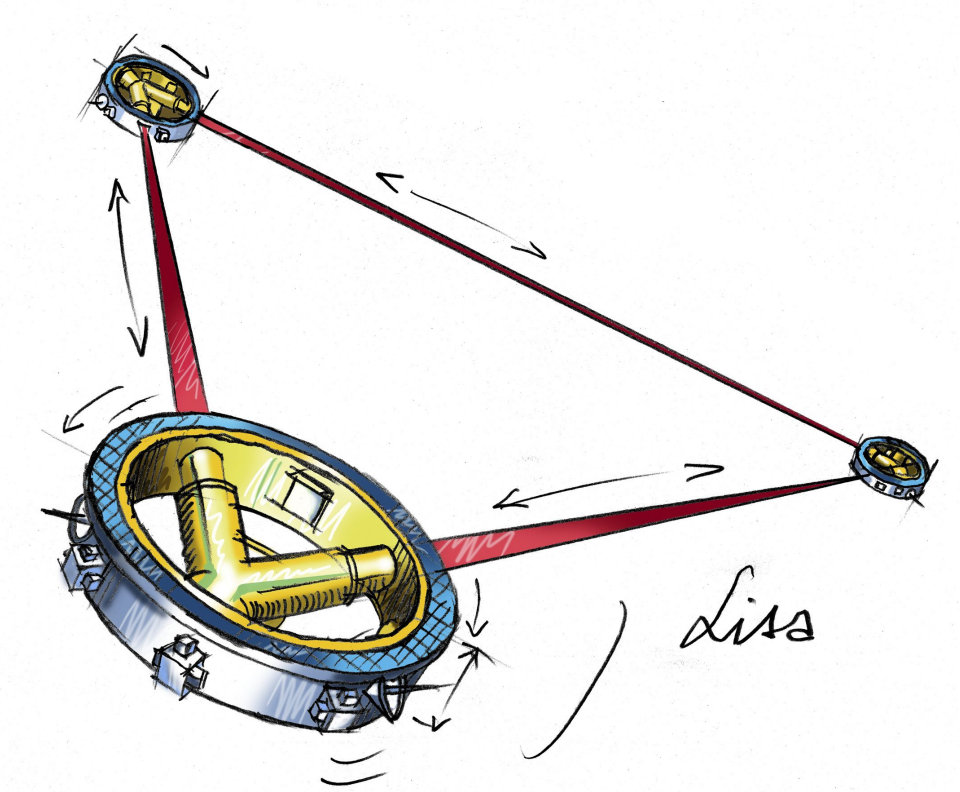


Interferometry

David Colling, Alie Craplet and lots of other people.

October 2021

1 Introduction

The interferometry experiment is an opportunity to build your own instrument with the components that we give you. Each couple have their own set set of apparatus and nobody else will touch your experiment during this lab cycle (only the computer you use will be shared with another group). We have tried to be slightly less prescriptive than in other second year labs so as to give you a chance to think about things and learn by yourself.

You will find that the lab script becomes less prescriptive as it goes along and that the tasks suggest things that you might try rather than telling you what to do. We have also made the later tasks more open ended to give you more freedom to think and investigate how you see fit. If you are stuck then remember that you have demonstrators to chat to about your ideas, but do talk in your pairs first. Because of this approach you will be assessed on what you achieve rather than what you have failed to do. So it is better to do some of it well than all of it badly. Remember also this lab focuses on the most conceptual side of things. It is therefore important to take the time to understand the concepts behind the results, make sure you understand what you are doing rather than rush the data taking.

We have also introduced a computational element to the lab as this allows you to explore different aspects of the experiment. This has been requested by previous generations of students.

The experiment will be conducted over a 4-week lab cycle. In general, you should prioritise experimental work in lab and make the simulations and computational analysis whilst your data is being taken. You are strongly encouraged to interact with your demonstrators as much as possible. They will be more than happy to talk to you and answer your questions. It is recommended however that you take a few breaks each lab session as it is impossible to concentrate for 3 hours at a time in a lab.

This lab is quite demanding and you are encouraged to familiarise yourself with the different pieces of code and any new theoretical concept between lab sessions. The programs used on the later tasks are relatively convoluted, it is important for you to understand how they are working in order to save yourself some time and obtain correct data samples. As always, record everything in your lab book, draw graphs and print important plots, it will help you later. Finally, it could be handy to come up with a naming system for the runs you will be taking.

1.1 Aims

The aims of the experiment are:

1. To understand the operation of a Michelson interferometer as a spectrometer;
2. To be able to construct a Michelson interferometer;
3. To record interferograms using sources with a variety of spectral composition;
4. To simulate the interferogram of a given source;
5. To use these interferograms to describe the spectra of the sources quantitatively;
6. To use a known monochromatic source to correct a systematic error.

1.2 Safety

This experiment involves lasers, very bright and hot light sources. Do not point the laser towards yours or any other person's eyes. The Hg light sources that you will be using also emit a lot of their light in the UV part of the spectrum so you must use UV protective goggles when you are using them. The mercury lamps tend to get very hot after some time, make sure not to burn yourself and always switch off every source of light at the end of the sessions. When in doubt ask a demonstrator.

1.3 Materials

The components you will be using are fragile and expensive, please be careful with them. Do not try to de-assemble any of the items, especially not the beam-splitters.

Remember that having fingerprints on lenses or mirror will greatly impact the quality of your data, if you notice one of your components to be dirty please see a demonstrator who will clean it for you.

1.4 Assessment

At the end of the four-week experiment cycle you are required to write a "report" on a topic of your choice. As you know, this year the "report" willbe different in different cycles. In week 4 you should discuss and agree with your demonstrator what should be in your report. If you feel uncertain about what is required, keep asking questions!

2 The Michelson Interferometer

2.1 Structure of the Michelson Interferometer

The layout of a Michelson interferometer is shown in Figure 1 below. Light is emitted from the source and is split into two beams by a partially-silvered mirror ('beamsplitter'). The reflected beam (A) travels to a mirror (M1), and the transmitted beam (B) travels to another mirror (M2). Both beams are reflected at their respective mirrors, and upon returning undergo a partial reflection and recombination at the beamsplitter.

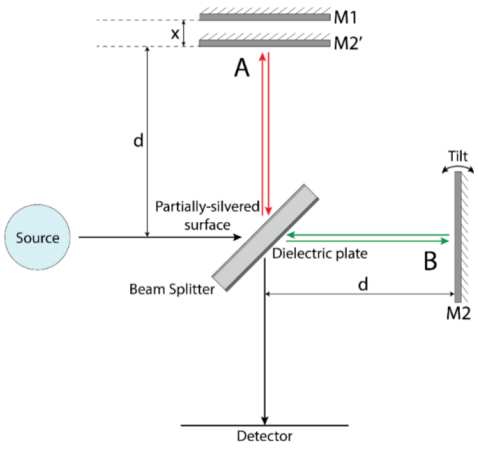


Figure 1: A diagram of the Michelson interferometer setup.

Consider monochromatic plane waves (of wavelength λ and uniform wavevector $\mathbf{k}$) emitted from the source. Plane waves recombining at the beamsplitter will interfere, and the type of interference will be determined by the path difference of the two beams. If the distance from the beamsplitter to M1 is exactly the same as the distance from the beamsplitter to mirror M2, then

we may expect these two beams to constructively interfere giving a bright plane wave output.

Alternatively, if the distances travelled by beams A and B differ by exactly $\frac{\lambda}{2}$ we might expect the two beams to destructively interfere, leading to no light being incident on the detector. The Michelson interferometer is therefore an extraordinarily precise ruler: moving mirror M1 or mirror M2 by a fraction of a wavelength makes the difference between a bright fringe appearing on the detector or a dark fringe appearing there.

The dielectric plate on one side of the beamsplitter causes a phase change for one of the beams. This means that destructive interference occurs at zero path difference, resulting in a dark fringe, instead of the expected bright output. See the Optics course for more informations.

2.1.1 Types of Visible Fringes

The nature of the fringes seen when looking into a Michelson interferometer depends on how you set up the instrument and on how you illuminate it. On the one hand, the two end mirrors may or may not be exactly at right angles to each other, and you may either send collimated light into it (parallel rays coming from infinity, i.e. plane waves) or you may use an extended source.

Consider first using an extended source and setting the mirrors at right angles to each other. A convenient construction, sketched in Figure 2, makes drawing ray diagrams easier. Referring first to Figure 1, looking into the instrument, mirror M2 appears to be at the position of M2'.

If the arms differ in length by t, an observer imagines seeing the light originating from an extended source (behind him/herself) being reflected from two mirrors separated by this distance t (see Figure 2). In this fictitious construction the mirror nearest to the eye appears both to let the light travelling to the far mirror through unimpeded and also reflect it!

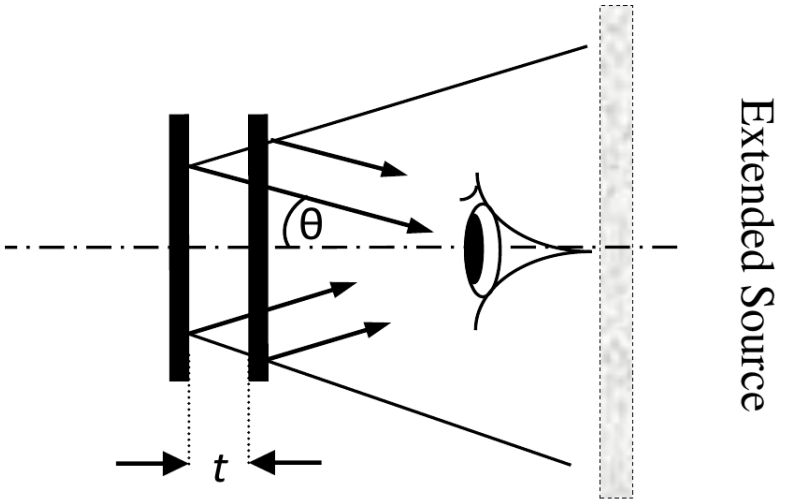


Figure 2: Simplified model of a Michelson interferometer to facilitate the drawing of ray diagrams.

We can use this construction to see what happens if we choose either to tilt slightly one of the mirrors or to leave it 'correctly' aligned (see Figure 3). In both cases we imagine light coming from an extended source so that the angle deg of the incoming rays will vary. Now rays of wavelength λ reinforce each other at angles which make the optical path difference between consecutive rays an integral number of wavelengths, so that constructive interference will only occur for specific values of θ. The cylindrical symmetry of the situation in Figure 3a suggests that the so-called Haidinger fringes will appear to be circular. The cylindrical symmetry is broken by tilting one mirror, so that so-called Fizeau fringes form straight lines.

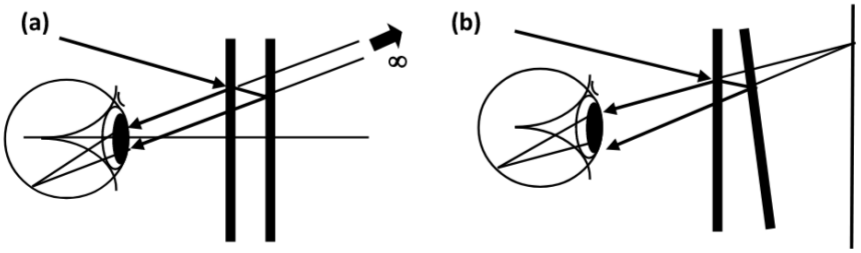


Figure 3: (a) Haidinger fringes of equal inclination appear to be at infinity. (b) Fizeau fringes of equal thickness appear to be close to the mirrors.

Task 1 - Pre-lab task
The equation governing the angle θ in Figure 3 is:

$$2t\cos\theta = m\lambda \tag{1}$$

In this equation t is the separation and m is known as the order of interference and it is assumed that the refractive index of the medium is 1. Derive this equation in your lab-book.

So, for an extended monochromatic light source a pattern of concentric circular fringes can be observed, with their bright maxima conforming to integral values of m in equation 1.

2.2 Using the interferometer as a spectrometer

We now return to considering the simpler case of sending a collimated beam (plane waves) into the input port and ask how the instrument can be used as a spectrometer. The trick is to scan the instrument about the setting where t=0 (called the null point) by slowly moving one of the mirrors.

For a single monochromatic wave the output is just a series of bright and dark fringes which can be recorded electronically. In frequency space, a monochromatic wave is simply a spike or delta function.

What happens if the light we send into the instrument consists of two distinct frequencies (see Figure 4)? The sequence of bright and dark fringes (interferogram) is modulated and the separation between the nulls in the interferogram is related to the separation of the two frequencies in frequency space. The relationship is a reciprocal one – the closer the two frequencies are to each other, the further separated are the nulls in the interferogram. To see how this occurs consider Figure 5.

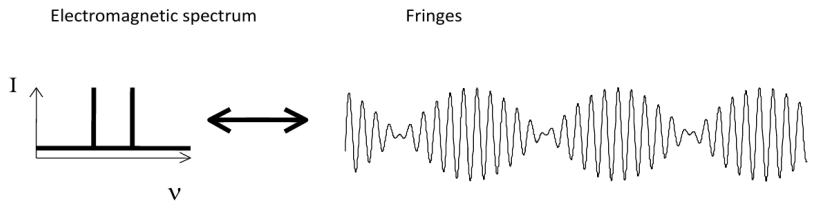


Figure 4: A simple electromagnetic spectrum and its resulting interferogram.

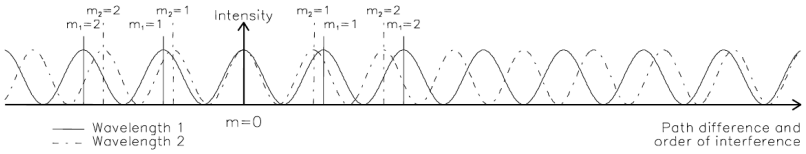


Figure 5: As t is scanned two waves of different λ get out of phase leading to a diminution of the contrast of the fringes. In due course the waves re-phase and the contrast is restored. The pattern repeats as t is scanned further.

We imagine initially setting up the interferometer with exactly equal arm lengths ($m = 0$). Then we monitor the output as we scan one mirror. If we were to 'filter out' one wavelength we would observe the usual sinusoidal fringes (i.e. either the solid line or the dashed one). The actual output seen is the sum of the two intensity distributions shown. Notice in Figure 5 that the length of the fringe train shown is such that as one moves away from the zero path difference point ($m = 0$) the fringes formed by the longer of the two wavelengths are almost beginning to 'catch up' with the fringes formed by the shorter wavelength. When that happens (when the two fringe patterns are in phase) the overall fringe pattern is more or less the same as it is at zero order; but this is only true at that point when there are only two wavelengths. If there are other wavelengths present their fringe patterns will not be in phase at that point.

Task 2 - Pre-lab task

Note also that when there are only two wavelengths, the contrast will be a minimum when the pattern from one is exactly out of phase with the pattern from the other. In the case of plane waves (i.e. when $\cos\theta = 1$), the required condition is: -

$$2nt = m_1\lambda_1 = (m_1 + 1/2)\lambda_2 \tag{2}$$

(where $\lambda_1 > \lambda_2$.)
Show that, for n=1, we have:

$$(\lambda_1 - \lambda_2) = \lambda_2\lambda_1/4t = \lambda^2/4t \tag{3}$$

(if $(\lambda_1 - \lambda_2)$ is small).

A rigorous treatment for a source with an arbitrary spectrum involves the mathematics of Fourier Transforms. While the mathematics can be quite involved, the basic ideas of Fourier theory are straightforward and very compelling. **If you have not yet covered this in lectures get your demonstrator to give you a brief introduction to Fourier Transforms**.

The spectral line shape of a lamp is approximately Gaussian, i.e. $I(\nu) \propto \exp[-\frac{(\nu-\nu_0)^2}{2\sigma^2}]$, where ν_0 is the line centre and σ is the width. **Discuss with your demonstrator why this should be the case.** An interesting result of Fourier theory is that a Gaussian spectral feature leads to a Gaussian temporal feature (interferogram) – see Figure 6.

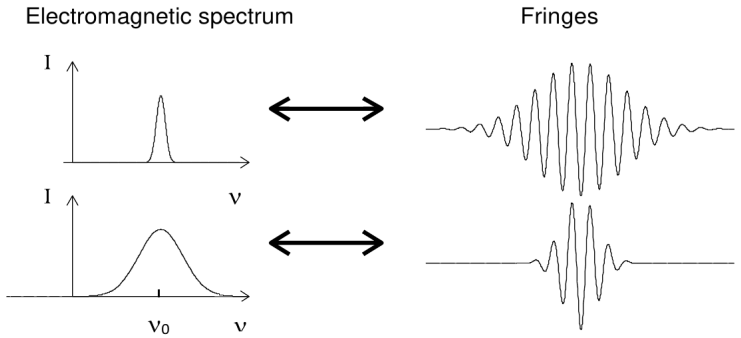


Figure 6: A narrow Gaussian spectral line leads to a wider Gaussian interferogram. The broader the spectral line the narrower the interferogram.

Complicated spectra produce complicated interferograms that require the use of a computer to perform the Fourier Transform.

2.3 Some technical terms

Spectral line: Narrow spectral features are called 'lines' because of the shape they make on a screen when using a conventional spectrometer – i.e. an image of the slit.

Spectral width: The spectral width of a source is a measure of the range of frequencies emitted by the source or, when referring to a single spectral line, the width of that line.

Spectral width of a filter: The spectral width of a filter, often called its "bandwidth", is a measure of the range of frequencies passed by the filter.

Coherence length: The spectral quality of a light source is often described by quoting its 'coherence length'. Practically speaking, for a given light source, this is a measure of the distance over which one arm of a Michelson interferometer can be scanned before the interferogram contrast becomes poor.

Fourier Transform Spectrometer: When a Michelson interferometer is used to perform spectroscopy it is called a Fourier Transform Spectrometer (FTS).

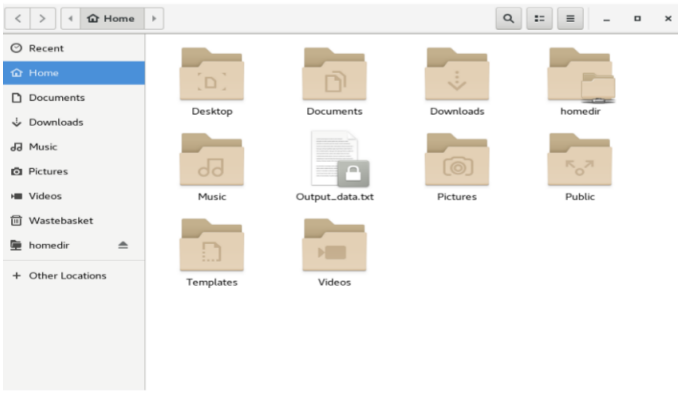
3 Quick Introduction to Linux

3.1 Basics

For this lab you will be using computers that are running the Linux operating system. I know that most of you will not be familiar with Linux, however it is the operating system in which most scientific computing is performed and so it is good that you become familiar with it. It is free but the license is such that you can take the free distribution, modify to suite yourselves and then charge for what results. This is exactly what Apple does.

You should log on with your normal college username and password. At that point you should see a screen that looks like:

If you click on Home you will see the home directory that you have on this machine. It will look like this:



Just as on windows everything is transient except your college home directory, this is your H: drive on windows and the directory called homedir on Linux. So anything that you want to keep needs to be stored in that directory.

In Linux you can do most things through "clicky pointy" interfaces but the command prompt (called a terminal) is a very powerful and useful interface that you will need to use during this lab. If you move your mouse pointer to the top left corner of your screen you will see a selection of applications and you can choose to launch a terminal. In a terminal you can do many things. I was going to write a guide to Linux commands but there are so many on the web already so you can look at any of:

https://files.fosswire.com/2007/08/fwunixref.pdf
https://www.dummies.com/computers/operating-systems/linux/common-linux-commands/
https://www-uxsup.csx.cam.ac.uk/pub/doc/suse/suse9.0/userguide-9.0/ch24s04.html

or a great many others.

The most regular commands that you will use are (just try them and see what happens):

- ls – (short for "list") this lists the files in your current directory
- ls *tt* – files in your current directory bearing 'tt' in their file name
- pwd – (short for "print working directory") tells you what directory you are in
- cd – (short for "change directory") changes the directory that you are in

- mv – (short for "move") renames or moves a file
- cp – (short for "copy") copies a file
- rm – (short for "remove") removes/deletes the file
- mkdir – (short for "make directory") creates a new directory

so for example if you are in your home directory on the computer and wanted to create a directory on your college home directory called interferometry you would type:

mkdir homedir/interferometry

If you then wanted move to that directory you would type:

cd homedir/interferometry

If you just type "cd" you will move to your home directory on that computer.

If you want rename a file or directory you would type:

mv old_name new_name

Similarly if you want to copy a file:

cp original_file copy_file

These all these have options associated with them that you look up either using the "man" command (short for "manual") for the instructions or google.

Simulating the experiment

You will be asked to simulate the experiments that you will perform. You will be asked to download to programs inter.py, quick_plot.py,read_data_results3.py and analysis.py from Blackboard. When you download them they will be downloaded into your Downloads directory. I suggest that you move them to somewhere on your college home directory before editing them so that they

are safe and not just transient.

Taking Data

When you come to start taking data you will need to connect the micro controller board to the PC. This in turn can take data from two separate photodetectors and controls the movement of the mirror on the stage.

The mirror on the stage is moved by a stepper motor. Inside the stepper motor there are 200 steps for a complete revolution. Each step itself is made up of 256 μsteps. The drive shaft from the motor then drives a gear box which has a reduction ratio of 100:1, this in turn rotates a micrometer which requires two revolutions to move 1mm. The micrometer then pushes a lever arm that moves the mirror and has a reduction ratio of 6.25:1.

To take data from the experiment you need to start a terminal and use the "mm" command which has four arguments, something like:

mm 1000000 30000 /dev/ttyUSB0

The first argument is the position to which you want to move the stage in μsteps, the second is the rate at which the stage will move in μsteps/s and the third is detector serial address. By default the detector samples at 50Hz. This default should work well but it is possible to change this using an optional fourth calling arguement. If you think that you have a good reason to change it then discuss it with your demonstrator.

It should produce a file called Output_data.txt This file will be overwritten next time you the program so you should rename it if you want to keep it. For example:

mv Output_data.txt my_meaningfully_named_file.txt

If you want to stop a run before is it finished, use the Ctrl+C command in the terminal, this will stop the data sampling. Make sure to open the file and delete the last line of data (which is usually incomplete) before saving your file. Otherwise the program will have difficulties analysis the run later.

There are 5 columns in Output_data.txt. The first is the reading on the first detector, the second is the reading on the second detector (or 0 if it is not connected), the third is number of seconds this epoch, the fourth is the number of microseconds this second and the fifth is where the stage thinks it is when the measurement was taken. You can plot these using quick_plot.py.

4 Simulating the Michelson Interferometer

You should download the program *inter.py* from blackboard and look at it as you read this description. You should note that the unit of length used in this simulation is metre.

When you build and run your Michelson interferometer you will move one mirror (M1) at a constant velocity and sample the intensity of light at the detector. M1 is driven by a stepper motor. Imagine that this motor has a minimum step of 20nm, which corresponds to a change in t of 40nm - do you understand why? These were actually the specifications of the previous stepper motor used on this experiment but they are as good as any for the purpose of the simulation. This should result in an interferogram evenly samples in t.

In your simulation you will set up an array of points corresponding to the different to the different t values (in the example code below this is the variable x). You will then set the intensity at each of these t values to be zero i.e. there is no light in the system. The intensity corresponds to the variable y in the example code below. So the code will look something like:

```
'''
 When you perform the actual experiment you will move
 one mirror to change the path difference.
'''
'''
Change these to set up the experiment
'''
nsamp=340000 #number of samples that you will take (set in
                                    the software)
dsamp=40.e-9 #path difference between samples


# set the starting point from null point
dstart= -3e-3 # start -3mm from null point

epoint=dstart+dsamp*nsamp

x= np.linspace(dstart,epoint,nsamp) #setting the x locations
                                    of the samples

y=np.zeros(shape=[len(x)]) #setting the array that will
                                    contain your results
```

So at this point you have an interferometer with no light going through. So the next stage is to add a light source. We have provided two functions

that can add light sources: one that simulates a Gaussian light source and another that simulates a "top hat" or square light source.

An infinitely narrow line would give a sinusoidal interferogram that would go on forever. These functions approximate a source of finite width by a series of infinitesimally narrow lines. Figure 7 shows a Gaussian spectral line with a mean $\lambda = 565nm$ and width $\sigma = 2nm$ being approximated by 50 infinitesimally narrow lines (over 5σ).

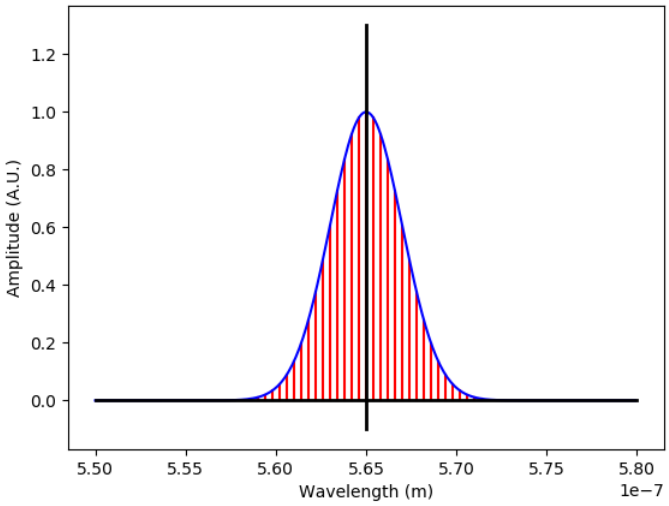


Figure 7: A Gaussian spectral line of finite width can be approximated by a series of (in this case 50) infinitesimally narrow lines (over 5σ).

The link between this approach and the interferogram being a Fourier transform of the original spectrum should be obvious. However, we are sampling at discrete intervals rather than through a continuous integral and this can introduce non-physical effects into your simulated interferograms.

The function that can add a Gaussian line to your spectrum is:

```
def add_line(x,y,wl,amp,width,nstep):
    """
    This little function adds the effect
    of a a new line on to the interferogram.
    It does this by assuming that each line is made up of
                                    lots of descrete delta
                                    functions. Also assumes a
                                    gausian line shape
    and calculates to +/- 5 sigma
```

```
    x is the separation between the mirrors
    y is the amplitude of the light
    wl is the wavelength
    amp is the amplitude (arbitrary scale)
    width is the line width (actually 1 sigma as we assume
                                gaussian)
    nsteps is the number of discrete lines used
    """
```

The amplitude (amp) is arbitrary in scale and only meaningful if you have two or more lines with different intensities. Hopefully, the desciptions in the code make the other calling arguements pretty clear, if they are not then ask a demonstrator.

We have already said that the interferogram is the Fourier transform of the original spectrum. However, this is not the spectrum in terms of wavelength, λ, but rather *wavenumber*, $\tilde{\nu} = \frac{1}{\lambda}$ so some manipulation is required to turn this into a wavelength spectrum. So inter.py has the the following code to do this and display the results:

```
# take a fourier transform
yf=spf.fft(y)
xf=spf.fftfreq(nsamp) # setting the correct x-axis for the
                            fourier transform.
                            Osciallations/step

#now some shifts to make plotting easier (google if
                            ineterested)
xf=spf.fftshift(xf)
yf=spf.fftshift(yf)


pl.figure(2)
pl.plot(xf,np.abs(yf))
pl.xlabel("Oscillations per sample")
pl.ylabel("Amplitude")


# Now try to reconstruct the original wavelength spectrum
# only take the positive part of the FT
# need to go from oscillations per step to steps per
                            oscillation
# time the step size


xx=xf[int(len(xf)/2+1):len(xf)]
repx=dsamp/xx

pl.figure(3)
```

```
pl.plot(repx,abs(yf[int(len(xf)/2+1):len(xf)]))
pl.xlabel("Wavelength (m)")
pl.ylabel("Amplitude")
```

Task 3

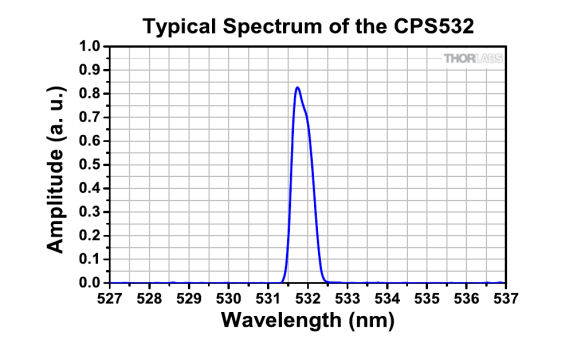


Figure 8: Green laser wavelength distribution from the Thorlabs data sheet.

When performing these two tasks you should concentrate on their conceptual aspects and use numbers that are approximately correct rather than worrying about the detailed numbers.

Task 3a
Figure 8 shows the spectrum of the laser that you will first use when you build your interferometer. Even though the spectrum is clearly not really Gaussian, approximate it by a Gaussian and add it to your simulation to see what you would expect to see in your interferometer.

Task 3b
Experience has shown that not all the lasers we have are actually monochromatic (despite what it says in the catalogue). In quite a few this single line is actually made of two lines which are very close to each other with a similar width. Simulate this situation with lines separated by about 0.7nm. Then see how the interferomgram changes as you vary the width and separation of these lines. You could try adding extra lines.

Task 3c
Experiment with different with different distances between data points and different lengths of run to see what difference it makes to your re-

constructed spectrum. Try googling the Nyqist theorem to help you understand your results.

The function that simulates a square light source will be described later in the script.

5 Building the Interferometer

5.1 Construction

Important notes:

- The mirrors are front surfaced. You should avoid touching them or clean them after touching them.
- Do not re-align the base of the linear stage.
- Do not remove the motor from the linear stage.
- Do not dissemble any component

Task 4
Start off by constructing an interferometer using the parts provided.

Task 5
Aligning the interferometer is one of the most important aspects of building an interferometer. If you get this right you will collect some lovely data, get it wrong and at best you will collect some ropy data and some parts of the experiments may not work at all.

Use the green laser to align the interferometer; how would you make sure the laser beam is level and parallel to the table's surface? Using the magnetic ruler and tubing provided might help. Once the laser is in place, adjust the tilt of one of the mirrors in order to have the laser spots from the two arms of the interferometer directly on top of each other at the output plane.

You will see the beginnings of fringes when they are directly on top of each other, although you will see the fringes more clearly if you use

two lenses – one to expand the laser beam into a broadened source and another to image to lasers onto the card.

Adjust the tilts of the mirrors so that you see both types of fringes – making notes in your lab book as you go.

6 Taking first data and analysing it

Now you have reached the stage of taking your first data and examining it. In order to do this you need to install the photodetector at the output of the interferometer and connect it to the PC. The photodetector is actually a photodiode attached to an amplifier with a variable gain and then fed out through a 24 bit ADC. You can change the gain of the amplifier by adjusting the knob on the front of the detector. The maximum gain is when the arrow is pointing straight down and gradually comes down as you turn it anti clockwise. By default this samples the signal at a rate of 50Hz. Once you have done this try moving the stage and taking some data with the lid off the light proof box. Adjust the gain to an appropriate level.

Task 6
Using the laser as the source take an interferogram by moving the mirror a few mm and recording the data. Decide the rate at which you move the mirror based on your simulations.
Task 6a Look at your data using quick_plot.py by typing "quick_plot.py my_file_name.txt"

Task 6b Calculate how far the mirror should move per μstep and then how many μsteps it should take to move the mirror such that the interferogram moves from one peak to the next.

Task 6c Having worked out how many μsteps it should take you now should compare this with the actual number. There are a number of ways that you can do this. Perhaps one of the most direct is to remove the "DC offset" from the data that you have taken and then see the points where the line crosses the zero line. The program callibrate.py does just this. It uses a high pass filter to effectively make the signal AC coupled. This program will then analyse the distance between

crossing points.
Task 6c - this can be done outside of lab time. Use the code in callibrate.py, inter.py and the real value for how far the mirror moves in a μstep to write your own program that makes a fourier transform of your data. When you do this does it look like you would expect it to look for a laser? You might want to discuss this with your demonstrator.

7 Simulating different light sources

You have already simulated a laser. Now you should try simulating different light sources. Even though they may not be Gaussian you can approximate them to a Gaussian. Later you will take data of a white light with a filter infront of it. The width of the filter is 10nm. However, different filters differ and some result in an approximately Gaussian distribution of wavelengths and others much more like "top hat" functions. So in inter.py we have the fuction:

```
def add_square(x,y,start,amp,width,nstep):
```

where x and y are the same as in the add_line function, start is the starting (lowest) wavelength of your top hat function, width is how wide your top hat is and, just as in add_line nstep is the number of lines that will be used in the approximation.

Task 7

- Use a Gaussian to simulate a white light source (make reasonable guesses for the central wavelength and the width.
- Simulate a broad light source that is coming through a filter (i.e. assume that the light source is flat for the region that is allowed through the filter). Simulate the interferogram that you will get if resulting wavelength distribution is a Gaussian and if it is a square function (remember that the Fourier transform of a square function is a sinc function (i.e. of the form $\frac{\sin x}{x}$)[a] Try varying the width of the filter and see how this effects your interferograms.

[a] If the top hat function has a width of l in wavenumber space (remember that

wavenumber is $\frac{1}{\lambda}$) the Fourier transform is of of the form $\frac{\sin(x\frac{l}{2})}{x(\frac{l}{2})}$. If when you record the interferogram from your white light with filter it looks like a sinc function you can use this to measure the width of the filter.

Now you need to compare this to what you see in the data and the first part of this is to find the null point where the two path lengths exactly match. Equation 1

Task 8 Finding the null point.

First make sure that the null point is within the range of the movement of your stage by measuring both arms of the interferometer. There are a number of different ways that you can try to find the null point and you will find 3 described below. Ultimately, you will use Method 1, however we suggest that you use either Method 2 or 3 to get you close to the null point first as otherwise this is a slow and long process. Method 2 and 3 can be more quickly achieved by disengaging the the stepper motor from the micrometer head. The methods are:

1. Scanning through the entire range of the stage with the white LED as a source. You will only see interference very close to the null point. So that this doesn't take too long you might want to move the stage at a faster rate. The coherence length of the white LED is about $10\mu m$ and so you can calculate the maximum speed that the stage can travel and still see any interference. Once you have spotted the rough position of the null point. Go back and scan through it slowly. Make sure that you look (with your eyes rather than the detector) at the interference pattern that you see.

2. Method 1. works but can be very slow and pains taking. You can get very close indeed using the Haidinger fringes and the laser. If you consider equation 1 for these fringes you will see that changing t changes the angle at which the fringes appear. This means that the number of fringes in your field of view will change depending on how close you are to the null point. So one approach is to start at one end of the stage's travel range; count the number of fringes; move the stage a mm; count again; repeat until you have definitely gone through the null point. Then scan through the reduced length with the white light LED. Make sure that you look (with your eyes rather than the detector) at the

interference pattern that you see.

3. This is a refinement on technique 2. If you move the stage by a mm, then scan a small distance looking at your interference pattern. You will either see fringes disappearing into the centre or new fringes appearing out of the centre depending on whether you are scanning towards or away from the null point (can you work out which is which?). So you can repeat method 2 but rather than just counting fringes, scan a little and see when the fringes change directions (i.e. when you have gone past the null point). Then scan through the reduced length with the white light LED. Make sure that you look (with your eyes rather than the detector) at the interference pattern that you see.

When you have found the null point make sure that you record its position as you will need it for what you do next.

Task 9 - Characterising different light
You have been given a white LED and a blue LED.

- Take interferograms of the white LED, the blue LED and the white LED with one of the filters.
- Find the mean wavelength of each of these sources (assuming constant distance between samples)
- Find the coherence length of each source
- Use this to find the spectral width of each source. You can use the formula:

$$\Delta\nu \times L = \frac{c}{2\pi} \tag{4}$$

  To turn this into wavelength you can use:

$$\Delta\nu = \frac{c}{\lambda^2}\Delta\lambda \tag{5}$$

- Try taking an FFT of these interferograms. Does what you see make sense?

8 Interferograms of a mercury discharge lamp.

You have been given a Hg discharge lamp. You should be very careful with this as it is a very bright source with a lot of energy in the UV. This means that it can damage your eyes. Avoid looking at it directly and use the safety goggles supplied. You will study a green spectral line and the yellow doublet with this source.

Task 10 - The mercury green line.
The laser may have had instabilities but QM means that the Hg spectral lines must be stable (in normal conditions). So take a long (several mm) interferogram of the green line.

- Use this run and equations 4 and 5 to estimate the width of this line.
- Investigate the stability and reproducibility of the distance moved by the stage. You might want to do this by looking at the crossing points of the interferogram using calibrate.py. The real wavelength 546.0nm
- What happens if you take an FFT of your interferogram.

You should quantify your measurements in this task and remember that measurements are meaningless without errors

Task 11 - Examining the yellow doublet
take a long interferogram of the Hg doublet and use it to measure:

- The mean wavelength
- The separation of the lines (using equation 3)
- The widths of the lines (using equations 4 and 5)
- Take the FFT of the of the interferogram. Does what you see make sense?

9 Correcting the mercury spectrum

This is section is very challenging but also very rewarding. It shows you how to correct systematic errors using a known metrology source. It also shows you the power of using a Michelson interferometer for spectroscopy. For this to work you will probably need to put in time working on the algorithm outside of lab time.

In this section you will use a known wavelength to correct for the motion of the stage. You will take two interferograms at the same time. You will then correct for the stage position by fitting a source of a known wavelength to correct the position of where the data were actually collected (i.e. fitting the position knowing the wavelength rather than the other way around). You will then use these this to build a new interferogram for the unknown source. FFTs require the data to be evenly spaced (at least the algorithms you are using do), so you will then fit this new interferogram to produce a third interferogram that has evenly spaced points. We provide you with a program analysis.py which will do this, although you may well wish to produce your own code using analysis.py as a helpful guide.

Task 12a Using the Hg green line to correct the yellow doublet

You should follow the program analysis.py for the steps in this analysis. This program should not be used as a black box but more as a temlate or starting point. There are many ways that you could make these corrections what we suggest here is only one possible way.

- Reconfigure your apparatus using the second detector and another beam splitter so that the interferogram of the green line falls on one detector and the yellow doublet on the other. It may be easier to align this with the green laser and then replace it with the Hg lamp as the Hg lamp with filter is so weak.
- Take a long interfeograms.
- Using the green line (wavelength 546.0nm) correct for the positions where the data were taken. The easiest way to do this is to use the crossing points as we did in callibrate.py to set the absolute distance scale for each half wavelength. Then correct the position of the points in that half wavelength then move on to the next half wavelength building on the already corrected point.

So the position of each point now is just

$$x_{corr} = x^{init}_{uncore} + \frac{\lambda_{fit}}{\lambda_{true}}(x_{uncorr} - x^{init}_{uncorr}) \tag{6}$$

where x_{corr} is the new corrected position, x^{init}_{uncore} is the inital uncorrected x position, λ_{fit} and λ_{true} are the true wavelengths from the number of μsteps the true wavelength of the green light. By doing this you are essentially streching or compressing the chunk of data that you have fitted to correct for irregularities in the stage's movement.

- Now that you have a corrected set of positions for where the data were actually taken. You now need to produce a "re-sampled" data set for the yellow doublet where the spacing between points is regular. Probably, the simplest way of doing this is to fit a cubic spline to your corrected but now unevenly spaced data and then call the cubic spline function with the regular space points that where you now want youregular points.
- Take the Fourier transform of this interferogram. Does what you see make sense?

Task 12b Using the Hg green line to correct the entire Hg spectrum

Repeat what you did for **Task 12a** but with the yellow filter removed. This should allow you to measure the entire Hg spectrum (or at least that part of it that is within the sensitivity range of the photodiode)

Task 13 - Using a red HeNe laser to correct the entire Hg spectrum
This is an optional task and if you do it you will need extra apparatus for this so ask your demonstrator to get this from the lab technician.
In research, Fourier transform spectrometers often have a metrology laser as a known calibration wavelength. In this task you can add a laser to your instrument and use it as a general purpose spectrometer.

- Using an extra beamsplitter, reconfigure your apparatus such

that light from the red laser goes down the same optical path as the light from the mercury lamp.

- Using the notch and bandpass filters configure your detectors so that only light from the red laser falls on one detector and only light from the mercury lamp falls on the other. The filter that filters out the red laser light must be perpendicular to the incoming beam. If it is not then some light will leak through so make sure you align it carefully (using an optical tube might help).
- Take long interferograms.
- Correct the mercury spectrum in the same way as you did the yellow doublet previously (except obviously using the the laser rather than mercury green line)
- Take the Fourier transform of the entire mercury spectrum. Can you identify the features that you see?

Clearly, the results from this task should be similar to those from **Task 12b**, but what you have now is a general purpose instrument that can be used to analyse many different sorts of light sources. So why not try some other light sources, for example the green laser and the white light (with filters) etc.