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Intensity Interferometry Experiment

Abstract:

In this experiment we investigate the correlations in the intensity of diffracted light using an interferometer similar to Hanbury Brown and Twiss'. We use a pseudo-thermal light source composed of a laser and a rotating ground-glass screen with detection by silicon photodiodes. The experimental results agree with the theory that describes the correlation between spatially separated parts of the intensity field.

Introduction:

Introduction to classical interferometers

Interferometry makes use of the principle of superposition to combine light waves in such a way that their final combination results in an interference pattern which can be used to make measurements (Hecht, 2002; Born, 1980) . Typically, a single beam of coherent light is split into two identical beams. Each beam travels a different path and both are recombined at a detector or screen. This is useful because when two waves with the same frequency go through different paths, and are rejoined, the path difference shows a phase change between the two waves, resulting in interference; either constructive or destructive, depending on the phase change.

An interferometer that is most relevant to this work is Young's two slits interferometer. In this interferometer a light source illuminates two parallel slits. Light from the slits propagates to a distant screen and creates an interference pattern of light and dark fringes. However, the fringe pattern differs depending on whether or not a point source (of the sort that can easily be derived from a laser) or an extended source is used.

To begin with, consider a coherent, monochromatic point light source, located a distance away from the two slits. As seen in Figure 1, when the wave fronts reach the two slits, they can be considered plane waves. When these wave fronts reach the two slits, the slits diffract the wave fronts into cylindrical waves. The wavefronts then overlap with each other, creating a diffraction pattern. Depending on the distance between the two slits, and where one observes on the screen, the diffraction pattern could either show constructive or destructive interference. With the observation screen sufficiently far away, the condition for constructive interference is given by

$$d sin(\theta) = n\lambda, \tag{1}$$

where *d* is the slit separation, θ is the angle of propagation, *n* is an integer, and λ is the wavelength of the light.

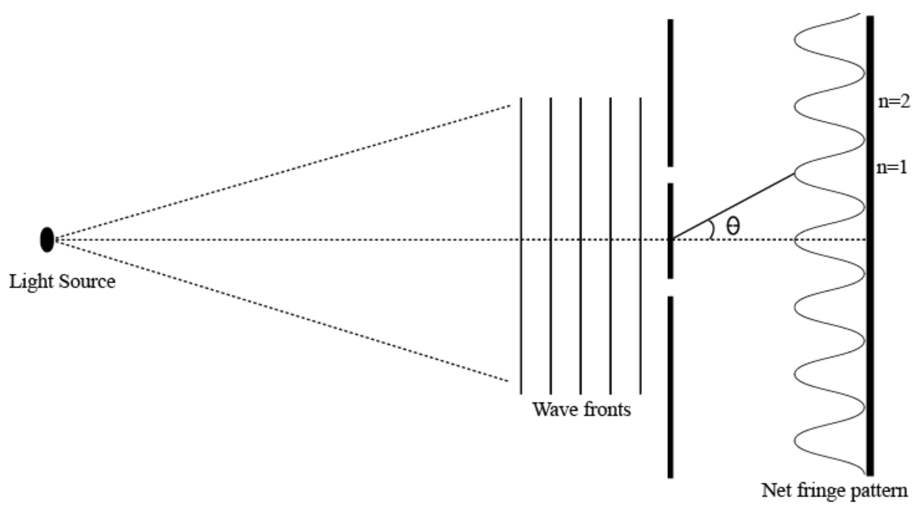

Figure 1: Young's Two-slit experiment with a point light source. The waves travel from an on-axis point source and are almost parallel plane waves by the time they reach the slits. After passing through the slits the light interferes at the observation screen to create a fringe pattern

Interferometry with an extended source

Consider now an extended source which can be thought of as composed of many individual point sources incoherent with one another. That is, the radiation at each point is uncorrelated with the radiation at any other point. The diffraction pattern associated with an extended light source is a combination of each point source's fringe pattern, as can be seen in Figure 2.

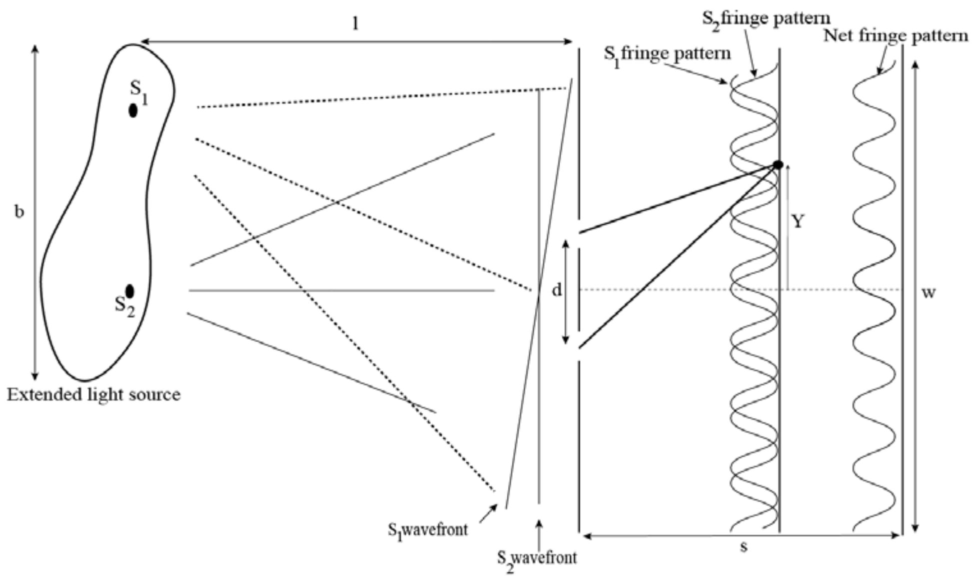

Figure 2: Young's two-slit experiment with an extended source. The waves from the extended source also become wave fronts but oriented in different directions, non-parallel to the slits. Each individual plane wave gives rise to its own fringe pattern, which ultimately changes the net fringe pattern.

It is important to realize that the light leading to the individual fringe patterns is uncorrelated with the light from the other fringe patterns, therefore the diffraction pattern of the extended light source is obtained by adding the intensities of the individual fringe patterns. Similarly to the single point source, each of the single point sources generates plane waves in the direction of the aperture screen. The on-axis point source, S_2, will propagate waves with wavefronts parallel to the aperture screen; whereas the off-axis point sources, such as S_1, will propagate waves that are not parallel to the aperture screen, as denoted by the S_1 and S_2 wave fronts in Figure 2 (Towne, 1967).

The fringe pattern can be determined mathematically by considering the contribution of each point on the source to the final pattern. Here we follow the arguments by Towne and Hecht where, to simplify matters, we imagine a lens inserted between the source and the aperture screen at such a position as to form an image of the source plane at the observation screen. Because of their different orientation to the waves from the on-axis point source, each off-axis point source creates a fringe pattern shifted a distance dy_0 with respect to an on-axis light source on a screen of height w, as shown in Figure 3. That there is a constructive interference at this point can be seen by considering what would happen if the aperture screen were removed. In that case there would be an image of the source point S, so there must be constructive interference (Hecht, 2002).

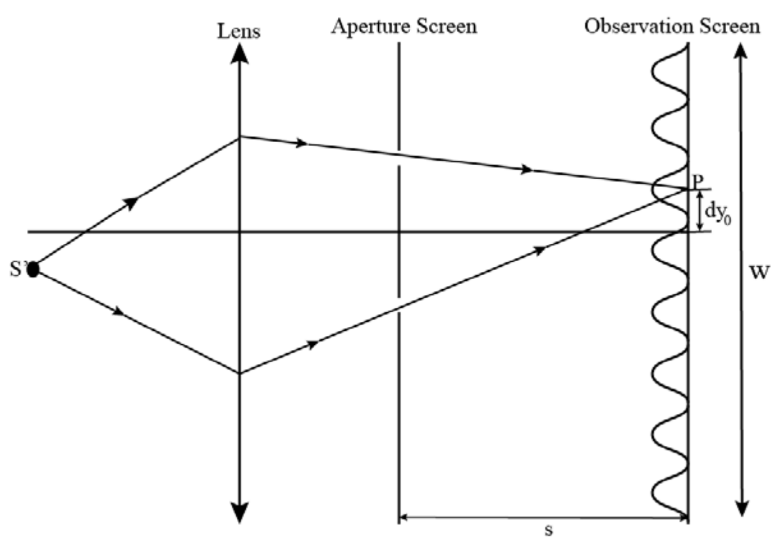

Figure 3. Fringe pattern associated with an off-axis point source

The intensity on the observation screen due to an on-axis single point of the extended light source is given by

$$I = 4I_0 \cos^2\left(\frac{Yd\pi}{s\lambda}\right), \tag{2}$$

where *Y* is the distance to the point of interest from the origin, *s* is the distance from the slits to the screen, *d* is the distance between the slits, and I_0 is the initial intensity. The intensity arising from an off-axis point source a distance dY_0 away from the center becomes

$$dI = AdY_0 \cos^2\left[\frac{d\pi}{s\lambda}(Y - Y_0)\right], \tag{3}$$

where A is an appropriate constant (Towne, 1967). As previously stated, the net fringe pattern from an extended source is a combination of all the individual point sources of the extended source. In order to obtain the final light distribution on the screen we integrate over the image of the source of width w.

$$I(Y) = A\int_{-w/2}^{w/2} \cos^2\left[\frac{d\pi}{s\lambda}(Y - Y_0)\right] dY_0. \tag{4}$$

After some manipulation, the total intensity becomes

$$I(Y) = \frac{Aw}{2} + \frac{A}{2}\frac{s\lambda}{d\pi}\sin\left(\frac{d\pi}{s\lambda}w\right)\cos\left(2\frac{d\pi}{s\lambda}Y\right). \tag{5}$$

The oscillation of the intensity gives an average value of $\bar{I}=Aw/2$, which increases proportionally to the breadth of the source. The relative intensity across the observations screen thus becomes

$$I(Y) = \bar{I} + \bar{I}sinc\left(\frac{d\pi}{s\lambda}w\right)\cos\left(2\frac{d\pi}{s\lambda}Y\right). \tag{6}$$

It follows that the maximum intensity I_{max} is

$$I_{max} = \bar{I} + \bar{I}\left|\text{sinc}\left(\frac{d\pi w}{s\lambda}\right)\right|. \tag{7}$$

Similarly, I_{min} is

$$I_{min} = \bar{I} - \bar{I}\left|\text{sinc}\left(\frac{d\pi w}{s\lambda}\right)\right|. \tag{8}$$

As stated before, the contrast of the net fringe pattern differs from that of a point source and an extended source, meaning the contrast of the fringes depends on the size of the source. To quantify the fringe quality a quantity called visibility is attributed to the interference pattern. The visibility, V, is defined as

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}, \tag{9}$$

Quantitatively, the relationship between the visibility of the fringes and source size is then

$$V = \left| sinc\left(\frac{d\pi w}{s\lambda}\right)\right| = \left| sinc\left(\frac{d\pi b}{l\lambda}\right)\right| \tag{10}$$

where *b* is the source size and *l* is the distance from the point source to the slits. Here, $w/s \approx b/l$ and $(d\pi w/s\lambda) \approx (d\pi b/l\lambda)$. Note, *V* is a function of source breadth *b* and aperture separation *d*. Varying either will alter *V* in the same way. Not only does visibility depend on the source size but on the slit separation as well; the smaller the distance between the slits, *d*, the smaller $(d\pi b/l\lambda)$ will be, and the larger *V* will be. Hence, a smaller source gives higher visibility and therefore clearer fringes. If the visibility of the pattern is known, the size of the source can be calculated. Figure 4 shows the relationship between the visibility and the size of the source.

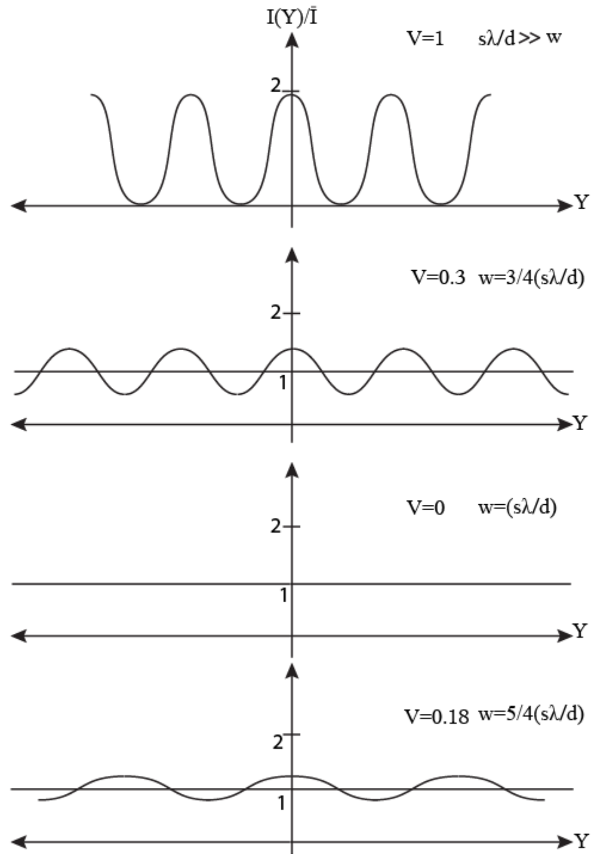

Figure 4. Fringes with varying source slit size. The pattern loses contrast as w is increased and the fringes completely disappear when w=sλ/d. Beyond this point an intensity variation reappears but with a low contrast (Towne, 1967).

The Michelson Stellar interferometer

In the mid-1800s, Hippolyte Fizeau suggested that with interferometers one can obtain the angular size of stars. His argument was that if the star was fairly small, then the light coming through the slits would form a clear fringe pattern but if the star was large, then the visibility would be reduced. His attempts failed because of the lack of stability in the instruments and the fact that atmospheric turbulence distorted the arriving wave fronts (Tango, 1980). In the late-1800s, Albert Michelson took Fizeau's suggestion and created the Michelson stellar interferometer to measure the angular size of astronomical bodies. Michelson created a more stable interferometer which measured the correlations in the fields of a distant star using two widely spaced mirrors, as seen in Figure 5.

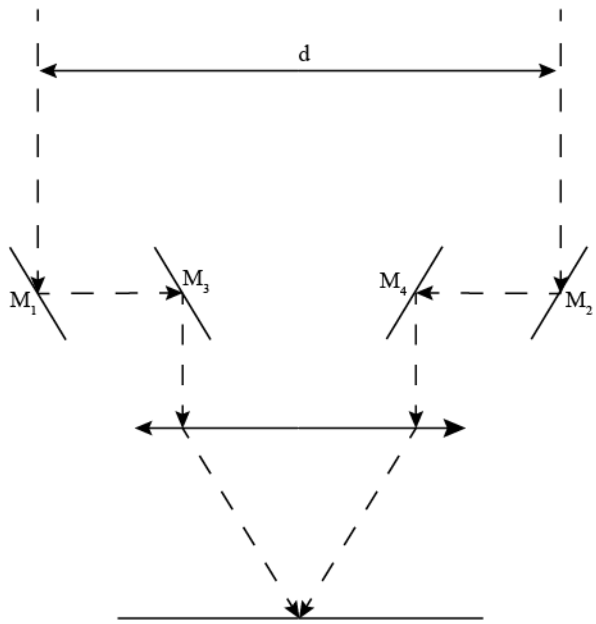

Figure 5. The Michelson stellar interferometer. Light from a distant star is incident on mirrors M_1 and M_2, separated a distance d, and reflected towards M_3 and M_4, respectively. That light is reflected towards a lens and focused by the objective lens of a telescope to create an interference pattern.

The rays incident on the mirrors are assumed to come in parallel. The rays captured are channeled by mirrors through some apertures and finally into the objective of a telescope. The apertures generate fringe patterns on the focal plane of the objective of the telescope, which follow Young's two slit theory. For an object with a large angular size, the mirrors only needed a small separation, to reduce the fringe visibility, but for smaller objects, the mirrors needed to be placed further apart.

When a fringe pattern appears for the Michelson interferometer, it is because there is some sort of correlation between the fields at M_1 and M_2. By this method, Michelson was able to make the first measurements of the diameter of an extra solar star.

Intensity Interferometry

Unfortunately, because of the lack of instrument stability, measuring the fringe patterns becomes very difficult when large mirror separations are needed- i.e. for small objects. For this reason, Hanbury Brown and Twiss created the intensity interferometer. Instead of measuring the fringe visibilities (the correlations in the field) they measured the correlations in the intensities of the light at different spatial positions.

A correlation interferometer works with two light detectors separated by some distance. Both light detectors are positioned in such a way that both face the same light source, and intensity measurements at different detector separations are made and correlated (Baym, 1998). This was a great improvement from the Michelson interferometer since high stability of the mirrors was not needed. A drawback, however, was that the sources need to be fairly bright.

While Hanbury Brown and Twiss had initially developed the idea for radio astronomy it was found that the basic idea carried over into the optical regime where the intensity fluctuations of the light are converted into fluctuations in the photocurrent outputs from photomultiplier tubes. The idea of the intensity interferometer was to find some correlation between the photocurrents. The initial laboratory experiment was conducted used a high-pressure mercury lamp, an aperture screen, beam splitter, and photomultiplier tubes as seen in Figure 6.

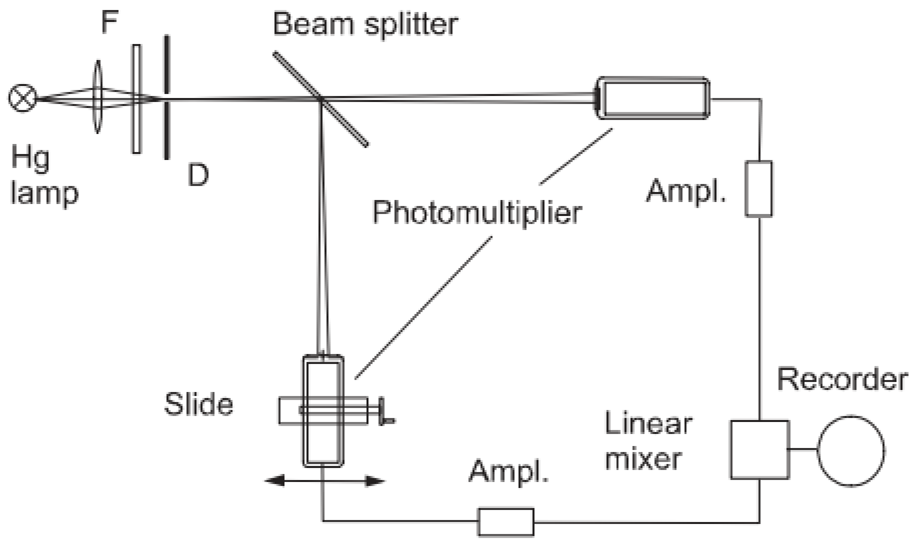

Figure 6. Original Hanbury- Brown and Twiss intensity experiment using a high-pressure mercury lamp as the light source, aperture screen D, a semi-transparent mirror as a beam splitter, two photomultiplier tubes (one movable on the horizontal plane) and a linear mixer and recorder to correlate the signals (Marchenko, 2011).

The light beam from the mercury lamp is filtered and focused onto an aperture screen. The light then travels to a beam splitter, splitting the beam towards two different photomultiplier tubes. The signal obtained by the photomultiplier tubes is amplified and sent to a linear mixer and recorder where the amplified signals are correlated. In order to monitor the correlation between the two light beams, the position of one of the photomultiplier tubes is varied.

The purpose of this experiment was to show the correlation of light intensities traveling the same distance towards the detectors. Since the detectors could not be placed close enough to sample locations close to each other the beam splitter is used to make this possible. This experiment did in fact show the correlation of the outputs from the photomultiplier tubes.

Returning to the case of a one dimensional line source of width s, it can be shown that the correlation is given by

$$C(d) = \left|sinc\left(\frac{sd}{\lambda z}\right)\right|^2 \quad (11)$$

where d is the distance between the detectors, λ is the wavelength of the light, and z is the distance from the source to the detectors. Note the similarity to the formula for the visibility of the fringes when interference between the fields is done and similarly that smaller apertures (sources) lead to correlations over greater detector separations.

Experiment

This experiment seeks to support the findings of Hanbury-Brown and Twiss using a similar experimental setup as that of Figure 6. Our experiment, in contrast to the original, does not use photomultiplier tubes but rather silicon photodiodes as the light detectors and uses a computer to correlate the information rather than an analog correlation of photocurrents. Another difference is that we use a pseudo thermal source in this experiment. The pseudo thermal source is created using a red diode laser of wavelength of 635nm with output power ~200mW, and a rotating ground glass screen (RGGS) on a clock motor, which creates low frequency fluctuations which are within the bandwidth of the detectors. The schematic for this experiment in shown in Figure 7.

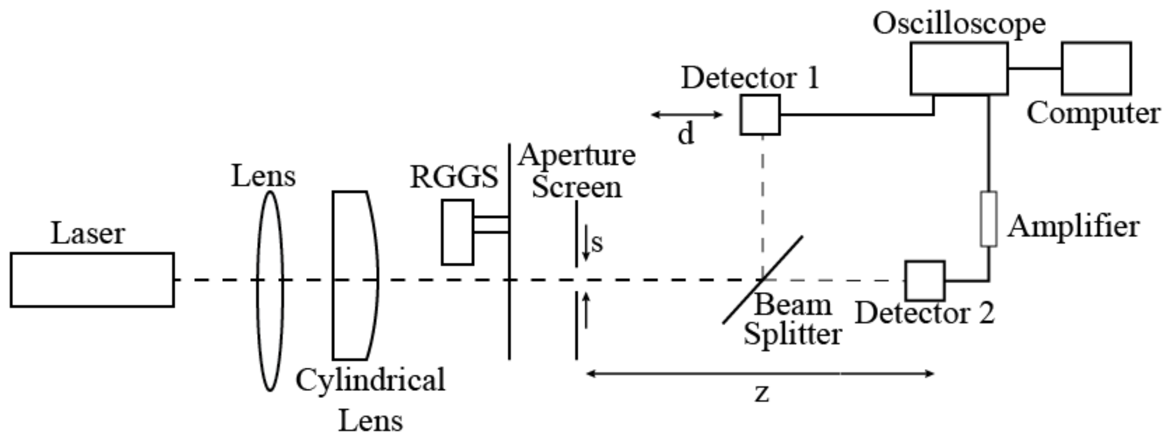

Figure 7. Our experimental arrangement. No photomultiplier tubes are used; instead, silicon photodiode detectors are used. The aperture screen is such that one can change the size of the aperture. Detector 1 is on an adjustable slide movable by distance d, and the signals from the detectors is recorded by the oscilloscope and correlated by computer.

The laser beam is expanded by the lens (of 30mm focal length) and brought to a line focus by the cylindrical lens (of 50.8mm focal length). The rotating ground glass screen (RGGS) and a clock motor creates a changing speckle pattern on the aperture screen, essentially creating a one-dimensional source of variable length. The light from the aperture propagates towards the 50/50 beam splitter which splits the beam equally. The split beams are detected by two Thor Labs Det 110 detectors each with 50μm wide aperture slits about 3mm in length. Detector 2 is held fixed while detector 1 can be translated on an adjustable slide. Detector 2 used a Thor Labs PDA 200C photodiode amplifier because the output signal was weaker than that of detector 1. The intensity signals from the two detectors are collected by an Agilent 54621A oscilloscope. The signals are then transferred to the computer using an Agilent 82357B USB/GPIB and correlated using Matlab.

In order for this experiment to show proper correlation, the distance from the source to the detectors must be the same. Just like the Hanbury-Brown and Twiss experiment, a beam splitter is used to allow the detectors to receive signals from adjacent parts of the field. The distance from the source to the detectors was 70cm.

Results

A program in Matlab (Appendix A) reads and correlates the data from the oscilloscope and a separate program (Appendix B) plots the correlated information. Correlation data is used for various aperture sizes. Figure 8 shows the correlation for 300, 400, and 600 micron slits.

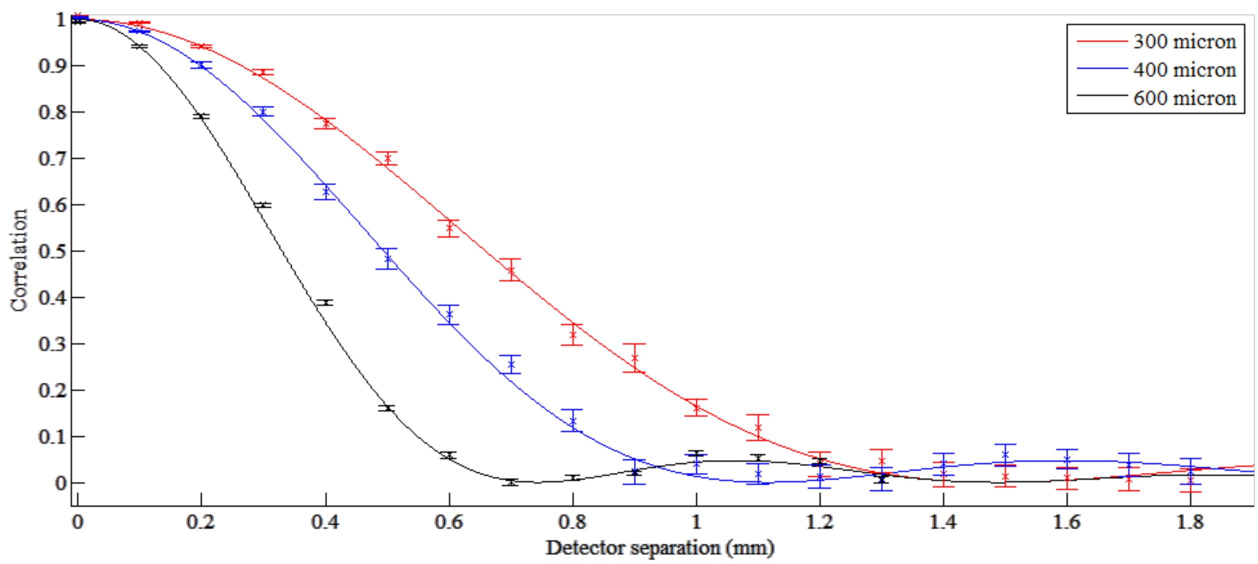

Figure 8. Normalized correlation of the intensities for various aperture sizes. Each data point is obtained from an average of 50 cross correlations where each correlation is measured over a period of 200ms. The solid curves are the theoretical correlation obtained from equation 11.

Superimposed on the experimental results are solid curves obtained from equation 11 showing an excellent agreement between the experiment and theory.

Discussion

This work has demonstrated that the famous experiment of Hanbury Brown and Twiss on intensity correlation can be recreated using simple apparatus. The experimental results and the theory relating the correlation between adjacent parts of the field are in good agreement.

References

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Appendix A

```
%% Data Aquisition and Correlating program
% This program will connect the computer to the oscilloscope via an Agilent
% GPIB Interface. The GPIB will convert the waveform data from the
% oscilloscope in byte format. Each detector is connected to one of the
% channels in the oscilloscope. This program will read the waveforms from
% each channel and correlate information 50 times. Note that this will
% correlate the information for only one slit width. Run this program for
% various detector separations, but the same aperture width.The detector
% distance, standard deviation and correlation must be recorded on a .txt
% file to later be imported and plotted.
%%
clear all
close all %clears all variables and closes all windows

g = gpib('agilent',7,23); %communicate with Agilent GPIB Interface
g.InputBufferSize=3000;%Total number of bytes that can be queued in the input
buffer at a time
fopen(g)%Open access to the Agilent GPIB Interface
get(g,{'EOSMode','EOIMode'});%connect to the oscilloscpe and return the
%default values of the EOSMode EOIMode properties

%Set up aquisition type and count
fprintf(g,'ACQUIRE:TYPE NORMAL');
fprintf(g,':ACQUIRE:COMPLETE 100');
%Get the data back in bytes
fprintf(g,':WAVEFORM:FORMAT BYTE');
fprintf(g,':WAVEFORM:POINTS 2000');
fprintf(g,':WAVEFORM:POINTS?');
%Read formatted data in a text file
fscanf(g);

cor_av= zeros(3999, 1);
num_samples = 50; %run 50 correlations
cor_coeff = zeros(1, num_samples);% create an empty array
for i = 1:num_samples
%Digitize information obtained
fprintf(g,':DIGITIZE');

%read data from scope Channel 1
fprintf(g,':WAVEFORM:SOURCE CHAN1');
fprintf(g,':WAVEFORM:DATA?')

dat=fread(g);%Read stream of data
chan1=dat(11:2010);%read 2000 bytes
m=mean(chan1);%Obtain the mean of Chan1 data
chan1=chan1-m;
msquare1 = sum(chan1.^2); %mean square of Channel 1

%read data from scope Channel 2
fprintf(g,':WAVEFORM:SOURCE CHAN2');
fprintf(g,':WAVEFORM:DATA?')

dat=fread(g);
```

```
chan2=dat(11:2010);
m=mean(chan2);
chan2=chan2-m;

msquare2 = sum(chan2.^2); %mean square of Channel 2
scale2 = msquare1./msquare2; %scale mean square of Channel 2 to mean square
of Channel 1
scalem2 = chan2.*sqrt(scale2); %scale Channel 2 to Channel 1

chan1=smooth(chan1);%Smooth Chan1
scalem2=smooth(scalem2);%Smooth scaled Chan2
cor=xcorr(chan1, scalem2, 'none'); %Correlate Channel 1 and scaled Channel 2
cor=cor/sum(scalem2.^2); %Average the correlation
cor_av = cor_av+cor; %Add the correlation of each iteration
cor_coeff(i)=cor(2000);%Value of maximum correlation

plot(cor); ylim([-1 1]); drawnow %Plot the correlation for this iteration
hold off
i
end

cor_av= cor_av/num_samples; %Mean of the correlation average
standev_mean = std(cor_coeff)/sqrt(num_samples); %Standard deviation of the
mean
p_std=['The standard deviation from the mean is  '
num2str(standev_mean)];%display standard deviation

figure
plot(cor_av)%plot correlation average of the 50 correlated samples

cor_av(2000); %average 2000th data point of correlation (highest point in
plot)
p_mean=['The mean is  ' num2str(cor_av(2000))];%Show what the average
correlation of the 50 samples was
disp(p_mean)
disp(p_std) %display standard deviation

fclose(g)%Close connection to the GPIB Agilent Interface
```

Appendix B

```
%% Plotting Program
%This program will plot the correlation data for various detector
%separations for slit widths of 300, 400 and 600microns,respectively. Data
%is imported from a .txt file which includes the detector separation,
%standard deviation and respective correlations

%all measurements are in mm
%%
%Constants for each plot
wavelength = 638*10^-6;%laser wavelength
distance = 70e1;%distance from source to detector (in mm)
x= 0:.0001:2; %theoretical distance between detectors

%300 micron slit
d1= (d-d(1));%measured distance (normalized) between detectors in millimeters
slitwidth =300e-3;%mm
y = (abs(sinc((slitwidth.*x)./(wavelength*distance)))).^2; %correlation
equation

figure
hold on
plot(x, y,'r')%theoretical plot for  300micron slit


%400 micron slit
d12= (d2-d2(1));%measured distance (normalized) between detectors in
millimeters
slitwidth2 =400e-3;%aperture size in mm

y2 = (abs(sinc((slitwidth2.*x)./(wavelength*distance)))).^2;
plot(x, y2)%theoretical plot for  400micron slit


%600 micron slit
d13= (d3-d3(1));
slitwidth3 =600e-3;

y3 = (abs(sinc((slitwidth3.*x)./(wavelength*distance)))).^2;
plot(x, y3, 'k')%theoretical plot for  600micron slit

legend('300 micron', '400 micron', '600 micron')

plot(d1, cors, 'rx')%correlation data for 300micron slit
errorbar(d1, cors, er, 'rx')
plot(d12, cors2, 'x')%correlation data for 400micron slit
errorbar(d12, cors2, er2, 'x')
plot(d13, cors3, 'kx')%correlation data for 600micron slit
errorbar(d13, cors3, er3, 'kx')
```