DCATT Dispersed Fringe Sensor (DFS)

-- Modeling and Experiment with Transmissive Phase Plates

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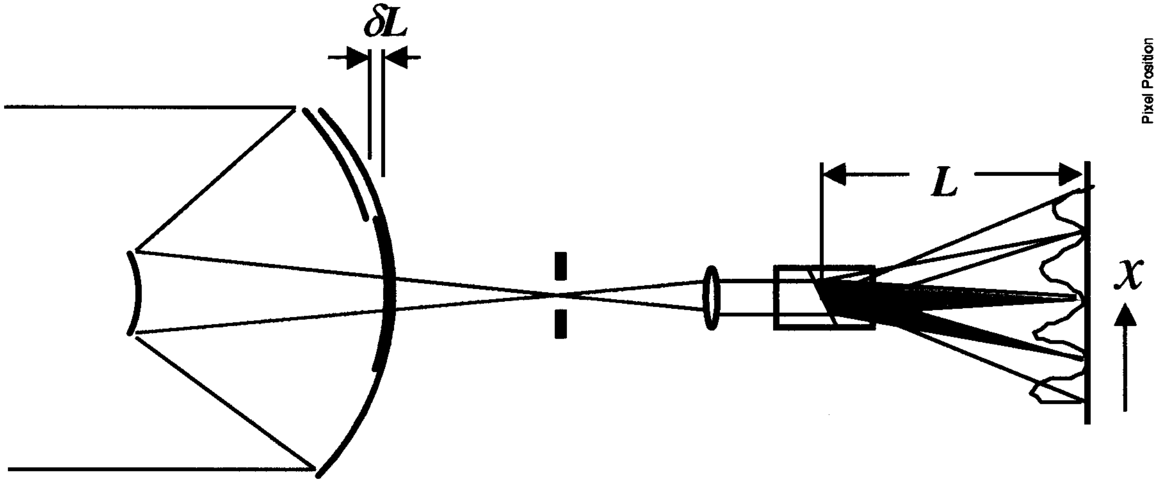
Introduction: Wavefront Control for NGST

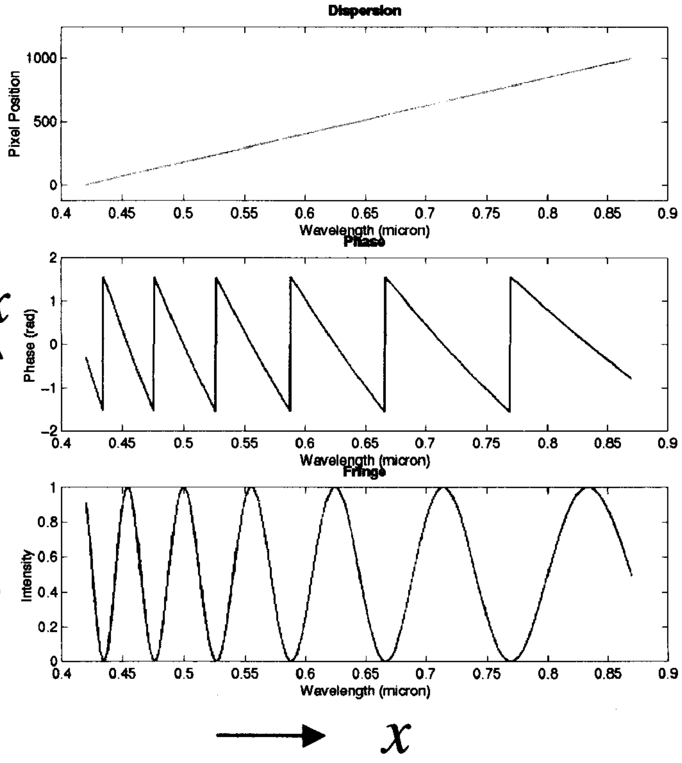
- The alignment and phasing control of NGST's segment primary mirrors use images from the science camera instead of dedicated instruments
- The segment mirror alignment and phasing is split into distinct phases:
  - Initial capture, coarse alignment and focusing:
    - Segment wavefront error goes from cm to sub-mm
  - Coarse phasing: uses Dispersed Fringe Sensor (DFS) and White Light Interferometer (WLI)
    - Segment wavefront piston error goes from sub-mm to a few nm
  - Fine phasing: uses Phase Retrieval to drive both the segment mirrors and the deformable mirror (DM)
    - Local wavefront error goes down to nm
- Developmental Comparative Active Telescope Testbed (DCATT) is developed to test the wavefront control techniques. Its primary has 7 hexagonal segment mirror with total diameter of 1 meter.

Dispersed Fringe Sensor(DFS): Introduction

- Dispersed Fringe Sensor (DFS) is used to detect the relative piston errors between segment mirrors
- DFS is used to further reduce the wavefront error after the initial capture and coarse alignment control phase
- DFS uses a grism as the dispersing element in the filter wheel of the imaging camera to generate a spectrum on the detector
- Coherent addition of the wavefront error due to the relative piston of the segment mirrors will result in the fringe modulations in the spectrum
- Piston errors can be determined by the period of the modulation
- Sign of the piston error can be determined by the orientation of the fringe modulation

DFS: How the Fringe is Formed

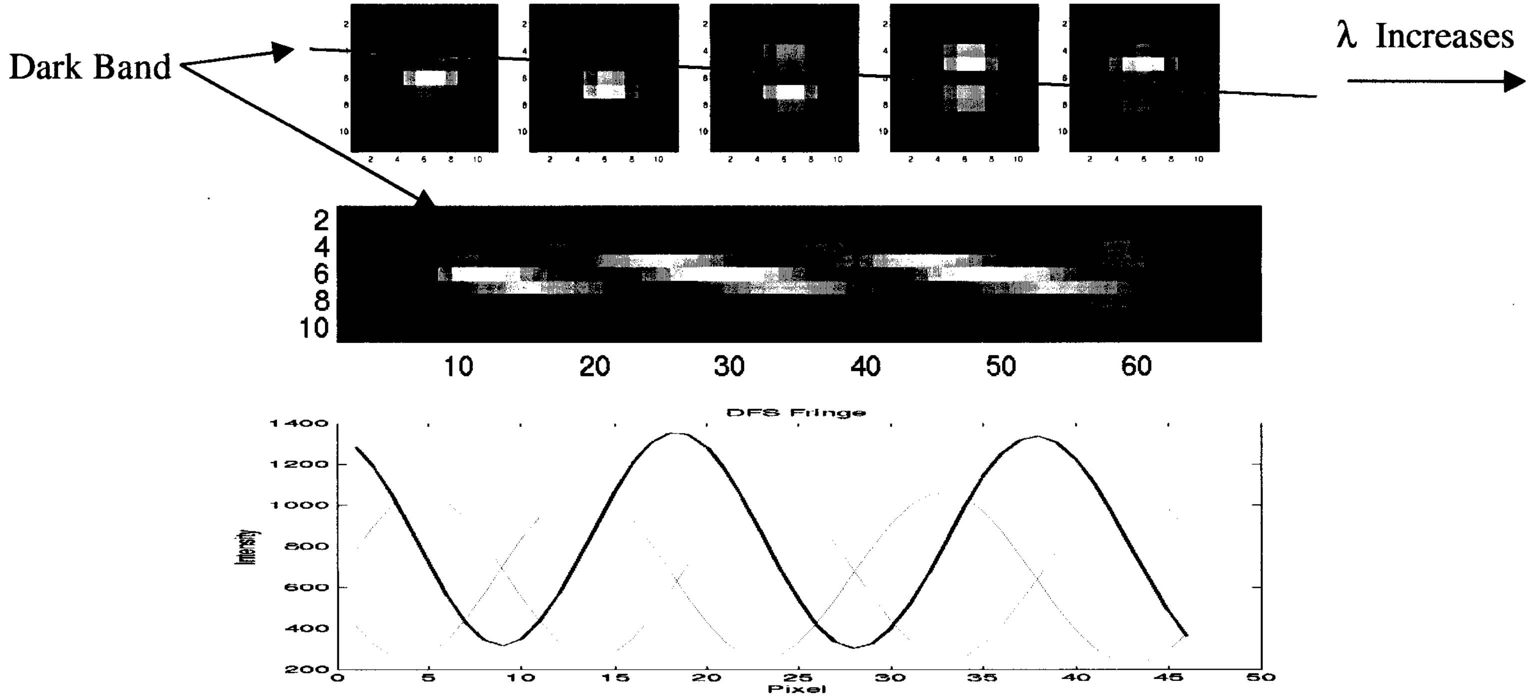




- Begin by co-aligning (tilt) the PSF from outer segment to that of center segment
- Insert the grism to form Dispersed Fringe Sensor
- Field at any point (x) along the dispersion is the sum of the fields from the de-phased segments:

  $E(x) = E_1 exp[i(2\pi/\lambda(x))L]+E_2 exp[i\,(2\pi/\lambda(x))(L+\delta L)]$
- Depending on wavelength the two wavefronts may add constructively or destructively, forming the modulation along the dispersion direction
- Grism disperses the light linearly with wavelength so the fringes are not equally spaced

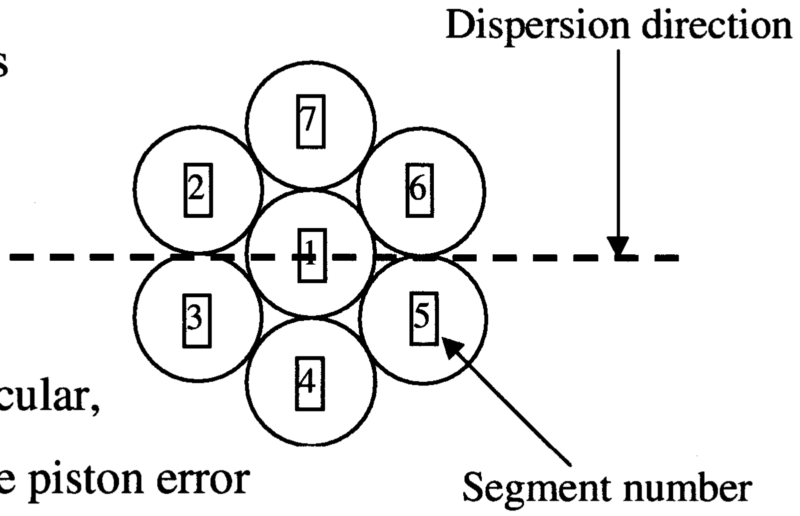
DFS: How the Fringe is Generated



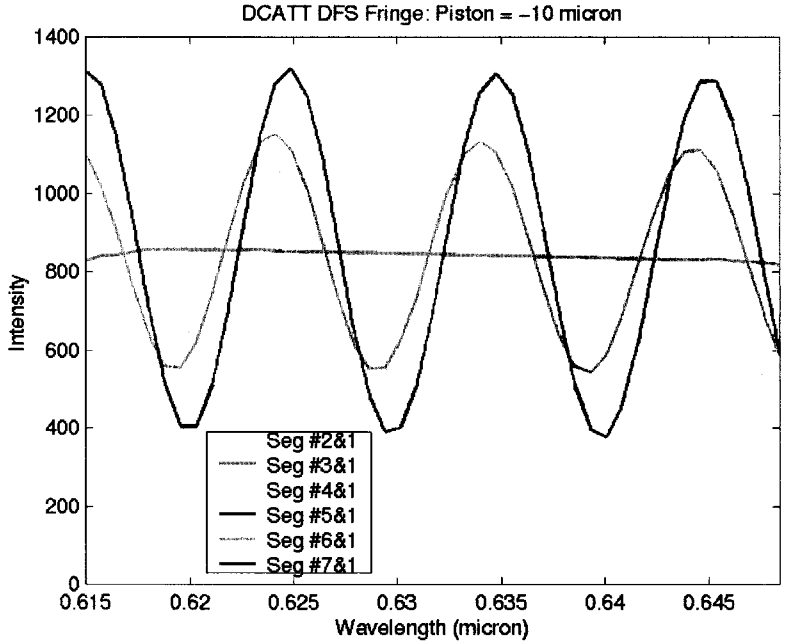
- Piston error between the two segments will form dark band on the PSF at the position which satisfies the destruction condition $(2\pi/\lambda)\delta L = \pi/2$. With the δL being constant the position of dark band shifts as the wavelength λ changes as shown in the top row images.
- The DFS spectrum combines many PSF's at different wavelengths to form a glancing dark bands.
- For a given spectral range, larger piston error will result in more dark bands
- If the sign of the piston changes the dark band glancing angle will flip by 180 degree
- Central (sub PSF) pixel row is extracted as the DFS signal (blue curve in the plots) and adjacent rows are used to detect the sign of the piston error (red and magenta curves)

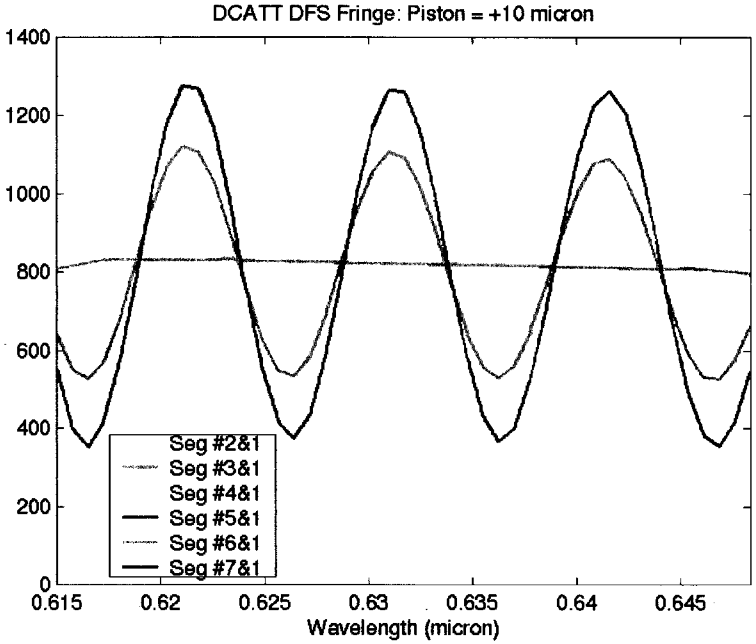
DCATT DFS: Model Setup and Fringe Generation

- Double pass DCATT MACOS model with grism as the dispersing element
- Fringe of any TWO segment mirrors of the DCATT primary is used to coarse phasing the two segments. All the other segment mirrors are tilt away to reduce the interference.
- Center segment is used as the reference
- Before inserting the grism the PSF of outer segment mirror is co-center with that of central segment
- Aberration can be put on the mirror surfaces
- The fringe visibility depends on the relative orientation between the base line of the segment pair and the grism
- When the segment base line is not perpendicular, the visibility also depends on the sign of the piston error



DCATT DFS: Model Fringes

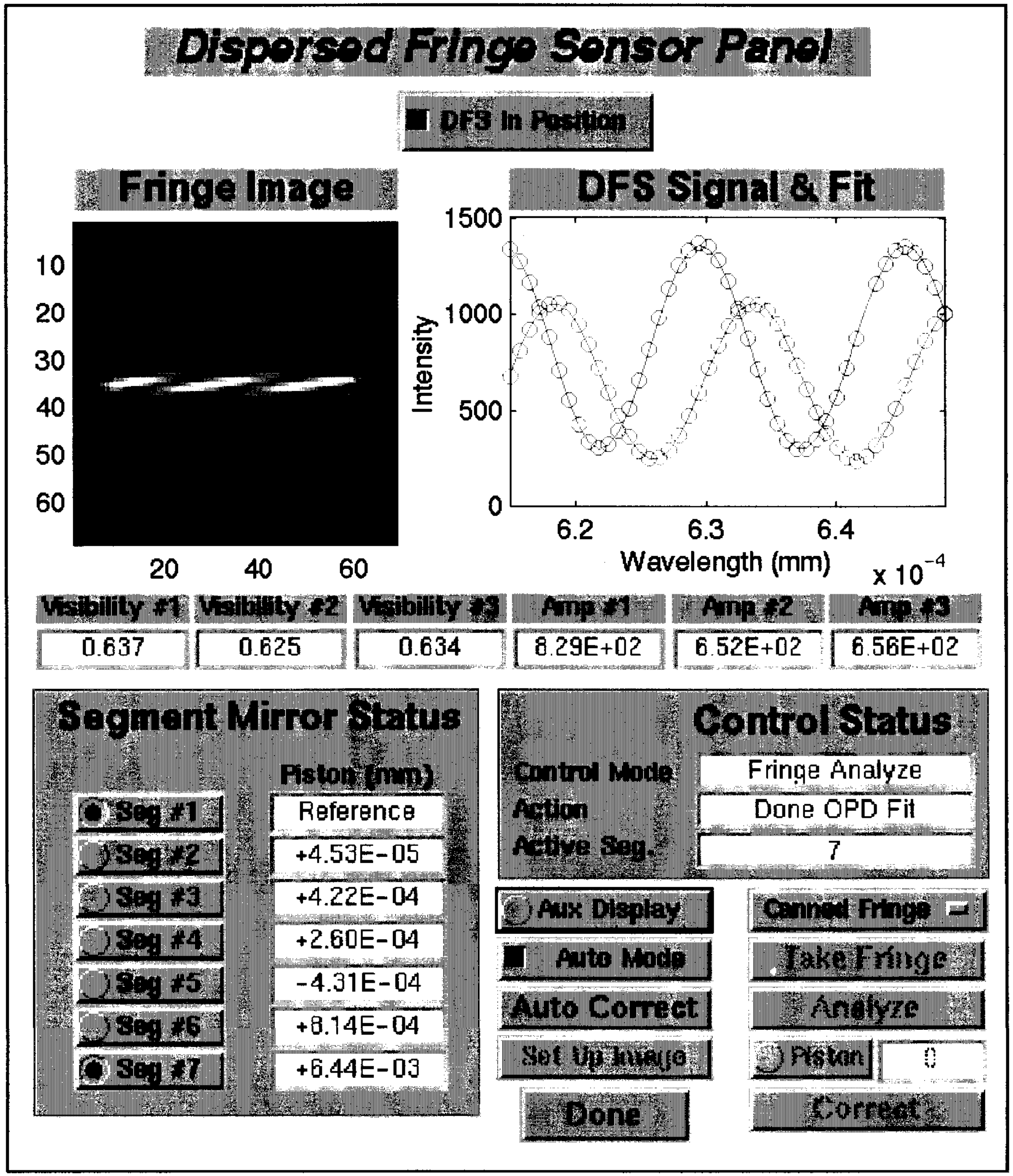

DCATT DFS Fringe: Piston = −10 micron


DCATT DFS Fringe: Piston = +10 micron

- The base lines of Segment #7 & #1 and Segment #4 & #1 are perpendicular to the dispersion direction and their fringes have the highest modulation (visibility)
- Fringes from other segment pairs have lower modulations because their base lines are at an angle (30 degree) to the dispersion direction.
- For negative piston errors the fringes from Segment #2 & #1 and Segment #3 & #1 have very low modulations
- For positive piston errors the fringes from Segment #5 & #1 and Segment #6 & #1 have very low modulations

DCATT DFS: DFS Control Software

- Shown on the right is the GUI panel of DFS control software which provides user with status and control input capability
- Functions of DCATT DFS control software include:taking DFS fringe and calibration images; image processing; DFS fringe extraction; fringe analysis; and controlling DCATT segment to correct the piston errors detected from DFS
- DFS control software can work with both model and hardware
- The DFS control software is part of the DCATT executive software which controls DCATT from initial capture to high order fine phasing with DM



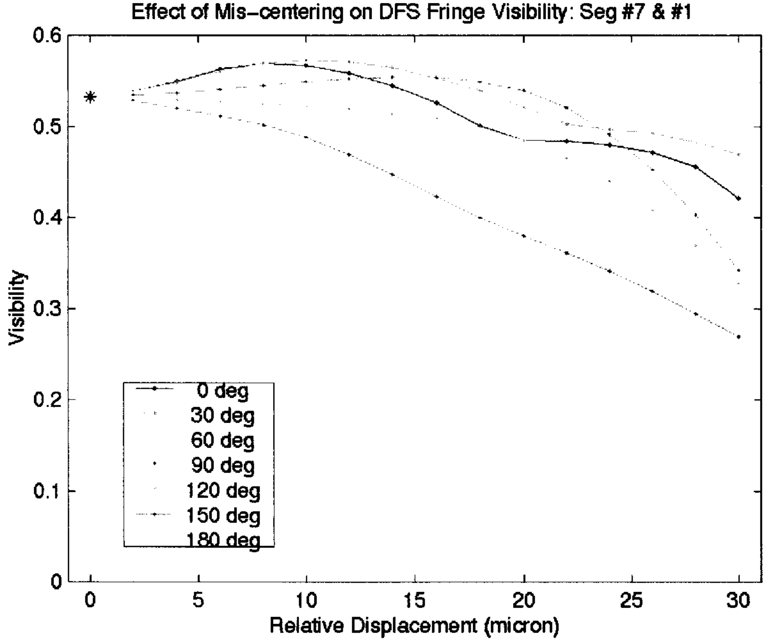
Visibility #1	Visibility #2	Visibility #3	Amp #1	Amp #2	Amp #3
0.637	0.625	0.634	8.29E+02	6.52E+02	6.56E+02

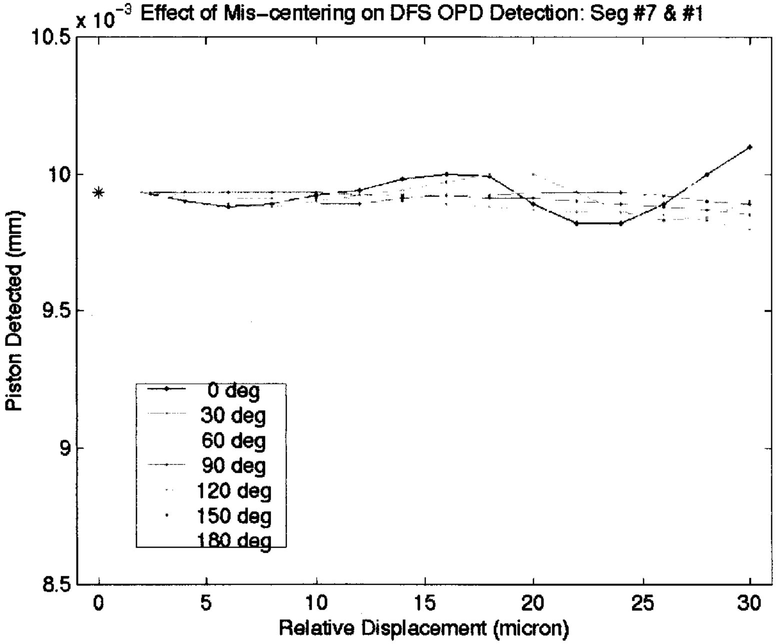
	Piston (mm)
● Seg #1	Reference
○ Seg #2	+4.53E-05
○ Seg #3	+4.22E-04
○ Seg #4	+2.60E-04
○ Seg #5	-4.31E-04
○ Seg #6	+8.14E-04
● Seg #7	+6.44E-03

Control Mode: Fringe Analyze
Action: Done OPD Fit
Active Seg.: 7

Piston: 0

DCATT DFS: Effects of Miscentering of Two Segment Mirrors on Accuracy of DFS





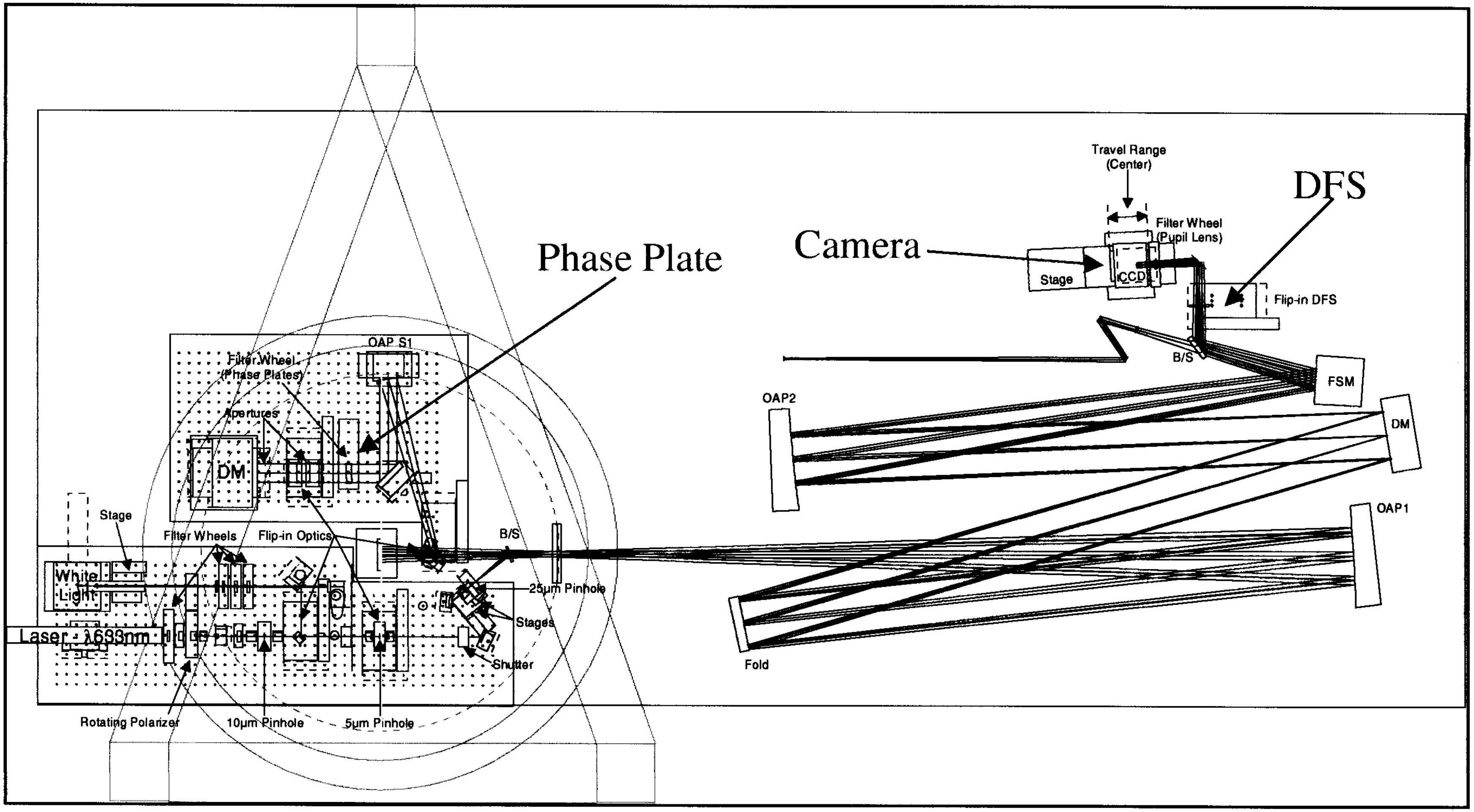
The effect of the mis-alignment of segment mirrors on DFS performance has been studied using the DCATT MACOS model. Tilt perturbation have been added to the segment pairs and DFS fringes generated and detected. Plot on the left shows the effect of spot mis-centering on the DFS fringe visibility and the plot on the right shows the actual detected piston values. Different color represent the different azimuth angles of the perturbed tilts relative to the dispersion direction with 0 degree being parallel to the dispersion. The mis-centering is quantified by the displacement between the two segment spots. The full aperture FWHM DCATT PSF is about 8.3 μm @ $\lambda = 0.5$ μm. The non-perturbed values are indicated by a star(*) on each plot. The plots show that although the visibility drops with the increase of the mis-centering the detected piston is much less sensitive to the mis-centering error.

The simulations have shown that the DFS performance is insensitive to the tilt mis-alignment upto 0.1 arcsecond

DFS Experiment with Etched Phase Plate

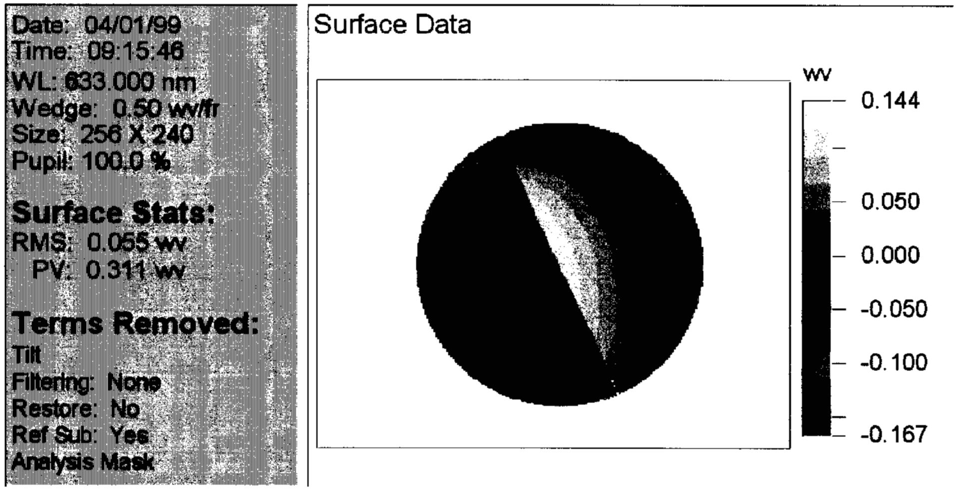
- DFS experiment has been carried out using specially designed etched fused silica plates with step size from 0.5 μm to 10 μm to simulate the piston errors between two segment mirrors. The purpose of the experiment was to test the DFS software and DFS detection algorithm
- Experiment was carried out on DCATT with a grism inserted into the beam before the camera to disperse the white light image
- Orientation of phase plates relative to the grism was changed to simulate the situation of different segment pairs in DCATT coarse phasing
- Phase plate was placed in the collimated beam before the DM. Light passed two times through the phase plate
- An arc xenon lamp was used as the white light source
- Image camera: 1536x1024 CCD camera
- Five narrow band filters (bandwidth = 3 nm) were used to calibrate the DFS

DCATT Source + Simulator + AO Bench + WFS Configuration



DFS Experiment: Measurement of Phase Plate

- The etched phase plates were measured to compare with DFS
- Half area of the fused silica plate was etched down to create a discontinued surface.
- The surface quality was measured with Wyko 400 phase shifting interferometer as shown on the right
- Step size was measured with white light interference microscope (Wyko TOPO) and the results are listed in table at right.



Date: 04/01/99
Time: 08:15:46
WL: 633.000 nm
Wedge: 0.50 wv/fr
Size: 256 X 240
Pupil: 100.0 %

Surface Stats:
RMS: 0.055 wv
PV: 0.311 wv

Terms Removed:
Tilt
Filtering: None
Restore: No
Ref Sub: Yes
Analysis Mask

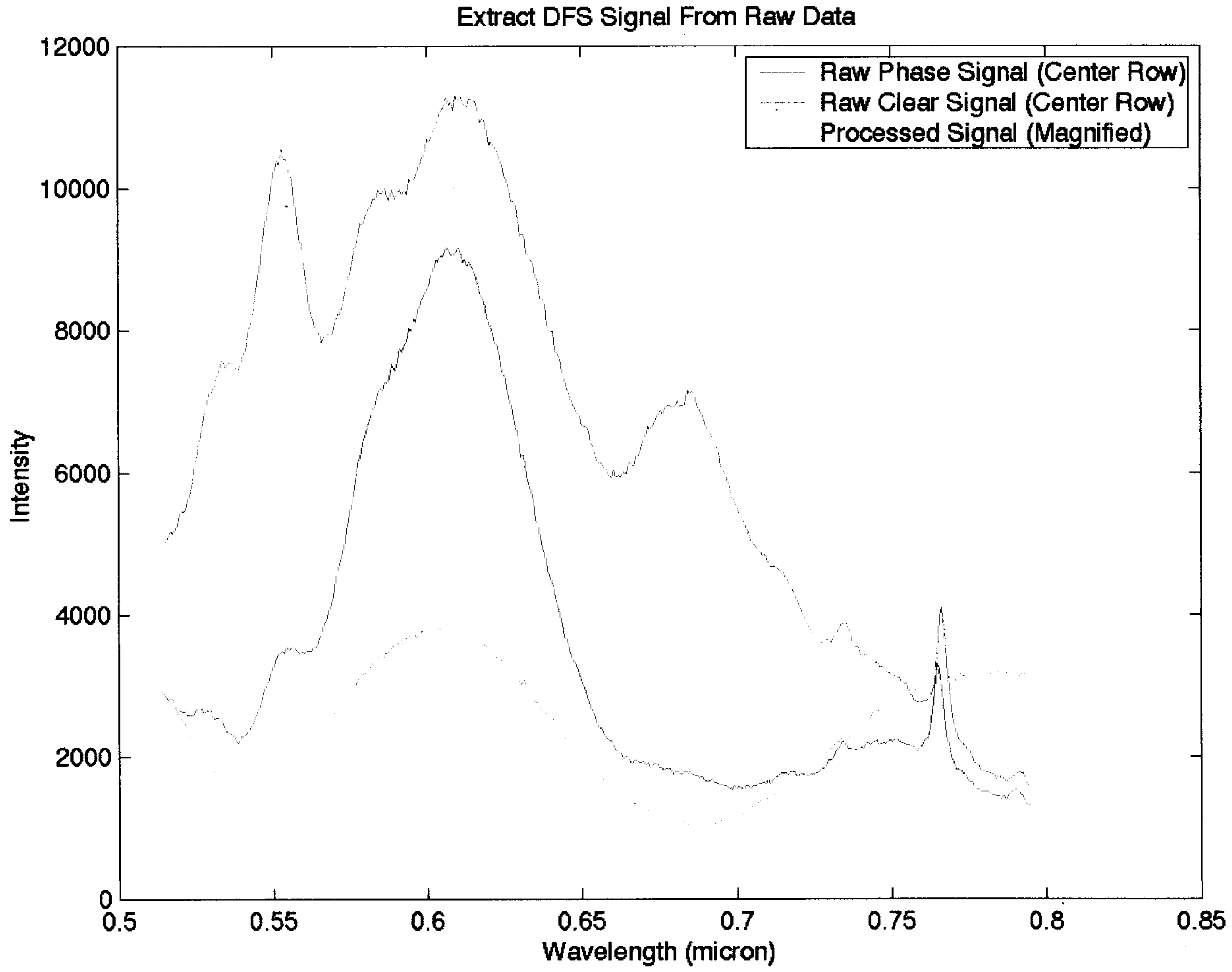
Surface Data

Nominal Step Size (µm)	0.5	2.0	2.5	5.0	10.0
Measured Step Size (µm)	0.525	2.08	2.54	5.14	

DFS Experiment: Fringe Image Processing and Signal Extraction

- Types of image taken in the experiment:
  - DFS image with a phase plate in: signal image
  - DFS image without phase plate: reference image
  - DFS image with narrow band filters: wavelength calibration image
  - Dark frame: background image
- Fringe image processing:
  - Remove dark frame from both signal and reference images.
  - Locally average reference image to get a reference fringe.
  - Divide the signal image by the reference fringe to remove the overall lamp spectrum and CCD response. Relative shifts are done with the help of a GUI interface panel.
  - Extract DFS signal fringe for OPD calculation and 2 adjacent fringes for OPD sign determination.
- Note: Accuracy of this method requires good sampling in both dispersion and cross dispersion directions. For these experiments we were near the minimal sampling (3 pixels cross dispersion).

DFS Experiment: Extract the DFS Fringe Signal



DFS Experiment: Calculation OPD from DFS Fringe

- Fringe formula:

$$I(OPD;\lambda)=I_0\left[1+\gamma\cdot\cos\left(\frac{2\pi}{\lambda}\cdot OPD+\theta_0\right)\right]$$

- Least square fit: Solve the I_0, γ, θ_0 and OPD by minimizing:

$$y=\left|I_{Fringe}(\lambda)-I_{Fitted}(OPD;\lambda)\right|^2$$

- The phase plates is in a double pass transmission system:

$$OPD=2\times Step(n_\lambda-1)$$

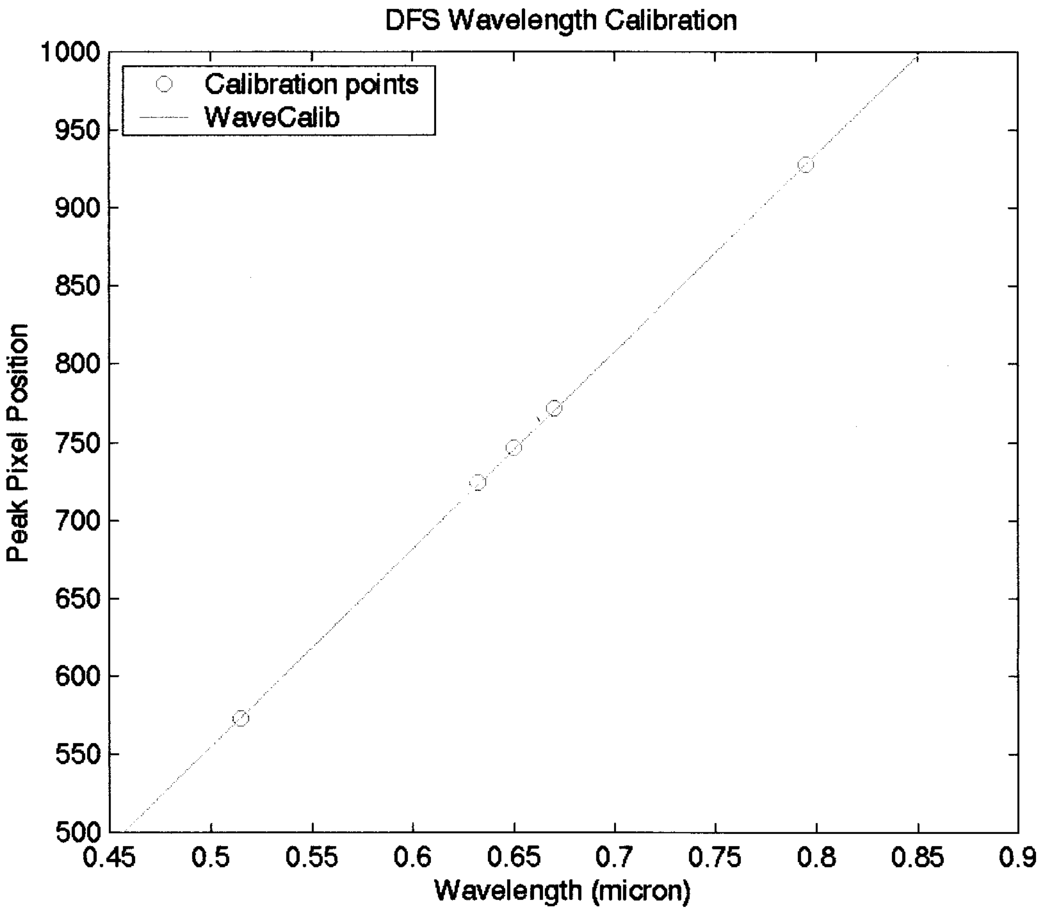
- Index of refraction: The index at each wavelength is calculated using Sellmeier 1 fomula:

$$n^2-1=\frac{K_1\lambda^2}{\lambda^2-L_1}+\frac{K_2\lambda^2}{\lambda^2-L_2}+\frac{K_3\lambda^2}{\lambda^2-L_3}$$

- Sign of OPD: detected from the orientation of the “dark band”. Two adjacent rows of signal are extracted and relative positions of their local minimum/maximum are used to determine the sign.
- Wavelength calibration: DFS images taken with narrow band filters are used to obtain the calibration between the wavelength and the pixel position on the CCD camera.

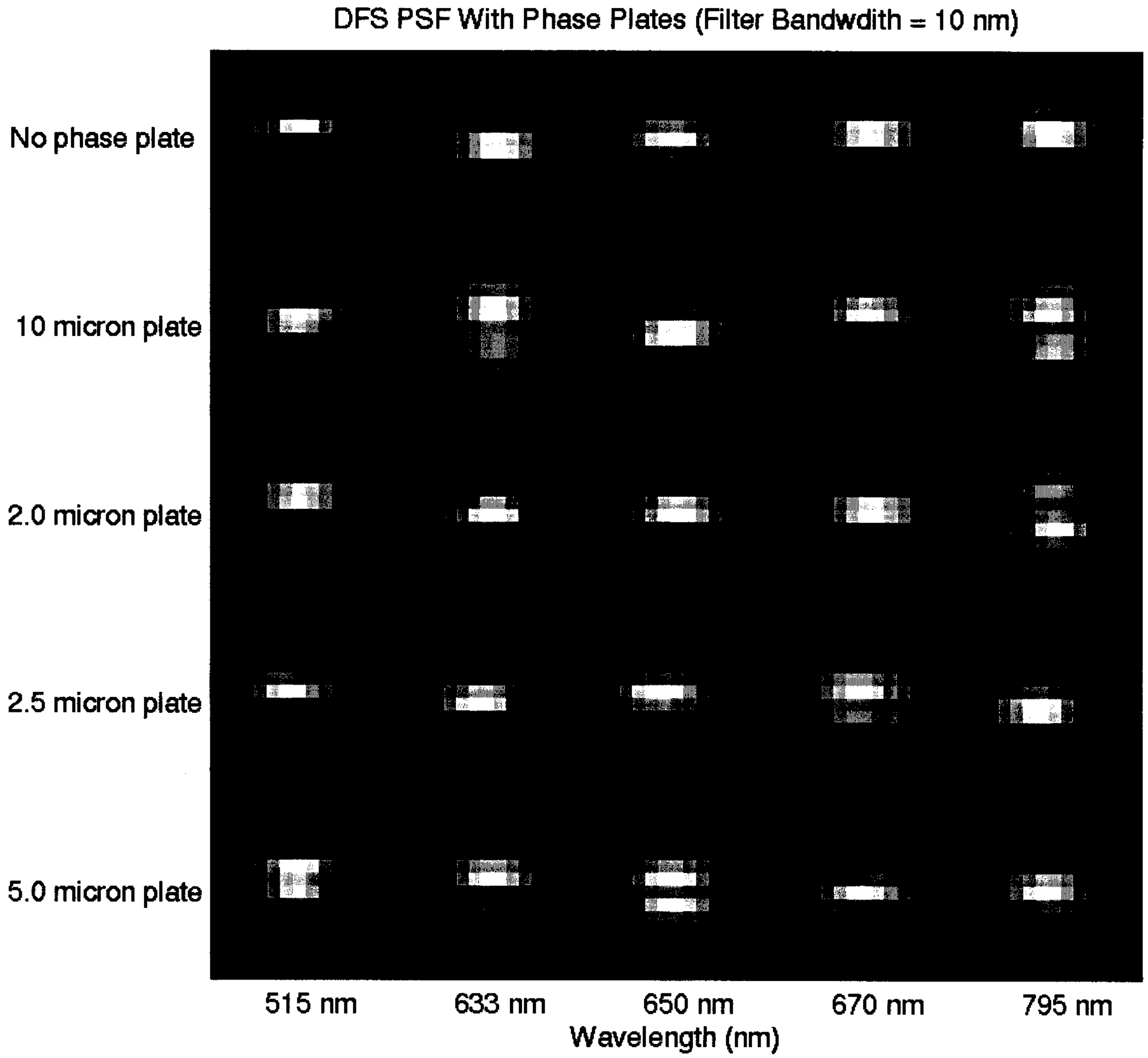
DFS Experiment: Wavelength Calibration

- Wavelength calibration is needed to provide the knowledge of dispersed position of the light and its wavelength
- Calibration was done by taking DFS pictures with narrow band (3 nm) filters centered at different wavelengths
- No phase plate is in beam during calibration. Due to the finite bandwidth the light through the filter forms a elongated spot.
- Centroid of the spot is used to determine the position

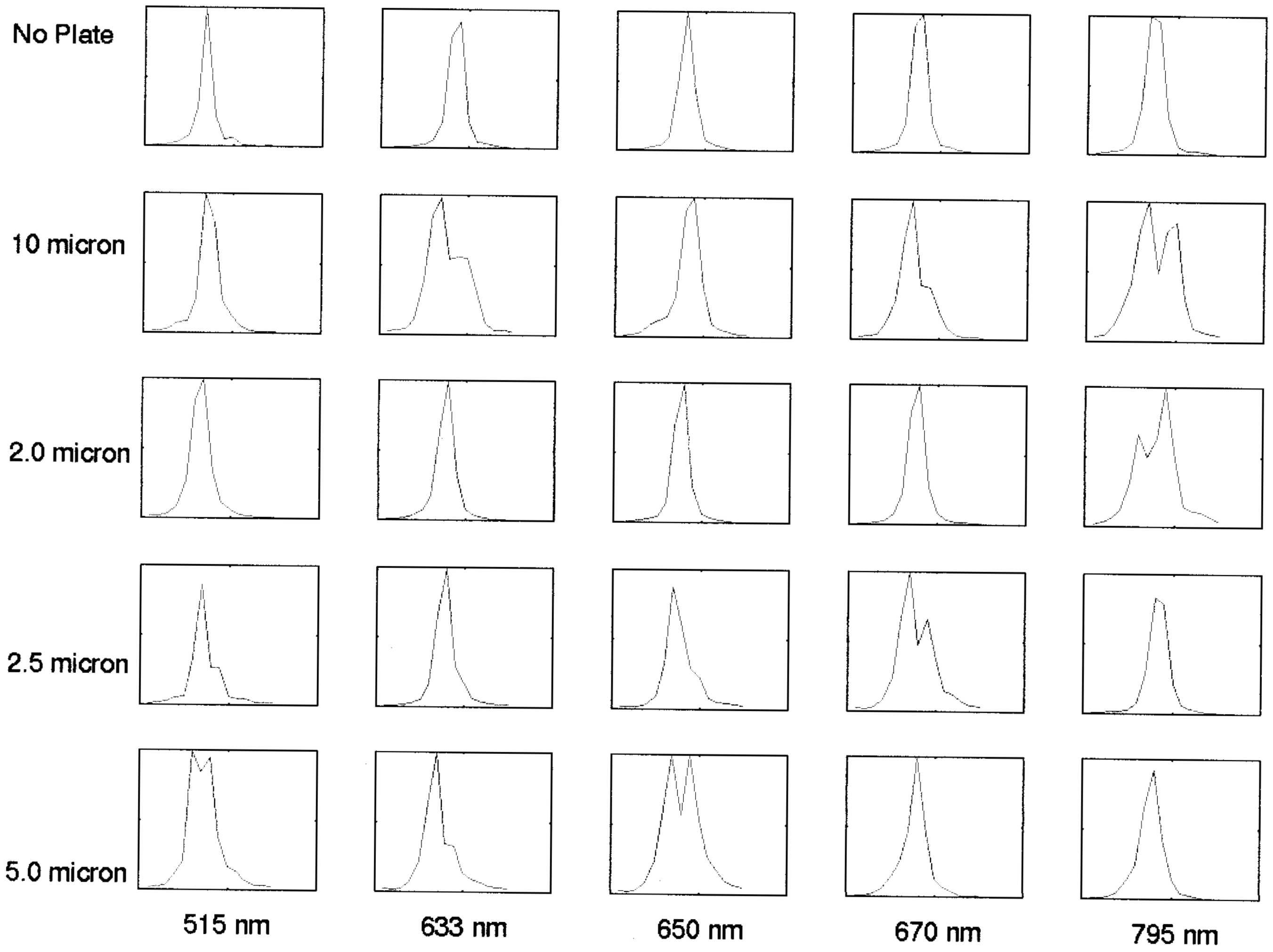


DFS Experiment: Point Spread Functions Images

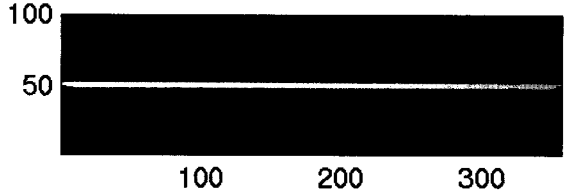
- Picture gallery on the right shows DFS pictures taken with different phase plates in the beam and using narrow band filters centered at different wavelengths. Depending on the OPD some spots have a dark band across the center or on the side. Spots are elongated due to the finite bandwidth of the filters. Cross section plots are presented in next page.
- The spots are similar to the modeled PSF's shown in page 5.
- Cross section plots are shown in the next page.

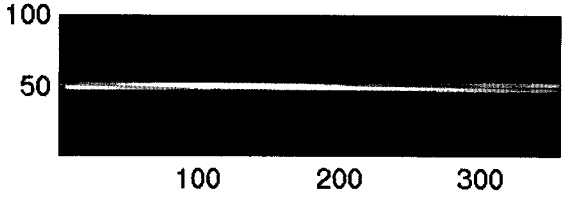


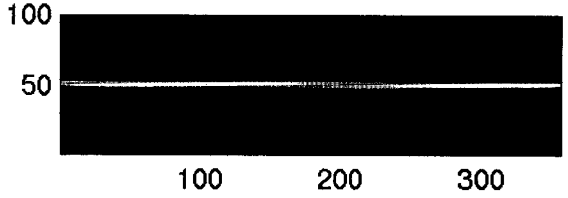
DFS Experiment: Point Spread Functions Plots

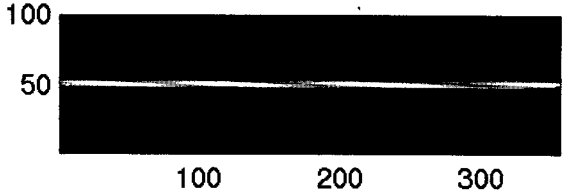


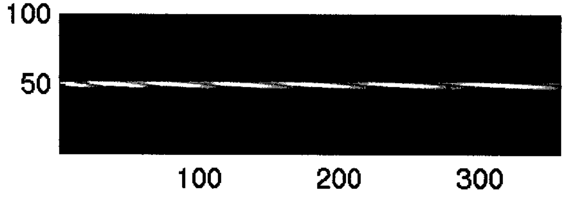
DFS Experiment: Fringes Image of Phase Plates


DFS Fringe: 0.5 micron Phase Plate


DFS Fringe: 2.0 micron Phase Plate

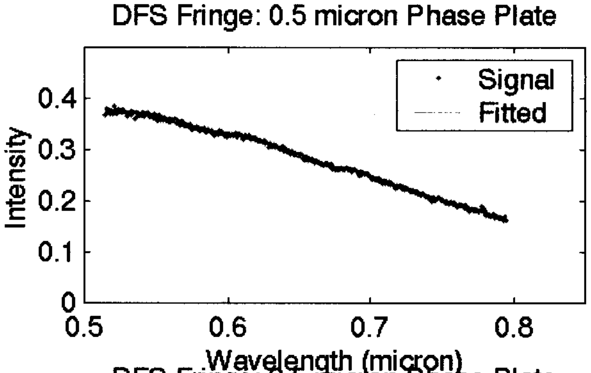

DFS Fringe: 2.5 micron Phase Plate

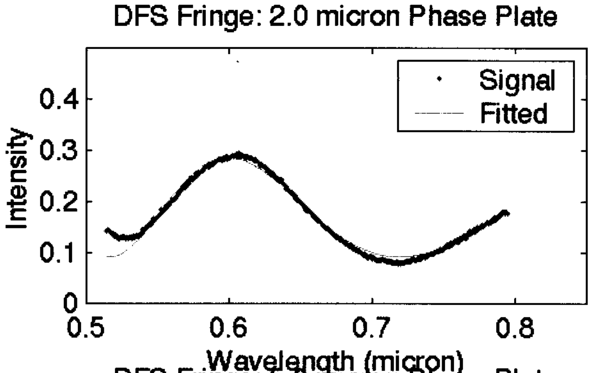

DFS Fringe: 5.0 micron Phase Plate

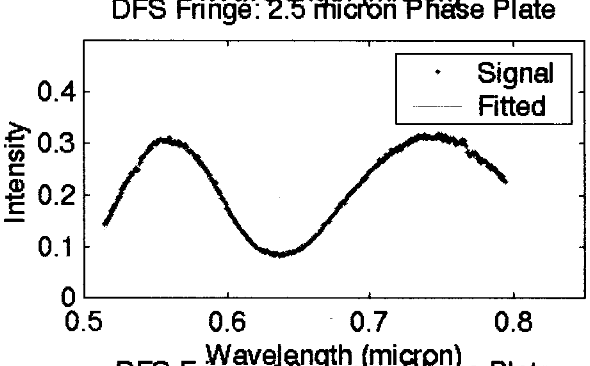

DFS Fringe: 10 micron Phase Plate

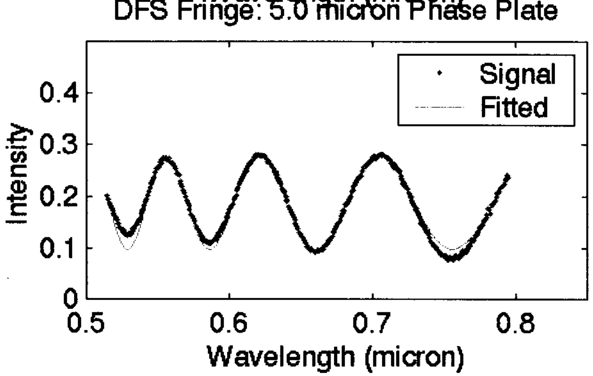
DFS fringes taken with phase plates of different step sizes. The spectral range is from 515 nm to 795 nm.

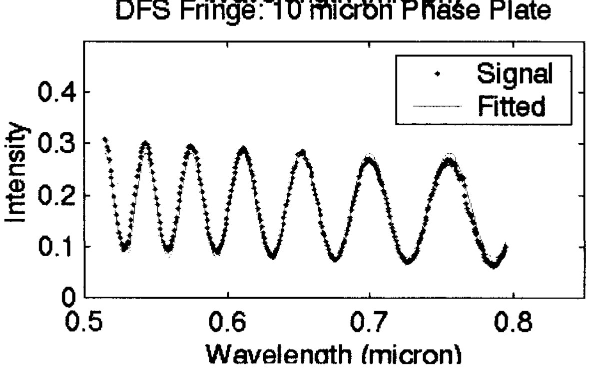
DFS Experiment: Fringes Signals and Fringe Detection Plots for Each Phase Plates





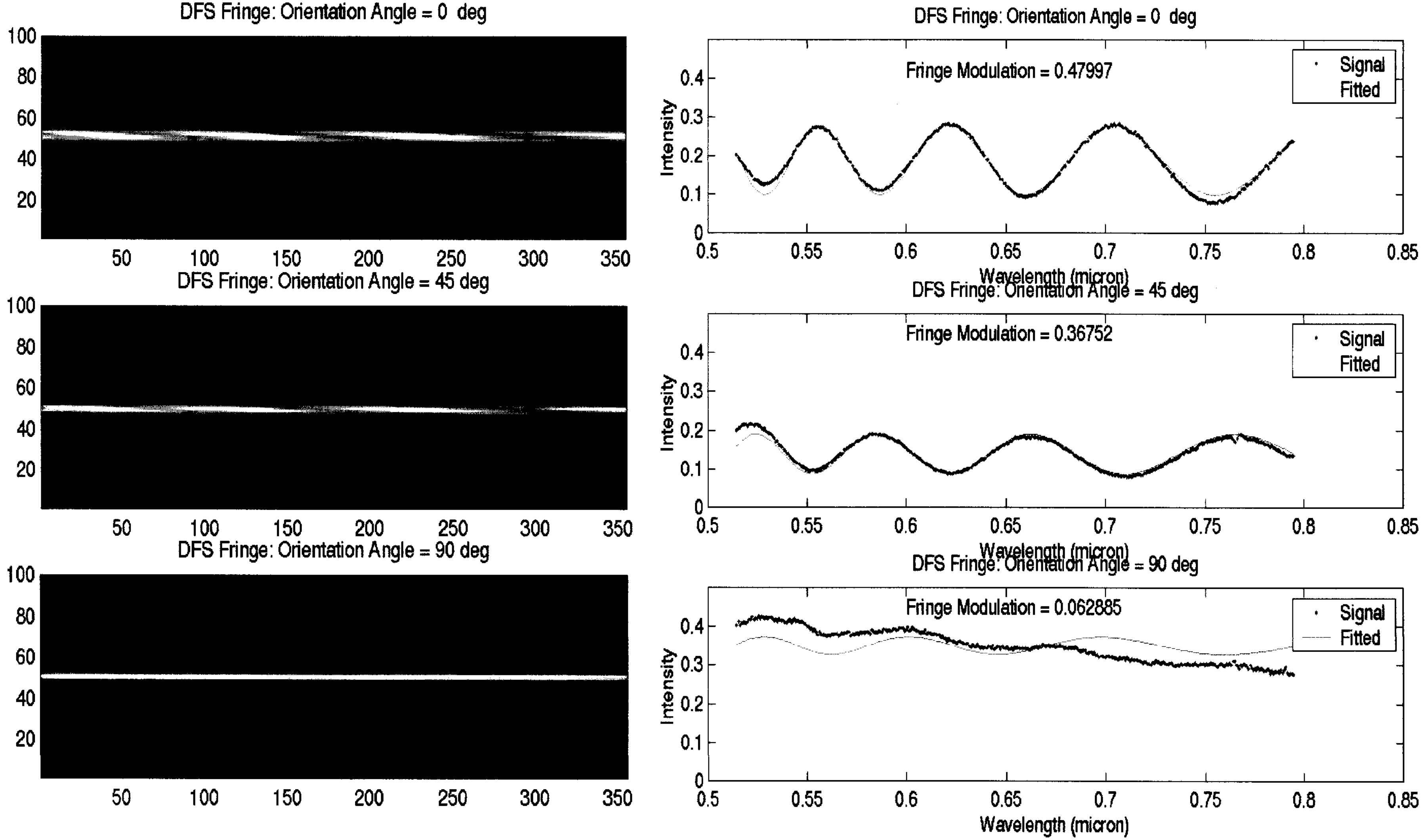






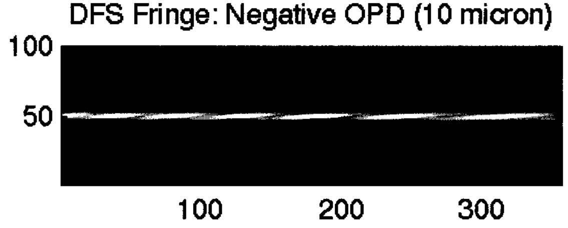
Plots shown the extracted fringe signals (blue dots) from the fringe images shown in previous page and the fitted curves (red line) from the solution of the OPD.

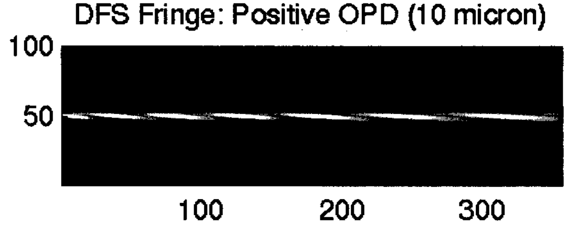
DFS Experiment: Relationship Between Fringe Visibility and Phase Plate Orientation -- Images and Plots

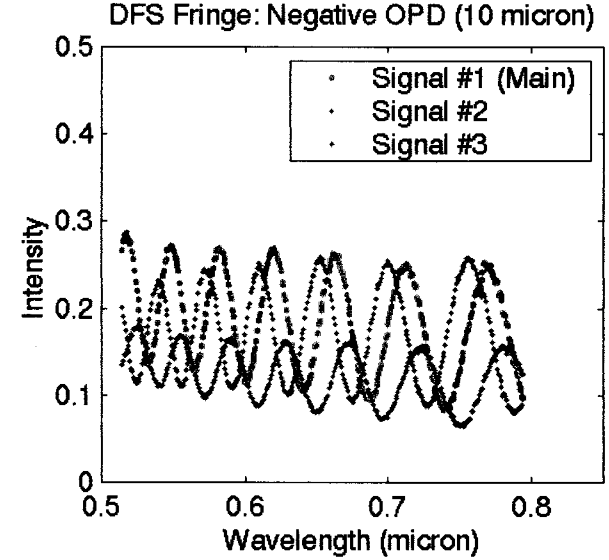


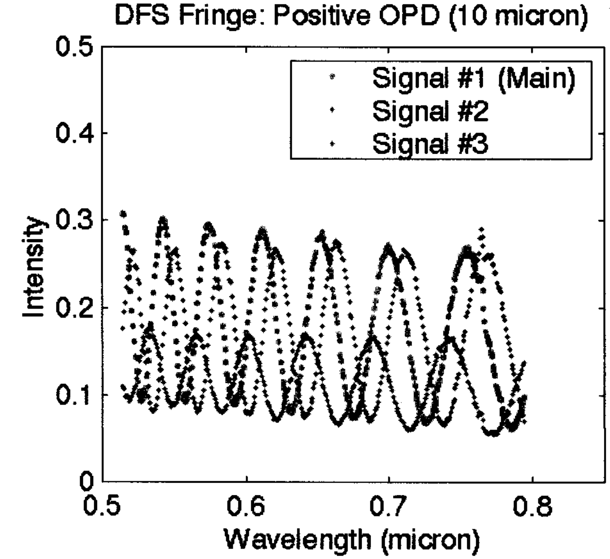
DFS Experiment: Sign of OPD

The sign of OPD is reflected in the orientation of the “fringe band”. Shown here are two DFS fringes using the same 10 μm phase plate. For one fringe the etched part of the phase plate is at top and the other at the bottom. On the plots are three signals from the fringe image, the central row of pixels which is the DFS signal (green) and two adjacent row on each side (red and blue). The relative phases between these signals can be used to determine the sign of the glancing angle of the bands hence the sign of the piston error.


DFS Fringe: Negative OPD (10 micron)


DFS Fringe: Positive OPD (10 micron)


DFS Fringe: Negative OPD (10 micron)


DFS Fringe: Positive OPD (10 micron)

DFS Experiment: Phase Plate Step Size Measurement Summary

Phase plate with different step sizes have been tested with the DFS software using the developed DFS fringe detection algorithm. Following table summarized the results. It is clear that the DFS can not accurately detect the piston error from the 0.5 μm step size phase plate because the OPD is too small to have a significant modulation. From left to right the columns in the table are: the phase step size measured with Wyko TOPO, the mean step size DFS measured, the maximum and minimum step sizes DFS measured and the number of DFS images taken for that phase plate. The sources of the measurement errors are: (1) wavelength calibration; (2) the sampling across the fringe is too coarse only about three pixel across the fringe; (3) low modulation due to non-orthogonal between the DFS dispersion dirrection and the piston base line.

Phase Plate Step Size (μm)	Mean (μm)	Max (μm)	Min (μm)	Number of Measurement
0.525	0.034	0.10	$1.1\text{x}10^{-5}$	3
2.08	1.98	2.08	1.91	6
2.54	2.47	2.69	2.30	6
5.14	5.26	5.55	5.02	5
10.0	10.17	10.29	10.06	3

DFS Experiment: Conclusions

- Using etched phase plate as a simulator of piston error, the DFS is able to generate modulated fringe signals as predicted in the modeling.
- The DFS fringe detection algorithm and software can detect and measure the phase plate piston error and the results agree with direct measurements by a white light interference microscope (Wyko TOPO).
- The DFS can detect the phase plate with step sizes as small as 2 µm. This is equivalent to a piston error of 0.5 µm for DCATT primary (double pass reflection).
- The DFS can detect the sign of piston error.
- Experimental data has also shown a change of fringe modulation due to the change of orientation of phase step relative to the dispersion direction.
- Image processing software has been developed in conjunction with fringe detection software to extract the DFS fringe signals from the spectral profile of the light source.

DCATT DFS : Future Work

- Explore the robust control algorithm which allows using multiple segments as the reference mirror to align any single segment
- Detailed study on the effect of the mirror surface aberrations on the DFS performance
- Refine the DFS fringe detection process to bring down the detection errors.
- Integrate the image processing code into the DCATT executive and use the DCATT executive to repeat the phase plate experiment
- Test DFS with DCATT telescope