IUCAA Finesse Workshop and Hackathon

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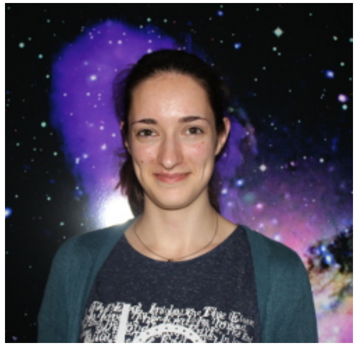
Your Mentors



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NB: Group Redistribution

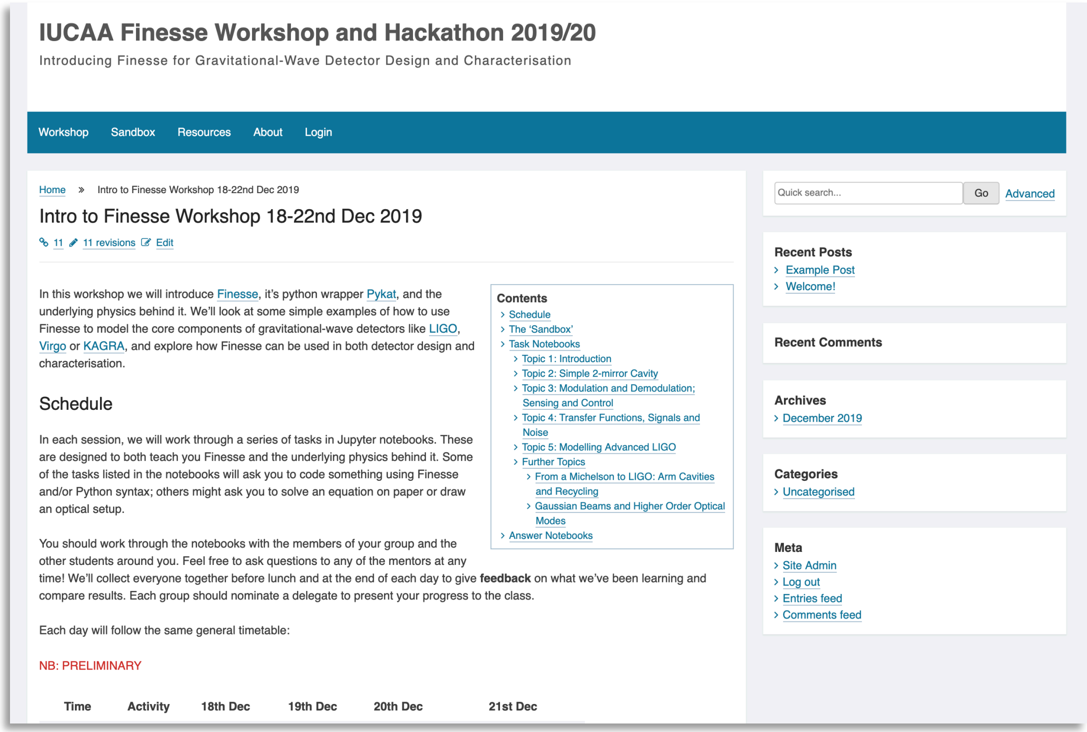
About these sessions

- Program to introduce interferometer modelling
- Now: 4-day workshop on core skills and techniques
- Longer-term: participants encouraged to tackle various modelling tasks towards LIGO-India
- Workshop is **hands-on** and **interactive**
  - Work on your own computers in Jupyter notebooks to learn both physics and modelling topics
  - Work *together* with your group and the others around you
  - Regular breaks to exchange results and report progress
  - Use the 'sandbox' to share common questions/issues
- Workshop goal: a simple model of LIGO!

About these sessions: materials

Main website: ifosim.sr.bham.ac.uk/iucaa2019

- Links for you to download notebooks
  - You should make one folder to store all of these
- Resources page
- ‘Sandbox’ to share questions
  - Via login (see email from Wordpress) – create posts about these simulations
  - First point of contact when you can’t talk to us in person
  - Collect examples that might help others



Why model?

“The beam entering the interferometer is jittering around. How will that affect our sensitivity to gravitational waves?”

“ Using higher power causes the mirrors to distort due to heating. How does this affect our ability to control the detector?”

“We want to swap to a different kind of sensing scheme when we upgrade the detectors. What optical configuration is best?”

Modelling helps us study **complex optical systems** that might be confusing to calculate by hand.

We can use models to **understand behaviours** of existing systems, and **design new** interferometer configurations

Why model LIGO-India?

- 3rd detector in LIGO Observatory network
- Timescale: joining in mid-2020's
- Aim: join the LIGO network with similar sensitivity to the existing detectors at that point
  - i.e. directly build LIGO-India to *upgraded* LIGO (A+) specifications
- Science Goals:
  - Improved source localisation
  - Better network duty cycle
  - Better parameter estimation

Why model LIGO-India?

- Before LIGO-India is build, we can consider design questions e.g.
  - Should we stick to copying aLIGO(A+) exactly or is there a better position for the mirrors or a better set of mirror properties?
  - aLIGO has learnt a lot since it was built, are there changes we could make based on this experience?

- Many ‘commissioning modelling’ tasks for current gravitational wave detectors – LIGO-India will also have these.

Finesse 2

PyKat develop

www.gwoptics.org/pykat

Finesse and PyKat:

What is it for, and (why) should I use it?

With slides adapted from talks by Dan Brown (LIGO-G1300538 and LIGO-G1400580) and Paul Fulda (www.phys.ufl.edu/~pfulda/FinesseTutorial_1.pdf)

What is Finesse 2 ?

- Many types of optical simulation tools:

FFT

- OSCAR

J. Degallaix
www.mathworks.com/matlabcentral/fileexchange/20607-oscar

- SIS (with FOG)

H. Yamamoto / R. Day
dcc-llo.ligo.org/LIGO-T1300942-v2/public

- DarkF

M. Pichot
artemis.oca.eu/fr/rechercheartemis/projets/virgo/2081-the-darkf-optical-simulation-code

Frequency Domain

- Finesse

A. Freise / D. Brown
www.gwoptics.org/finesse

- Optickle

M. Evans
dcc.ligo.org/LIGO-T070260/public

- Phasor

L. McCuller
pydigger.com/pypi/phasor

- MIST

G. Vajente
sourceforge.net/projects/optics-mist/

Gaussian beam propagation, ray tracing

- IFOcad / Optocad

R. Schilling / G. Waner
(on request from AEI)

- JamMT

A. Thuring / N. Lastzka
www.sr.bham.ac.uk/dokuwiki/doku.php?id=geosim:jammt

Time Domain

- E2E

H. Yamamoto
labcit.ligo.caltech.edu/~e2e/

What is Finesse 2 ?

“**F**requency domain **IN**terf**E**rometer **S**imulation **S**oftwar**E**”

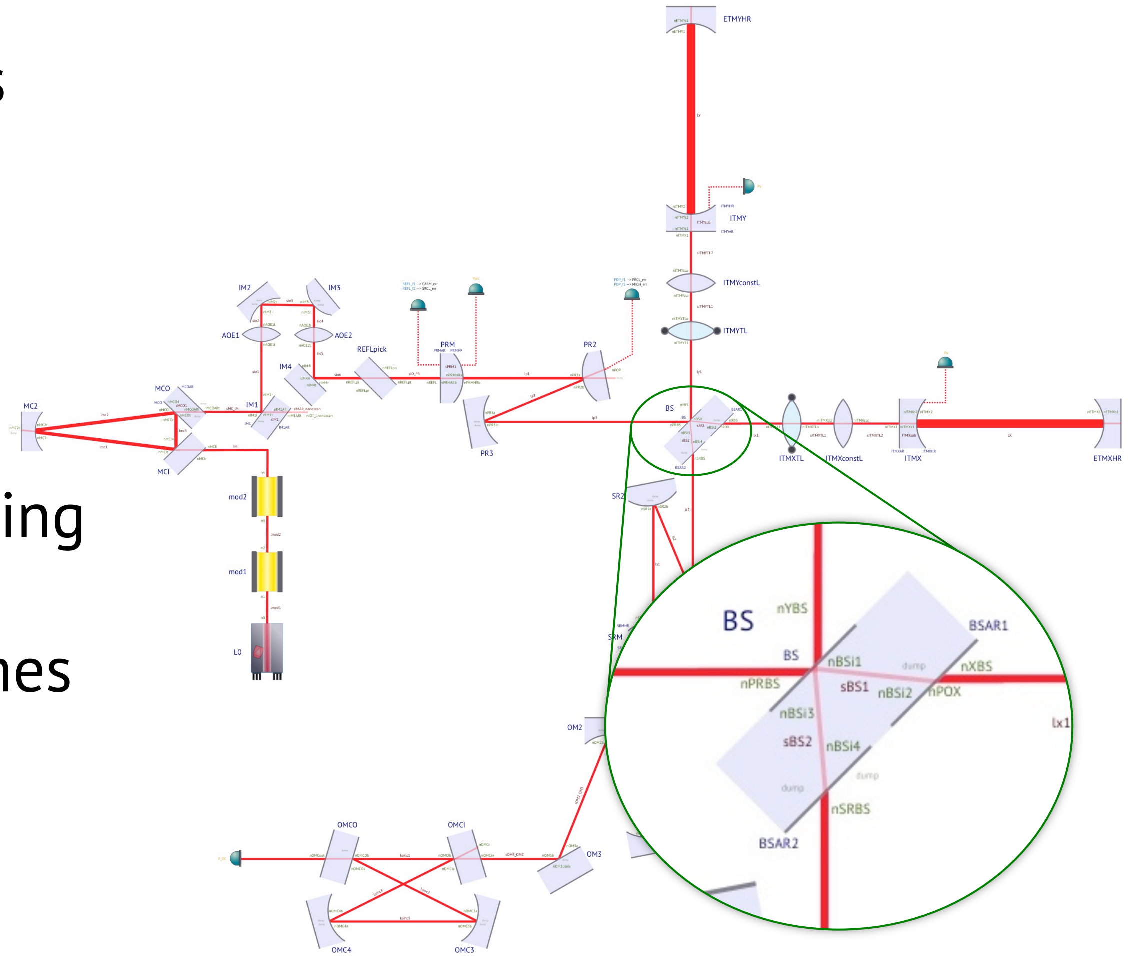
Frequency Domain:
Understand the *steady state* behaviour of an interferometer, noise couplings, error signals,…

Modal Model:
Look at the effects of misalignments, mode mismatch, mirror defects, etc., within the paraxial approximation.

Developed at GEO600 for designing & debugging interferometers

What is Finesse 2 ?

- To understand an optical experiment it’s useful to know the electric field everywhere in the setup
- We can use matrices to describe optical components, which couple fields in different locations together.
- We get a series of linear equations relating all the fields to each other
- Can be done by hand, but quickly becomes tiresome.
- Finesse solves these equations for us numerically!



What is Finesse 2 ?

Eases the pain of trying to solve all the linear equations by hand or your own script
Good tool to learn optics

Good for:

- Computing noise couplings for detector characterisation
- Designing and understanding control signals
- Designing optical readout systems
- Computing optical transfer functions
- Higher order mode couplings (Thermal distortions, misalignments, surface maps)

Not so good for:

- Scattered light simulations
- Non-linear optics, non-static and non-quasi-static setups

Finesse won't build/design an optical setup for you...
It won't do the hard thinking for you either...

How does it work? | User Perspective

```
%% INTERFEROMETER COMPONENTS

l L0 1 0 n1
s s0  1 n1 nbsp1
bs BSP 0.01 0.99 0 45 nbsp1 dump nbsp3 dump

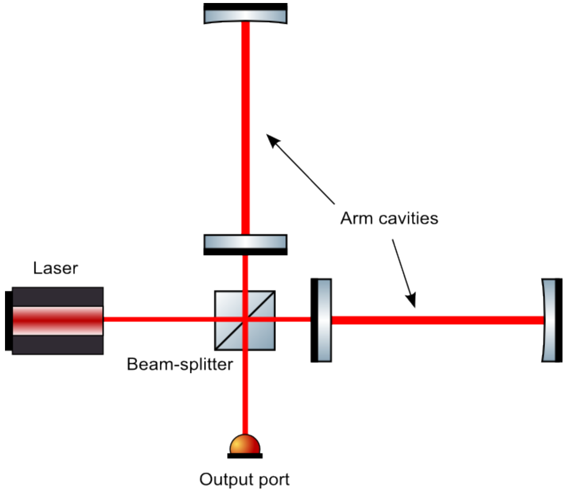
s s01 1 nbsp3 n2

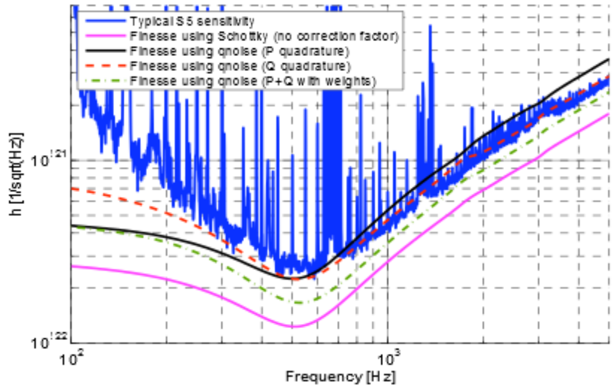
bs BS0 0.5 0.5 59.6 45 n2 n3 n4 n5          # Beam Splitter

const T_ITM 7e-3 # 7000ppm transmission from ET book
const T_ETM 0E-6 # 6ppm transmission from ET book

s sNin  1           n3 n6
m1 IMN $T_ITM 0 0   n6 n7
s sNarm 10000       n7 n8
m1 EMN $T_ETM 0 180 n8 dump

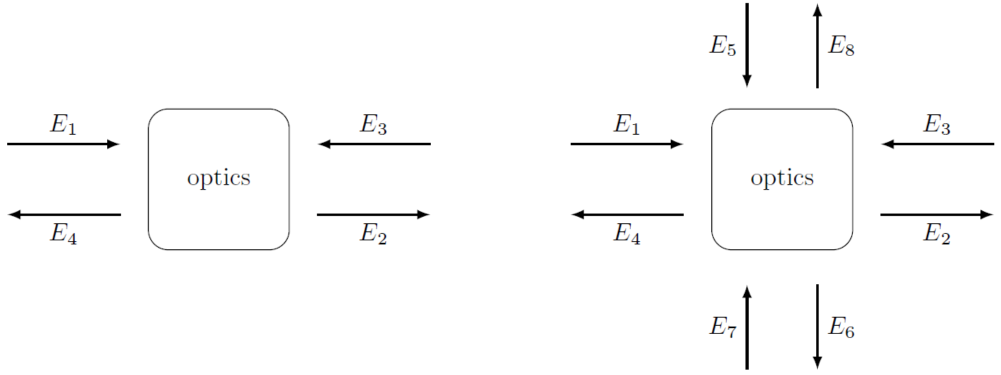
s sWin  1           n4 n9
m1 IMW $T_ITM 0 0   n9 n10
s sWarm 10000       n10 n11
m1 EMW $T_ETM 0 180 n11 dump
```



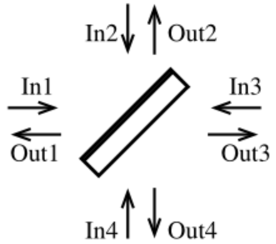


How does it work? | Nodal Network

- Only interested in linear, paraxial, well behaved optics
- Creates a nodal network of components
- From this, knowing the coupling matrix of each component, multiple simultaneous equations are generated
- Solved using a sparse matrix inversion routines

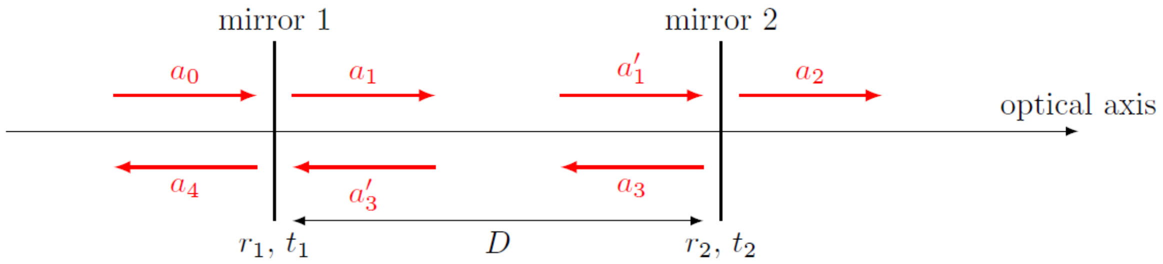


$$\begin{pmatrix} \mathrm{Out1} \\ \mathrm{Out2} \\ \mathrm{Out3} \\ \mathrm{Out4} \end{pmatrix} = \begin{pmatrix} 0 & bs_{21} & bs_{31} & 0 \\ bs_{12} & 0 & 0 & bs_{42} \\ bs_{13} & 0 & 0 & bs_{43} \\ 0 & bs_{24} & bs_{34} & 0 \end{pmatrix} \begin{pmatrix} \mathrm{In1} \\ \mathrm{In2} \\ \mathrm{In3} \\ \mathrm{In4} \end{pmatrix}$$

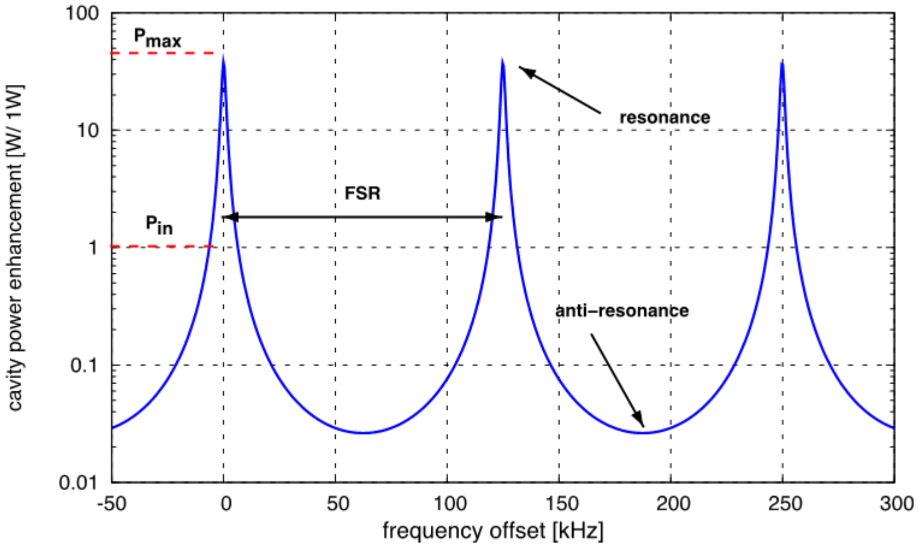


$$\begin{aligned} bs_{12} &= bs_{21} = r\ \exp\left(\mathrm{i}\,2\phi\omega/\omega_0 \cos\alpha\right), \\ bs_{13} &= bs_{31} = \mathrm{i}\,t, \\ bs_{24} &= bs_{42} = \mathrm{i}\,t, \\ bs_{34} &= bs_{43} = r\ \exp\left(-\mathrm{i}\,2\phi\omega/\omega_0 \cos\alpha\right), \end{aligned}$$

How does it work? | Interferometer Matrix



$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\mathrm{i}\,t_1 & 1 & 0 & -r_1 & 0 & 0 & 0 \\ -r_1 & 0 & 1 & -\mathrm{i}\,t_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & -e^{-\mathrm{i}\,kD} \\ 0 & -e^{-\mathrm{i}\,kD} & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\mathrm{i}\,t_2 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & -r_2 & 1 \end{pmatrix} \begin{pmatrix} a_0 \\ a_1 \\ a_4 \\ a'_3 \\ a'_1 \\ a_2 \\ a_3 \end{pmatrix} = \begin{pmatrix} a_0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$



From this we can plot the amplitudes and phases as we change some variable in the system

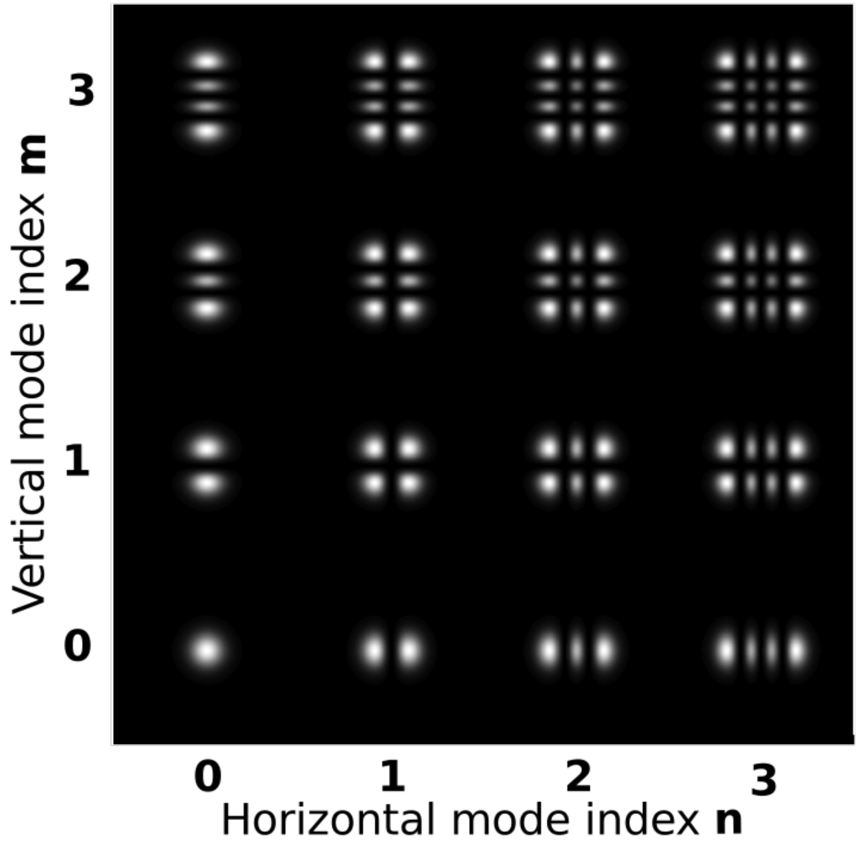
But this is only a plane wave solution!

How does it work? | Modal Model

Finesse can also model the transverse shape of the beam using Gaussian Beams.

Gaussian modes are used to represent perturbations to a perfect beam such as misaligned or distorted optics.

This week we will focus on plane waves models, but you will hear more about this soon.



What can it do?

Finesse can simulate:

- Beam shapes
- Optical losses
- Quantum noise
- Squeezing
- Radiation pressure effects
- Diverse detectors
- Error signals
- Transfer functions

... so long as the model is frequency domain (i.e. static or quasi-static), paraxial, and suits modelling using a modal basis.

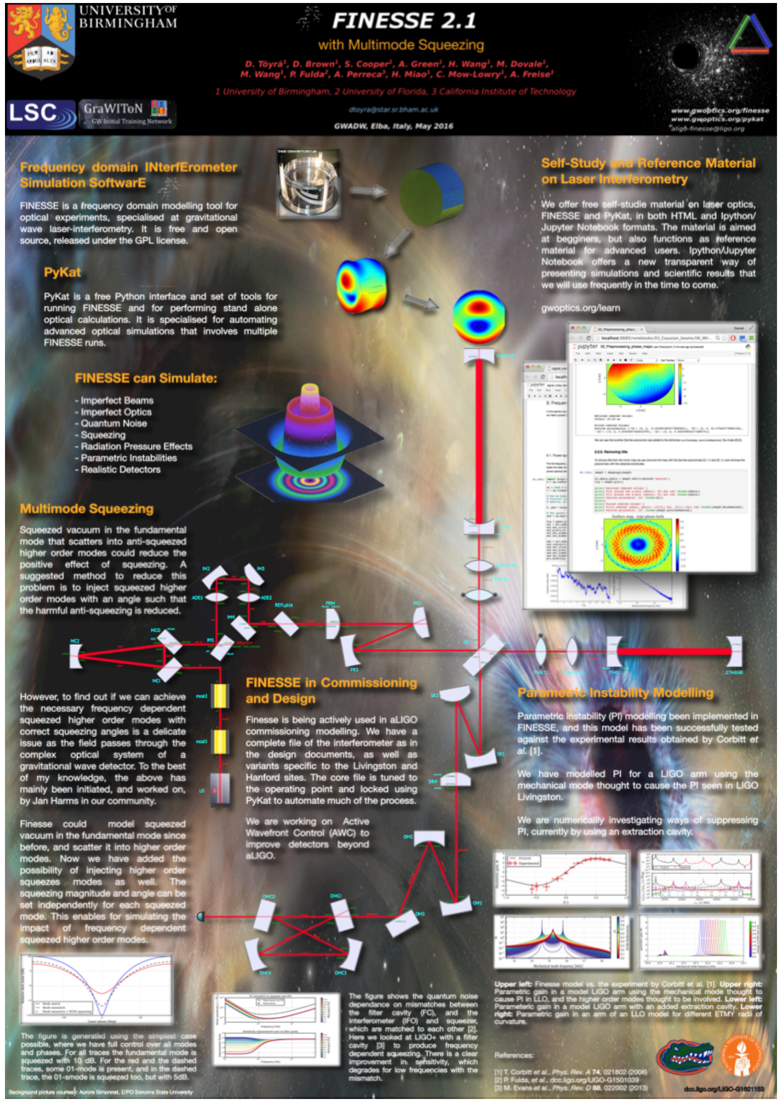


Image: 'Finesse 2.1' poster by D. Töyrä, LIGO-G1601153

What is PyKat?

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 ..`--...___`.  .     ,
  `^-....____:   +.                   www.gwoptics.org/pykat
```

- Finesse can be used stand-alone, with workflow
    1. Write `myfile.kat` file, in Finese syntax, to make a specific plot.
    2. run `kat myfile.kat` in the terminal (produces many output files)
    3. display the plot through e.g. gnuplot, matlab, python,…
    4. Edit/duplicate and edit `myfile.kat` to plot something else or change a parameter in the optical setup
    5. Repeat 2-4 as required.

- Fine for getting started / quick models, but inefficient longer term

- Pykat is a **python wrapper** for Finesse that allows this process to become more efficient and flexible (and also contains many other handy modelling features).

- It's been in constant development as people make and add their own tools

What is PyKat?

```
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  PyKat develop                   _                '(
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   ..`--...___`.   .    ,
    `^-....____:    +.            www.gwoptics.org/pykat
```

- Typical workflows:
  - Use a jupyter notebook. Write Finesse syntax, parse it to Finesse using pykat, and plot the result directly in the notebook. Edit the finesse code to meet your needs as you go.
  - Write python scripts to automate particular Finesse plots or processes (e.g. tuning a Michelson to a dark fringe)
  - Use a static `.kat` file to store a reference optical setup (e.g. LIGO), then play with parameters using pykat in notebooks or scripts

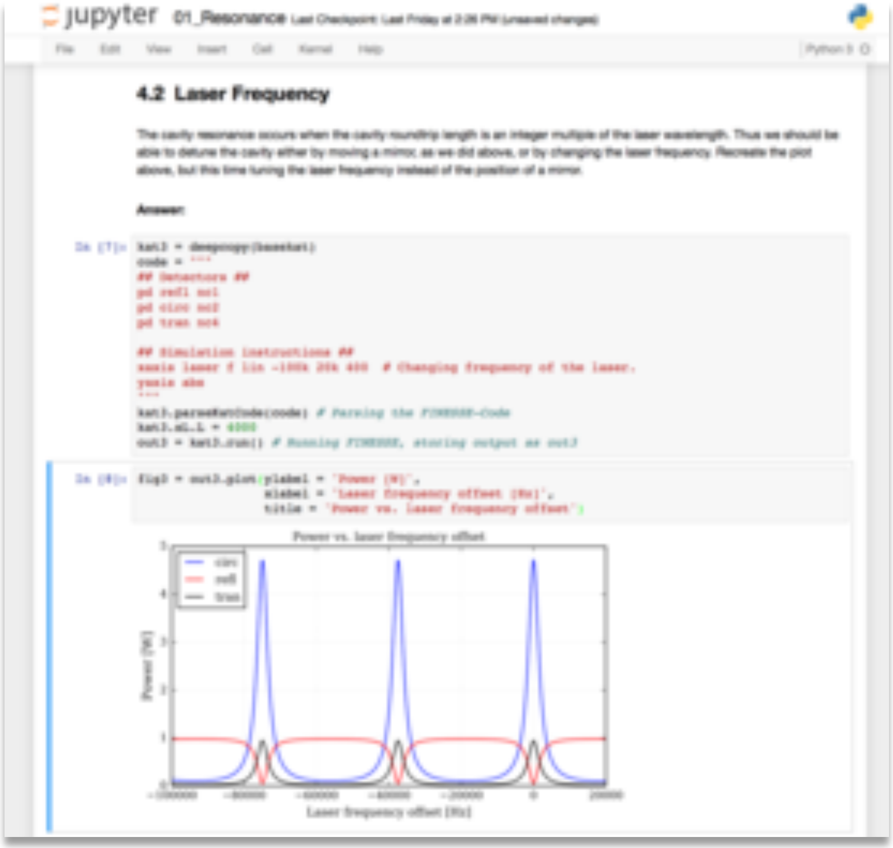


Image source: https://www.gwoptics.org/pykat/

What is PyKat?

1997	Prof. Andreas Freise starts Finesse as a side project during his PhD
2006	Simtools started (Matlab utility functions for optical simulations & using Finesse)
2012	Finesse made open source
2013	Finesse 1.0 released PyKat started (python wrapper for Finesse, replaces Simtools)
2014	Finesse 2.0 released - now models radiation pressure effects and quantum noise
	PyKat released
2015	Simtools *no longer updated.*
2019	Finesse 3 in development

Other parts of the Finesse 'ecosystem'

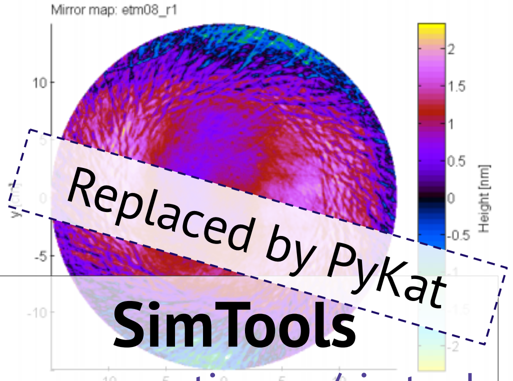
- Various other tools available that directly work with, or complement, Finesse simulations

- Functionality of some can now be found, or replicated in, PyKat

New version in development (S. Leavey, AEI)

Luxor

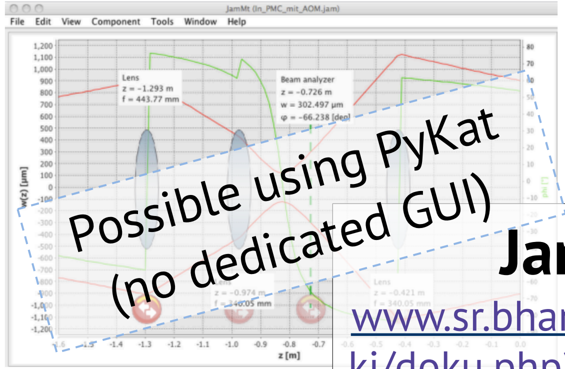
www.gwoptics.org/finesse/luxor.php



Replaced by PyKat

SimTools

www.gwoptics.org/simtools/



Possible using PyKat (no dedicated GUI)

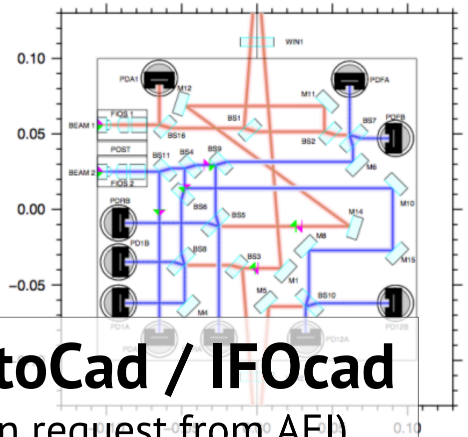
JamMT

www.sr.bham.ac.uk/dokuwiki/doku.php?id=geosim:jammt

Python version integrated into PyKat (WIP)

Oscar

www.mathworks.com/matlabcentral/fileexchange/20607-oscar



OptoCad / IFOcad

(on request from AEI)

Finesse 3.0 – coming soon…

- Started late 2017
- Rebuilding Finesse entirely – python based
- Should still be usable in the ways you are familiar, but with new ‘Pro’ mode with additional functionality
- Merge and extend the functionality available using Finesse 2 / PyKat combination
- New features e.g. electronic signals (i.e. realistic control loops), multiple carrier field frequencies, maybe polarisation, …
- Developers: Dan Brown (Adelaide), Andreas Freise, Phil Jones, Sam Rowlinson (Birmingham), Sean Leavey (AEI), and others
- Updates: LVC members only at the moment (it’s early days!)
    - IFOsim working group calls/emails
    - finesse_development chat channel on LIGO mattermost

Today:

- Getting familiar with Finesse, PyKat and Jupyter notebooks
- Learning the base physics behind Finesse
- Goal: Modelling a 2-mirror cavity

Leader: Phil Jones