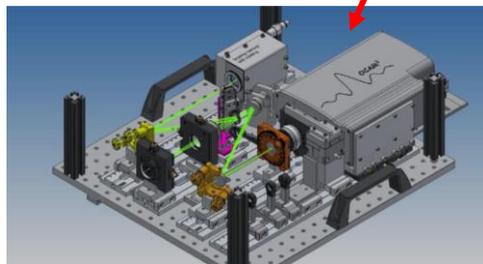
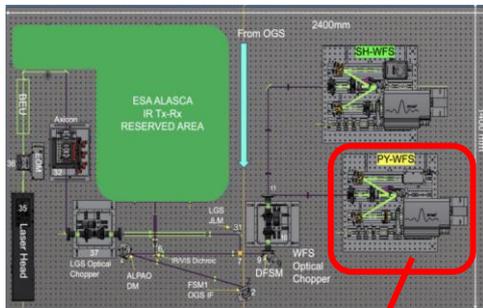
Single tent values



Future Measurements – Pyramid Piston Testbench

- Want to be able to do similar measurements on a test bench which we understand and control all the individual components.

- The Pyramid Piston Testbench is the prototype for the PyWFS arm from CaNaPy.



Conclusion

- Previous results using non-normalized data reduction methods showed encouraging results.
- Addition of rotating lens mount for phase plates improved the quality of images.
- Different normalisation methods investigated.
 - No normalisation, usable if all data taken with exact same parameters.
 - Averaging across several pixels over the edge produced better results than using a single value.
 - Normalisation by detector image with averaging over edge gave best results.
- Future work planned
 - Pyramid Piston Testbench at ESO.
 - Plan to perform similar measurements and compare results.