FINESSE

Numerical modeling for optical design and detector commissioning

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http://www.gwoptics.org/finesse/

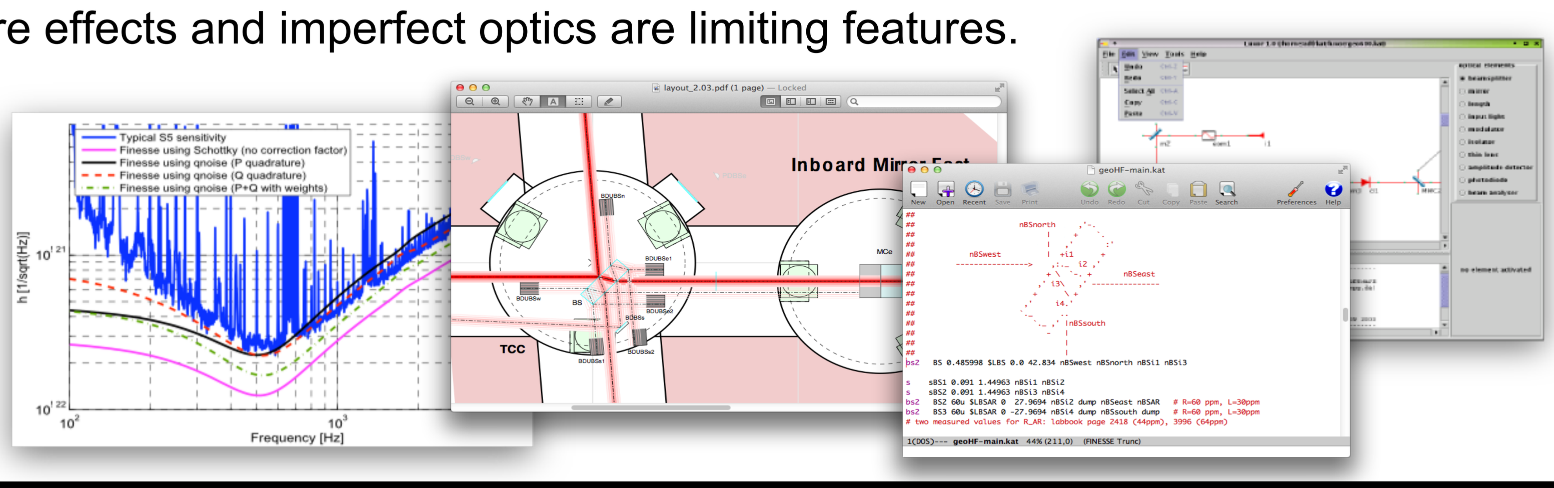
UNIVERSITY OF BIRMINGHAM · LSC · ET EINSTEIN TELESCOPE

Frequency domain INterfErometer Simulation SoftwarE

FINESSE is a free and open source tool for modelling optical experiments in the frequency domain. It is a fast and flexible simulation tool with an intuitive scripting language that runs on all platforms. FINESSE has a strong heritage with roots stemming back to the first generation of high-precision gravitational wave detectors and is actively developed and used worldwide today. FINESSE is the ideal tool for:

- *Designing optical interferometry experiments*
- *Studying how noise couples into optical signals*
- *Computing optical input-output signals*
- *Computing beam deformations due to imperfect optics*
- *Learning how high-precision interferometry experiments work*

This poster outlines the challenges that lie ahead for FINESSE for modelling the next generation of gravitational wave detectors where quantum noise, radiation pressure effects and imperfect optics are limiting features.

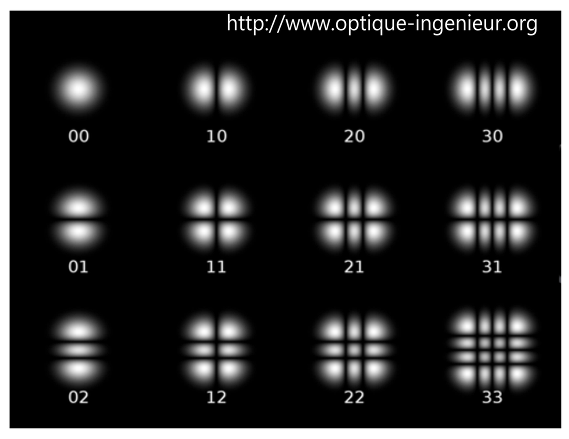


The Modal Model

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. The basis chosen for FINESSE are the Hermite-Gaussian modes.

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

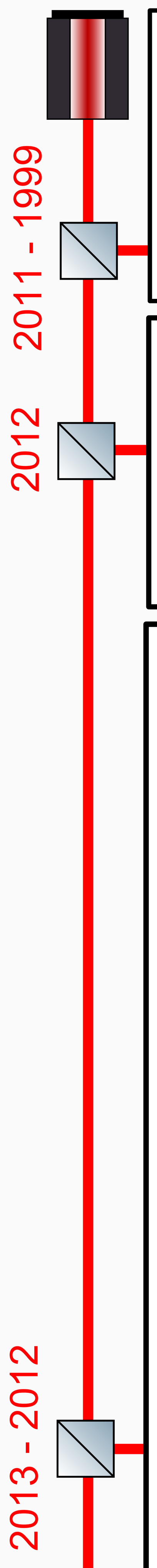
$$u_n(x,z) \propto H_n\left(\frac{x\sqrt{2}}{w(z)}\right) e^{-i\frac{kx^2}{2q(z)}}$$



A.Freise, Living Reviews lrr-2010-1

Testing and Validation

The testing and validating of FINESSE is a high priority. Substantial work is put into comparing FINESSE results to known theory and new experimental results where possible to ensure the code is functioning properly as well as determining numerical limitations and artefacts. FINESSE also undergoes testing against other comparable numerical methods such as FFT based. A nightly test suite also runs the latest development code against several 100 tested scripts, to ensure that during development bugs are caught as early as possible. *D.Brown, LIGO DCC G1200548-v1*



FINESSE was developed out of the need for faster and more flexible simulation software than what was available at the time. Its ease of use and adaptability has led it to be used in all major gravitational wave detector design so far as well as being integrated with many other simulation software.

See Impact History, www.gwoptics.org/finesse/impact.php

FINESSE became open source under the GPL license as of 2012 with the aim of allowing anyone to improve or validate results. To encourage outside participation and manage the project the Redmine management tool has been used to host FINESSE development.

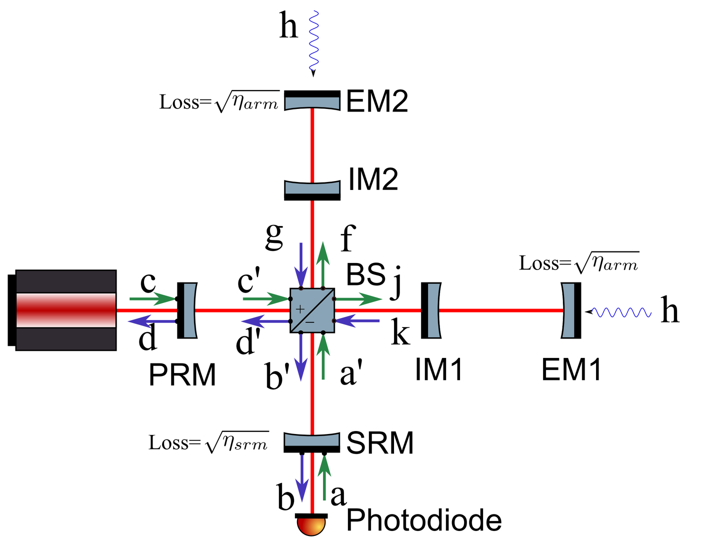
GPL Free as in Freedom · REDMINE flexible project management

D. Brown and A. Freise, www.kvasir.sr.bham.ac.uk/redmine/

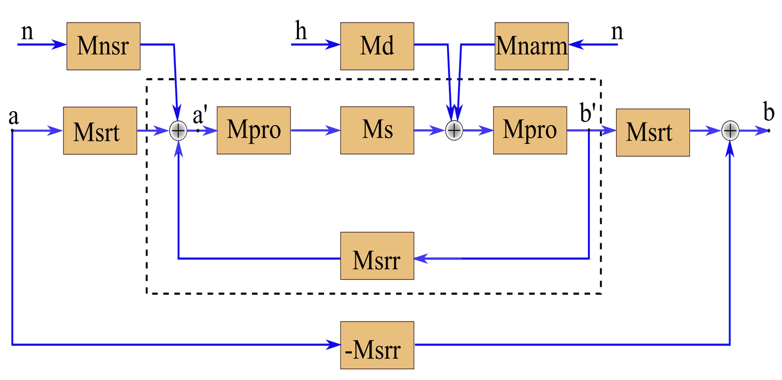
Quantum Noise and Radiation Pressure Effects

Future detectors will be limited by quantum noise and influenced by radiation pressure effects. Thus a simulation tool such as FINESSE with those features will be required.

Quantum noise calculations can be represented by transformation matrices of the input and output quadratures for each optical component. We combine these with classical fields to form a complete input-output system to compute shot noise and radiation pressure noise.



Radiation pressure effects will also change the mechanical response function of suspended mirrors. This will create an optomechanical coupling between the laser and the mirror creating an optical spring, which will in turn create a coupling between the individual optical components in the experiments.

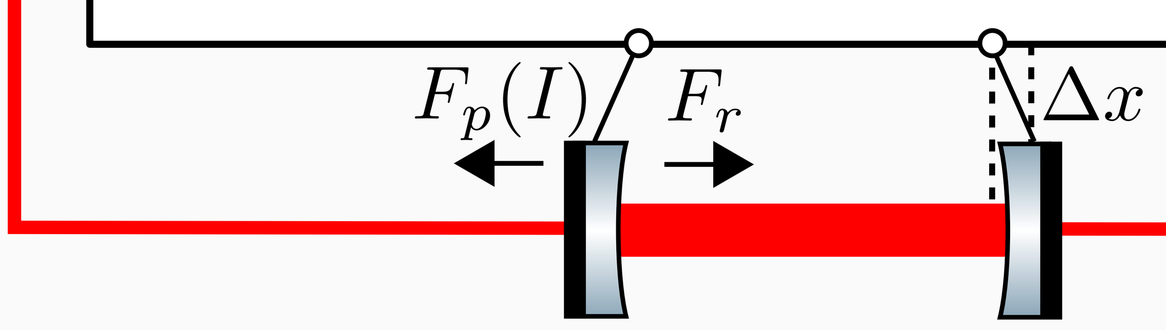


M. Wang

Future detector design will require the design tools to model multiple effects at once, such as: imperfect optics (higher order modes), radiation pressure and quantum noise.

Implementation roadmap for quantum noise and radiation pressure effects into FINESSE:

- Implement longitudinal radiation pressure induced changes to transfer function
- Add user defined suspension transfer function
- Complete matrix implementation for quantum noise quadratures
- Automatically compute optomechanical coupling between all components
- Implement quantum noise computation for: shot noise, radiation noise and squeezed light
- Investigate further effects of torques on mirrors and higher order modes



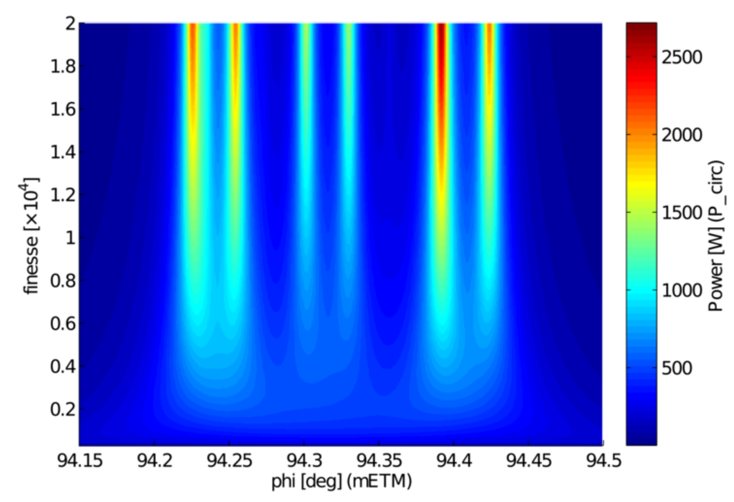
2013 and beyond

Simulating Imperfect Optics

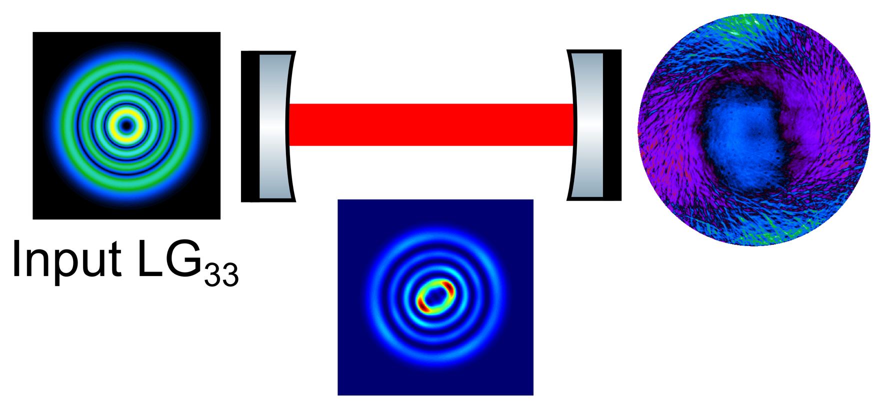
As the modes are a complete orthogonal basis they can be propagated individually through the optical system and summed where required for each frequency component. An imperfect optic will cause an incoming mode nm to couple into an outgoing mode *n'm'* which is described by the coupling coefficient $k_{nmn'm'}$.

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

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 mirrors and simulate their effect on optical setups. This allows us to calculate exact beam shape deformations on reflection and transmission and losses down to parts per million levels that are necessary for future GW detector designs.



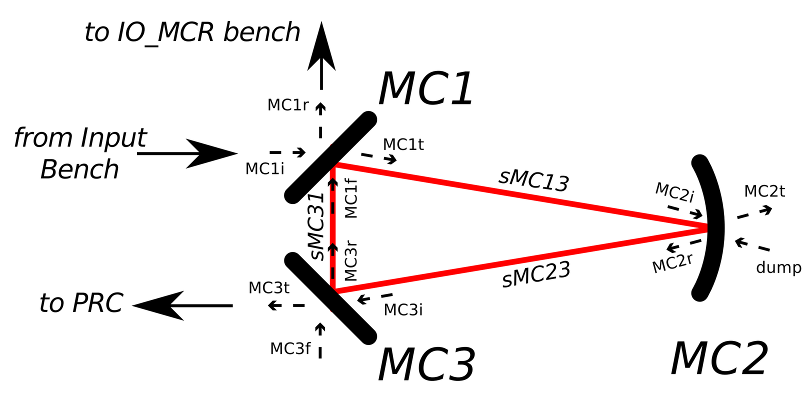
Intracavity power whilst scanning cavity with LG_{33} for different cavity finesse values



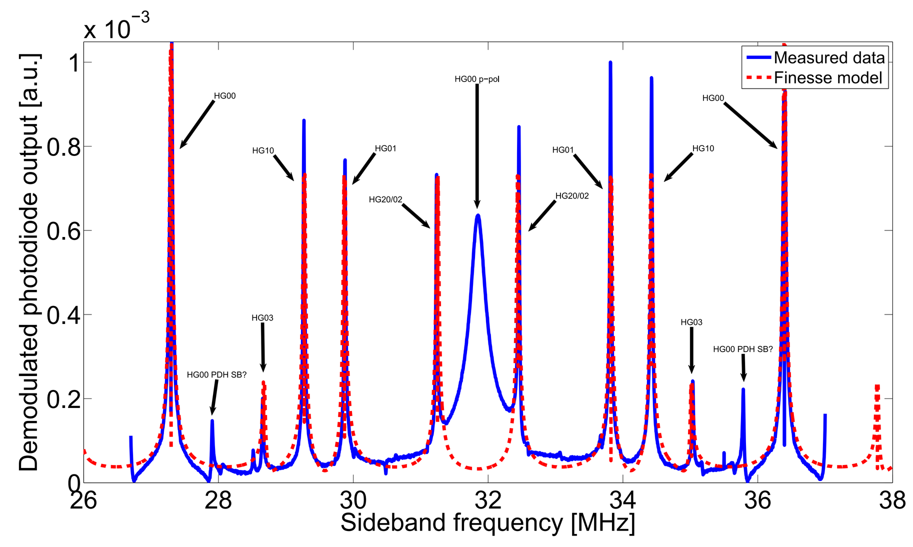
C.Bond, Phys. Rev. D 84, 102002 (2011)

Advanced LIGO Commissioning

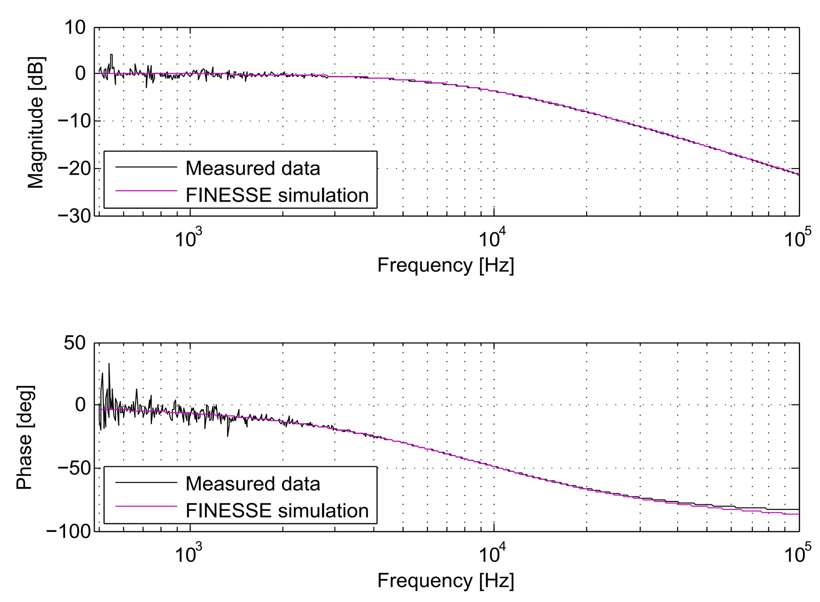
FINESSE is being actively used in the commissioning of the aLIGO input mode cleaner in Livingston. It has and will continue to provide a unique and ideal testing ground for new FINESSE features, such as: imperfect optics, radiation pressure effects, and squeezing. This oppurtunity will ensure that such features will be tested and validated for use in designing and commissioning future detectors such as ET.



aLIGO IMC FINESSE schematic



Cavity scan of IMC showing resonant modes comparing FINESSE simulation to measured data



FINESSE cavity pole calculation of IMC compared with measured data

L.Carbone, P.Fulda, C.Mueller, DCC LIGO-T1200473_v1

Performance Increases

Simulating all these effects at once can become computationally expensive removing one of FINESSEs main benefits, speed. In the future we plan to take advantage of parallel processing such as GPUs and multicore CPUs, as well as investigating smarter algorithms, such as transfer matrix reduction and discrete Hermite transforms.