Modelling mirror surface distortion effects in low-loss, near-unstable Fabry-Perot cavities

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FINESSE v1.0

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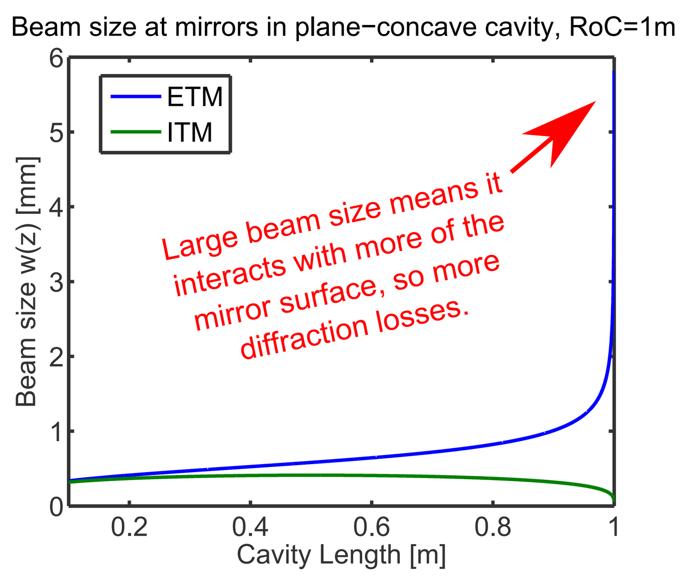
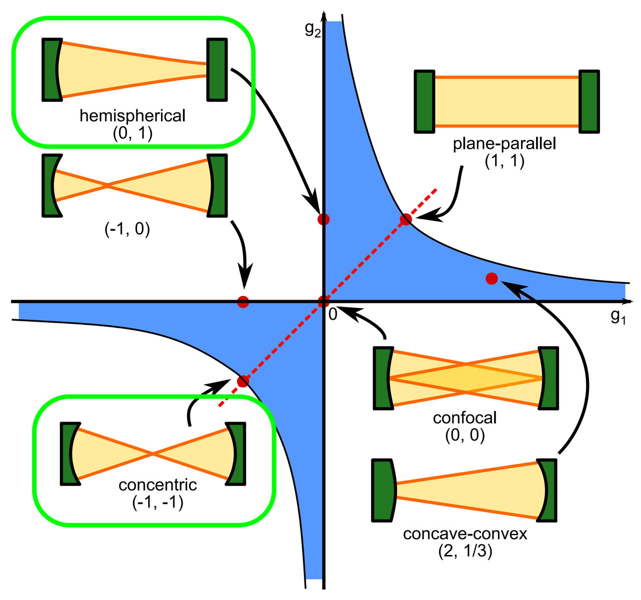
Gravitational wave detectors utilise optical cavities in several ways. When squeezed light is injected to reduce the quantum noise, optical losses can significantly degrade its effect, in particular losses in the filter cavities such as from surface defects. At the same time, thermal noise can be reduced by increasing the spot size on the mirrors leading to near-instable cavity geometries. We use numerical models to investigate such low-loss, near-instable cavities with nanoscale defects present on the mirror surfaces and the effect they have on the cavity performance along with the possible effects measurable via an optical experiment.

This poster shows the result of a preliminary numerical investigation for an optical experiment being conducted at the University of Birmingham. We show how the simulation tool ***FINESSE* v1.0** [3] (*www.gwoptics.org/finesse*) has been used to model the effects mirror surface distortions will have on our experiment studying near-instable cavities and surface losses.

The stability of an optical cavity is quantified by its g-factor, determined by the cavity geometry: L the length of the cavity, R_{itm} the input mirror curvature and R_{etm} the end mirror curvature.



$$0 < g_1 g_2 < 1$$
$$g_1 = 1 - \frac{L}{R_{itm}}$$
$$g_2 = 1 - \frac{L}{R_{etm}}$$



Beams resonant in cavities near **Near-Instability** have large spot sizes. This has the advantage of reducing the effect of **mirror coating brownian noise** by averging over a larger surface area.

However, such cavities are more sensitive to **misalignments** of the input beam and generally have **greater diffraction losses**.

Such near-instability cavities are planned to be used in the 10m AEI prototype g=0.998 [1] and if benficial for future detectors.

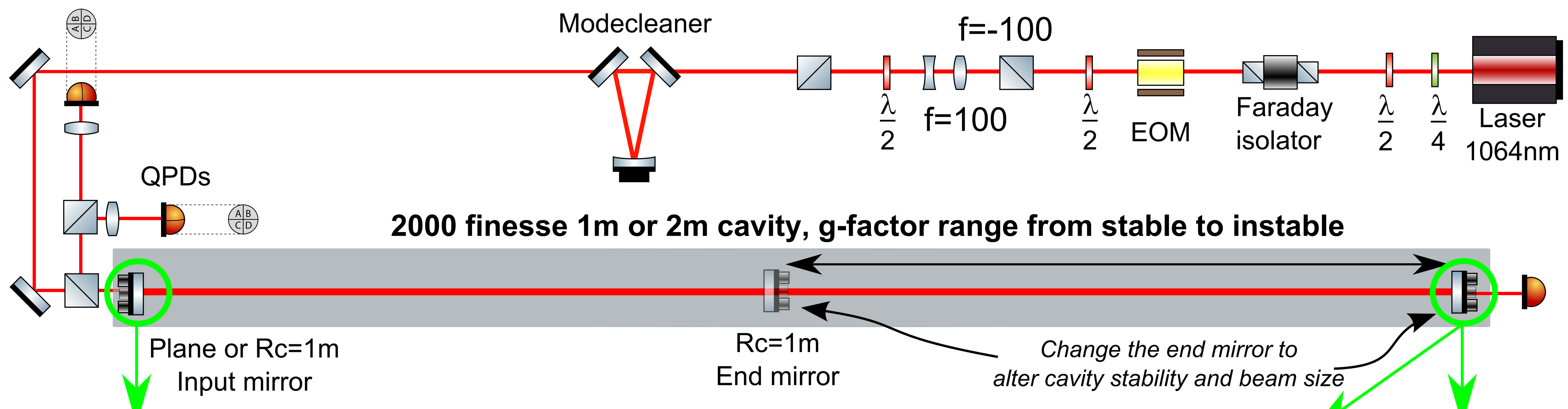
The experimental setup

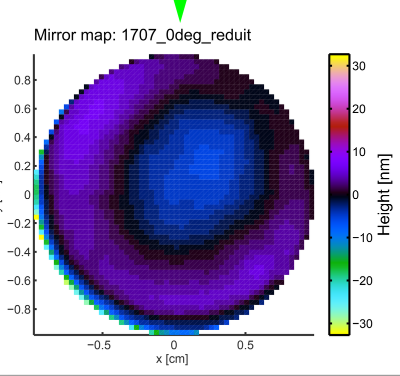
An experiment has been setup at Birmingham to create a cavity to better understand the behaviour of cavities near to instability and the losses present. A linear cavity is used with the option for a **1m hemi-spherical cavity** and a **2m concentric cavity** to explorer different regimes of cavity stability.

The aim is to have a **finesse of ~2000**, to reach this a laminar flow cabinet will be used to reduce contamination of the mirror.

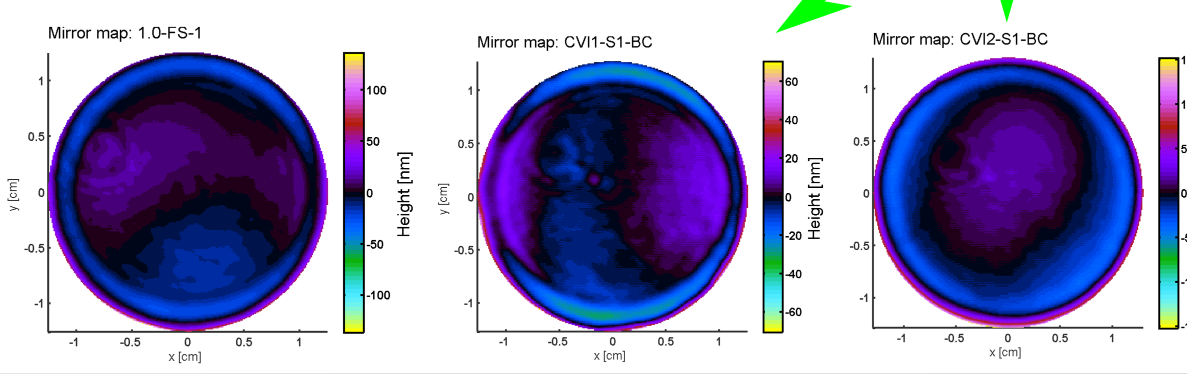
Both high and low quality mirrors have been purchased for the cavity mirrors and surface distortions (mirror map) have been taken to use within ***FINESSE*** the simulation tool.

The final aim is to characterise optical losses in variable lenth Fabry Perot cavity and test near-instable cavity control.





Mirror surface distortions measured before and after coating, a mixture of good (smooth) and bad (rough) mirrors will be used to vary optical losses per mirror.



Modelling an imperfect cavity

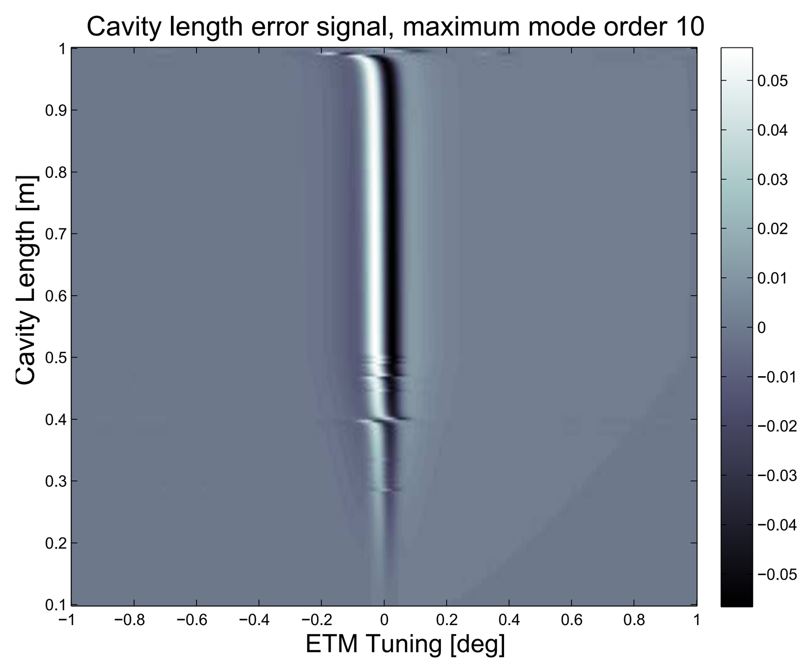
An imperfect optic will cause an incoming mode nm to couple into an outgoing mode $n'm'$ which is described by the coupling coefficient [2] $k_{nmn'm'}$

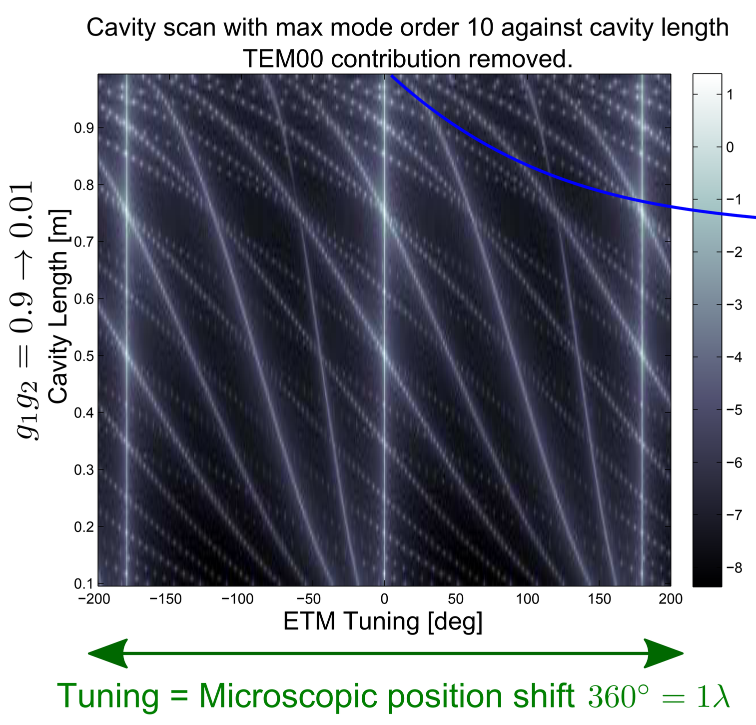
$$k_{nmn'm'} = \iint u_{n'm'} A(x,y) e^{i\phi(x,y)} u^*_{nm} dx dy$$

where A and φ are the amplitude and phase change of the distortion. For accurate simulations we can take metrology information (mirror maps) for A and φ for individual optic surfaces and simulate their effect on reflected or transmitted beams. The simulation tool ***FINESSE*** is the most advanced tool for computing these higher order modes with surface maps along with their effects on an optical setup in the frequency domain and makes the computation simpler and faster.

A cavity can be *"scanned"* by microscopically moving one of the mirrors as shown in the plot on the right and measuring the intracavity power. The bright lines show the points at which the modes n+m>0 are resonant in 1m hemi-spherical cavity with mirror surface defects present, the **TEM00 contribution has been removed for better visibility of modes.** The frequency separtion between a HOM and the fundamental mode is given by:

$$f_{nm} = \frac{FSR}{\pi}(n+m)\arccos(\sqrt{g_1 g_2})$$





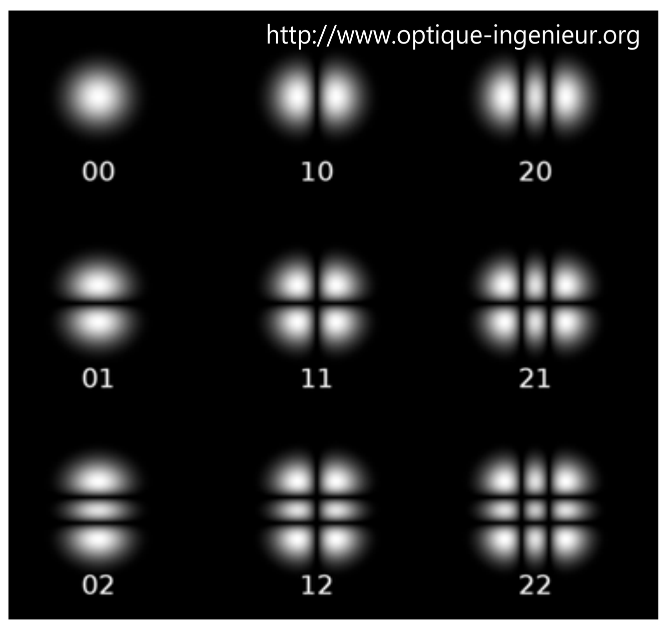
As $g_1 g_2$ tends to instability i.e. 1 or 0, the HOMs bunch together as the separation frequency is on the order of the Free Spectral Range (FSR). This mode bunching ruins error signals as seen on th left and can make the cavity inoperable even before it has reached instablity.

The modal model

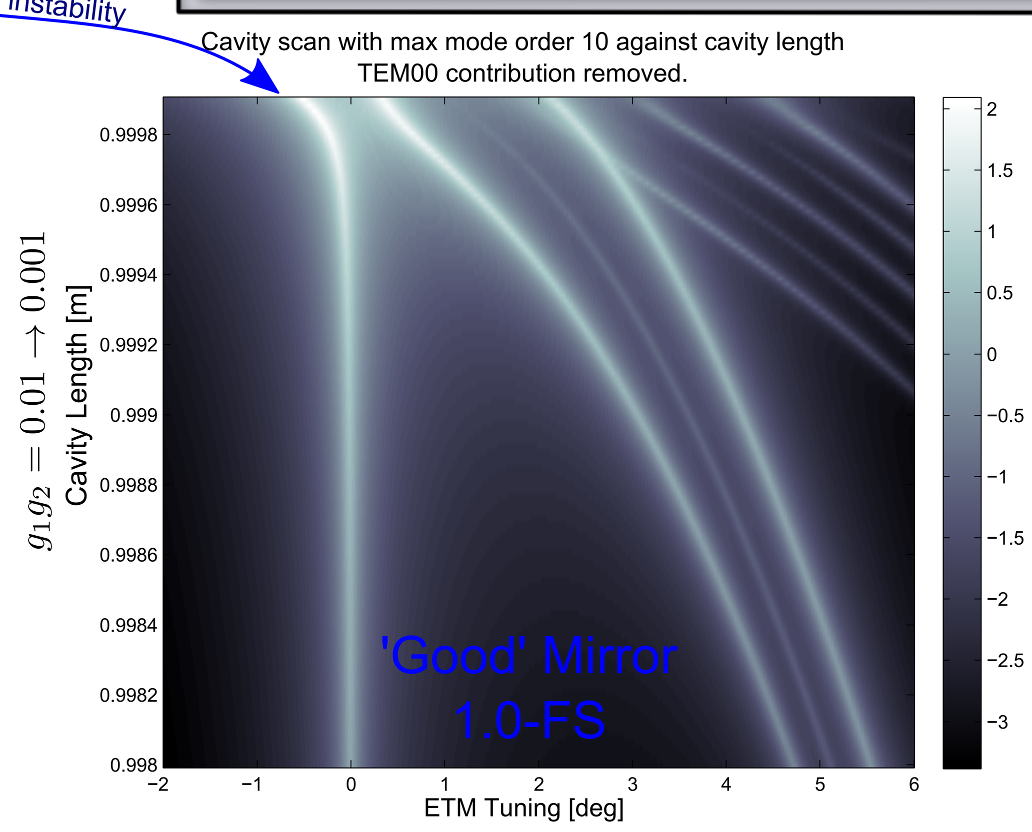
For high-precision experiments modelling the effect imperfect optics and other physical distortions have on the beam is required. These distortions however are usually very small due to the high quality optical components. Thus, the modal model is a suitable perturbative expansion of the beam's shape due to the distortion into higher order modes (**HOM**). The orthogonal function basis chosen for ***FINESSE*** are the Hermite-Gaussian modes.

$$E(x,y,z) = \sum_{n=0,m=0}^{\infty,\infty} a_{nm} u_n(x,z) u_m(y,z)$$

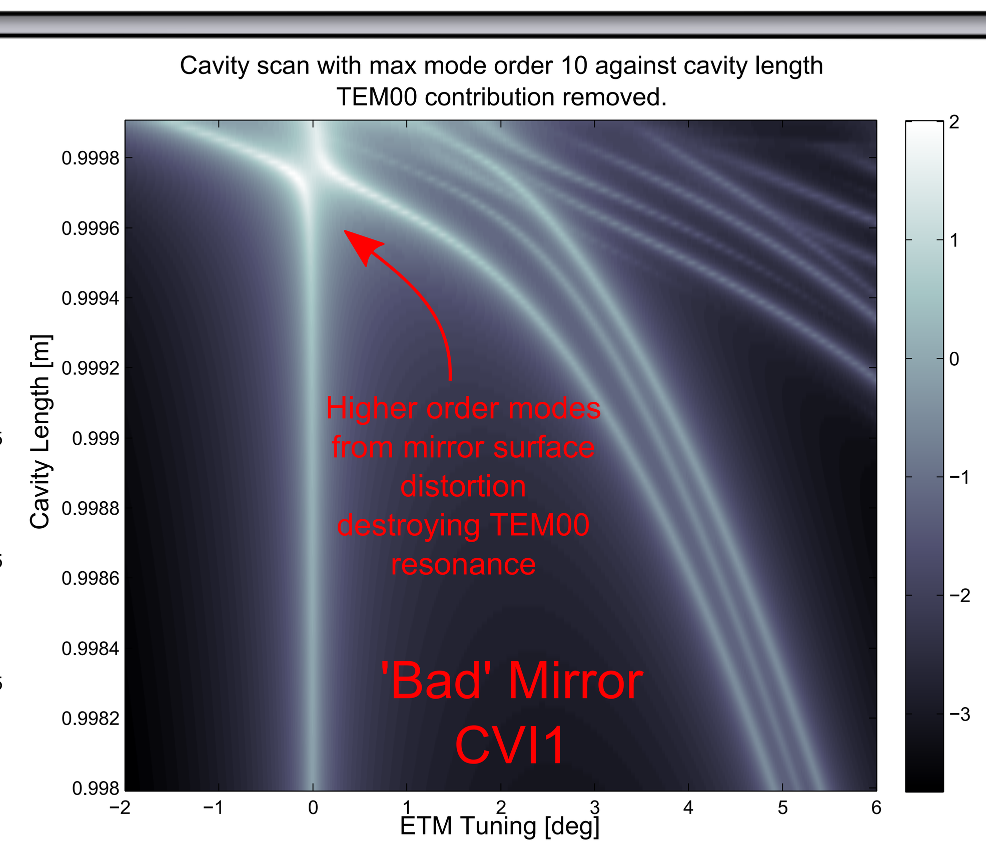
$$u_n(x,z) \propto H_n\left(\frac{x\sqrt{2}}{w(z)}\right) e^{-i\frac{kx^2}{2q(z)}}$$



See K.Strain and A.Freise, Living Reviews lrr-2010-1 [2]



The surface maps measured for both the 'good' and 'bad' mirrors purchased for use in the experiment are used in ***FINESSE*** to compute the maximum cavity length we achieve



It was found that the difference between many of the good and bad mirrors was minimal and likely the differences would not visible in our experiment. One mirror, CVI1, appeared the worst and resulted in greater round trip losses which will likely provide a visible difference.

Conclusion and what next...

If the surface profile of an optic can be measured to a significant accuracy it can be used with ***FINESSE*** to model its expected behaviour, such as error signals. Using such a method we can determine whether a mirrors surface distortions will limit the reachable stability levels due to the HOMs generated in the cavity.

- Finish contruction of experimental setup
- Experimentally measure maximum achieviable finesse and stability for different mirror configurations
- Compare results for validation of map measurement and computation in FINESSE
- Investigate injection of Laguerre-Gaussian beams as potential probe of cavity mirror surfaces

[1] Status of the AEI 10 m prototype, K. Dahl, et.al 2012

[2] Interferometer Techniques for Gravitational-Wave Detection, A. Freise and K. Strain 2010

[3] Frequency-domain interferometer simulation with higher-order spatial modes, A. Freise, et. al. 2004