Hartmann Sensor for advanced gravitational wave interferometers

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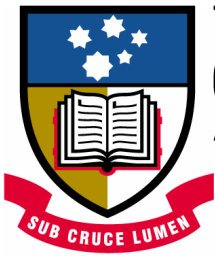

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Outline of Talk

- Hartmann wavefront sensor
- Experimental validation
- Tomographic capabilities

Objectives

- Develop versatile, robust wavefront sensor
- Distortion must ultimately be corrected to $\lambda/100$
- Sensor needs to have sensitivity << $\lambda/100$
- Sensor should not interfere with input mirrors or GWI laser beam.
- Sensor suitable for wavefront servo

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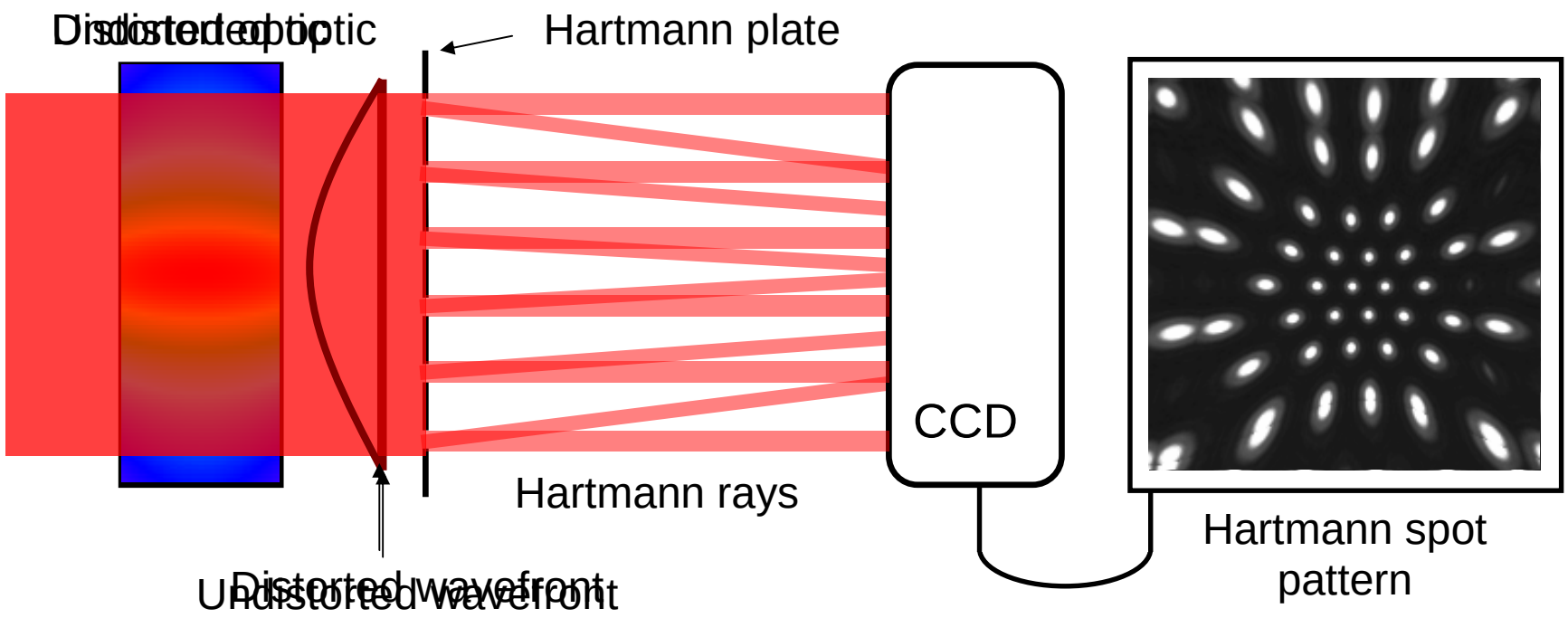
Hartmann Wavefront Sensor: How It Works



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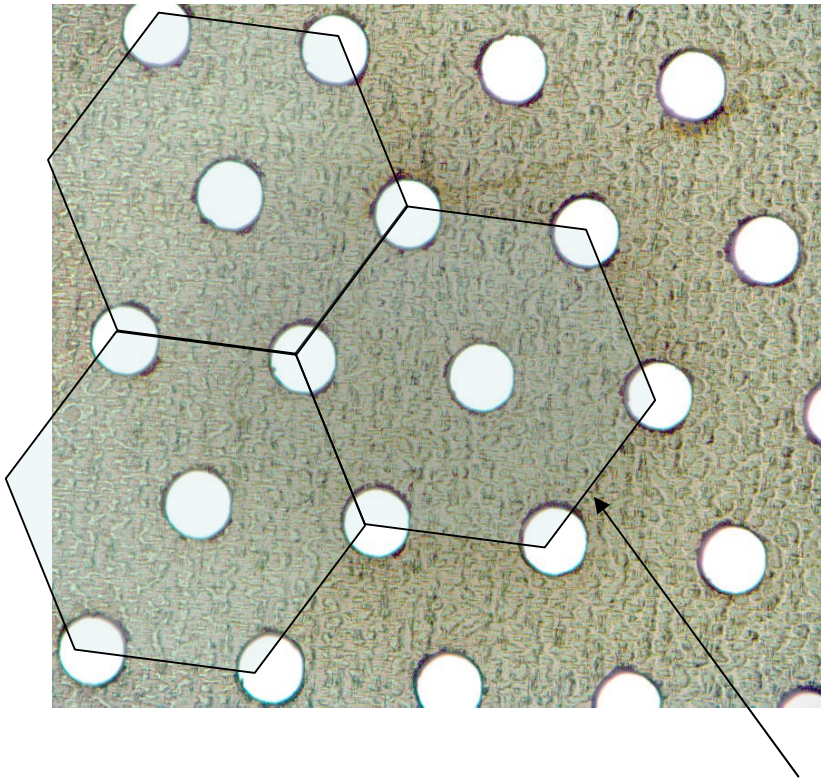
Optimized Hartmann Plate



Hexagonal cells added to highlight arrangement

- Optimized for distortion in advanced GWIs
  - Spatial resolution
  - Sensitivity

Hole size	150μm
Hole spacing	430μm
Distance to CCD	10mm

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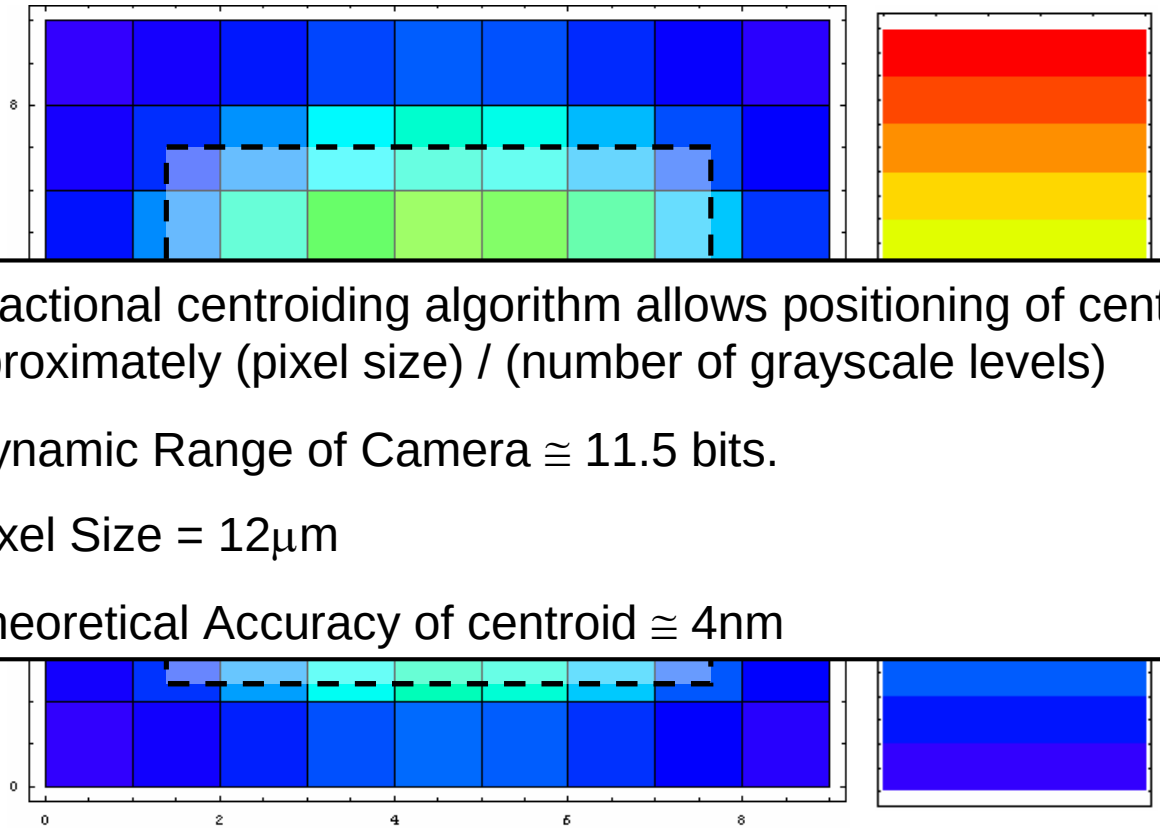
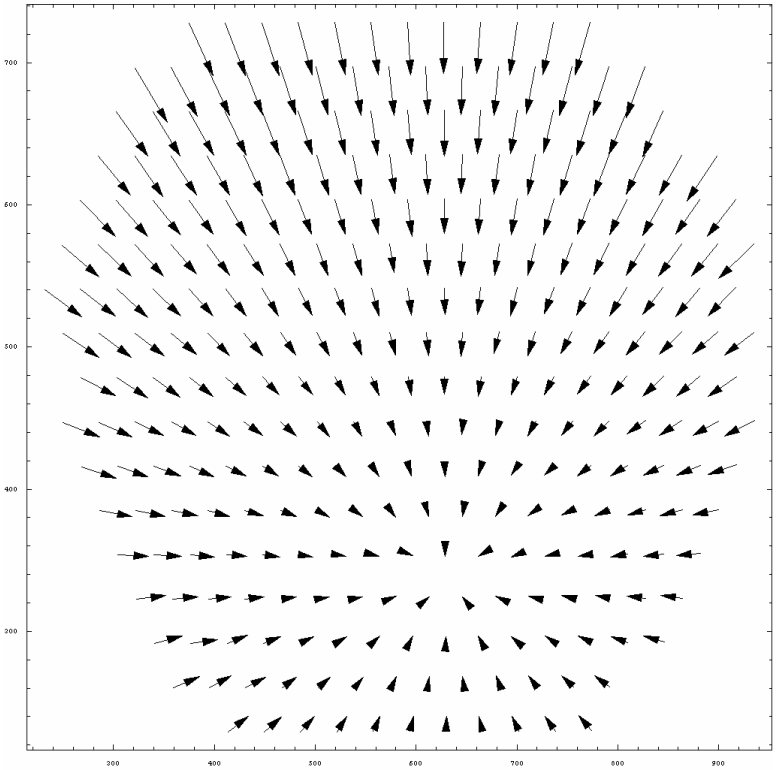
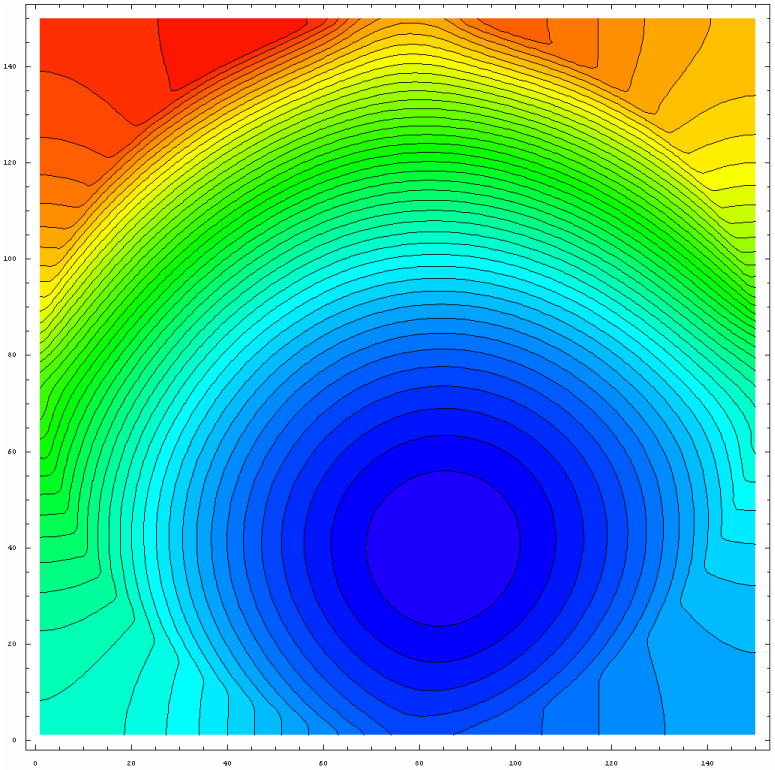
Centroiding Single Hartmann Spot to Sub-Pixel Accuracy



- Fractional centroiding algorithm allows positioning of centroid to approximately (pixel size) / (number of grayscale levels)
- Dynamic Range of Camera ≅ 11.5 bits.
- Pixel Size = 12μm
- Theoretical Accuracy of centroid ≅ 4nm

Hartmann Wavefront Sensor: How It Works





- Spot displacement proportional to ***gradient*** of wavefront
- We can locate spots ± 20nm

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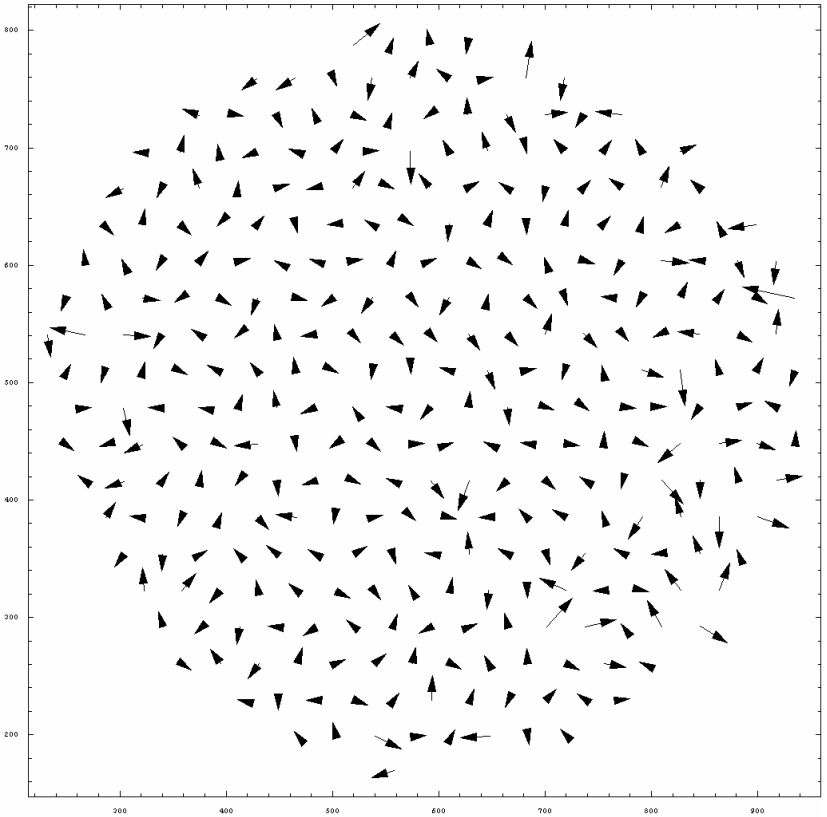
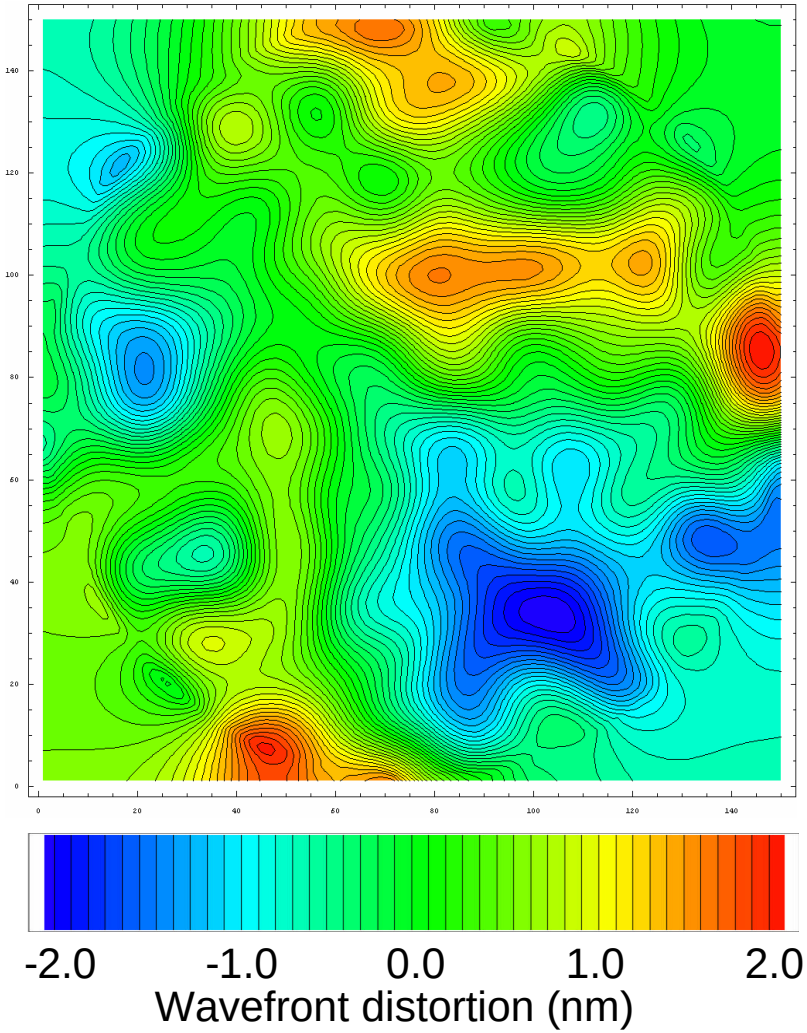
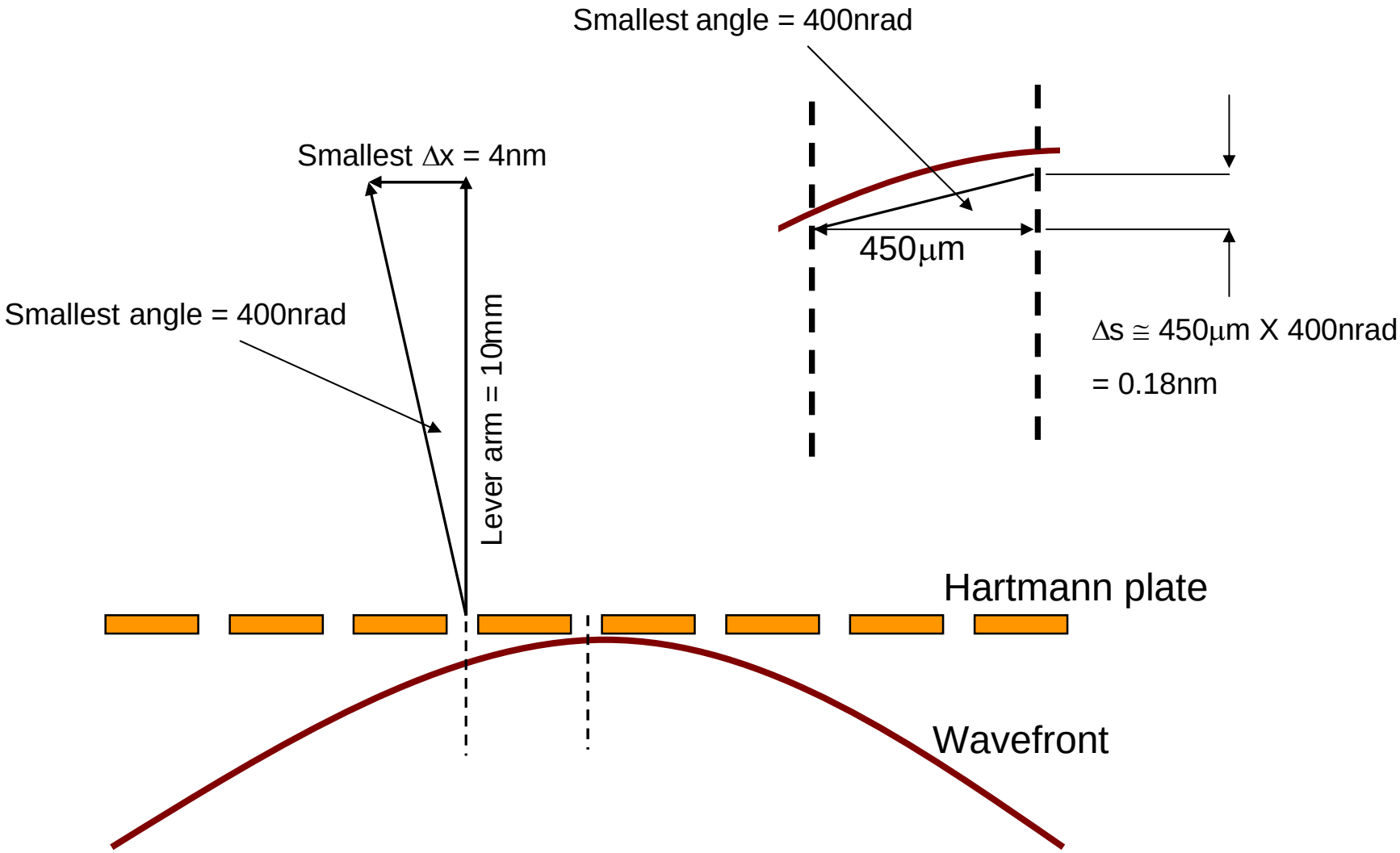
Sensor Has Very Low Noise





RMS noise = λ/1100

Sensor accuracy



Hartmann Sensor

- Very low noise, because each pixel is separate against a dark surround, due to the optimization of hole size, separation and lever arm

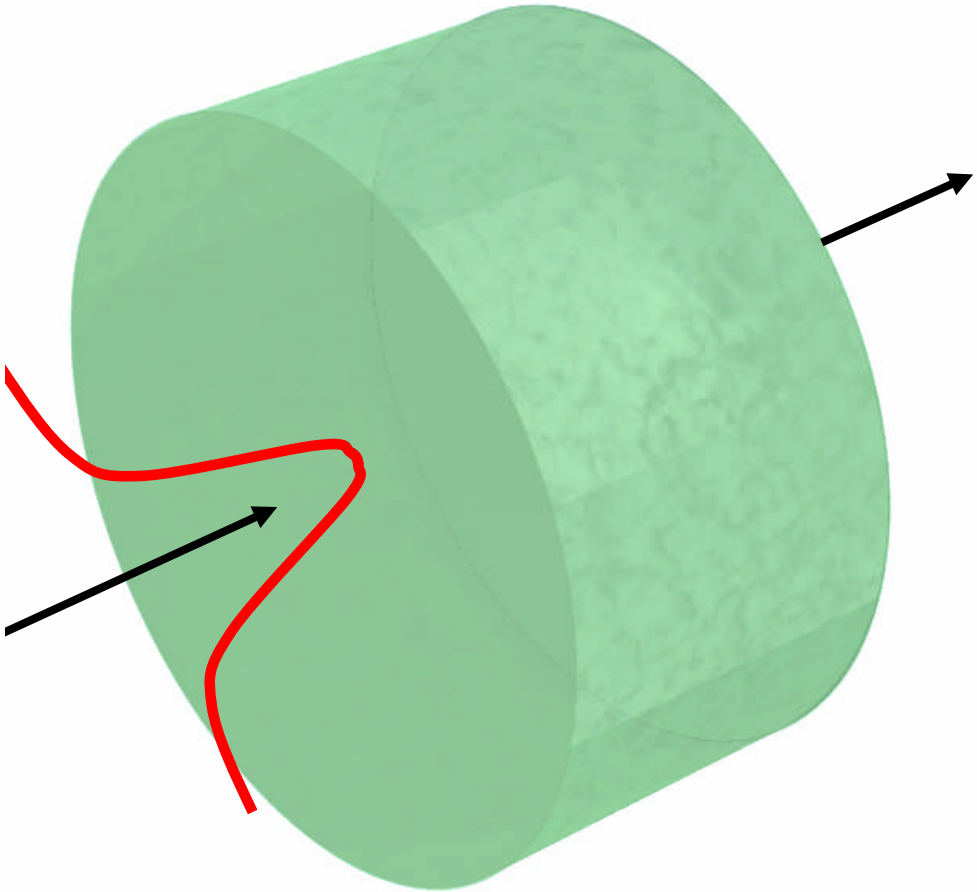
- Superior to other sensors (eg Shack Hartmann, Interferometers etc)
- Suitable for wavefront correcting servo system

Hartmann Sensor

- On axis
- Off axis
- Tomography

  (more than one off axis view)

Single View Optical Tomography Works for Cylindrical Symmetry



- E.g. Distortion induced by absorption of Gaussian beam heating an isolated optic

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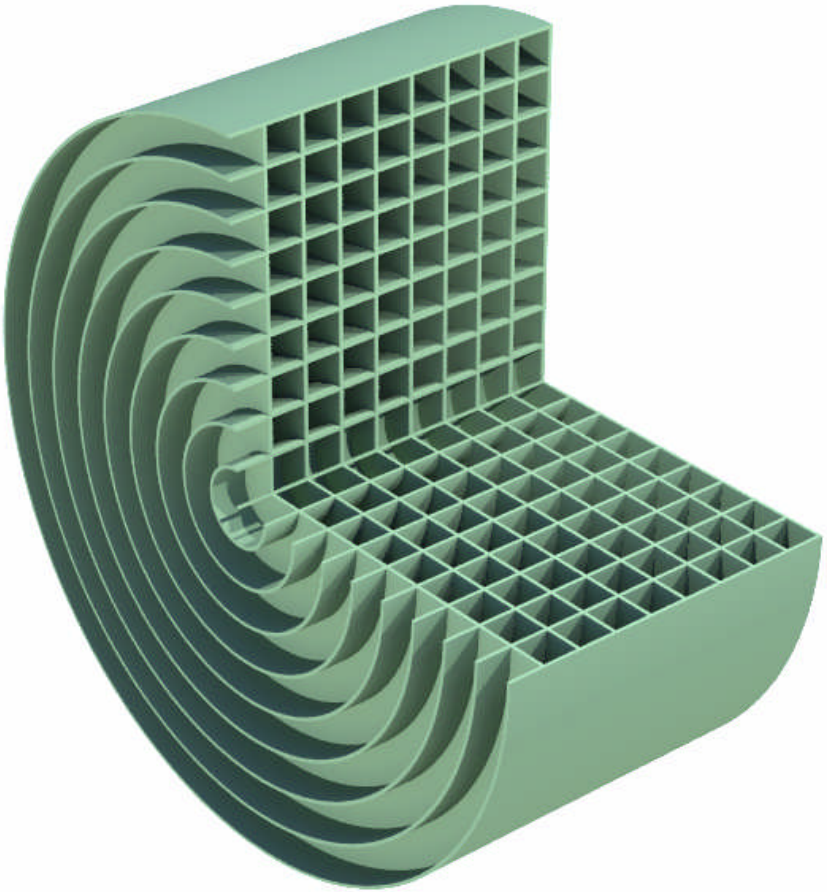
Representation of Refractive Index Distribution in Distorted Optic



- Divide into annular volume elements (voxels)
- Cylindrical symmetry assumed

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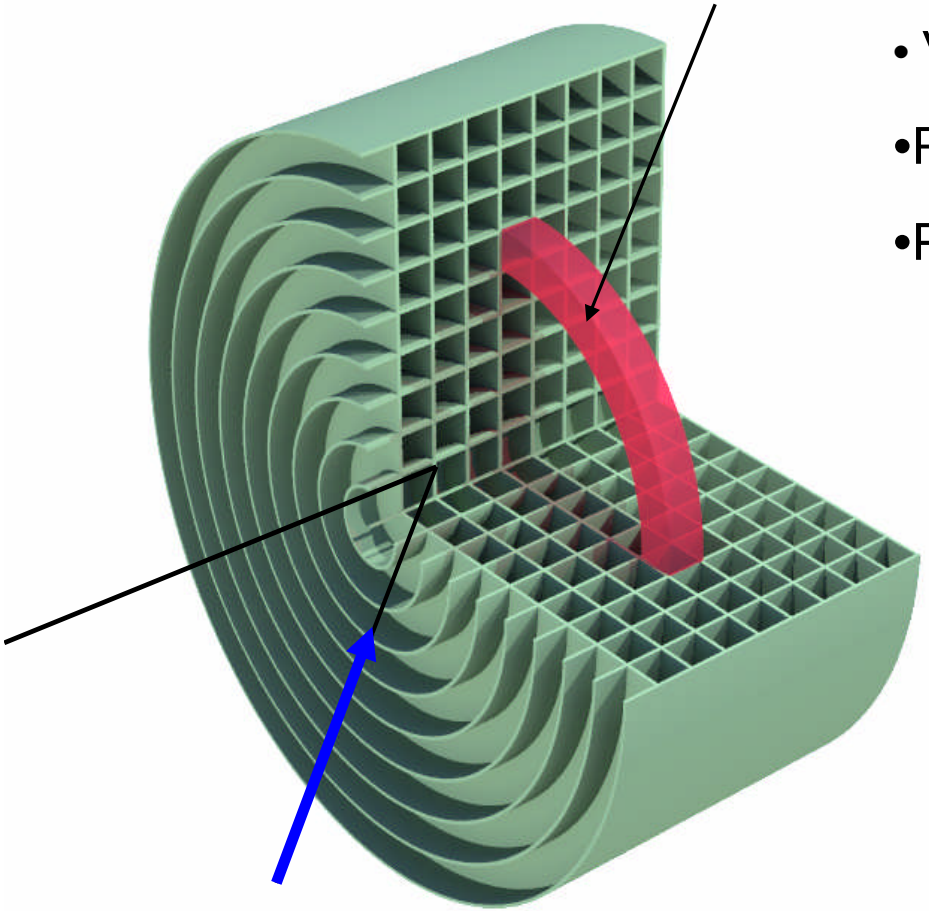
Wavefront Distortion Analyzed with Radon Transforms



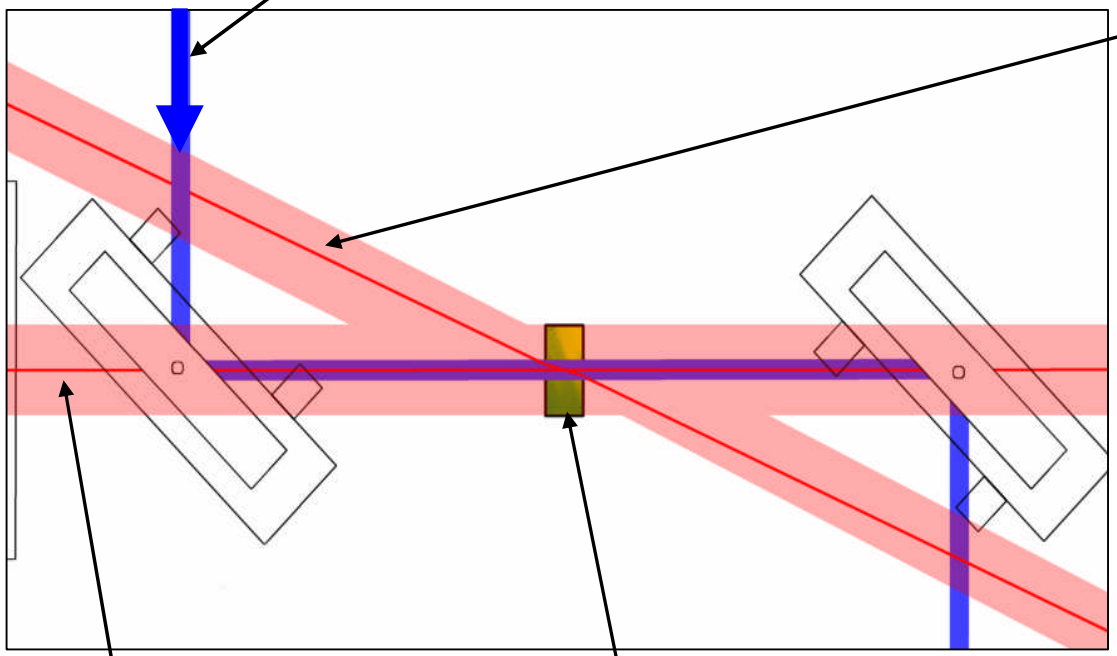
Off axis viewing angle, θ

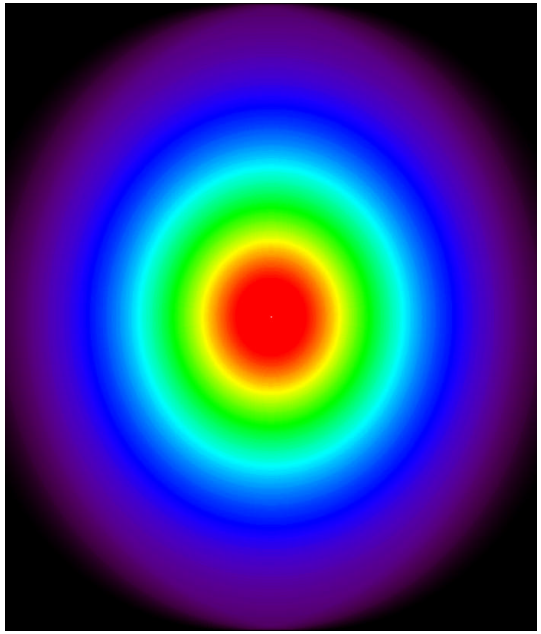
- $Voxel_{IJ}$ has uniform refractive index
- Radon Transform of $Voxel_{IJ}$
- Fit mode to wavefront distortion

Experimental Objectives

- Demonstrate that tomographic sensor works
- Validate results with independent high precision on-axis interferometer
- Experiment constructed to mimic distortion in Advanced LIGO

Experiment to Show Sensor Works





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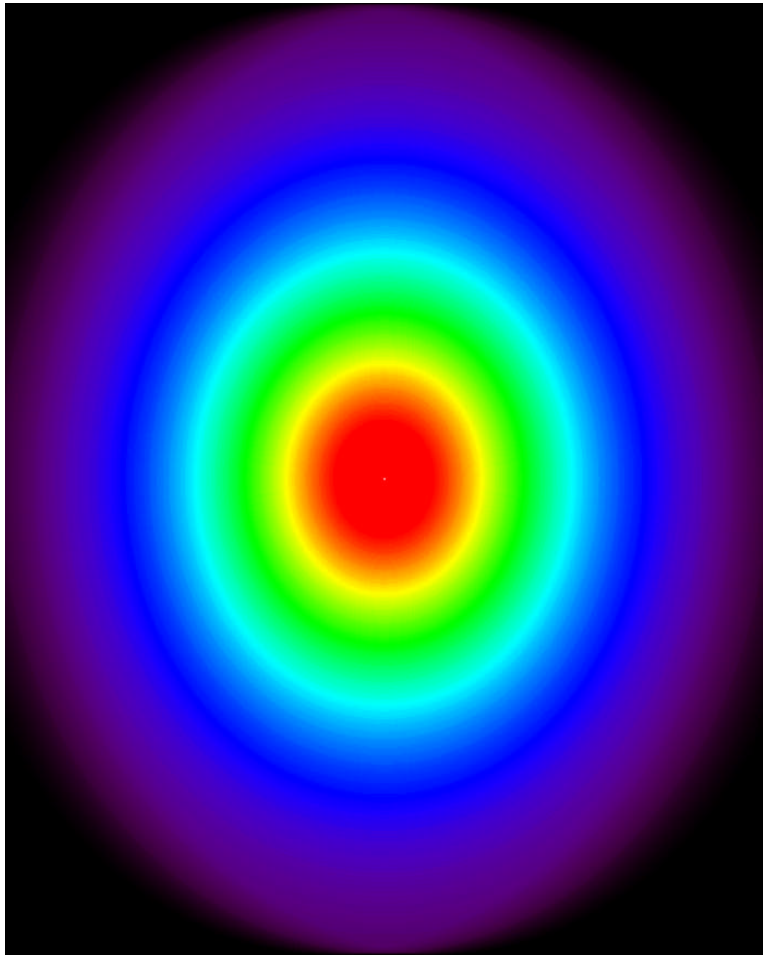
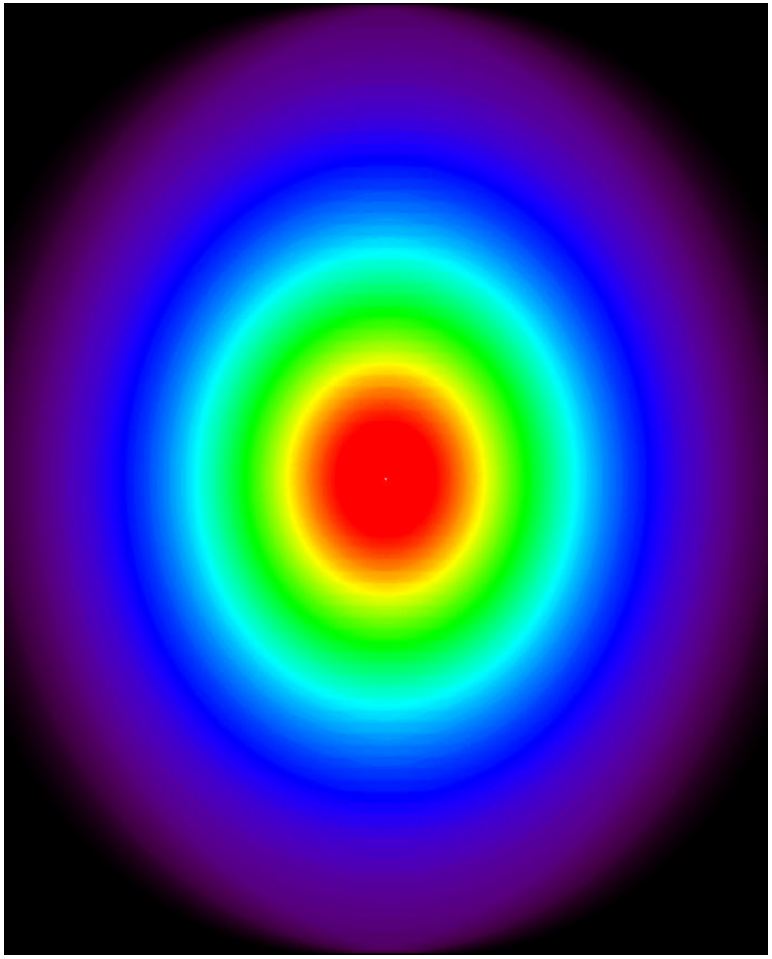
Simulation of Experiment Results

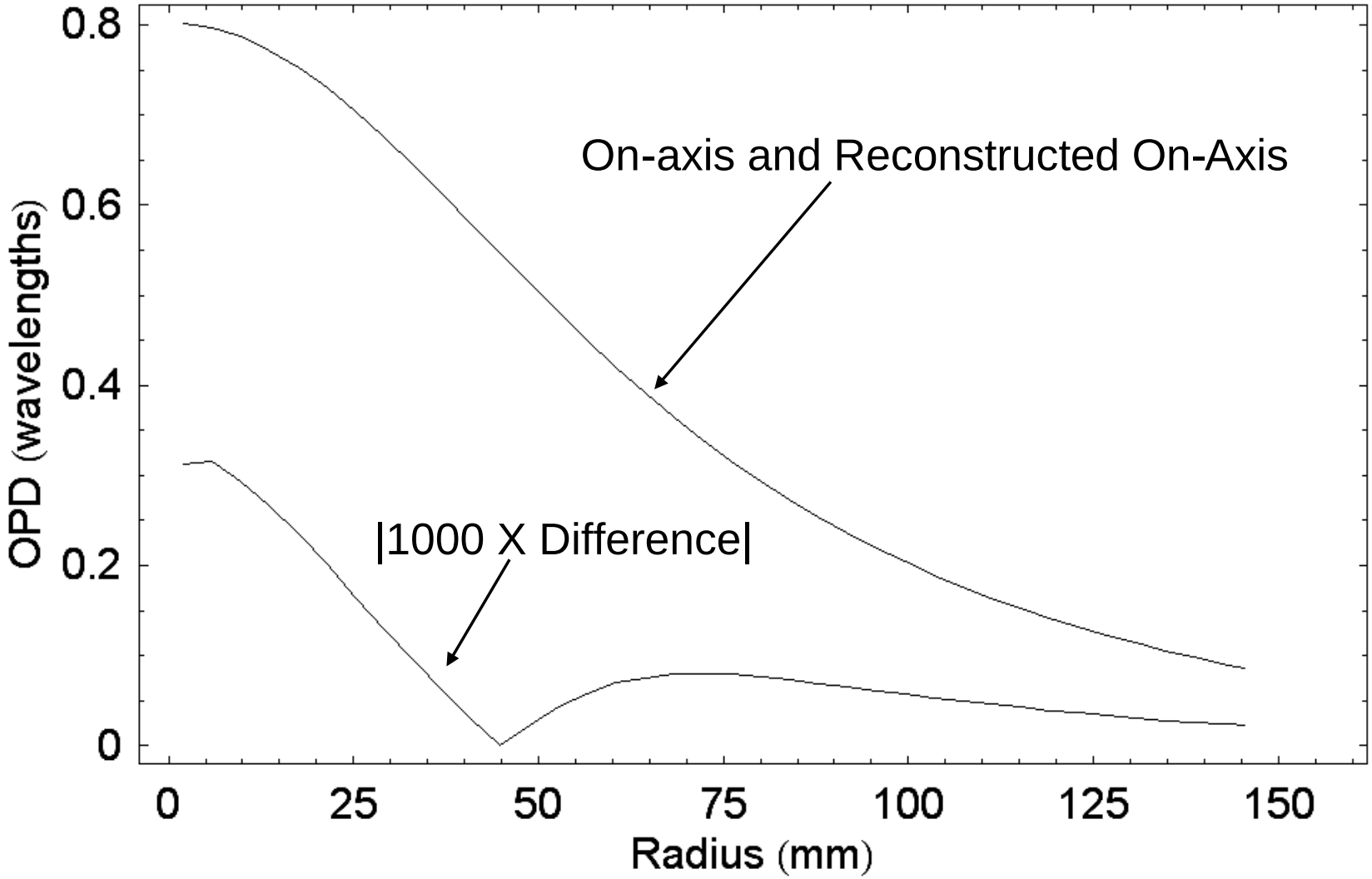


Original off-axis OPD

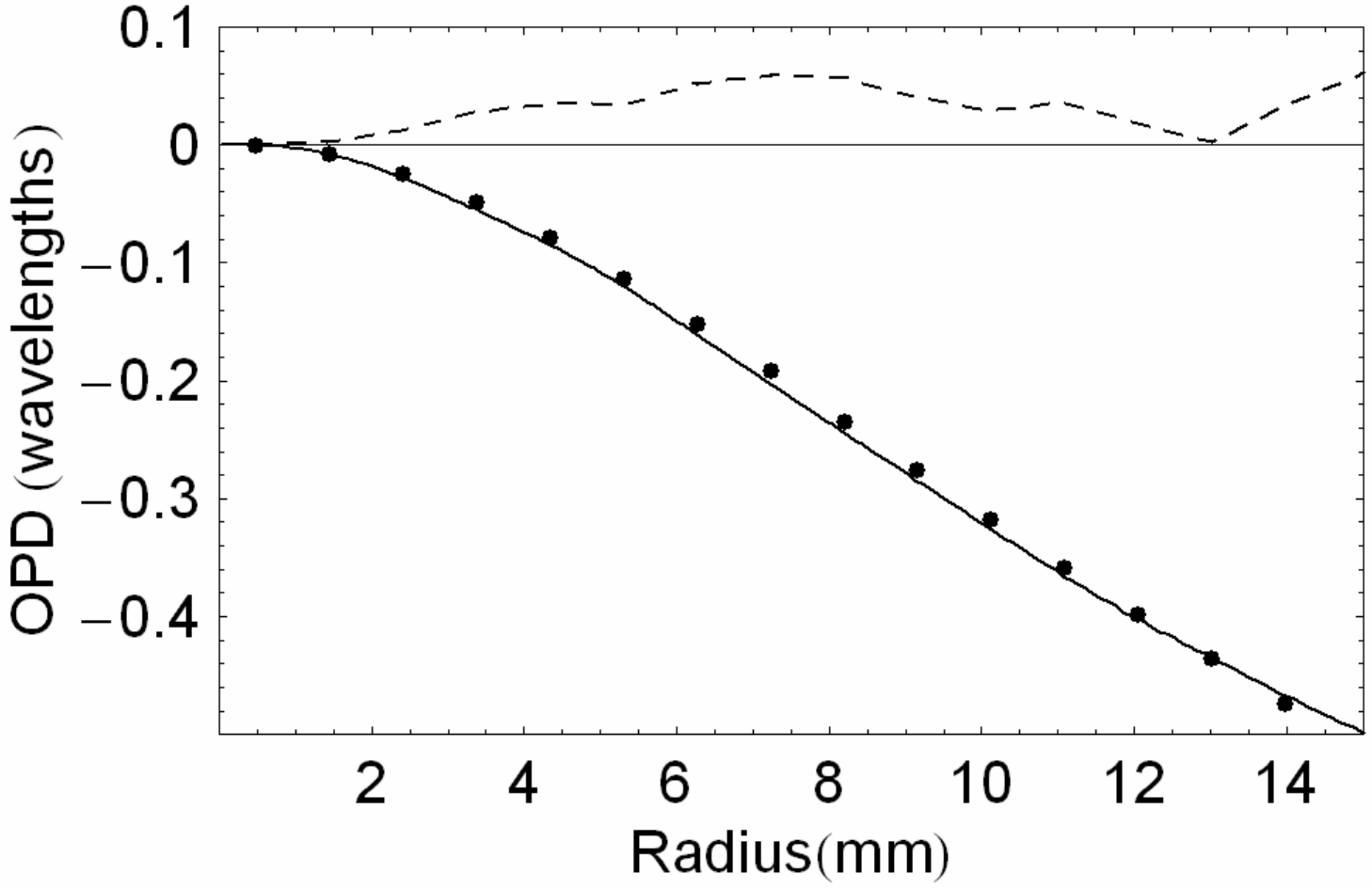


Best fit with voxel projections

Simulation shows Tomographic Analysis is Accurate



Off axis reconstruction agrees exactly with on axis interferometer



Dashed line: 5 x absolute difference, dots: reconstruction

Conclusion

- Hartmann sensor has accuracy and sensitivity required for advanced interferometers
- Current RMS Noise of sensor~ λ/1100
- Advantageous for both **on axis** and **off axis**
- Voxel analysis shown to be accurate
- Initial experimental results are promising
- Can extend to non-cylindrically symmetric distributions – use multiple views and azimuthal voxelation
- Ideal for active feedback servo systems

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