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Hartmann Wavefront Sensing for the Gingin Experiment

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ACIGA

Layout of Talk

- Thermal distortion and compensation in Adv. GWIs
- Off-axis Hartmann wavefront sensor – design and analysis
- Bench top tests of Hartmann sensor
- Implementation of sensor in the Gingin experiment

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ACIGA Objectives

- Investigate the operation of active thermal compensation systems for use in Adv. GWIs.
- University of Adelaide is providing a sensor to measure thermo-refractive distortion and effectiveness of compensation in the Gingin High Power Test Facility (AIGO).

The Australian International Gravitational Observatory (AIGO)

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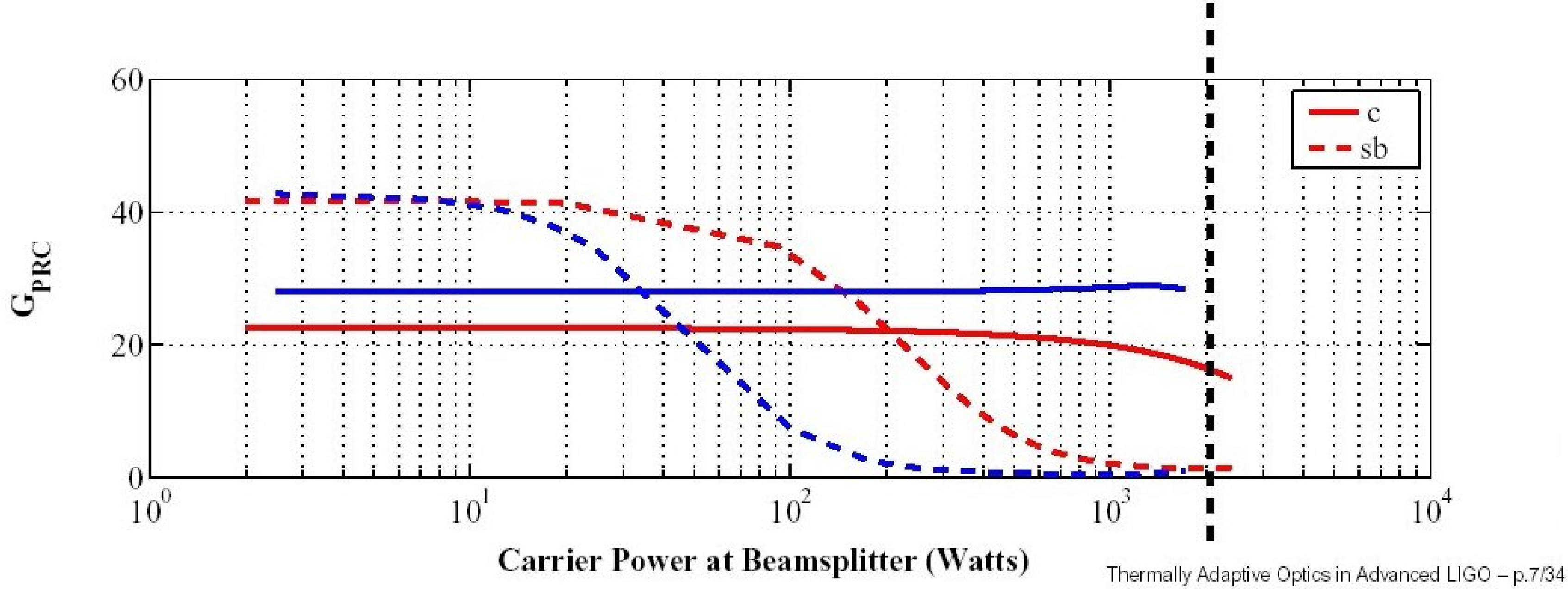
Crux of Thermal Problem



Courtesy of Ryan Lawrence and David Ottaway, MIT

- Figure shows prediction of MELODY model of Advanced LIGO
- Absorbed power, in coatings and substrates, causes thermal lensing
- Sideband power is coupled out of TEM00
- Power recycling cavity eventually loses lock
- Adv. LIGO cannot achieve desired sensitivity unaided

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How to Maintain Locked Cavity?

- Measure distortion in ITM with an off-axis wavefront sensor
- Employ active compensation system, reducing distortion to < $\lambda/200$. Heated compensation plate will be used in Gingin experiment
- Hartmann sensor selected
  - not sensitive to alignment
  - simulated sensitivity < $\lambda/1000$

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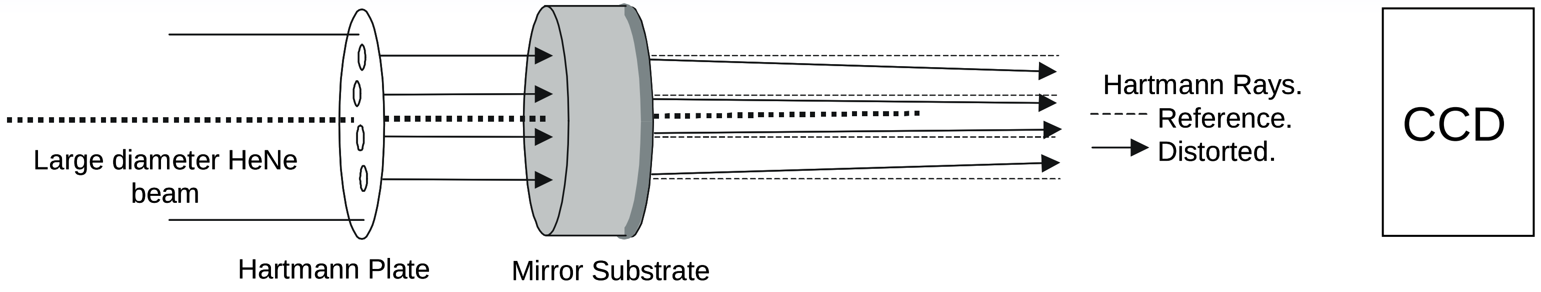
Hartmann Wavefront Sensor



- Each Hartmann ray propagates normal to the wavefront
- Subsequently, rays are incident on a CCD forming a pattern of spots
- Centroid of each spot is found using a 1^{st} moment calculation on spot intensity
- When the wavefront changes, the spots are displaced on the CCD
- Spot displacement is proportional to gradient of the change in wavefront
- Simulated Hartmann measurement had an precision of $< \lambda/1000$

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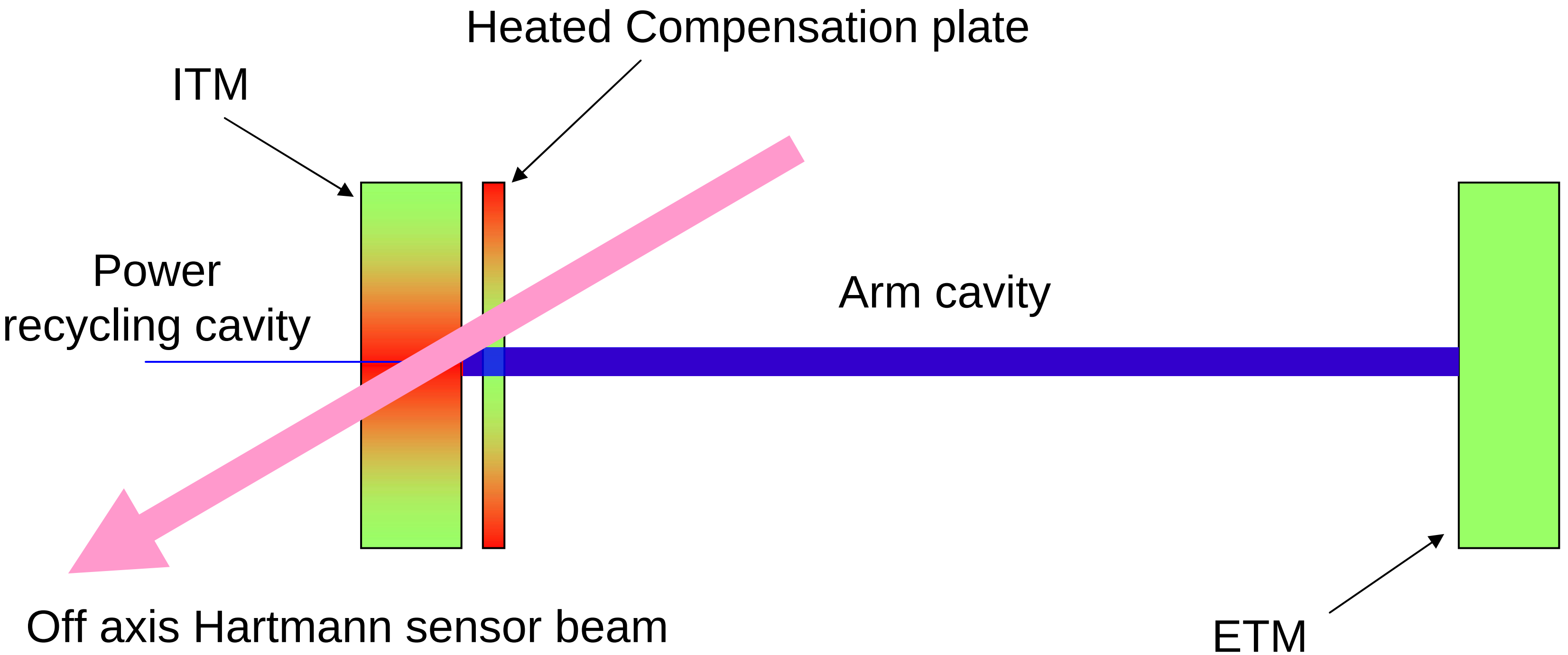
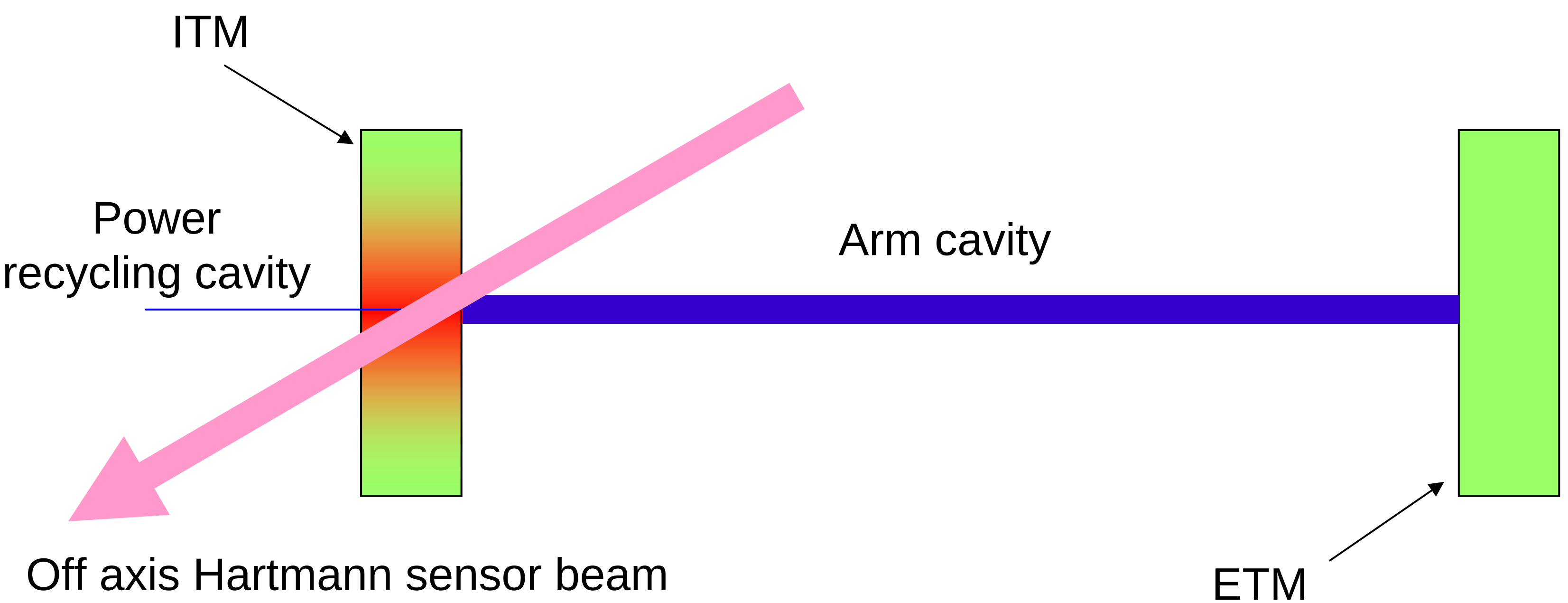
Example of Compensation System



Example of Compensation System



- How do you relate the off-axis OPD to the on-axis OPD?

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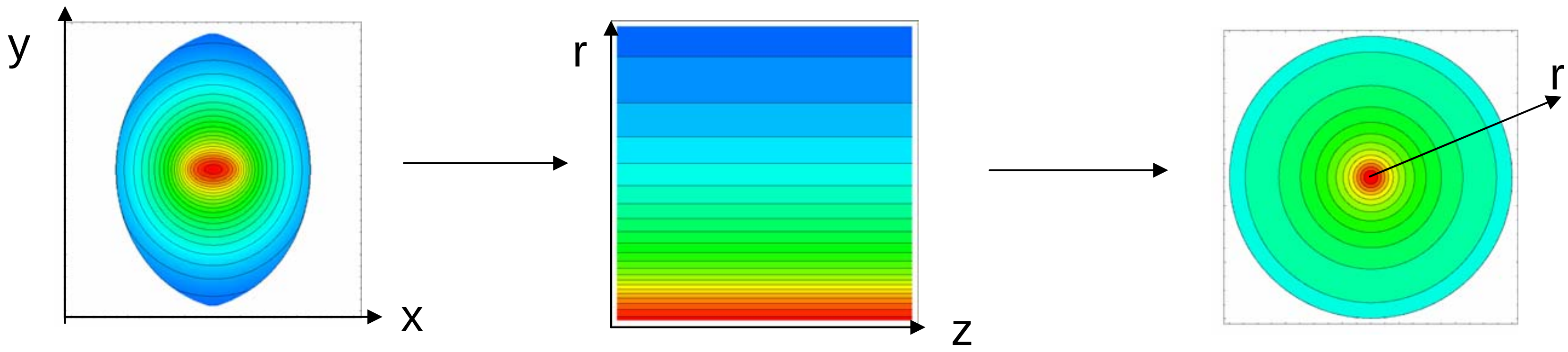
Modal Analysis of Off-Axis OPD



$\varphi(x, y) = \Sigma\, a_i\, g_i(x, y)$ $\quad$ $n(r, z) = \Sigma\, a_i\, f_i(r, z)$ $\quad$ $\varphi(r) = \Sigma\, a_i\, F_i(r)$ *

- Functions $g_i(x, y)$ are path integrated versions of $f_i(r, z)$
- Parameters a_i found by a least squares fit of off-axis OPD to functions $g_i(x, y)$
- Ideally, both sets $\{f(r, z)\}$ and $\{g(x, y)\}$ are orthogonal and there exists a simple path integral relating them
- No ideal sets have been found – currently using a small set of non-orthogonal functions (Gaussians) for $f(r, z)$

* $F_i(r)$ is the integral of $f_i(r, z)$ along the z-axis

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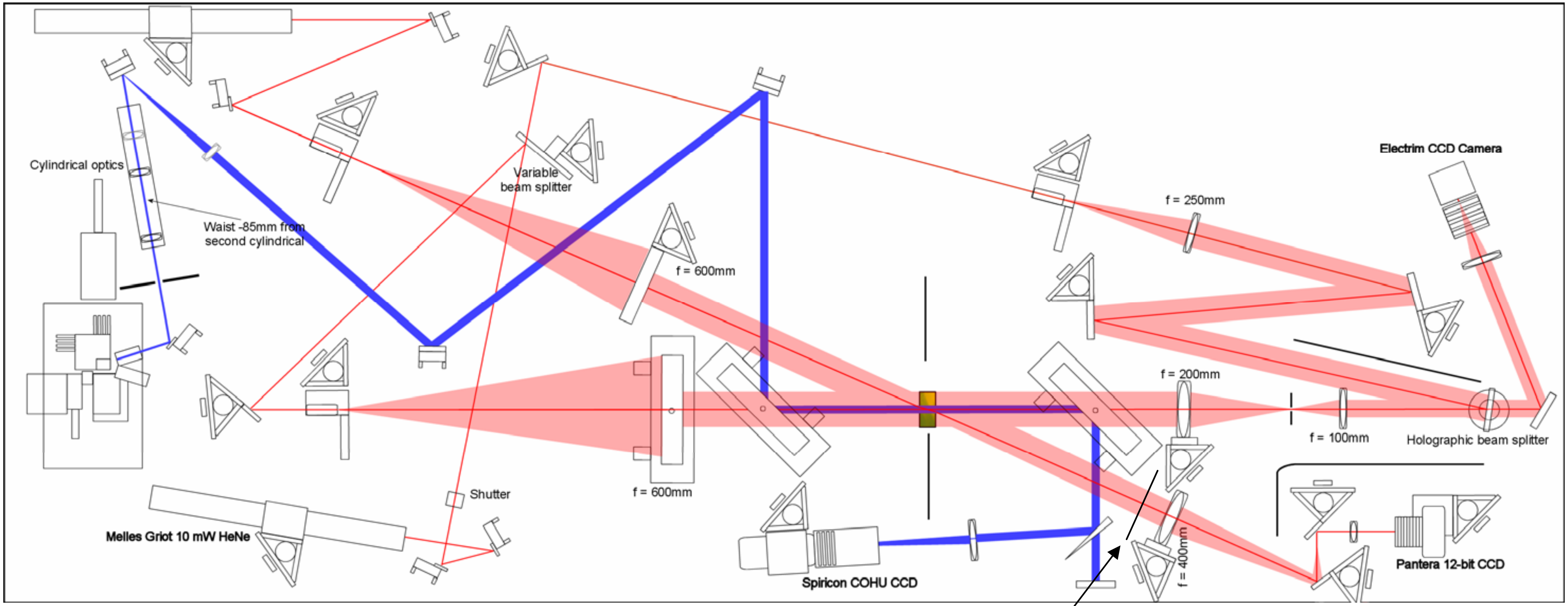
Off-Axis Bench Top Test



Hartmann plate

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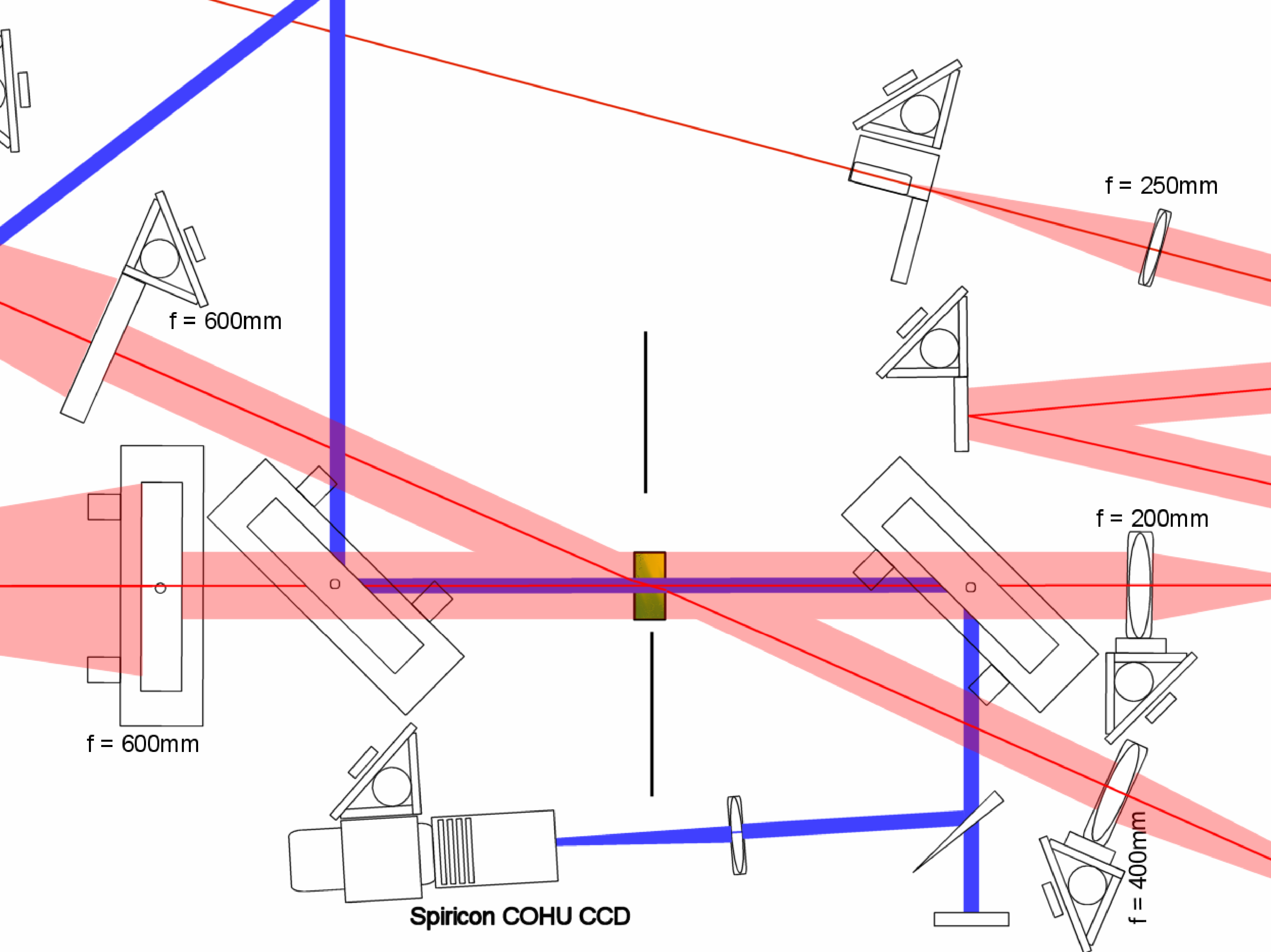
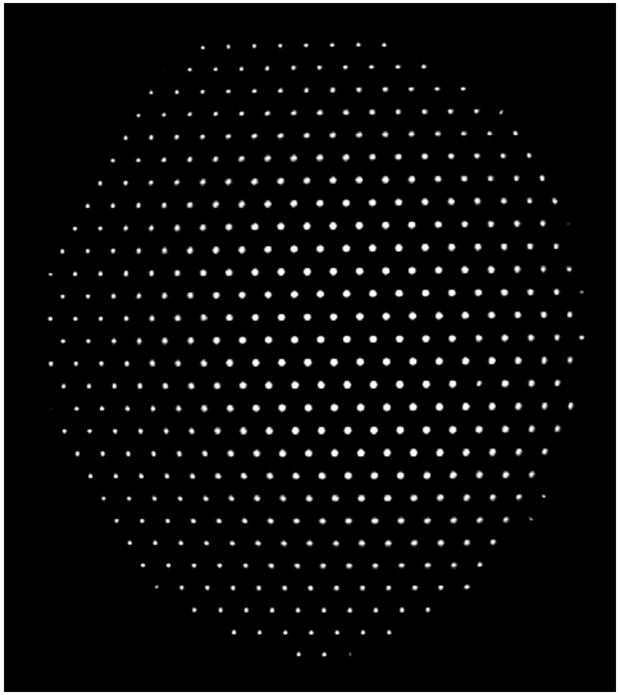


f = 250mm
f = 600mm
f = 200mm
f = 600mm
f = 400mm
Spiricon COHU CCD

Results – Angular Noise

- Differences in successive images yield the angular noise of the Hartmann sensor
- Minimum detectable angle
  $\approx$ 3.5 μradians
- Min OPD $\approx \lambda/200$ (based on .9mm separation between holes in Hartmann plate)



Hartmann spot pattern

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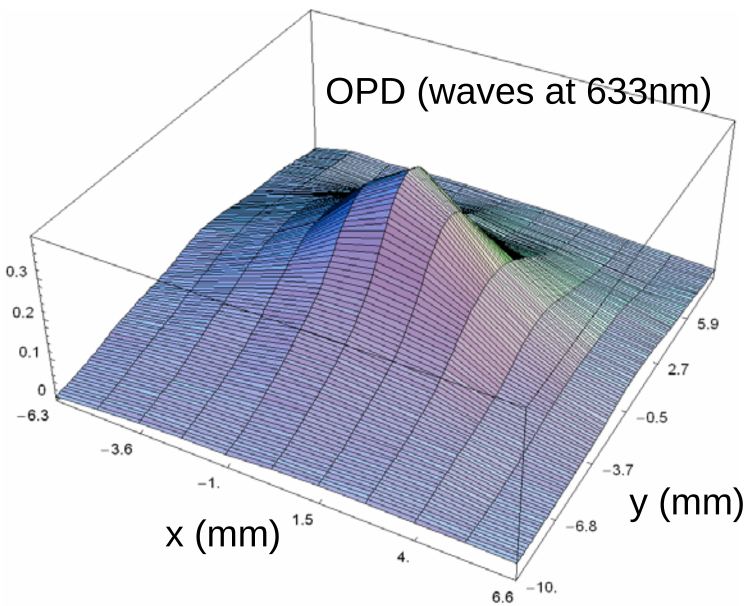
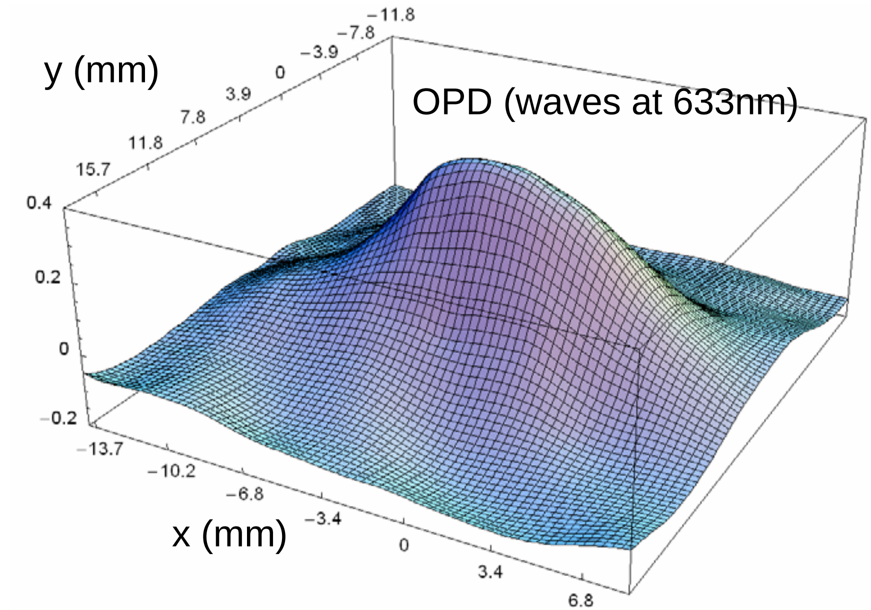
Coincidence Measurement – Raw Data

On axis OPD (interferometer)



Off axis OPD (Hartmann)
(reconstructed from gradient map)



<u>Sanity Check on data</u>

✓ OPD's roughly the same size

✓ Off-axis OPD elongated in the x direction as expected

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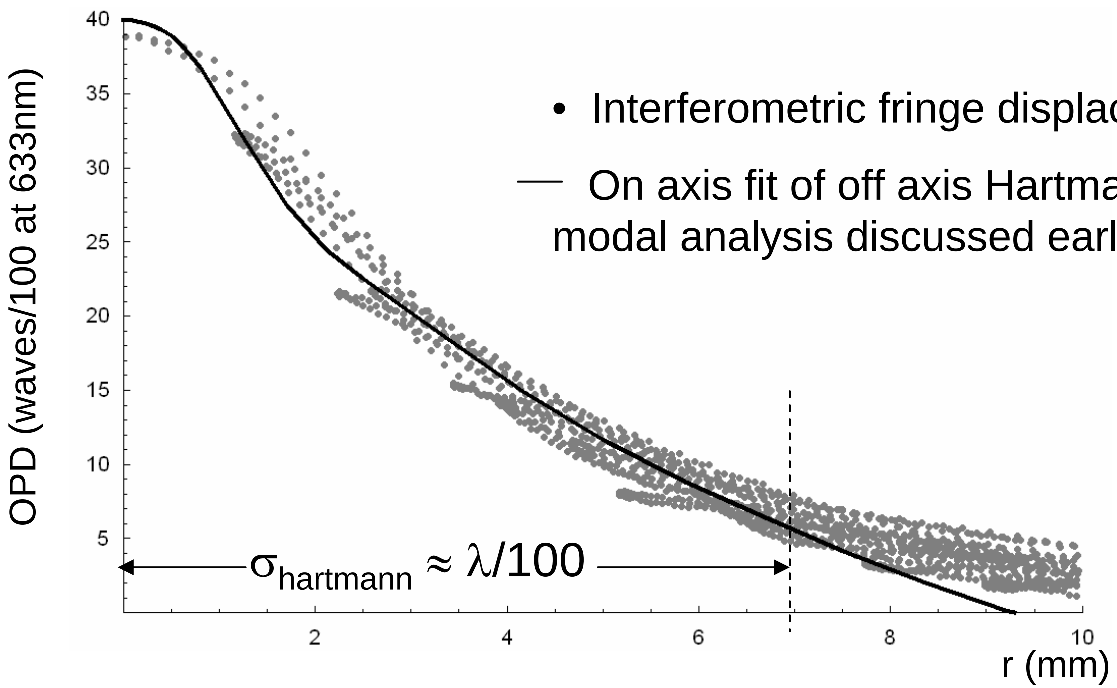
Results – Radial OPD



- On-axis distortion is elliptical (minor axis = 90% major axis)
- Systematic error since analysis assumes axial symmetry
- Worst case analysis: ignore systematic error, average elliptical data to circle. In this case standard deviation between on-axis data and analyzed Hartmann data ≈ λ/100

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Sensitivity of Hartmann sensor

Precision

Required	< λ / 200
Simulated	< λ / 1000
Experiment	< λ / 100

Issues to address before final experiment at Gingin

- Systematic errors: - number/type of fitting functions
  - elliptical heating beam
- Random errors: - air currents – use tent?
  - can illumination of Hartmann plate be more uniform?
  - precision of interferometer

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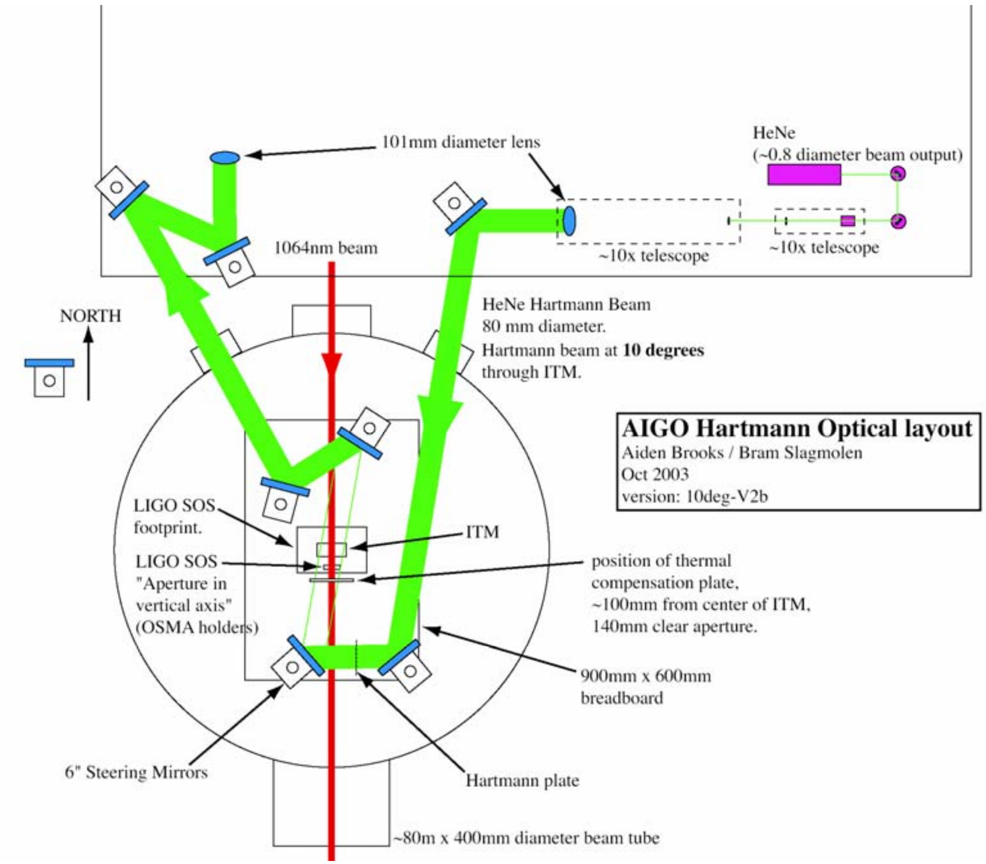
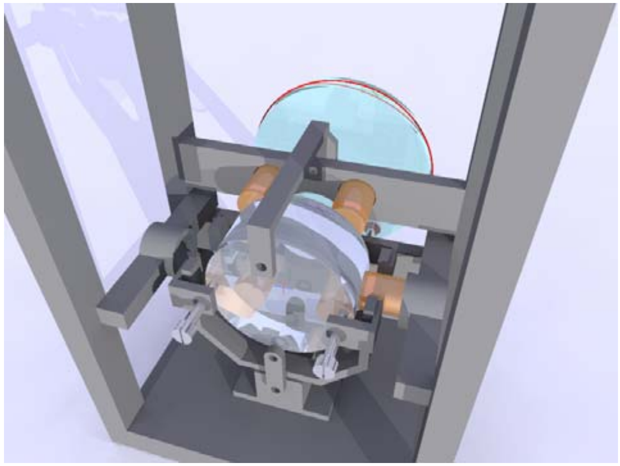
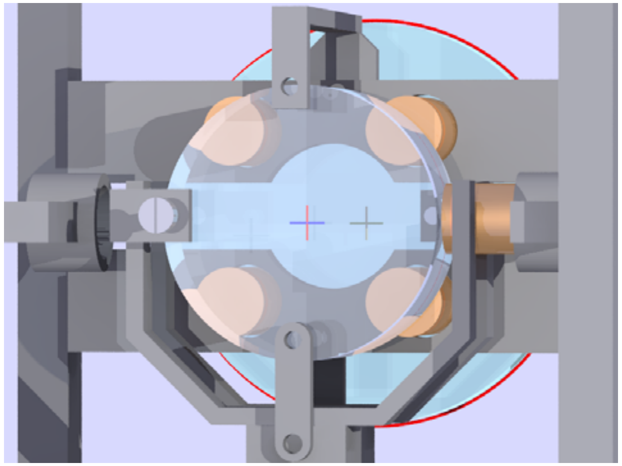
Gingin Experiment Design







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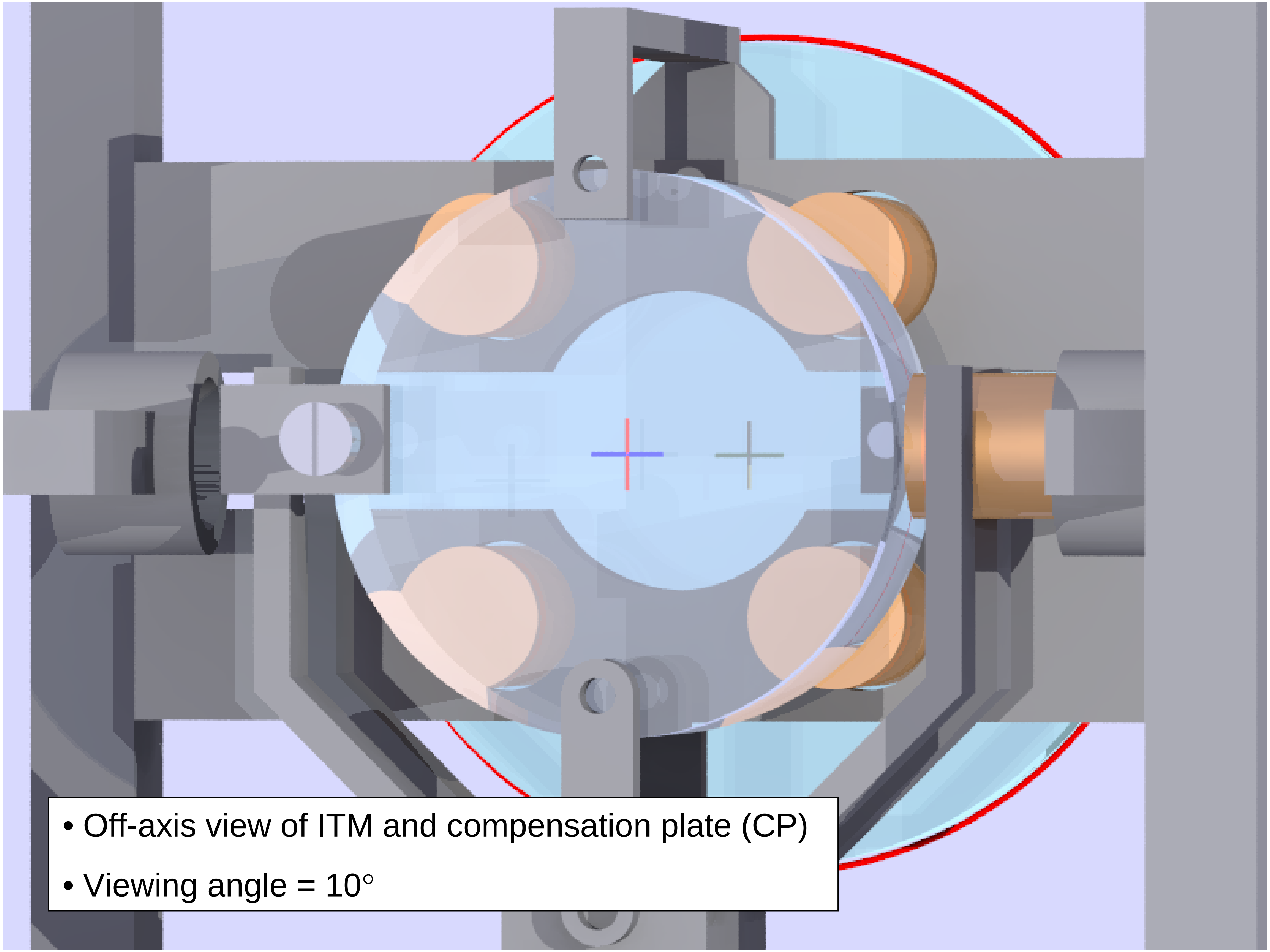
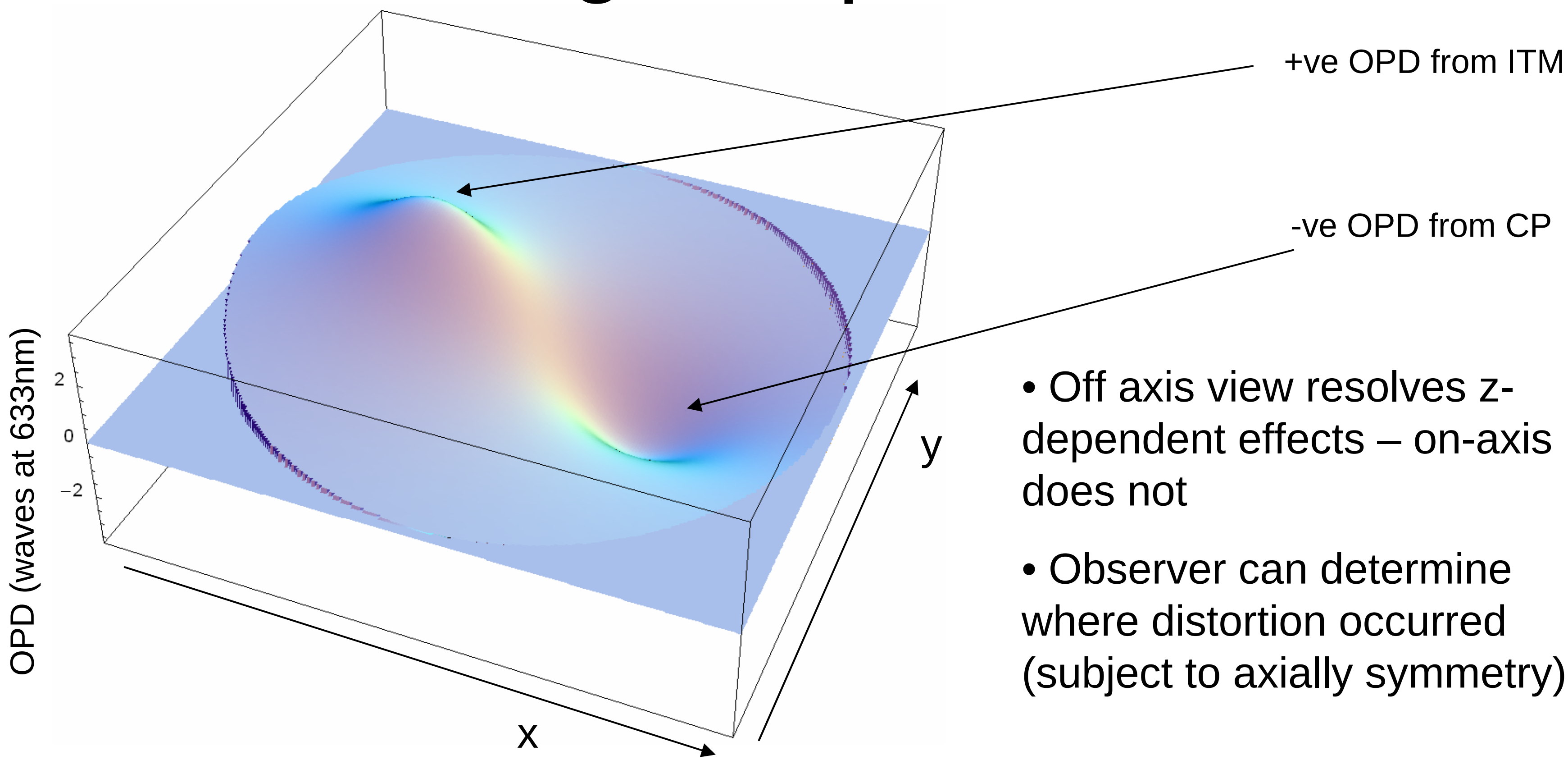


- Off-axis view of ITM and compensation plate (CP)
- Viewing angle = 10°

Prediction of Off-Axis OPD for Gingin Experiment



- Off axis view resolves z-dependent effects – on-axis does not
- Observer can determine where distortion occurred (subject to axially symmetry)

- Distortion and compensation recorded in a single measurement
- Analyzed data can be used as an error signal for CP

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Closing remarks

- Current off-axis Hartmann sensor has achieved accuracy of approximately $\lambda/100$ in the lab.
- Should be able to improve this by addressing issues covered earlier.

<u>Gingin installation schedule</u>

MAR-APR '05	Installation of Hartmann beam steering optics and compensation plate
MAY-JUN '05	Test of Hartmann system - on-site sensitivity test - measure compensation plate OPD
JUL-DEC '05	ITM distortion and compensation plate combined phase measurement

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