FINESSE

Numerical Simulations for Optical Design and Comissioning

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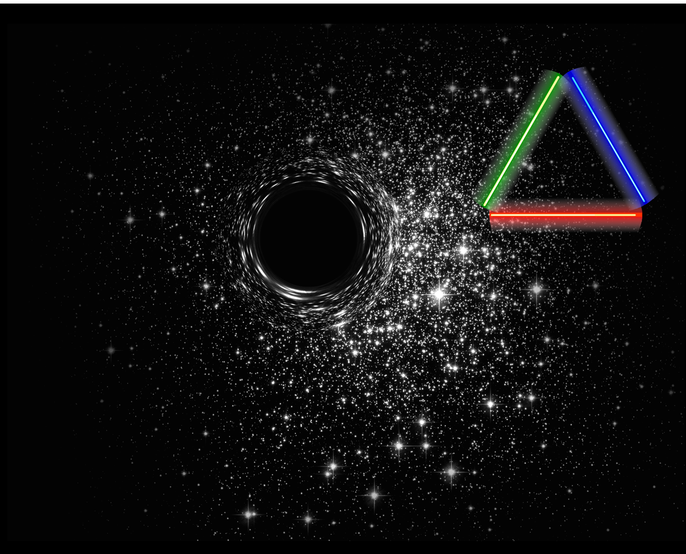
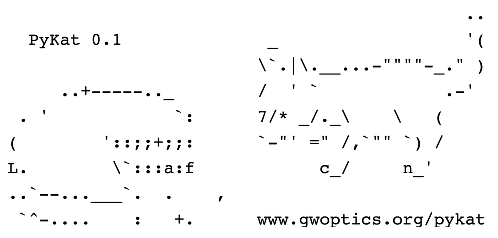


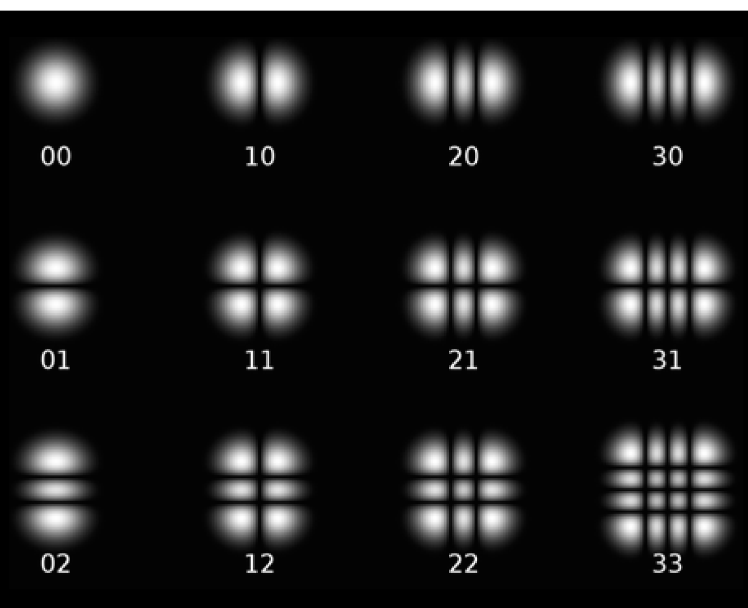
Frequency domain INterfErometer Simulation SoftwarE

Finesse is a frequency domain modelling tool for optical experiments. It is free and open source, released under the GPL license. This poster outlines some tasks that can be modelled by using Finesse and Pykat, with emphasis on the more recent modelling projects.

PyKat

PyKat is a free Python interface and set of tools for running Finesse and for performing stand alone optical calculations. It is specialised for automating advanced optical simulations that involves multiple Finesse runs. Pykat is now our primary Finesse wrapper, taking over the role from MATLAB-based Simtools.





1. Intensity pattern of HG_{mn} modes [1].

Features

As LIGO has developed and new frontiers of physics encountered, FINESSE has also evolved. Amongst its many tools, FINESSE can now simulate:

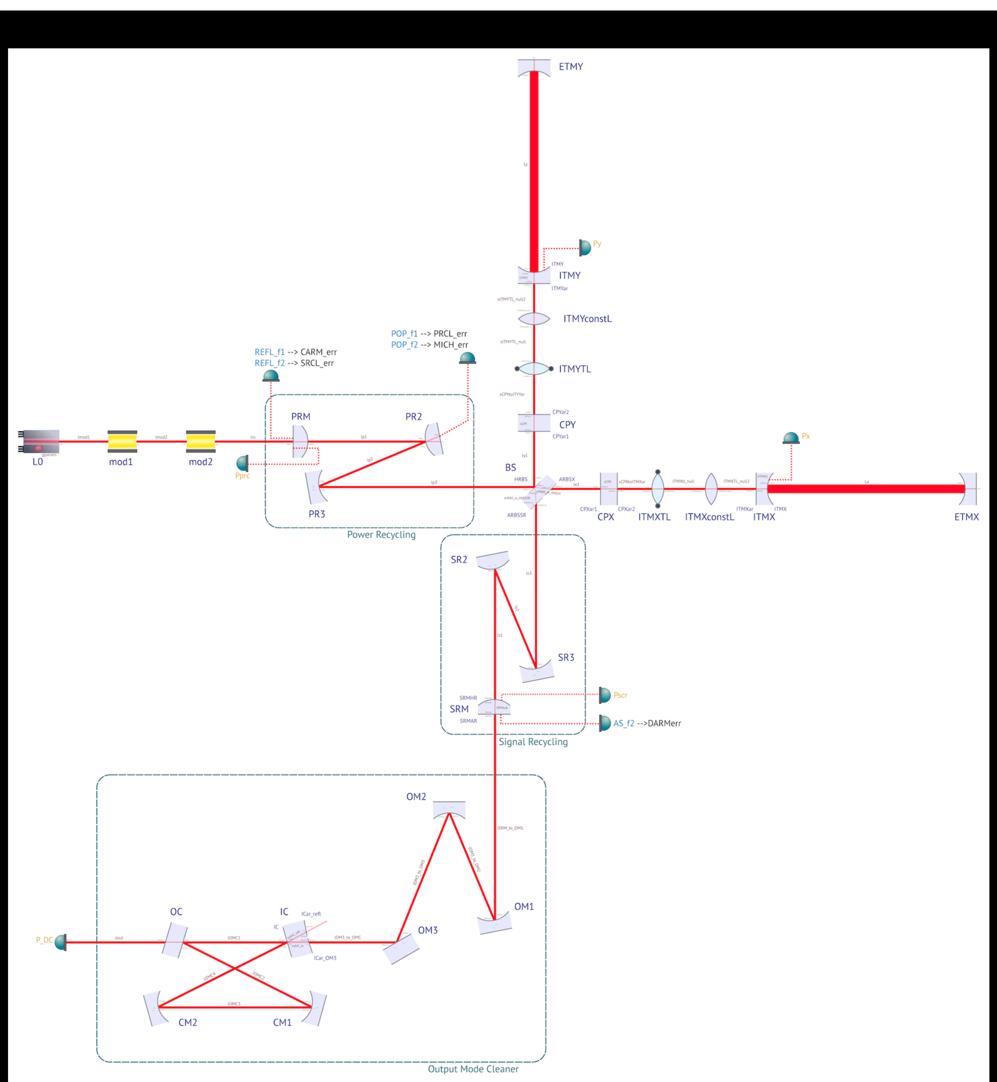
- **Imperfect Beams** - modelling small beam distortions as a perturbative expansion of the beam shape into higher order modes (HOMs). In FINESSE the basis chosen is Hermite-Gauss modes (Figure 1):

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

$$u_n(x,z) \propto H_m\left(\frac{x\sqrt{2}}{w(z)}\right) e^{\frac{-ikx^2}{2q(z)}} e^{\frac{1}{2}i(2m+1)\Psi(z)}$$

$$\Psi(z) = \tan^{-1}\left(\frac{\lambda z}{\pi w_0^2}\right)$$

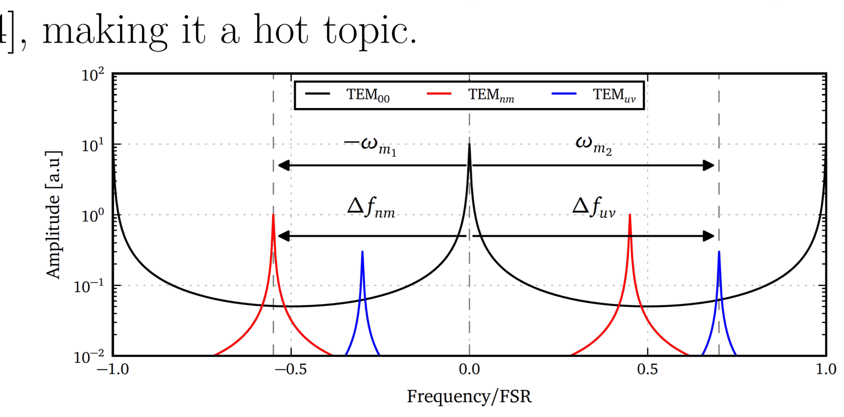
- **Imperfect Optics** - scans of real mirror surfaces are input as 2-dimensional arrays containing phase, transmission or absorption information. FINESSE then integrates over the mirror surface to calculate the scatter into HOMs.
- **Quantum Noise Calculations, including Squeezing** - are described as transformation matrices of the input-output quadratures for each optic. These are combined with classical fields to compute the complete quantum noise covariance matrix, from which the quantum noise at each PD can be found with various demodulations.
- **Radiation Pressure Effects** - Optical Spring effects for longitudinal, yaw, pitch and higher order surface motions, and Parametric Instabilities.
- **Realistic Detectors** such as QPDs and Bullseye sensors



2. representation of a FINESSE file for LLO

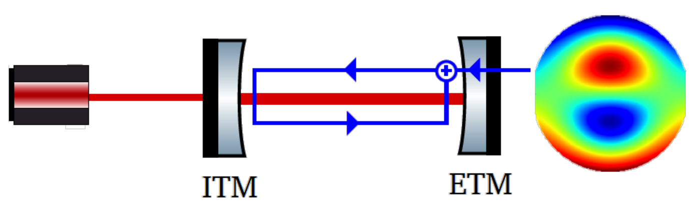
Parametric Instability in Finesse

Parametric instability (PI) is the effect that shows up when a vibrational mode of a mirror scatters the fundamental optical mode, resonating in a cavity, into a HOM with lowered frequency that is also resonant in the same cavity. This is possible when the frequency of the vibration matches the separation frequency of the HOM (see figure 3), and the optical HOM and the vibrational mode spatially overlap. Since the optical frequency is lowered, energy flows from the optical mode to the vibrational mode of the mirror, making the system unstable if the damping in the mirror material is low enough. PI was recently observed in LLO [4], making it a hot topic.



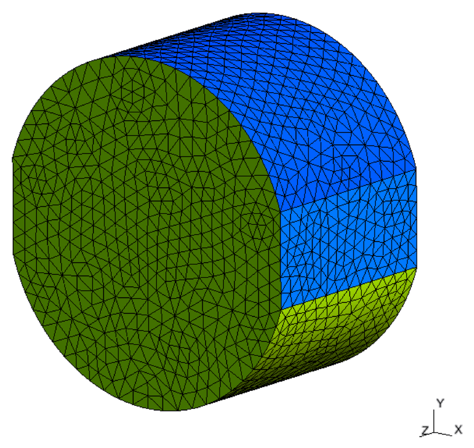
3. The TEM$_{00}$ carrier field (black), a TEM$_{nm}$ mode (red) with separation frequency matching the lower modulation sideband created by the mechanical vibrations, and a TEM$_{\mu,\nu}$ mode (blue) with separation frequency matching the upper modulation sideband. The red peak could cause PI while the blue peak would supress the vibrations.

FINESSE has a feature that, given the vibrational mode of the the mirror and its frequency, calculates the parametric gain $\mathbb{R}$ (PI if $\mathbb{R} > 1$). This feature was tested against the experimental results obtained by Corbitt *et al.* [5]. The test setup can bee seen in figure 4 and was carried through as follows:



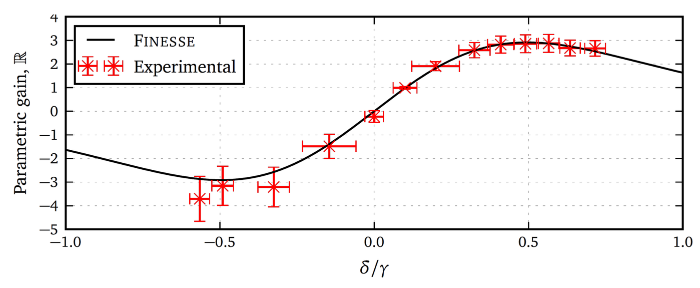
4. The setup used for the Finesse PI tests.

- A 3D model of the mirror was created, discretised into tetrahedrons (see figure 5), the equation of motion connecting the elements was determined, and ultimately the unforced vibrational modes of the system was computed. All these steps was performed in COMSOL.
- The vibrational mode of interest was converted into a mirror map.
- Computed how the vibrational modes of the mirror are excited in presence of a force, here exerted by the radiation pressure. This part was performed in FINESSE by applying the mirror map to one of the cavity mirrors and then extracting the parametric gain from the interferometry matrix.

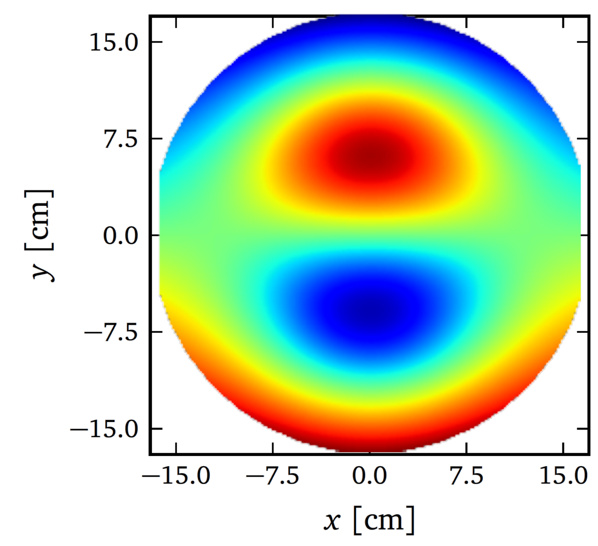


5. Example of a test mass geometry created and discretised in COMSOL.

As seen in figure 6, this test turned out to agree well with the experimental results.

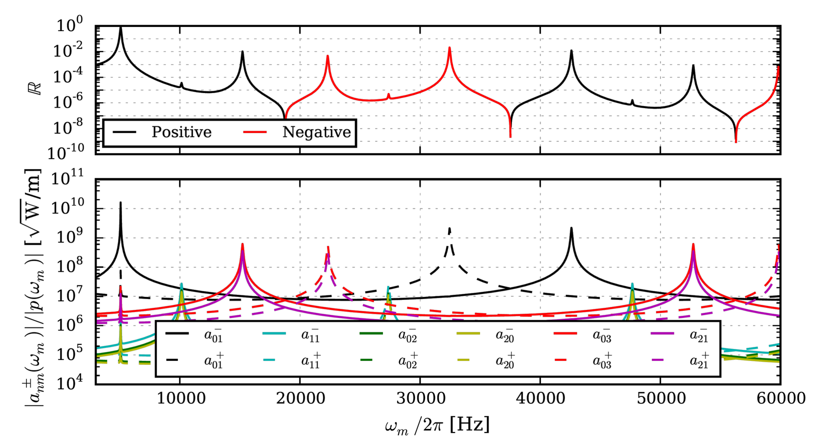


6. Parametric instability in Finesse compared to Corbitt's experiment.



7. The 15.5 kHz mechanical mode thought to cause the PIs recently seen in LLO.

PI has also been modelled for a LIGO arm by using the mechanical mode thought to cause the PI seen in LLO, which is visualised as the mirror map in figure 7. From figure 8 one can see for which vibrational frequencies the system is stable or unstable, as well as which optical modes that are responsible for the PI.

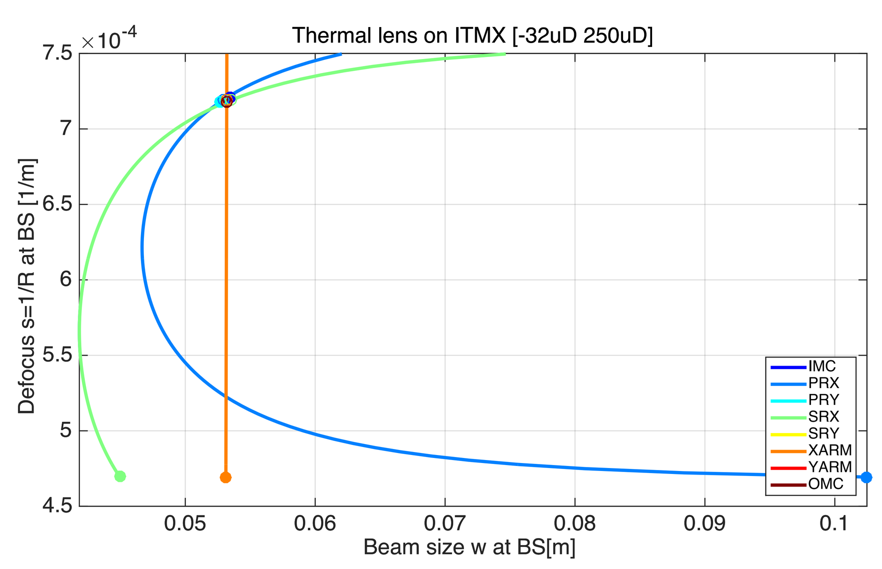


8. Parametric gain in a model LIGO arm for the vibration seen in figure 7

Use in aLIGO Comissioning

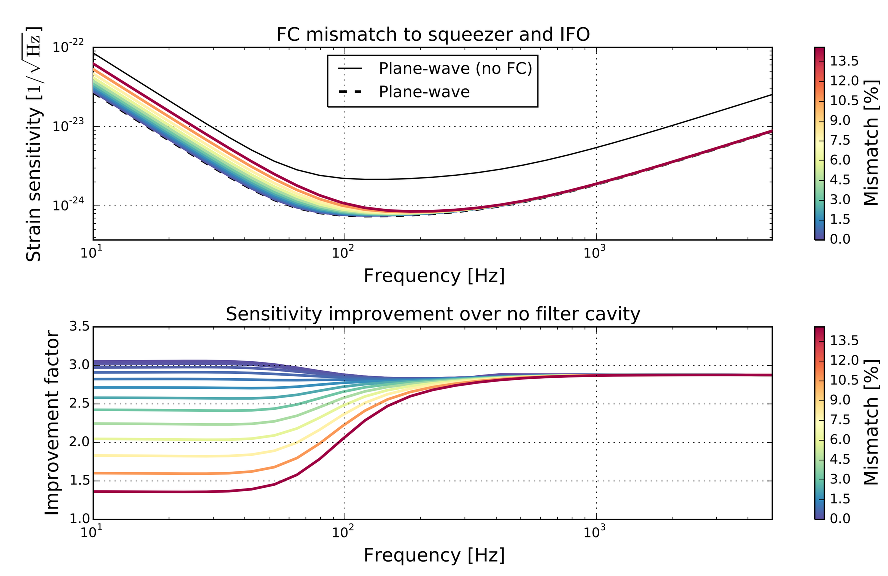
FINESSE is being actively used in aLIGO commissioning modelling. We now have a complete file of the interferometer [2] as in the design documents, as well as variants specific to the Livingston and Hanford sites. These includes the IMC, central IFO and OMC, and the core file is tuned to to the operating point and locked using Pykat to automate much of the process. We are also studying ideas beyond aLIGO: currently our work is focussed on Active Wavefront Control. This has several components:

- Visualising the effect of AWC actuators by studying their effect on beam parameters at the central beam splitter.
- Impact of mode mismatches between different cavities on the quantum noise curve.
- Effect of input mismatch on sensing noise for auxiliary dof.
- Changes to technical noise couplings
- Testing mismatch sensor designs



9. Mode Trajectories on scanning a thermal lens on ITMX [3]

- Starting from the perfectly matched core file, each actuator is scanned in turn and all cavity eigenmodes computed. These are then traced back to the BS and the beam parameters returned.



10. Quantum noise dependance on filter cavity to interferometer/squeezer mismatch [3]

- Here we have looked ahead to aLIGO+, adding a filter cavity based on *M. Evans et.al. Phys. Rev. D 88,022002* to produce frequency-dependent squeezing. There is a clear improvement in sensitivity, which degrades for low frequencies with the mismatch.

Contact us...

FINESSE is open source and can be downloaded from www.gwoptics.org/finesse.

We have regular telecons to discuss our commissioning work. If you are interested, feel free to subscribe to our mailing list aligo-finesse@ligo.org.

References

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[4] M. Evans *et al.*, *Phys. Rev. Lett.* **114**, 161102 (2015)
[5] T. Corbitt *et al. Physical Review A* **74**, 021802 (2006)