Measurement of Beacon Anisoplanatism Through a Two-Dimensional, Weakly-Compressible Shear Layer

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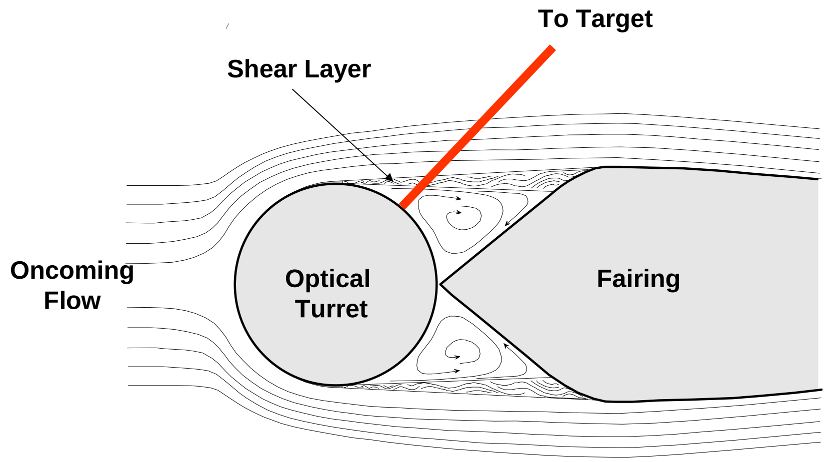
Aero-Optics Problem



Aero-Optics poses a limitation on
Exploitable Field of Regard

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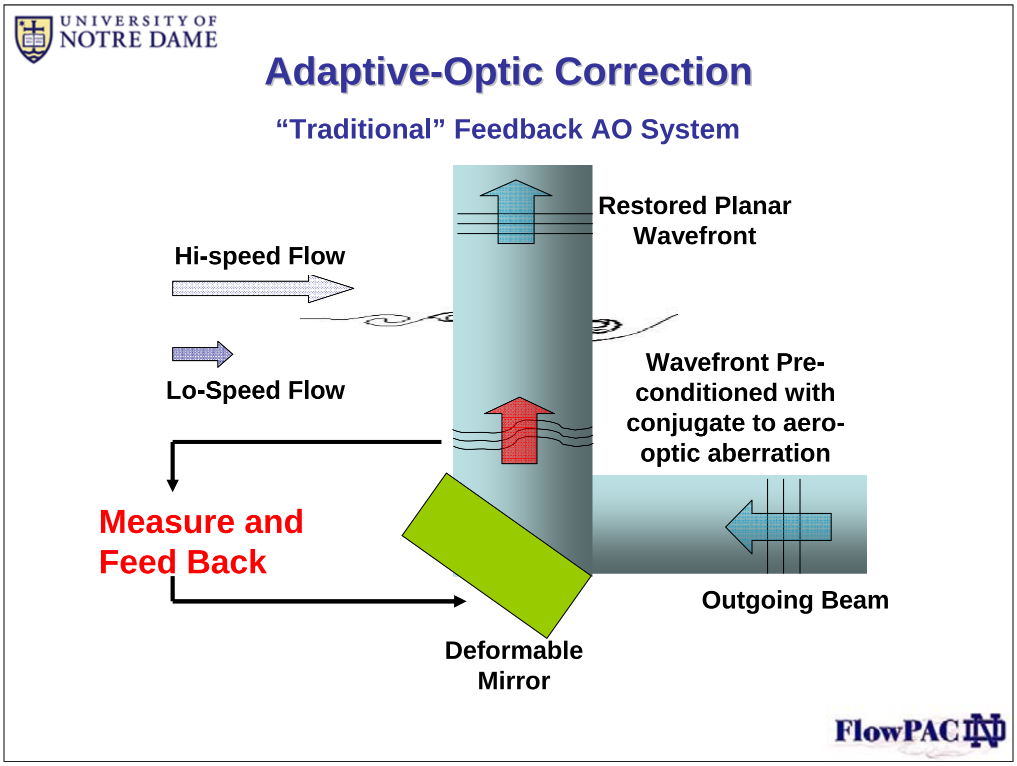
•General definition of the aero-optics problem

•For aft-pointing direction, beam typically passes through a separated shear layer – aero-optic aberrations

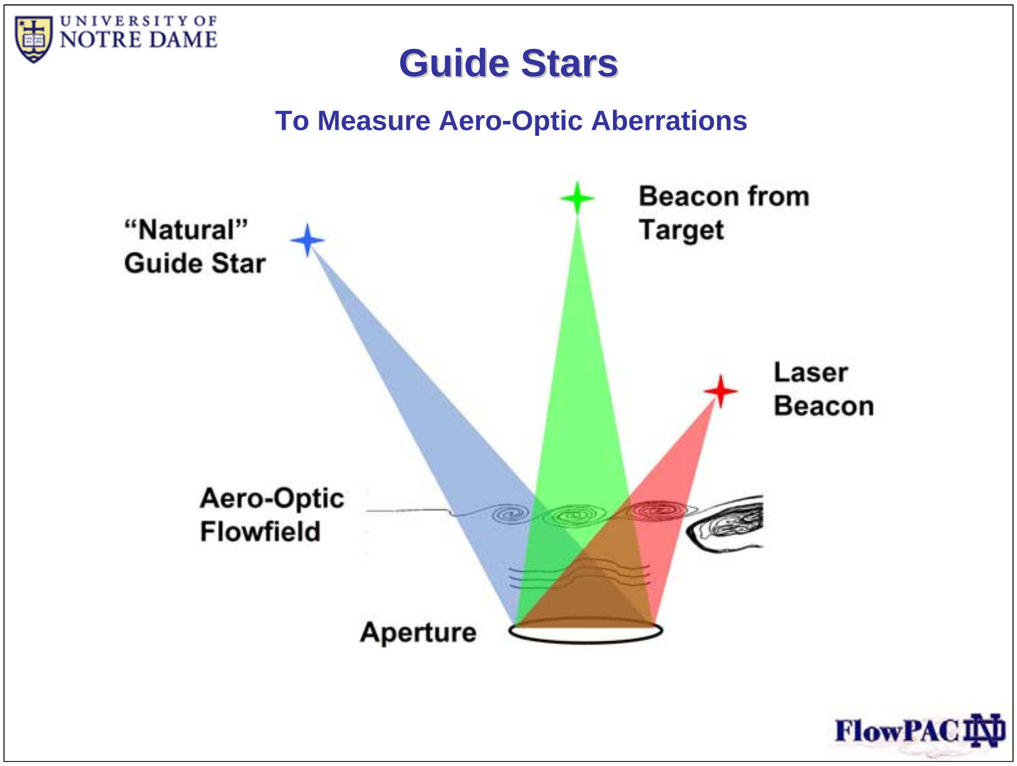
•Aero-optics therefore poses a limitation on exploitable field of regard



•Aero-optic aberrations can be corrected using adaptive-optic system

•(read slide)

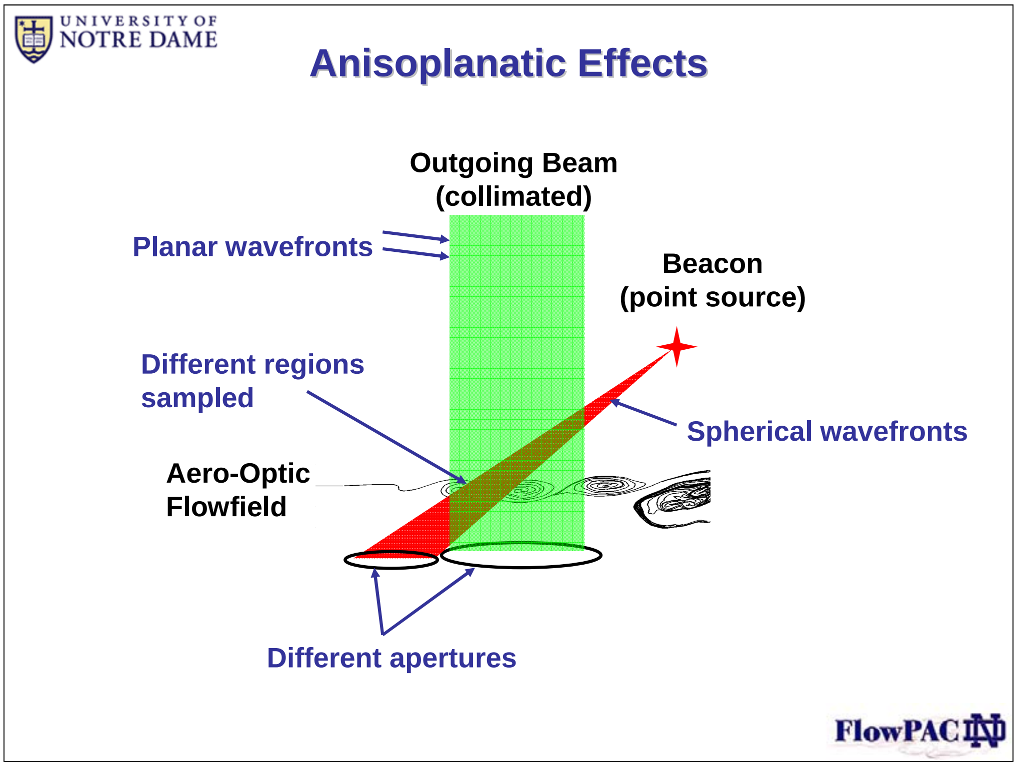
•Key is that aero-optic aberrations must be measured in order to close the feedback loop



•One way to measure aero-optic aberration is using guide stars

•Examples include … (read slide)

•Most reliable is probably the artificially-created near-field beacon; our research focuses on this option



•When a beacon is used, problems arise in the form of anisoplanatism between the beacon and the outgoing beam that is being corrected

•Anisoplanatic effects include, for example, different regions sampled, different wavefront shapes, different apertures

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Objectives

1. Design an experiment that incorporates significant anisoplanatism
2. Test whether anisoplanatic effects can be mitigated using a “Minimum Mean Square Estimation” (MMSE) Approach

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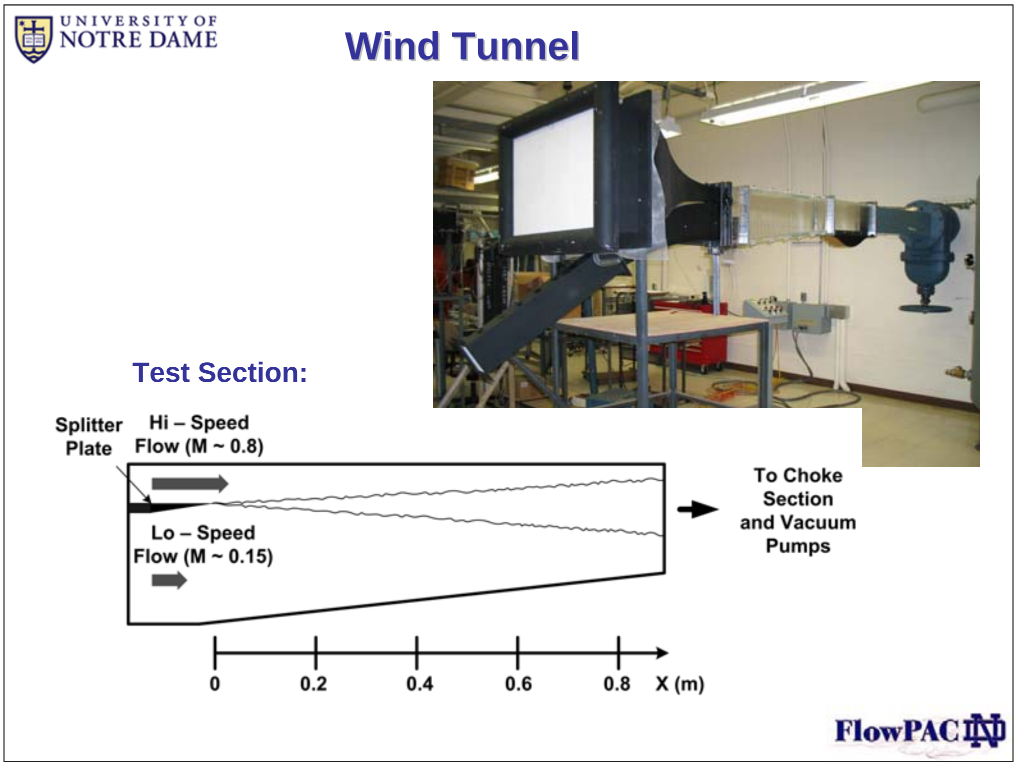
Objectives of this research are therefore … (read slide)



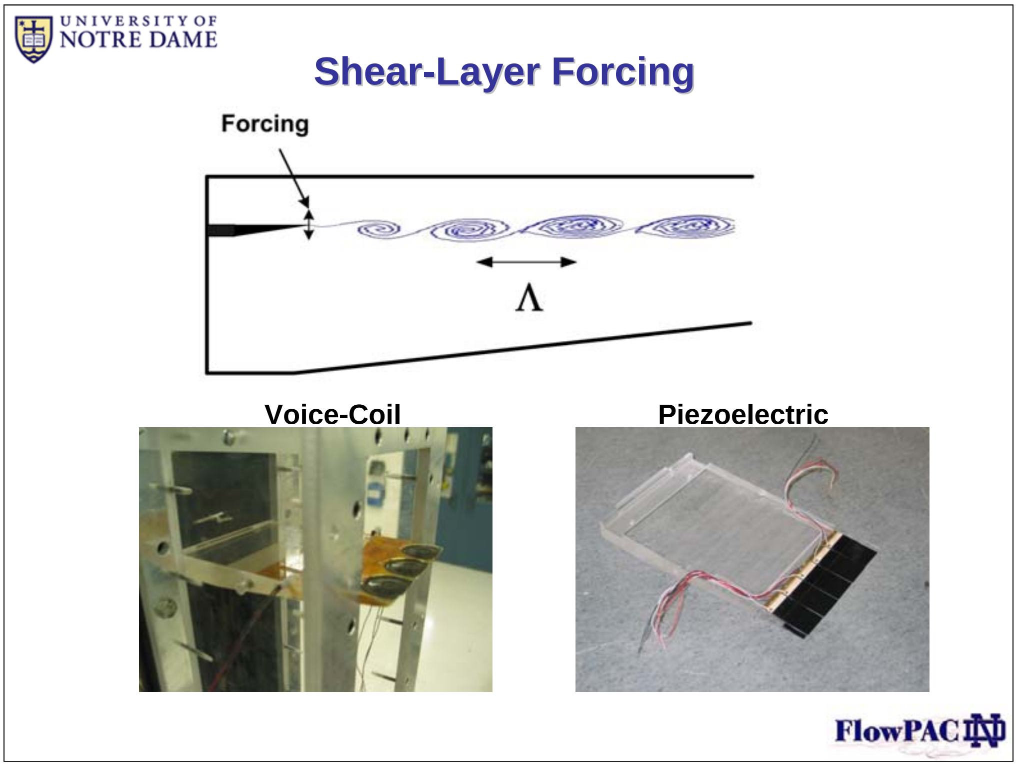
Experimental investigation using ND’s Compressible Shear-Layer Wind Tunnel

•Experimental flowfield models aero-optic environment of a separated shear layer

•Indraft configuration with separate inlets for high-speed and lo-speed flows

•Air drawn through TS, choke section and diffuser to pumps located behind wall

•0.9 m long test section, contracts slightly to reproduce conditions of unconstrained flow



We also have capability to force the shear layer

•Regularizes shear layer

•Larger-amplitude aberrations (signal to noise)

•Two types of forcing actuators

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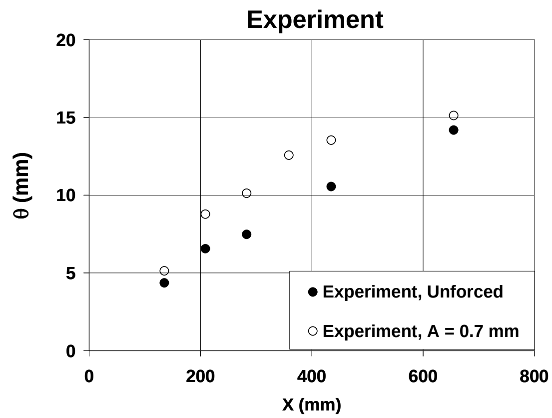
Forced Shear Layer Growth



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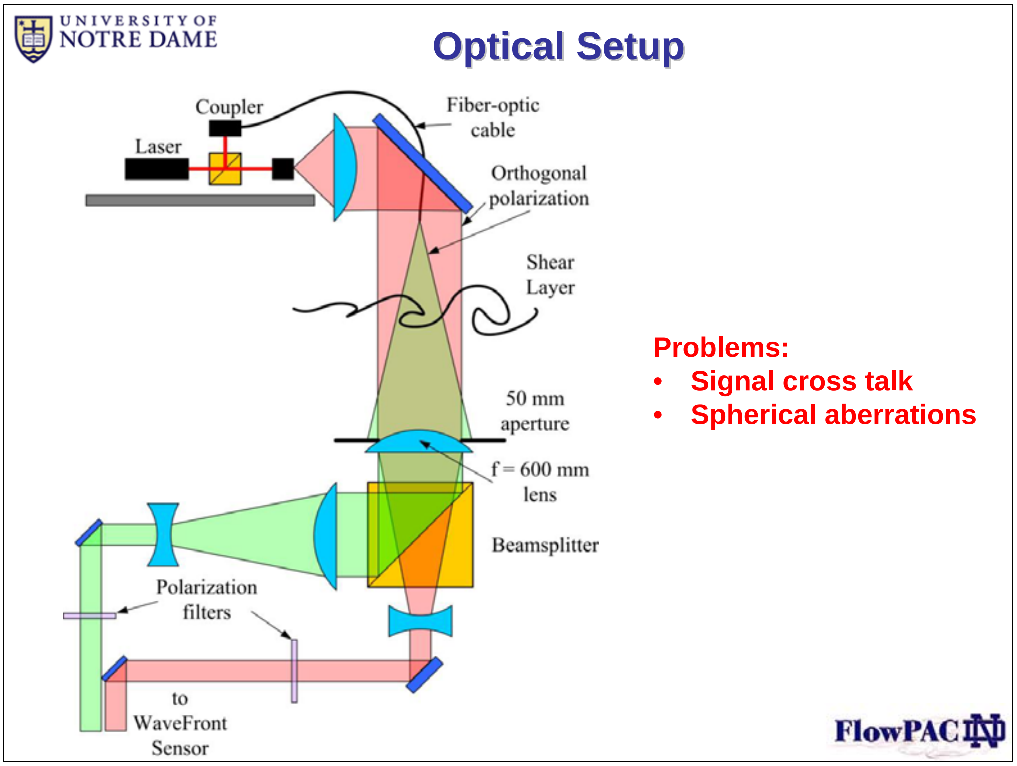
This shows the effect of forcing.

For our application, primarily interested in increasing the amplitude of shear-layer aberrations, as indicated by increased momentum thickness



Optical setup

•Pulsed YAG laser f-doubled to 532 nm

•Split into collimated reference, diverging beacon beams

•For beacon, used output of an optical fiber (3.6 um dia effectively a point source)

•Passed co-axially thru shear layer

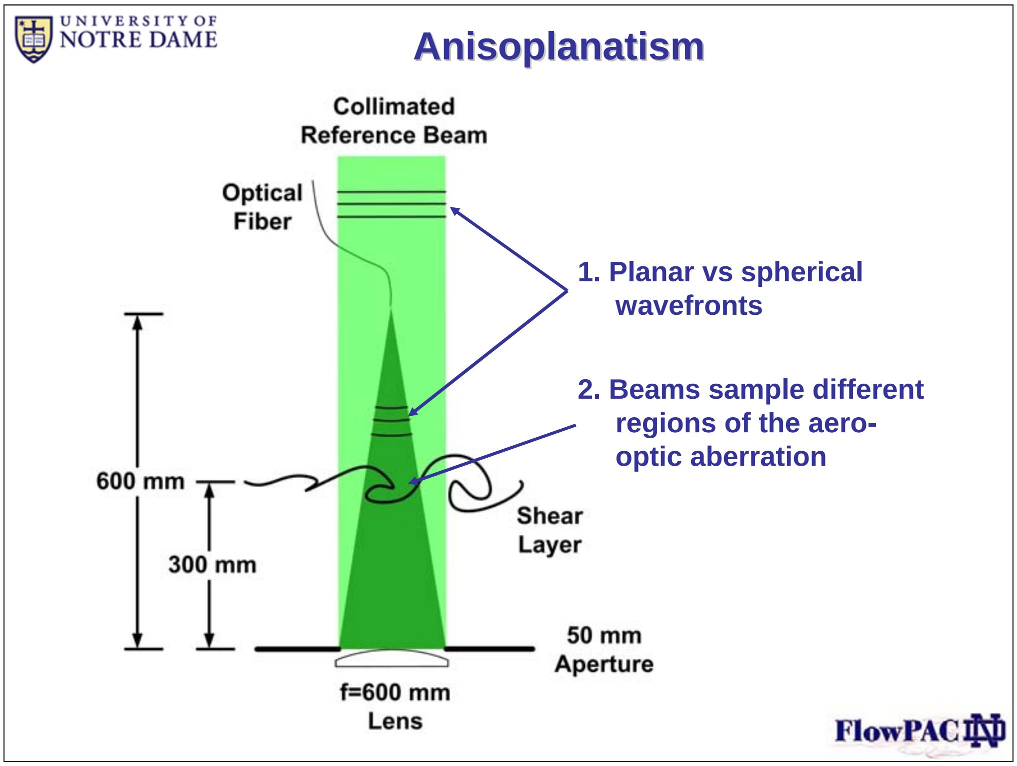
•Collected with f600 mm lens apertured to 50 mm

•Reason for 50 mm aperture is size limit on beamsplitter (didn't have time for larger custom beamsplitters)

•Beams reduced and oriented parallel into WFS

•Crosstalk eliminated by orthoganal polarization of beams, but in practice this was negligible due to different wavefront shape of beams

•Talk about spherical aberrations later



Anisoplanatism effects (read slide)

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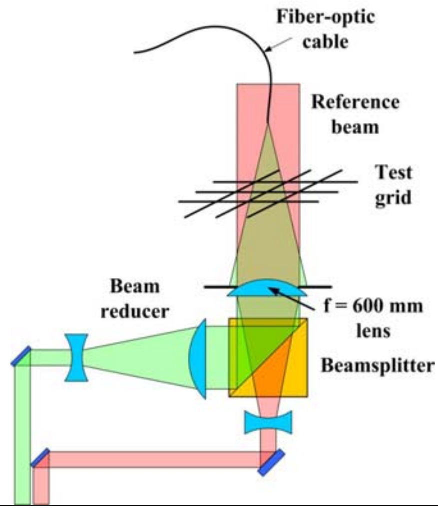
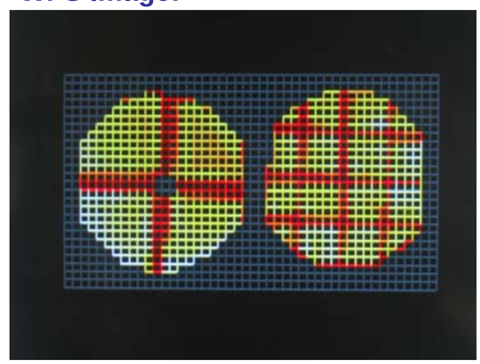
Image Quality/ Spherical Aberrations

- **Extra care with lens selection and orientation**
- **“Staged” beam expanders**
- **Minimized beam path lengths**



WFS Image:



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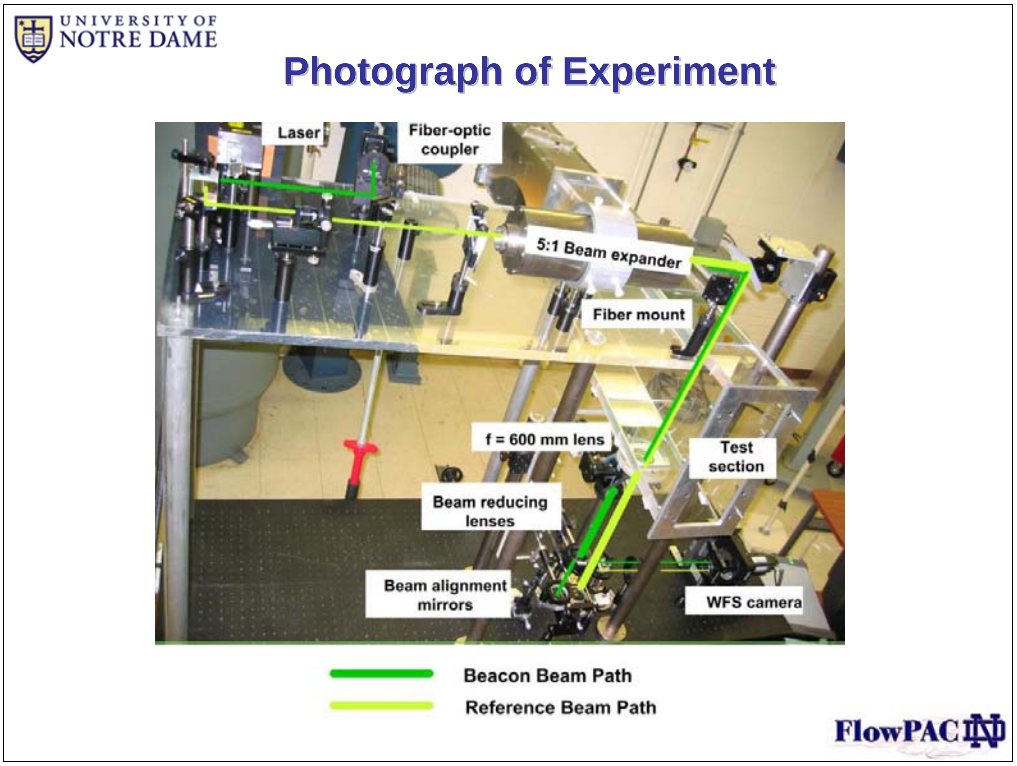
The anisoplanatism analysis compares spatial details of reference and beacon beams and this means that minimizing spherical aberrations to improve image quality is a big issue.

Spherical aberrations reduced by … (read slide)

Example image of test grid (course image since it was acquired thru lenslet array of WFS)

•No noticeable spatial distortions

•Beacon maps to inner 50% of reference



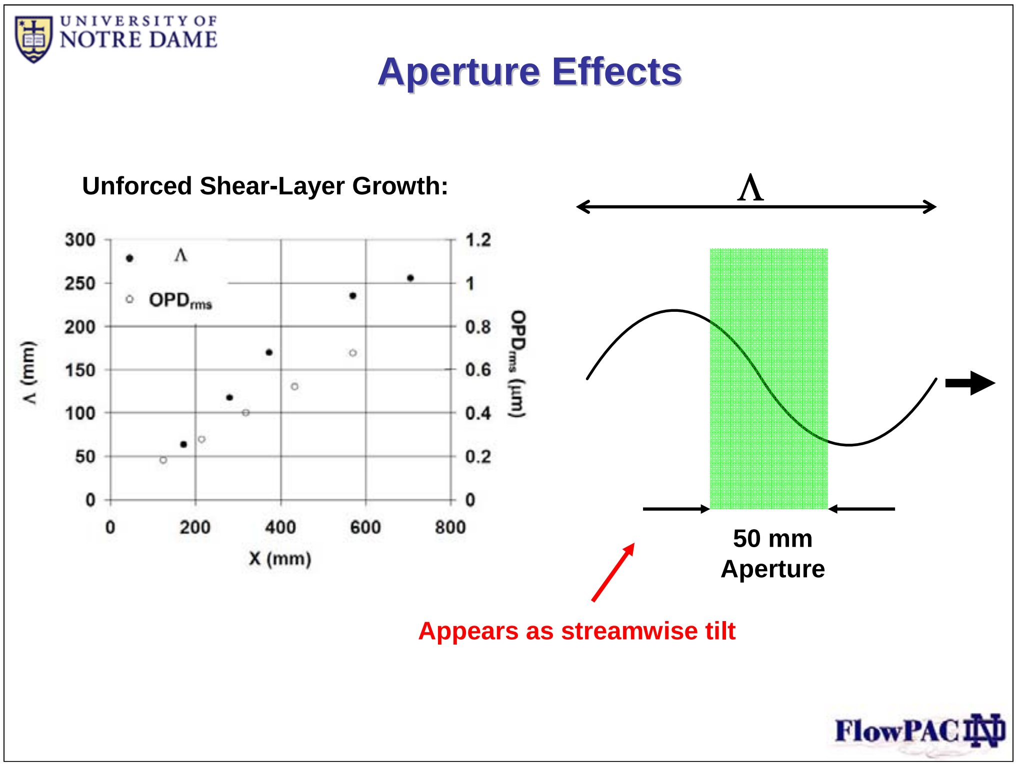
Picture of final experimental layout

•Laser, beam expanders for reference beam and fiber-optic coupler located on raised platform above test section

•F600mm lens located beneath test section

•Beam reducers and alignment mirrors below test section

•WFS camera

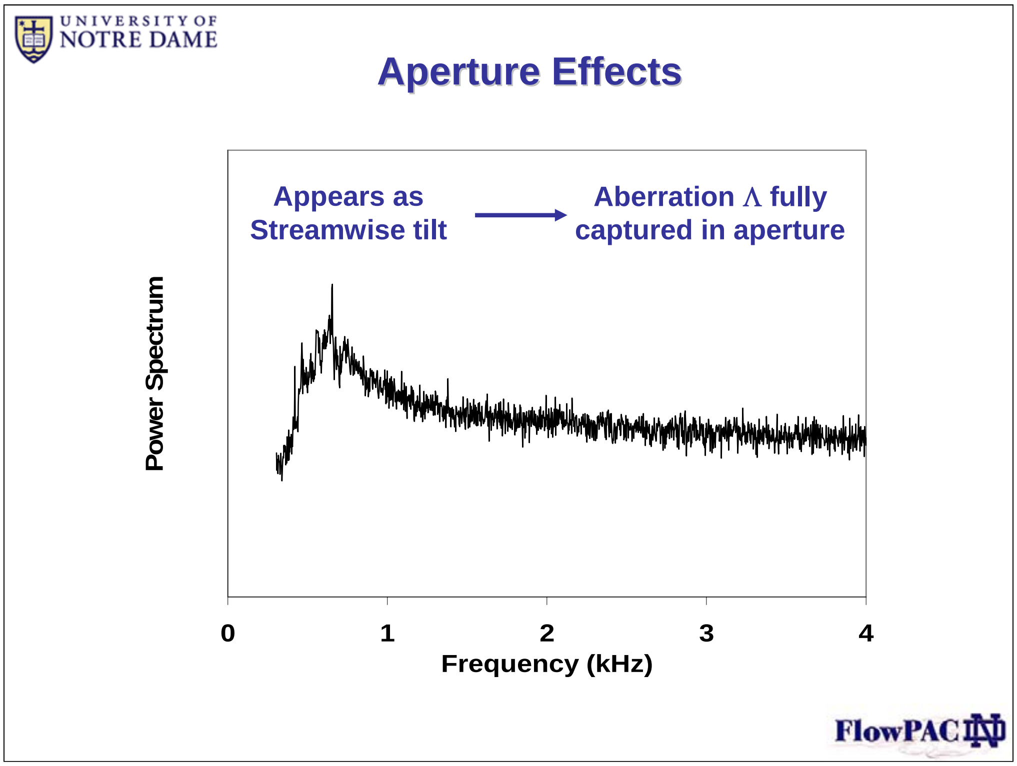


Comment on aperture effects

•Dominant shear-layer structure size and aberration strength both grow with downstream distance

•Favorable to run experiments farther downstream where aberrations are strong (better s/n)

•However, longer downstream aberration scales mostly as streamwise tilt in 50 mm aperture



Power spectrum shows that strongest aberrations appear as streamwise tilt. Only higher-frequency aberrations are fully captured in the aperture.

Therefore ran at several downstream locations, wi and w/o forcing to generate different conditions.

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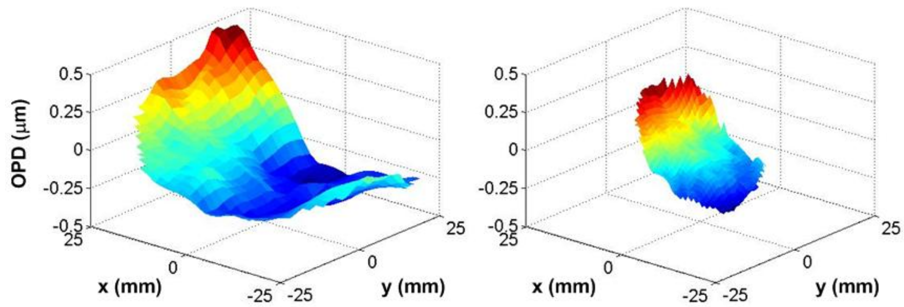
Example Wavefronts

x = 300 mm, Shear layer forced at 750 Hz

Reference Beam: **Beacon Beam:**



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Example wavefronts

•Mostly streamwise tilt

•Beacon matches the inner ~50% of reference beam

•Aberrations appear fairly 2-D

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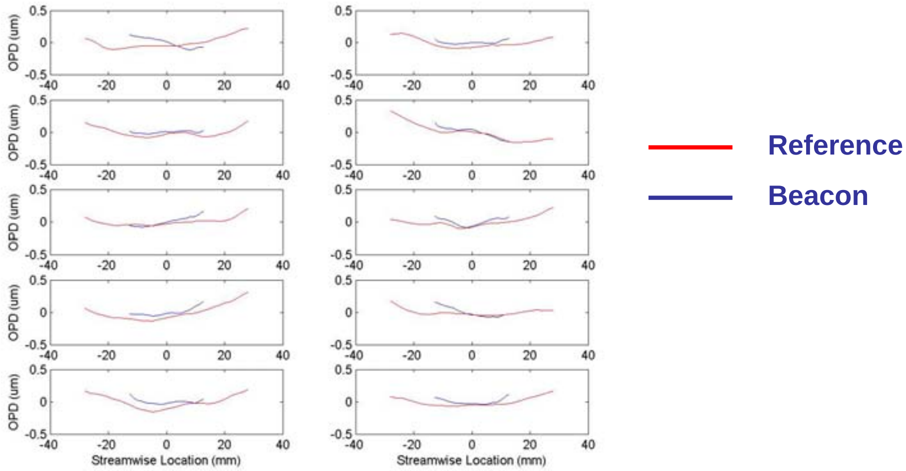
Example Wavefronts

Wavefronts Averaged in Cross-Stream Direction



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Slide shows several other example wavefronts, averaged in cross-stream dimension since wavefronts have 2-D appearance

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Mitigation of Anisoplanatism

Linear Estimation Theory

Define:

$$\hat{c}_h = \mathbf{A}\, c_m$$

Minimal Mean-Square Estimation (MMSE)

Determine A that minimizes difference between measured and estimated reference wavefront

$$\mathrm{diag}\left[\ (c_h - c_h)(c_h - c_h)^T\ \right] = \mathrm{diag}\left[\ c_h c_h^T - \mathbf{B}\,\mathbf{C}^{-1}\,\mathbf{B}^T\right]$$

where:

$$\mathbf{A} = \mathbf{B}\,\mathbf{C}^{-1} \qquad \mathbf{B} = \langle c_h\, c_m^T \rangle \qquad \mathbf{C} = \langle c_m\, c_m^T \rangle$$

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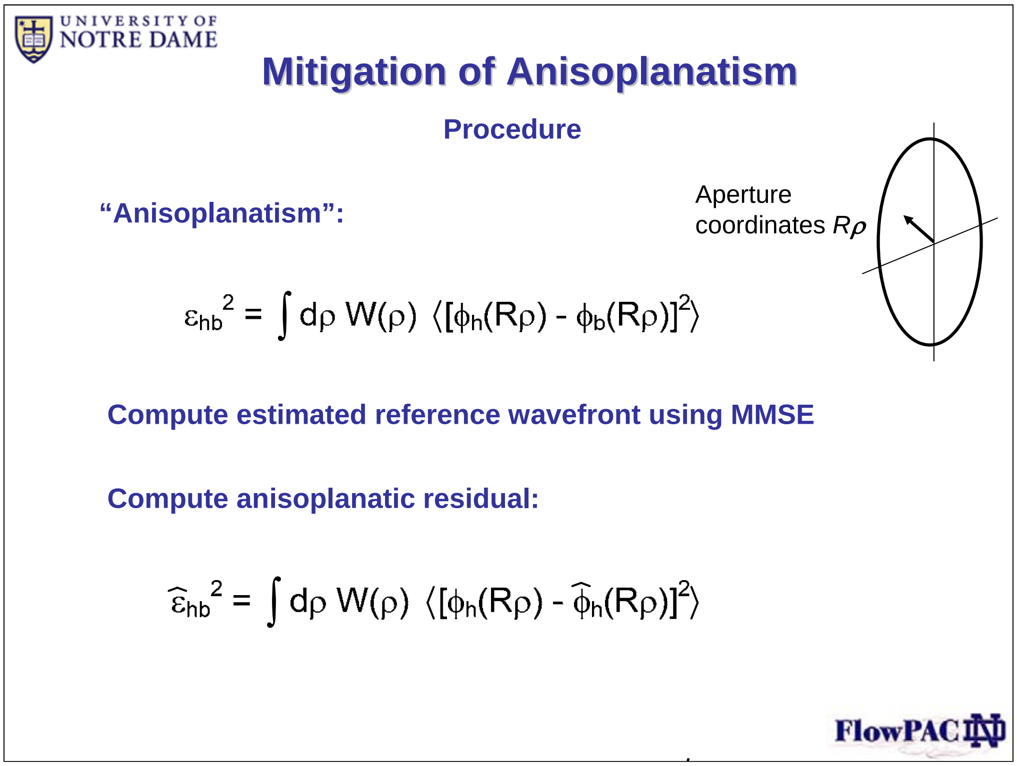
Linear estimation theory used to mitigate anisoplanatism between beacon and reference beams

•Define an estimate for the reference wavefront that will be computed from the measured data using an estimation matrix A

•Determine A that minimizes … (read slide)

•This is satisfied when …

•Where these matrices are defined as …

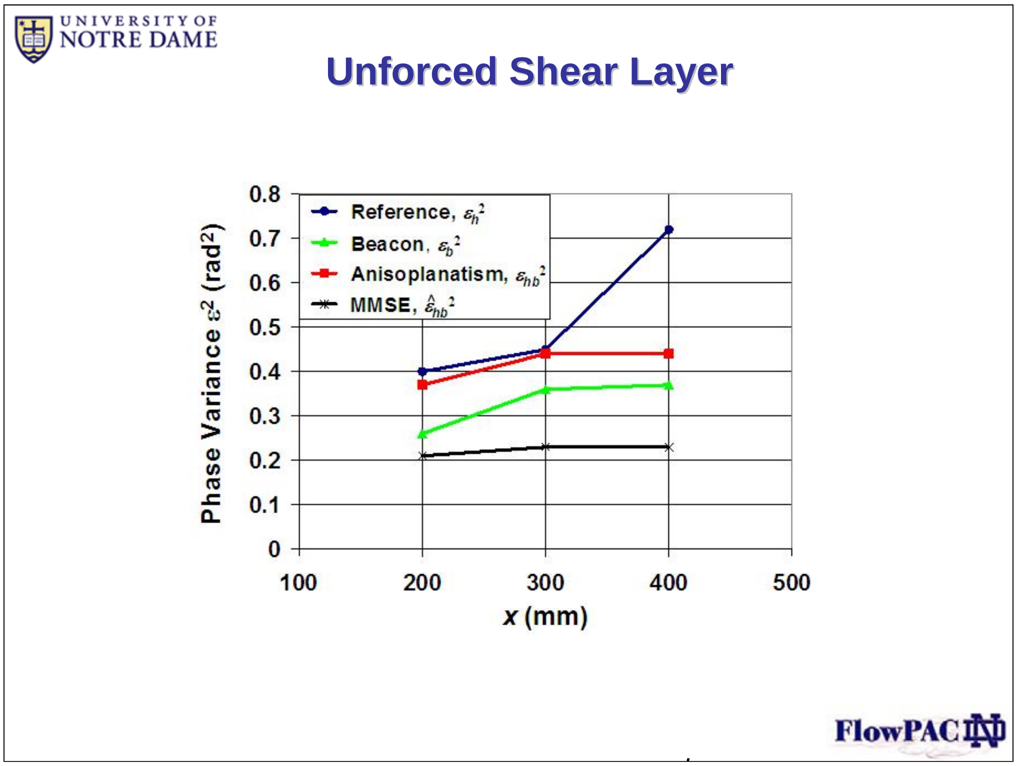


So our procedure to mitigate the anisoplanatism of the beacon measurements was as follows:

•Compute anisoplanatism

•Apply MMSE

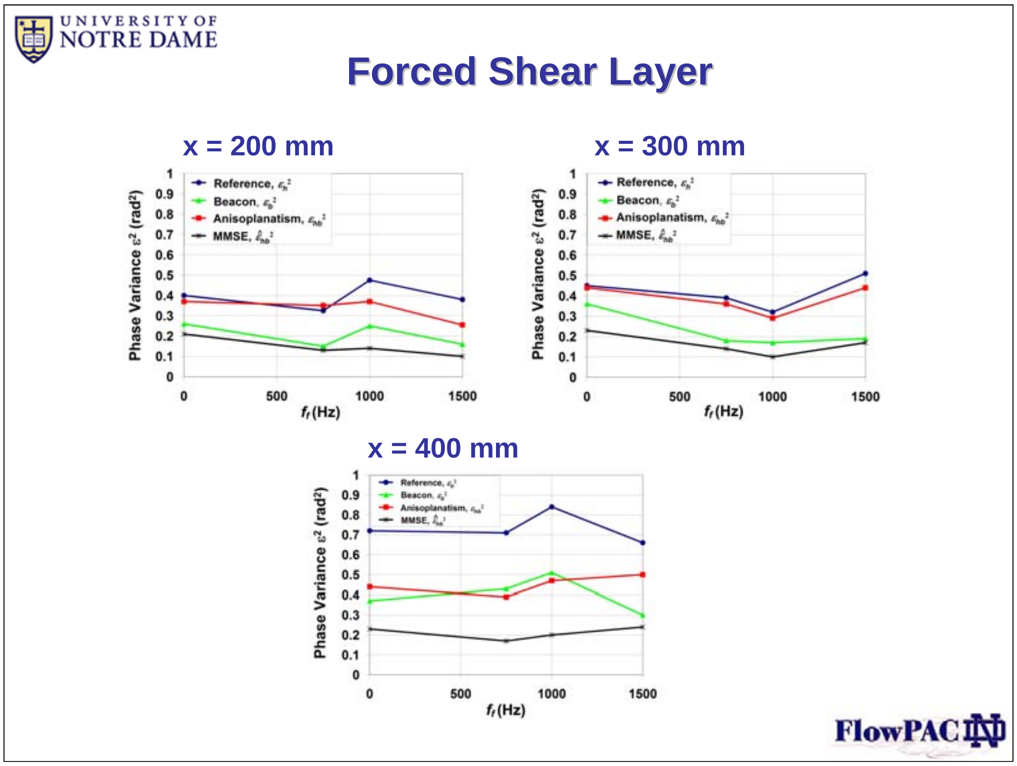
•Compute residual anisoplanatism between reference beam and estimated reference



Results for unforced shear layer

•Anisoplanatism is nearly as large as variance on the original reference beam – hence attempting to correct reference beam using unmodified beacon measurements would introduce additional errors despite the similarity of the wavefronts shown earlier

•MMSE reduces anisoplanatism by ~50%



Forced shear layer

•Similar results with shear-layer forced

•Note slight improvement in MMSE with shear layer forced

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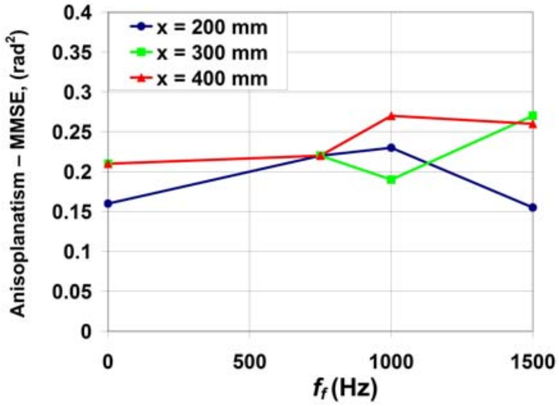
Summary

Reduction in Anisoplanatism



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Shows slight improvement in MMSE with shear-layer forced/regularized

•May be due to larger signal to noise

•Or due to regularization of shear layer

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Conclusions

1. Experiment design was successful in creating measureable anisoplanatism in a realistic aero-optic flow (compressible shear layer)

2. MMSE estimator reduced residual anisoplanatism to ~50% of initial value

3. Shear-layer forcing had a slightly beneficial effect on the ability of the MMSE estimator to correct the beacon wavefronts.

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Conclusions … (read slide)

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Future Work

1. More experimental data to more fully test the technique
2. Investigate guide stars from laser-induced air breakdown
   - Spark wavefront quality
   - Flow effects on breakdown spark
3. Investigate “realistic” flight applications

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Future Work

•We have recently been funded to carry on the investigation using actual laser-induced air breakdown rather than fiber-optic simulation

•“realistic” flight applications – “calibrate” a system and check performance in off-design conditions