Development of a cryogenic compact interferometric displacement sensor

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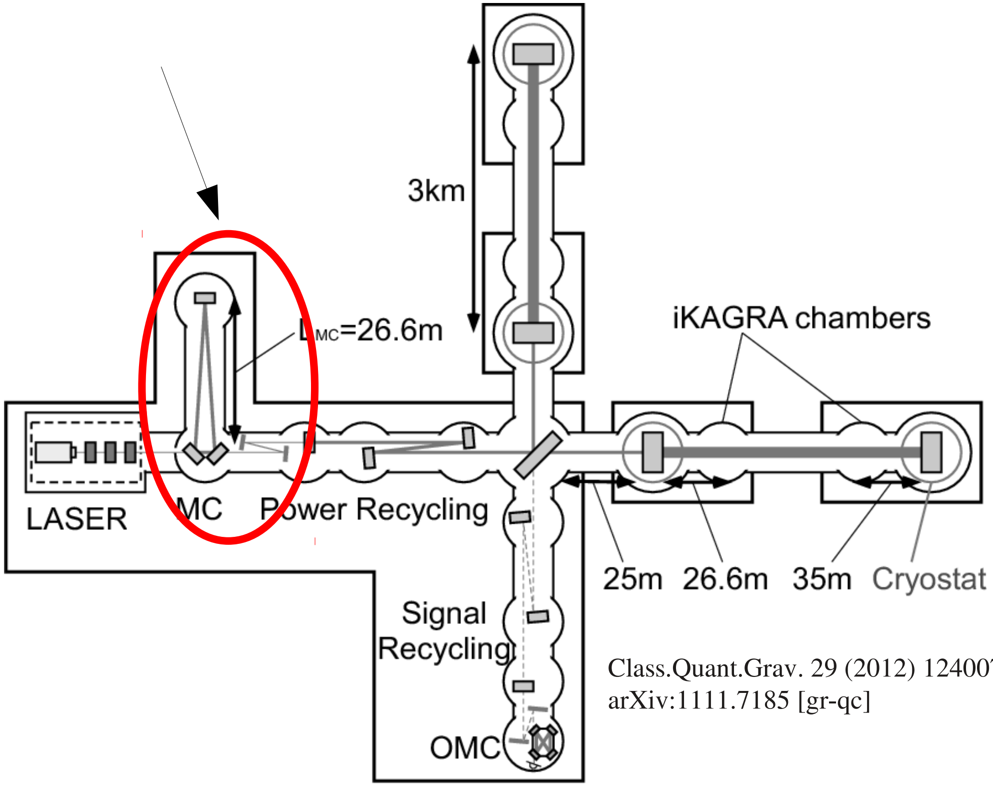
Outline of the presentation

- Motivation: local position sensor for some components of iKagra.
- Challenges set by the thermal cycle: misalignment of the optics and mechanical stress.
- Immunity to misalignments: an imaging system realized as a cat's eye retroreflector in double-pass interferometer.
- Current status: search for optical components capable to resist the thermal cycle.
- Conclusions.

Motivation

Local position sensor for the individual components of the mode cleaner of iKagra.

Mode cleaner



Class.Quant.Grav. 29 (2012) 124007
arXiv:1111.7185 [gr-qc]

Sensitivity requirement:

- at 10 Hz: $\sim 1\times 10^{-11}\, m/\sqrt{Hz}$
- at 1 Hz: $\sim 6\times 10^{-9}\, m/\sqrt{Hz}$

Source: Yoichi Aso

Statement of the problem

The contraction and expansion of the materials upon the thermal cycle produces misalignment of the optics and mechanical stress between adjacent components.

Requirements:

- Immunity to misalignments.
- The optical assemblies must be able to resist the thermal cycle: beam splitters cubes or plates, wave plate assemblies and optic fibre assembly.
- Mechanical stress on the polarization maintaining fibre must be minimized and accounted for in the fringe counting system.

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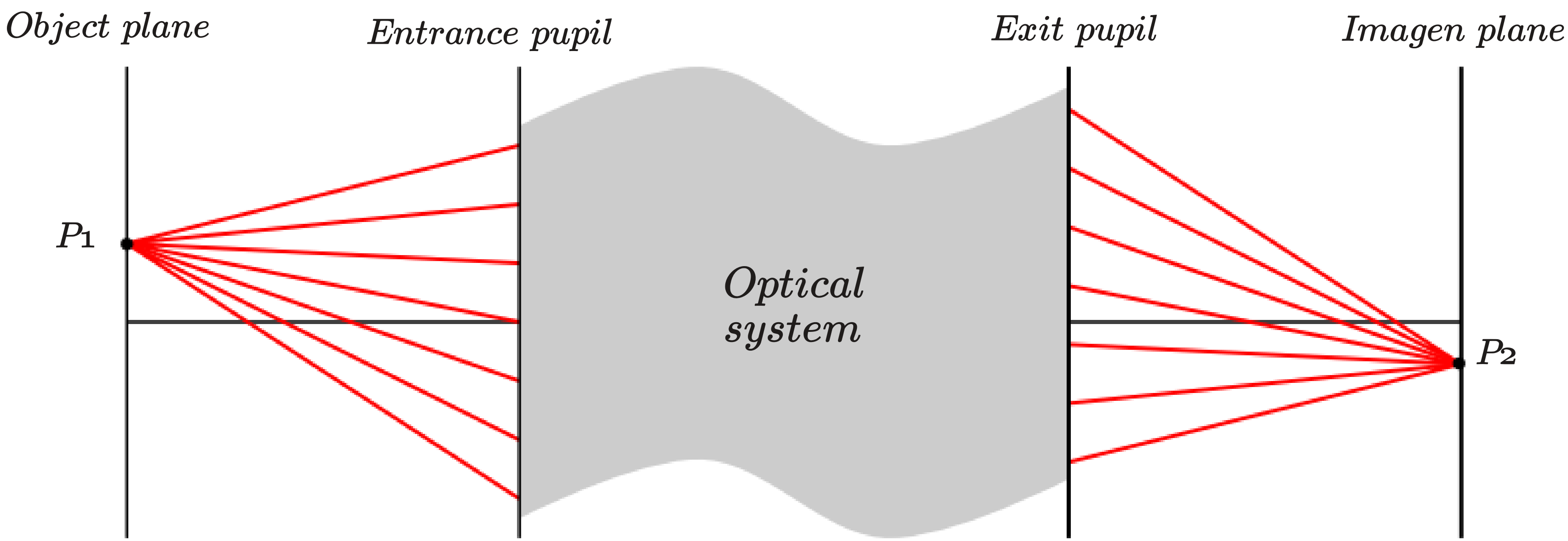
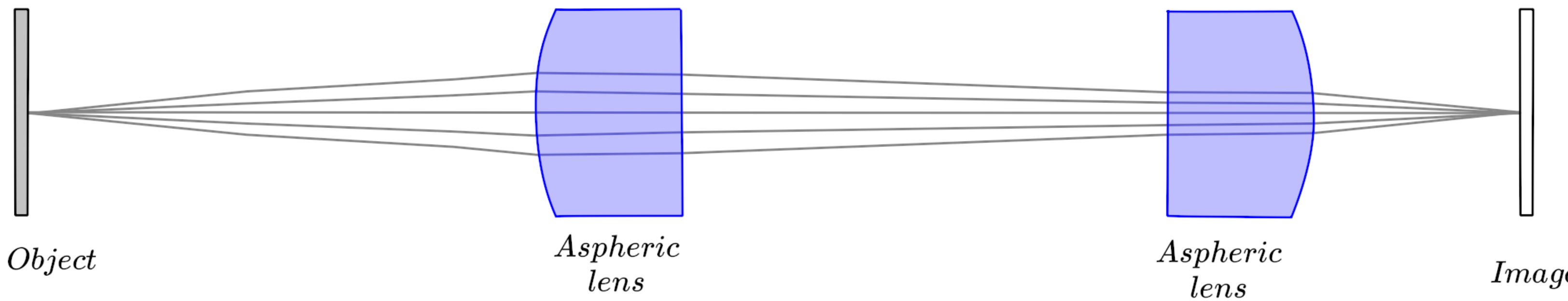
Immunity to misalignments

Conjugate points in an imaging system (1)

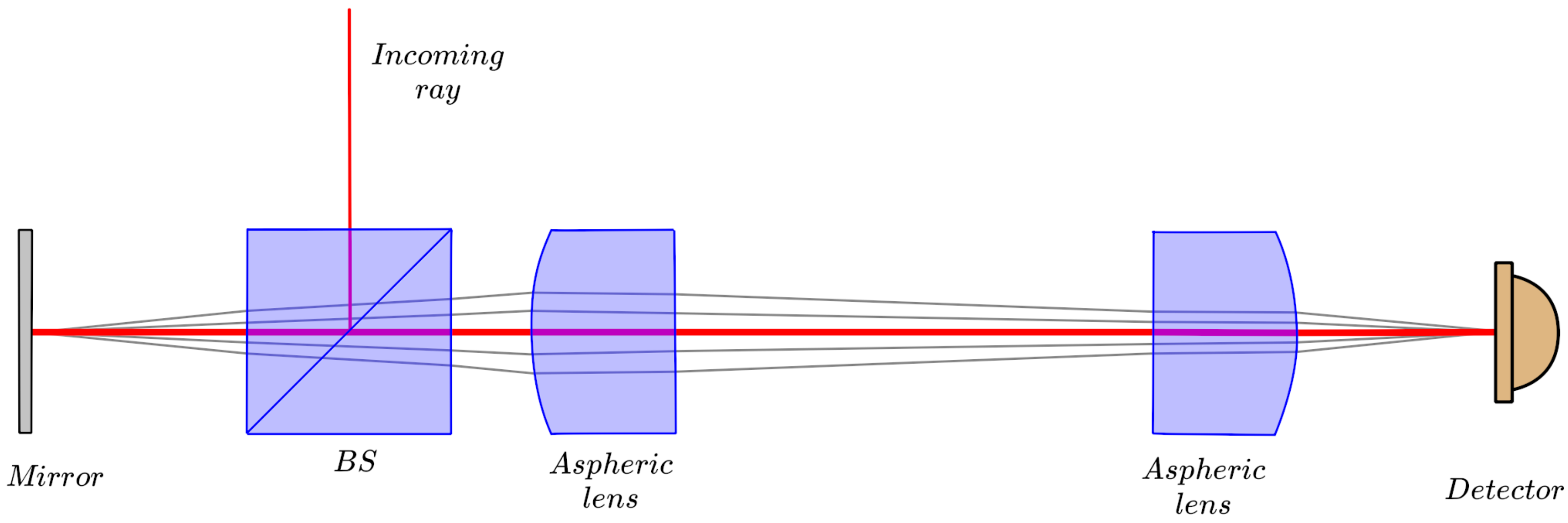


The optical path length between the conjugate points P_1 and P_2 is independent of the trajectory of the ray.

Conjugate points in an imaging system (2)



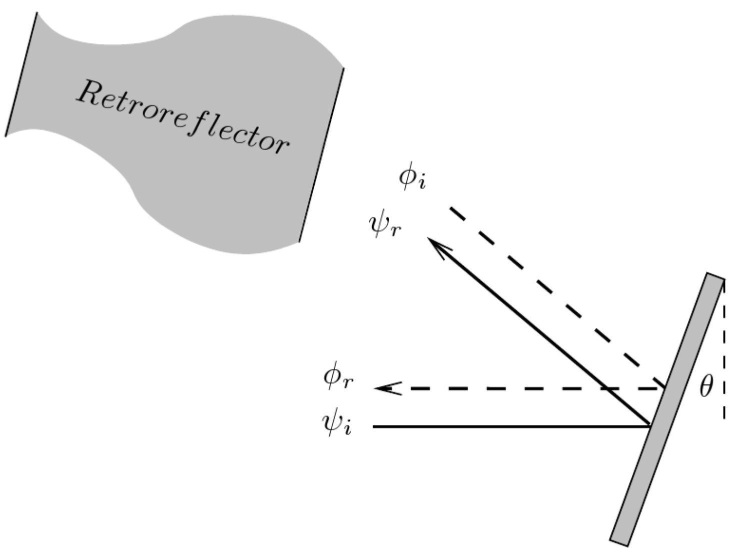
Conjugate points in an imaging system (3)



Conjugate points in an imaging system (3)

This approach does not work since the wavefront still tilts: visibility drops to zero for 250 μrad mirror tilt.

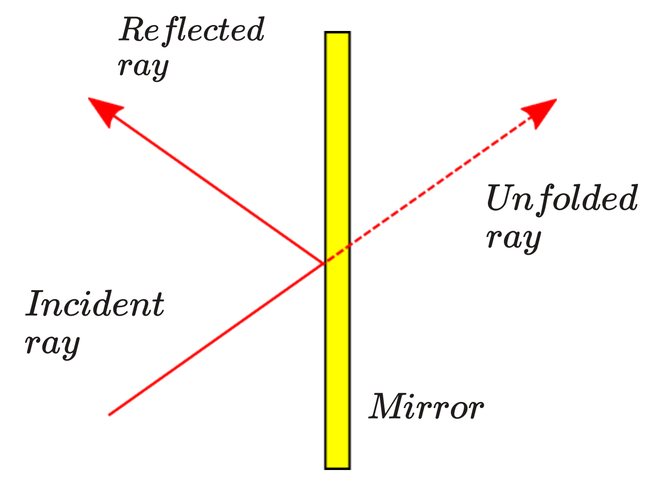
Wavefront parallelism is achieved with a retroreflector

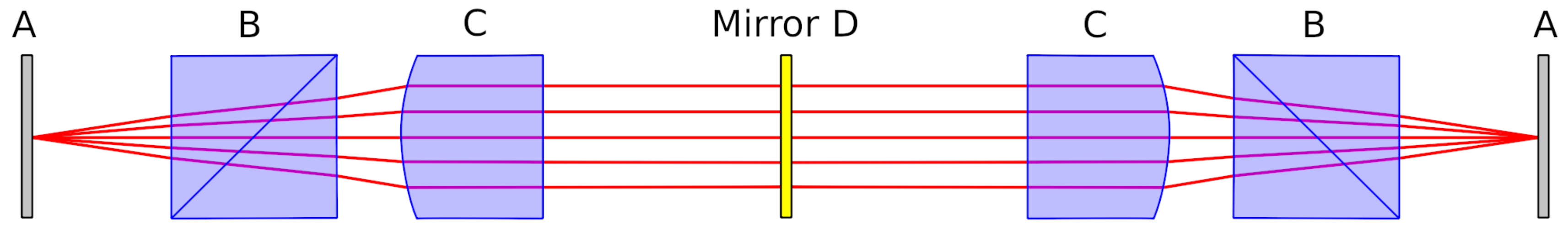


- Retroreflectors reflects the light back in the same direction it came from.
- Together with a mirror it produces a final wavefront parallel to the initial wavefront.
- Retroreflectors are symmetric for the light traverses every component twice.

How to build a retroreflector using an imaging system?

- The imaging system can be considered an unfolded propagation diagram.
- The system has to be symmetric:
  - The detector is replaced by the mirror.
  - The lenses have to be identical.
  - At the plane of symmetry an aligned mirror is placed.





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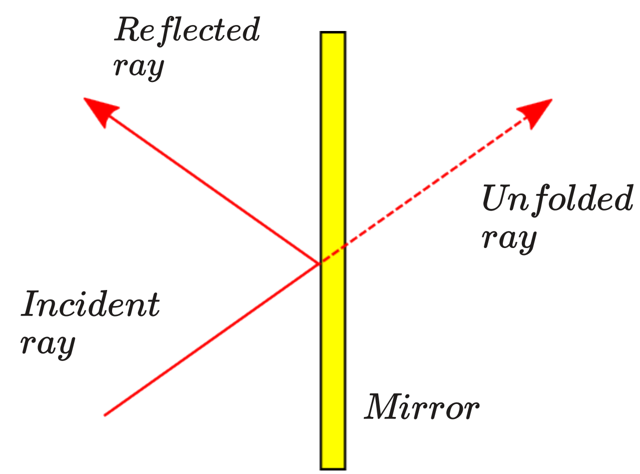
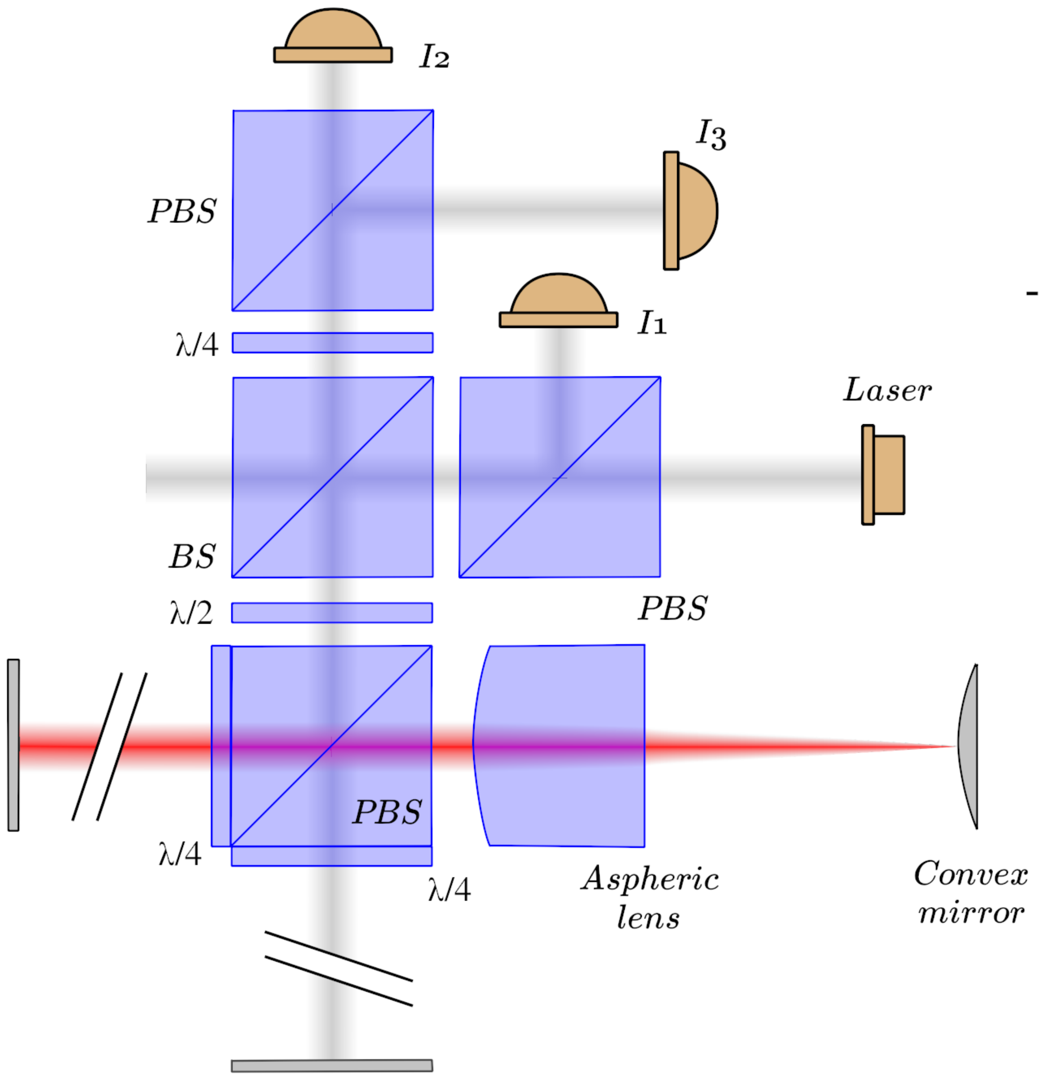


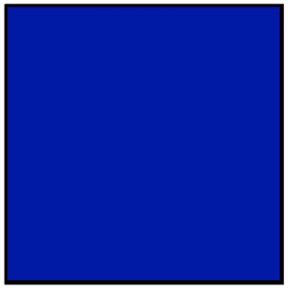
Cursory account of some properties of the cat's eye

- As the diagrams suggest, there is a place of the mirror where the maximum immunity to tilts is realized. This *sweet plane* is where the mirror coincides with its *real* image.
- The position of the sweet plane can be adjusted by an appropriate selection of the focal length of the lens and curvature of the mirror within the cat's eye.
- Since the retroreflector reflects the light in the same direction it comes from, when the target mirror is at the sweet plane, the tilt immunity is extended to the other optical components which may have been misaligned by the thermal cycle.
- The amount of tilt immunity allows the alignment of the components by placing them at their nominal positions and orientations without relying upon supports with adjustments (an example will be shown).

The retroreflector in a double-pass interferometer



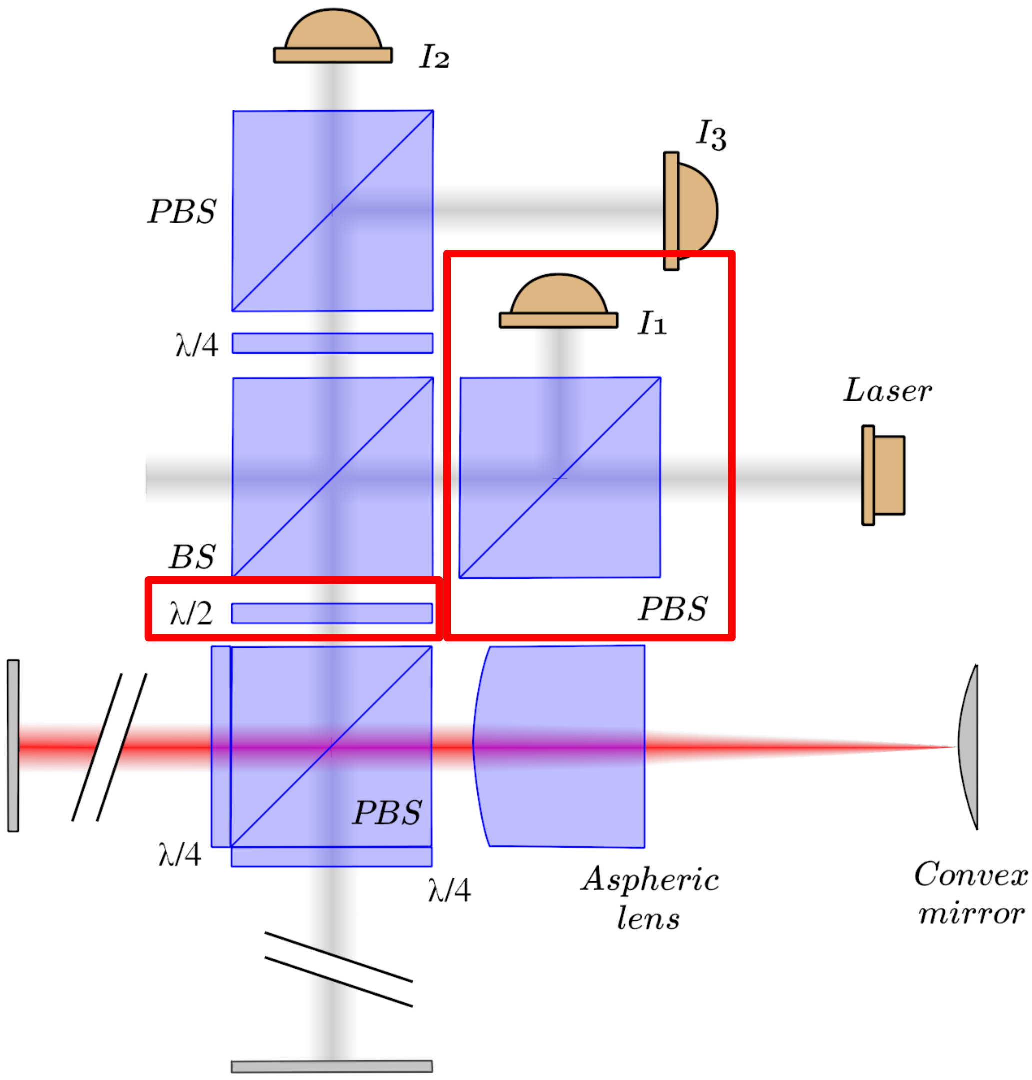
-1.25°< tilt angle < 1.25°

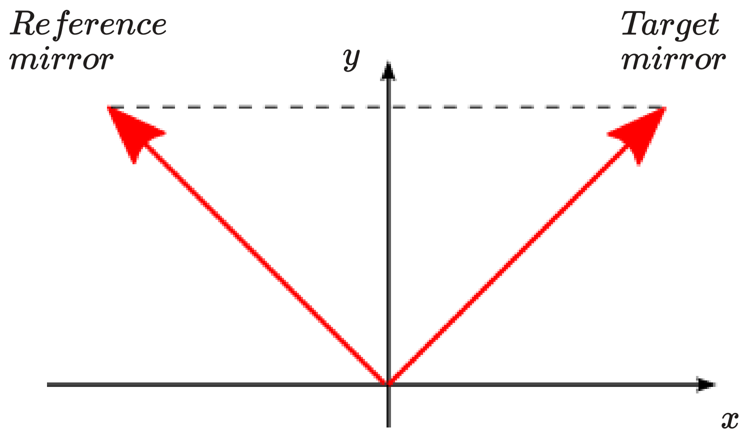


Interferogram

The retroreflector in a double-pass interferometer

Reversible fringe counting (1)

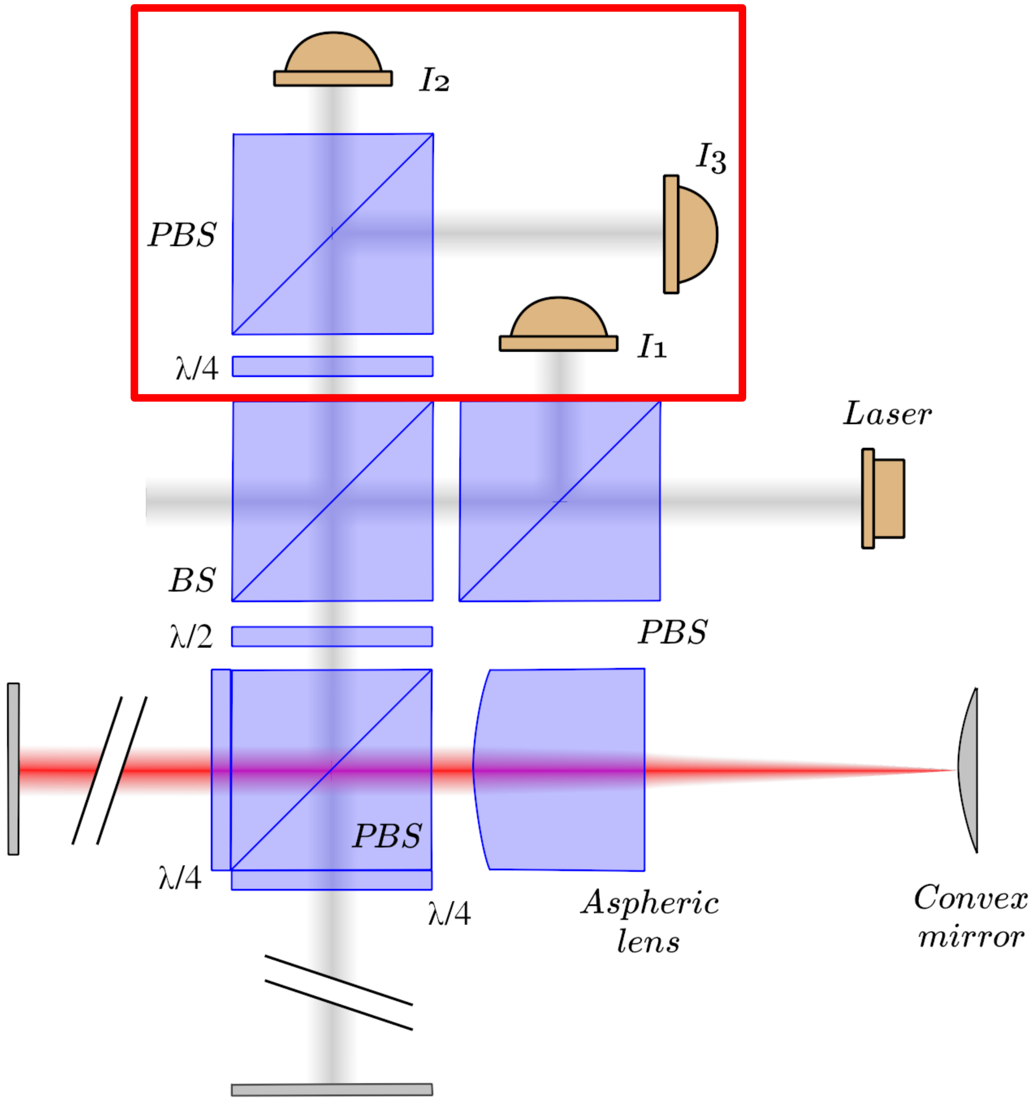


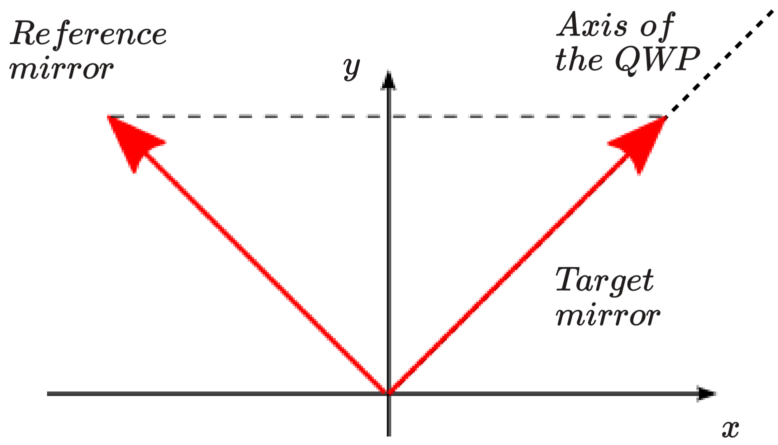


- The HWP rotates the electric fields 45°,
- The projection of the fields along the *y* axis produces the interference pattern I_1:

$$I_1 = \frac{I_0}{8}\left(1 + \sin 2\varphi\right)$$

Reversible fringe counting (2)





- The QWP introduces an additional 90° difference between the electric fields.
- The projections of the fields along the x and y axes produce the interference patterns I_2 and I_3:

$$I_2 = \frac{I_0}{8}(1+\cos 2\varphi), \quad I_3 = \frac{I_0}{8}(1-\cos 2\varphi)$$

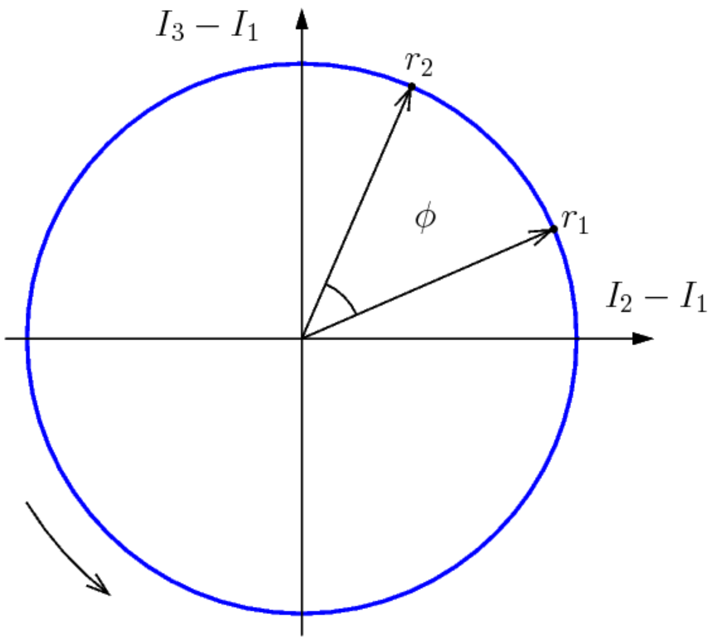
Reversible fringe counting (3)

$$I_1 = \frac{I_0}{8}(1 + \sin 2\varphi)$$

$$I_2 = \frac{I_0}{8}(1 + \cos 2\varphi)$$

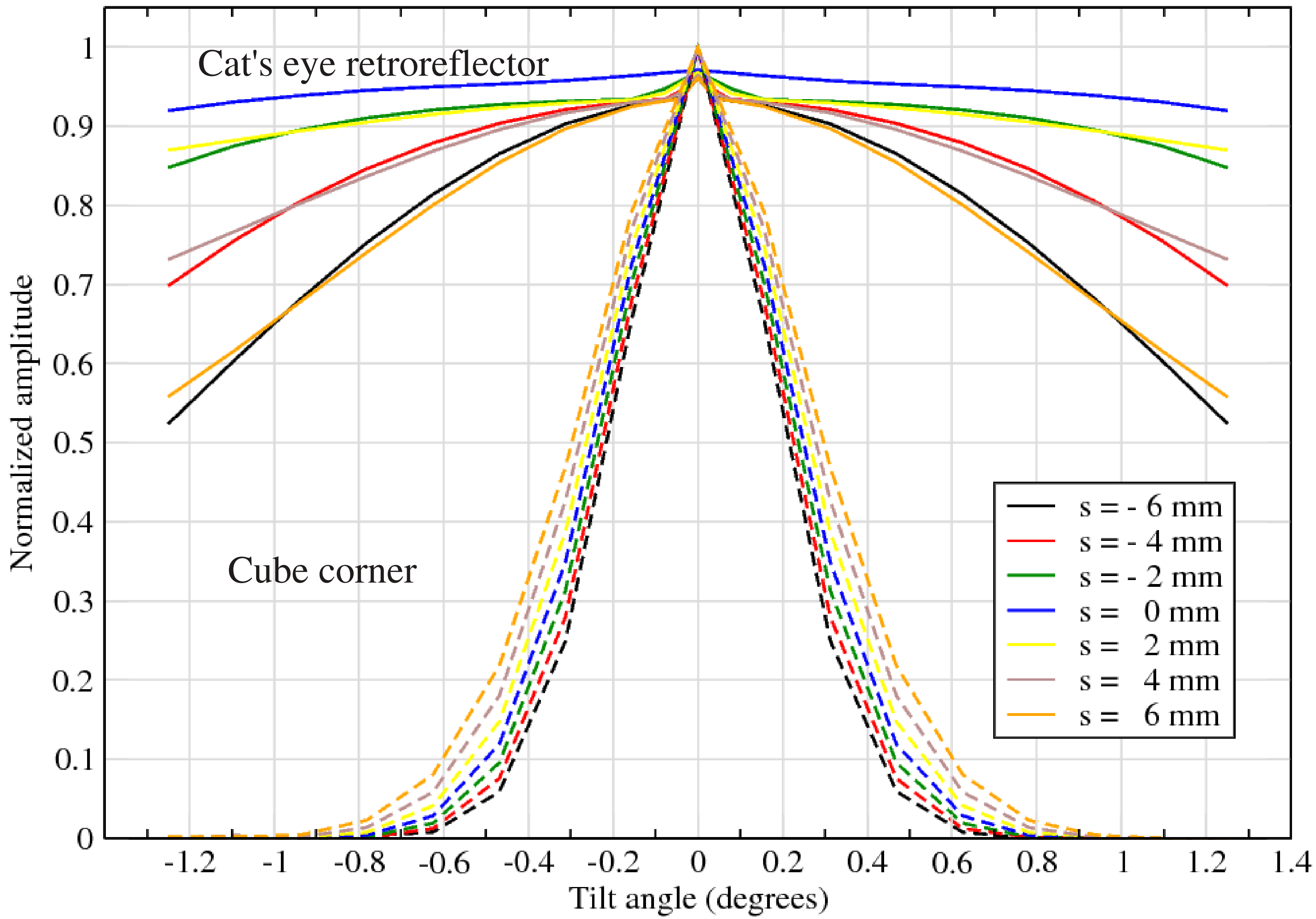
$$I_3 = \frac{I_0}{8}(1 - \cos 2\varphi)$$

$$d = \frac{1}{4}\left(\frac{\lambda}{2\pi}\right) \arctan\left(\frac{x_1 y_2 - y_1 x_2}{x_1 x_2 + y_1 y_2}\right)$$



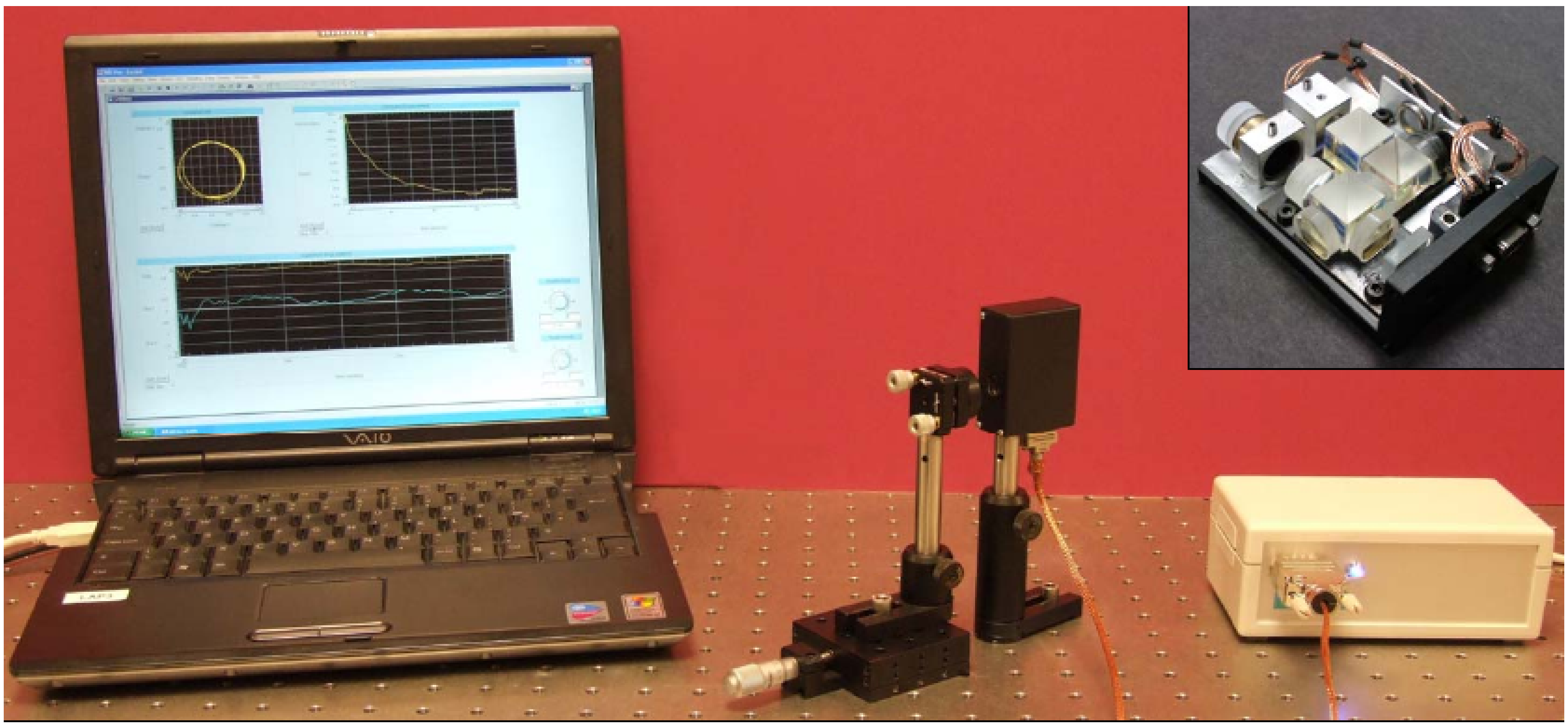
In the real case this is an ellipse whose geometry must be characterized.

Theoretical signal amplitude



Example at room temperature (1)

Euclid: Easy to Use Compact Laser Interferometric Device

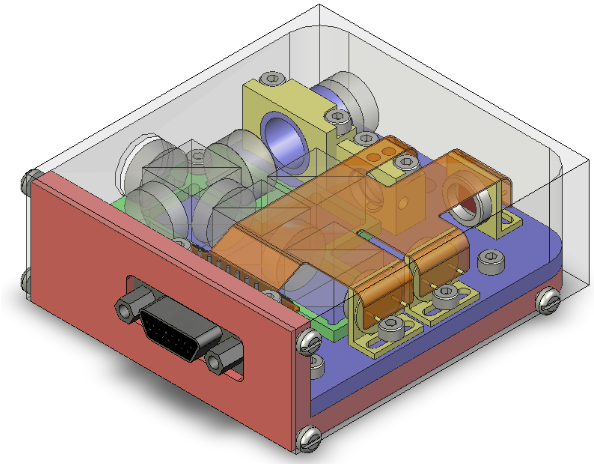


Designed at the University of Birmingham by Stuart Aston, Fabián Peña
Clive Speake and Tim Coppland

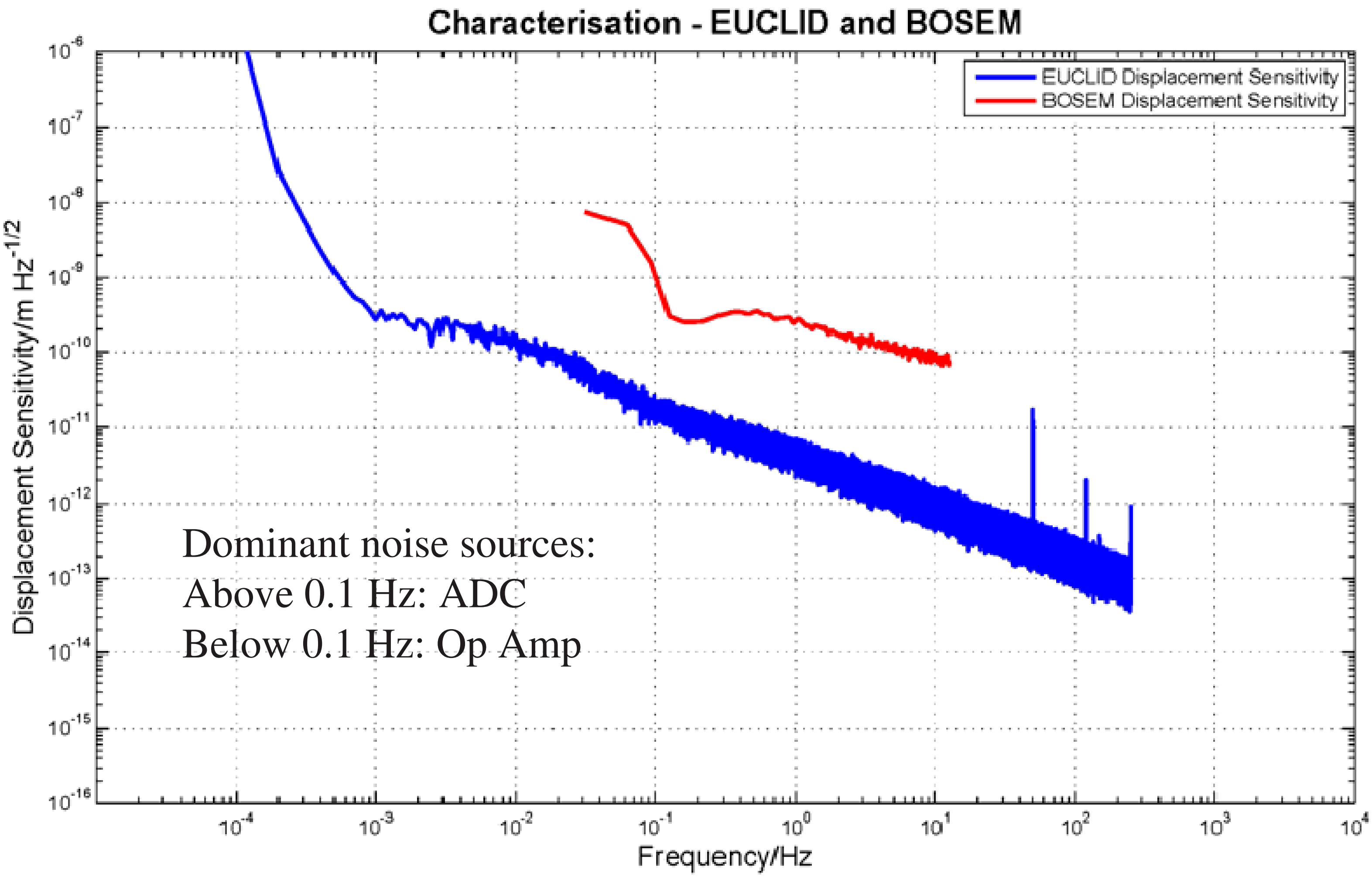
Example at room temperature (2)

- The cat's eye is affected by aberrations and must be optimized with an optical design software package (e.g. Zemax).
- Tolerance to misalignments: $\pm 1^\circ$ (along a diastance of 2 mm).
- Sensitivity at 10 Hz: $\sim 1 \times 10^{-12} m / \sqrt{Hz}$ ✓
- Sensitivity at 1 Hz: $\sim 4 \times 10^{-12} m / \sqrt{Hz}$ ✓
- No optoacoustic modulators, no piezos nor adjustable supports.
- The case includes a laser diode.
- Made with components from stock (10 mm).

Size: 60 × 55 × 22 mm



Sensitivity



Dominant noise sources:
Above 0.1 Hz: ADC
Below 0.1 Hz: Op Amp

Courtesy: Stuart Aston

Current status: experiments which will be made soon

The cat's eye retroreflector:

- A diffraction limited cat's eye retroreflectors have been designed already using Zemax and will be incorporated to a room temperature interferometer for testing.
- The cat's eye will be aligned at room temperature with a shearing plate and the effect of the temperature change can be quantified with the same plate using a cryostat with a window.

The optical components must resist the thermal cycle:

- Individual components where no adhesive is required: *bidirectional* BS and NPBS *plates* designed by Sigma Koki.
- All dielectric optical contacted BS and NPBS cubes.
- All dielectric BS and NPBS cubes bonded with the EP30-2 adhesive by Masterbond, which is the only cryogenic optical adhesive certified by LIGO for its low outgassing rates.

  Since it is very hard (Shore D 75) it may change the polarization state of the light due to the induced stress at cryogenic temperatures.

- The effect of the stress induced by the EP30-2 on the polarization maintaining fibre should be quantified and accounted for in the fringe counting system.

Conclusions

- Immunity to misalignments can be achieved with a cat's eye retroreflector in a double-pass polarization homodyne interferometer. The alignment of the cat's eye can be tested at 20 K.
- We are about to start testing different beam splitter cubes and plates at 20 K in order to discover which ones resist the thermal cycle.
- In a later stage of development the effect of mechanical stress on the polarization maintaining fibre will be assessed and accounted for in the fringe counting system.

References

App. Opt. **50**, 981 (2011); http://dx.doi.org/10.1364/AO.50.000981

Rev. Sci. Instrum. **84**, 043101 (2013); http://dx.doi.org/10.1063/1.4795549