King’s College London (KQC) University of London

SCIENCE SIMULATIONS LABORATORY

INTERFERENCE AND DIFFRACTION OF WAVES

STUDENTS’ MANUALS (Version 1.02.2003)

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STUDENTS' MANUAL A - REVIEW AND REVISION

This unit is about the use of models in physics; in particular the wave theory of light and how effective the theory is in explaining observed phenomena. You should be familiar with a number of laboratory experiments before starting work on this unit. These include:

1 The production of light and dark fringes on a screen placed some distance from two parallel slits through which light passes.

2 The fringe pattern which results when a single narrow slit is illuminated by a parallel beam of white light.

You should know that the two slit pattern can be explained as being a result of the superposition (adding up) of waves from the two slits. You should also know that the wave theory of light is able to explain the general shape of the intensity distribution in the fringe pattern of a single slit. This explanation involves imagining the slit to be divided into a number of elements, each element contributing by superposition to form the final intensity distribution. If you are not clear about this you should look up the theory in one of the references given in Manual B. If you have not done the "Young's experiment" before, you should do it before going any further. See Manual B.

In later sections you will be asked to compare the predictions of theory with actual experimental observations. As it is easier to measure the intensity at different points in an interference pattern formed by 3 cm microwaves we will use this radiation instead of light waves in the experiments and in the computer calculation. Of course the theory is basically the same whatever wavelength of electromagnetic radiation we consider.

To help your memory:

Before going into any detail it might we wise to revise a few fundamental points.

A1 *Will there be a maximum or minimum disturbance at PO?*

A2 *What is the condition for the disturbance at P to be a minimum?*

A3 *What is the condition for the disturbance at P to be a maximum?*

A4 *Make a rough sketch to show the intensity varies along the line AZ.*

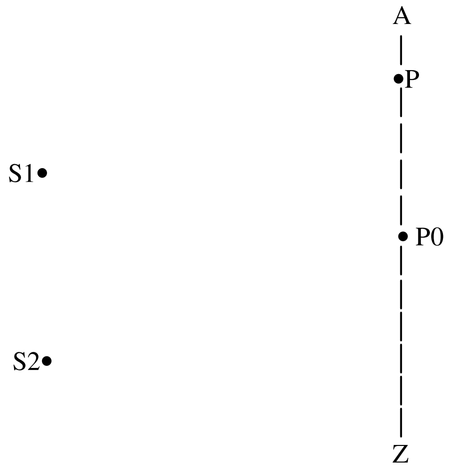


Figure A1 S1 and S2 are two sources of waves (emitting continuously and in phasewith each other) with a wavelength λ.

The wave theory says that we can find the resulting amplitude at any point such as P by simply adding the contributions of each source, taking account of the phase of each contribution. S_1 and S_2 emit continuous waves in phase with each other. Then if P is exactly

0, 1, 2, 3... or any whole number of wavelengths further from one source than from the other the two waves will be in phase: the result is a maximum disturbance at P. But if the path difference is exactly ½, 1½, 2½... wavelengths then the two waves are out of phase and the disturbance at P is zero.

A5 *Refer to Figure A1 again. What other condition is necessary for two waves to give exactly zero disturbance at P?*

As you know plane waves are diffracted by a slit, (Figure A2) and as a result there are intensity variations along a line such as AZ.

A6 What must be the path difference S P-S' P, in wavelengths, for P to be a point of minimum disturbance?

A7 Make a rough sketch of the intensity variations along AZ.

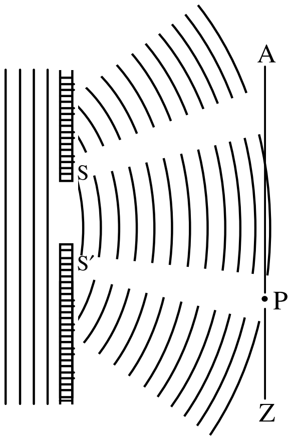


Figure A2 Waves passing through a slit.

If you have had any difficulty in understanding the work up to this point you should look up the theory in one of the references given in Manual B.

The basic ideas of the wave theory of light which we have been considering have been incorporated into a computer program specially written for use with this unit. The program is called ***Interference and Diffraction of Waves***. Later in this unit you will be able to use it to predict intensity distributions for which it would be quite difficult to obtain a mathematical formula.

STUDENTS' MANUAL B – "YOUNG' S EXPERIMENT"

This leaflet is to help you if you have not already seen experiments in which light – or other radiation – from two sources can add up to give an unexpected result, a so called "interference pattern". The leaflet cannot really tell you all the details you might need to know to do the experiments, so you may need to refer to one of the sources listed below.

a Using visible light

This experiment, which was first done by Thomas Young in 1802, provided excellent evidence that light has the properties of a wave motion.

Because the wavelength of light is so small the two sources must be small and they must be close together. The effect is easy to demonstrate with a laser; otherwise the usual method is to use two narrow slits which are illuminated by light from a lamp with a straight filament.

Figure B1 shows the kind of set up you need. The slits can be made by scratching two fine lines on a microscope slide that has been coated black. Make the scratches with a pin – or perhaps a fine ball point pen. They shouldn't be more than about 0.5 mm apart. You may have a special device to move the slide this sort of distance between one scratch and the next; or draw the pin along the edge of a ruler and tilt the pin a little (without moving the ruler) for the second slit.

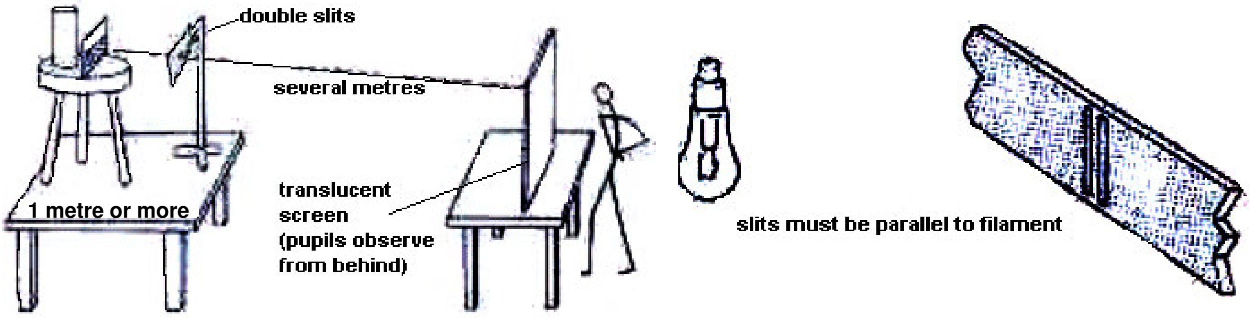


Figure B1 A simple arrangement for Young's experiment. Try to prevent any light that has not passed through your slits falling on the screen.

Look from behind the screen at the pattern formed by light that has passed through your slits. Use filters of different colours to see what effect changing the wavelength of light has on the pattern.

Sketch a graph showing how the brightness of the pattern varies with distance along the screen.

B1 Does increasing the wavelength (changing from green to red filter) make the pattern spread out more or less?

If you have time, repeat the experiment with another pair of slits which have a different separation.

B2 Does changing to a more widely separated pair of slits make the pattern spread out more or less?

Finally repeat the experiment with a single slit.

B3 What difference is there in what you see on the screen when light has passed through a single slit rather than a pair?

b Using ' 3 cm waves'

This radiation comes between the infra-red and very high frequency radio waves in the electromagnetic spectrum. It is near to the radiation used in microwave ovens and radar. Many of the effects that show the wave nature of light can be observed rather more easily using this longer wavelength. Later in this unit you will be comparing the predictions made by a computer program with your own observations using 3 cm waves.

Figure B2 shows the kind of arrangement you need, using metal screens to make two slits. The slits can be about 5 cm wide, and 10 cm apart (distance between centres). Try to keep reflections from bodies, walls and so on to a minimum they could complicate things for you.

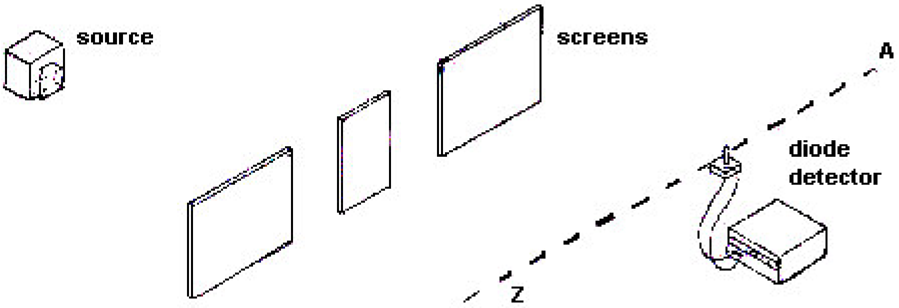


Figure B2 Arrangement for experiment with ' 3 cm waves'

Move the detector along a line parallel to the two slits, and note how the signal strength varies. Sketch a graph of signal strength against position.

You can' t vary the wavelength of this radiation but you should try the effect of changing the slit separation and slit width.

B4 How does your graph change if the slits are further apart?

B5 What effect does using wider slits have on your graph?

Finally, if you have time you should replace the pair of slits by a single slit opening between two metal sheets.

B6 How is the result produced by '3 cm waves' going through a single slit similar to what you observed with a double slit? And in what ways is it different?

Why does it happen?

We don' t attempt in this leaflet – or in this unit – to explain how the effects you observed with light, or 3 cm waves come about. They are a characteristic of all wave motions, and you should certainly see the effect on water in a ripple tank. For explanation of why waves behave like this look in one of the books listed below.

REFERENCES

Akrill, Bennett & Millar., (1979), Physics, Chapter 27, London: Edward Arnold.
Bolton, (1974) Patterns in Physics, Chapter 6, McGraw Hill.
Duncan, (1981) Advanced Physics: Fields, waves and atoms, Chapter 8. John Murray.

STUDENTS' MANUAL C – SOURCES: POINTS OR SLITS

Investigation 1 - Points

First use the program ***Interference and Diffraction of Waves*** to investigate a familiar situation so that you have a pretty good idea of what results to expect, e.g. two equal intensity point sources emitting in phase.

It is fairly easy to obtain an expression for the Intensity at different places in an interference pattern caused by waves from two point sources. It is

$$1 = 4a^2 \cos^2 \frac{\delta}{2} \quad \text{where } a \text{ is the amplitude of each wave.}$$

and $\delta = 2\pi(S_2P - S_1P)/\lambda$ is the difference between waves from the two sources (S_2 and S_1 in figure A1, Leaflet A).

Figure C1 shows a plot of this relationship which is found in many books.

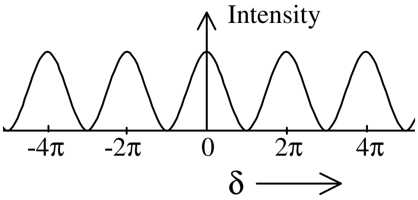
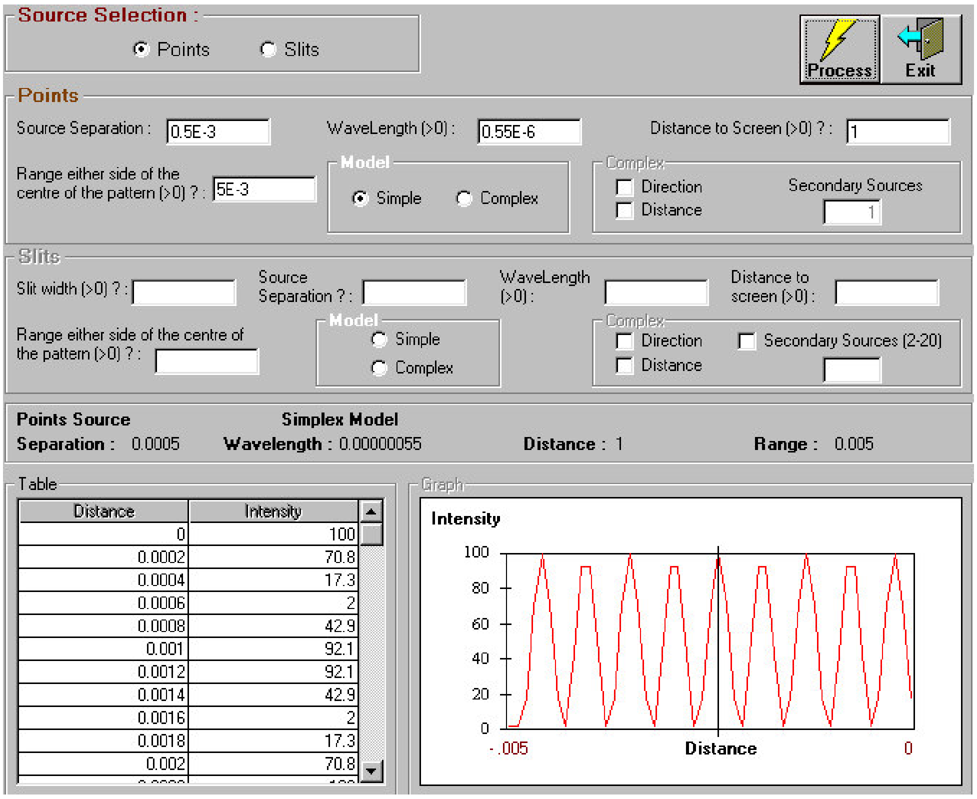


Figure C1 Intensity distribution in a two source interference pattern.

Note that the phase difference does not necessarily increase steadily with distance along the screen (AZ in Figure A1 of Manual A), although for some experimental situations this is a good approximation.

You can use the computer program ***Interference and Diffraction of Waves*** to calculate the intensity distribution in an interference pattern by defining two POINT sources as shown in the example. You have to supply values for the SEPARATION of the sources; the WAVELENGTH of radiation; DISTANCE to the screen on which the pattern is formed. You will also be asked for RANGE - that is how much of the pattern on each side of the centre do you want to see. You can choose the units for distance (cm, mm, etc) but all distances must of course be in the same units. The units here are metres - the sources are 0.5 mm apart, the wavelength is 0.55 μm and the screen 1 m away. Values for intensity will be calculated at 0.2 mm intervals, out to 5 mm from the centre of the pattern.

Specifying values for ***Interference and Diffraction of Waves***. The program calculates intensities at 25 points on each side of the centre of the pattern.



Source Selection :

● Points ○ Slits

Points

Source Separation : 0.5E-3

WaveLength (>0) : 0.55E-6

Distance to Screen (>0) ? : 1

Range either side of the centre of the pattern (>0) ? : 5E-3

Model: ● Simple ○ Complex

Complex: ☐ Direction ☐ Distance

Secondary Sources: 1

Slits

Slit width (>0) ? :

Source Separation ? :

WaveLength (>0) :

Distance to screen (>0) :

Range either side of the centre of the pattern (>0) ? :

Model: ○ Simple ○ Complex

Complex: ☐ Direction ☐ Distance ☐ Secondary Sources (2-20)

Points Source **Simplex Model**

Separation : 0.0005 **Wavelength :** 0.00000055 **Distance :** 1 **Range :** 0.005

Table

Distance	Intensity
0	100
0.0002	70.8
0.0004	17.3
0.0006	2
0.0008	42.9
0.001	92.1
0.0012	92.1
0.0014	42.9
0.0016	2
0.0018	17.3
0.002	70.8

Graph

The computer will give you a graph and a table of the theoretical intensity distribution for a two source interference pattern. You will certainly want to compare the computer' s predictions, with observations you make yourself, or with Figure C2, so choose values for wavelength etc. which you could use in an experiment.

C1 *Does the computer produce reasonable results - i.e. what would you have expected? You might care to make a scale drawing, or a calculation, to check that the path difference, for say the second or third maximum, is exactly 1 or 2 wavelengths.*

Does this model predict that the maxima are equally spaced, and all of the same intensity?

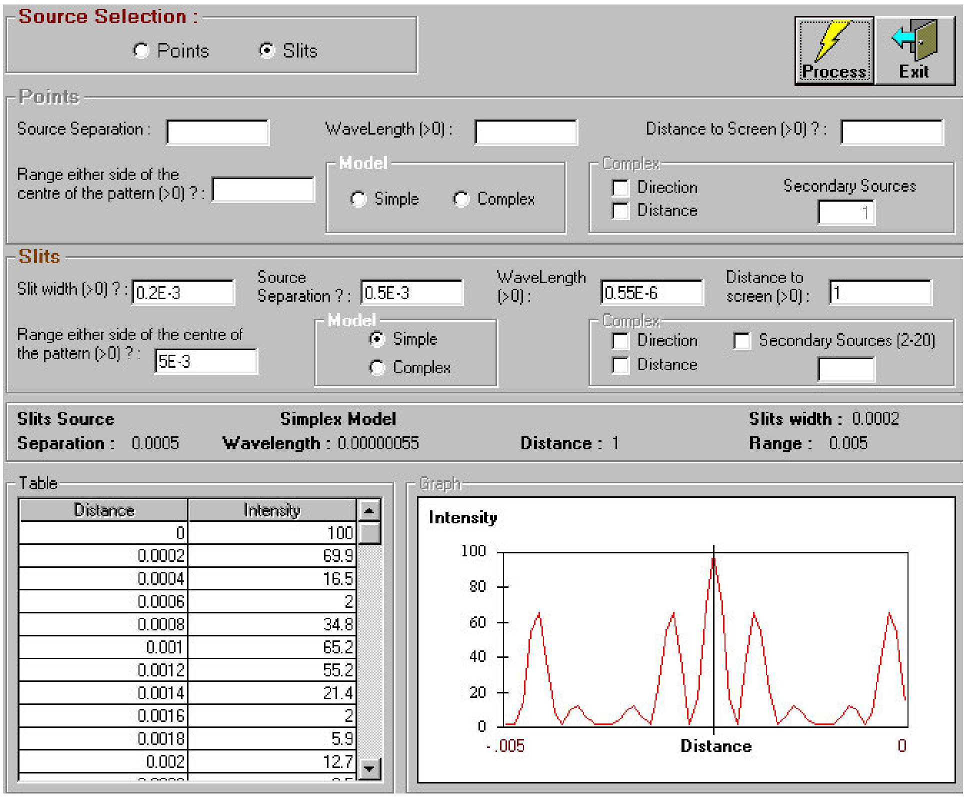
You should know what effect changing the wavelength, or distance between the sources, should have on the pattern. Run the program again as a check.

As you know real interference experiments are usually done by allowing radiation from a single source to pass through two slits. If by now you trust the computer program to produce sensible results, you should go on to the next stage of refinement of the model which considers two slits rather than two points.

Investigation 2 - Slits

Use the computer to predict the pattern produced by plane waves passing through two equal width slits.

Let the separation of the slits (distance between centres) be the same as the distance between sources you used in the previous investigation. Keep the wavelength and other parameters the same so that you can compare the predictions made by the two point model (Investigation 1) and the two slit model (Investigation 2). Your answers to the computer's initial questions might be:



Source Selection : ○ Points ● Slits

Points
Source Separation :
WaveLength (>0) :
Distance to Screen (>0) ? :
Range either side of the centre of the pattern (>0) ? :
Model: ○ Simple ○ Complex
Complex: ☐ Direction ☐ Distance
Secondary Sources: 1

Slits
Slit width (>0) ? : 0.2E-3
Source Separation ? : 0.5E-3
WaveLength (>0) : 0.55E-6
Distance to screen (>0) : 1
Range either side of the centre of the pattern (>0) ? : 5E-3
Model: ● Simple ○ Complex
Complex: ☐ Direction ☐ Distance ☐ Secondary Sources (2-20)

Slits Source Separation : 0.0005
Simplex Model Wavelength : 0.00000055
Distance : 1
Slits width : 0.0002
Range : 0.005

Table

Distance	Intensity
0	100
0.0002	69.9
0.0004	16.5
0.0006	2
0.0008	34.8
0.001	65.2
0.0012	55.2
0.0014	21.4
0.0016	2
0.0018	5.9
0.002	12.7

Again choose values for wavelength, slit-width, etc. that you could work with experimentally: you will want to check the computer's predictions against observations. Let the separation of the slits (distance between centres) be the same as the distance between sources you used in the previous investigation.

C2 *In what way(s) are the results of investigation 1 and 2 similar, and in what way(s) are they different?*

C3 *Now look at Figure C2 which shows the interference pattern formed when light passes through two slits (Young's experiment). Does it have features which are better represented by Investigation 2 than by Investigation 1?*

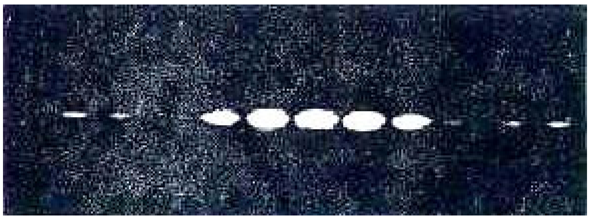


Figure C2 Two slit interference pattern

C4 *Can you account for the differences) between Investigation 1 and 2 using the sketches you drew in answer to questions A4 and A7?*

STUDENTS' MANUAL D - MEASURING THE WAVELENGTH

Although the apparatus you will be using may be labelled ' 3 cm wave equipment' , this is not a precise value for the wavelength of the radiation it emits.

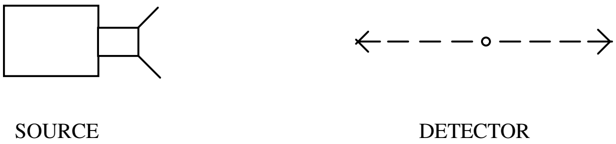


Figure Dl Measurement of wavelength in stationary wave system

To make any kind of comparison between theoretical predictions and experimental results, you will need to know the wavelength of the radiation more precisely. Probably the simplest way to do this is to set up a stationary wave system between the source and a metal reflector (Figure D1).

Move a simple diode detector (not one mounted in a horn) along the line between transmitter and reflector. Measure the distance for, say, ten minima of intensity. Remember that the distance between successive minima (or maxima) is half the wavelength.

STUDENTS' MANUAL E - SECONDARY SOURCES

idea we use to calculate the diffraction pattern due to a slit is Huygens' principle - that every point on a wave can be regarded as a source emitting secondary waves in all directions. For a single slit all we need to do to calculate the amplitude at P (Figure El) Is to add the contributions of all of the secondary sources, always of course paying due attention to the phase of each one.

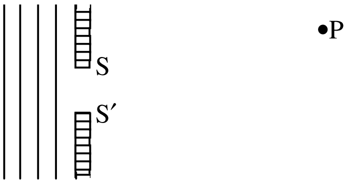


Figure E1 We imagine the slit SS’ to be made up of a very large number of secondary sources

Consider this statement of Huygens' principle:

> ' All points on awavefront act as point sources for the production of spherical secondary wavelets' .

Suppose you want to apply this principle to finding the intensity at P (Figure El).

E1 *Would a secondary wavelet originating near one end of the slit make the same contribution as one originating near the other end?*

E2 *If each point acts as a source of spherical wavelets would you expect any waves to reach Q (which is on the side the waves are coming from), after being diffracted by the slit?*

E3 *How many secondary sources do you think you should consider?*

The rest of this unit is concerned with the effect that the answers to these questions have on the fit between the predictions made by the model, and experimental observations.

Wavelength of ' 3 cm' waves

Because it is easier to make measurements using ' 3 cm' microwave radiation than on the very fine interference patterns produced by light, we shall use microwave radiation in the rest of this unit.

To test the fit between the predictions of a model and observations you will need to know the wavelength of the radiation emitted by the transmitter you will use. Note that for the older type of equipment labelled ' 3 cm' the wavelength is unlikely to be exactly 3 cm. The easiest way to make the measurement is to set up a standing wave pattern: See Manual D for experimental details.

STUDENTS' MANUAL F – IMPROVING THE MODEL

Your answers to questions E1 and E2 should have drawn attention to two simplifications of the model:

- assuming all the secondary sources are equidistant from P
- assuming that the secondary sources emit equally in all directions

These assumptions and the question ' How many secondary sources?' is each discussed in some detail below. You can use the computer to explore the effect of each one on the predicted intensity pattern.

a How many secondary sources?

More than one, clearly: otherwise we should have the same result as Investigation 1 – superposition of waves from POINT sources. When the problem is treated analytically the formula for intensity distribution is obtained by integration – which makes it possible to add the contributions of an infinite number of infinitely narrow slits. But when using a digital computer it is necessary to specify actual numerical values for such things. In the SIMPLE model the number of secondary sources is set to be two per slit. This is one of the aspects of the model that the COMPLEX model part of the program allows you to explore: you might expect that increasing the number of secondary sources from 2 to 3 will have a bigger effect than a change from 22 to 23.

b Direction

In its simplest form the model assumes that each of the secondary sources in the aperture (Figure F1) emits equally in all directions:

F1 *Light falls on the slit in Figure F1 from a source to the left. If the 'secondary sources' in the slit emit equally in all directions would you expect to see any Light if you Looked at the slit from A? From B? From C? From D?*

F2 *Do your answers, based on the assumption that each source emits equally in all directions agree with experience – if you were to look at the slit from behind (from D) would, you see any Light?*

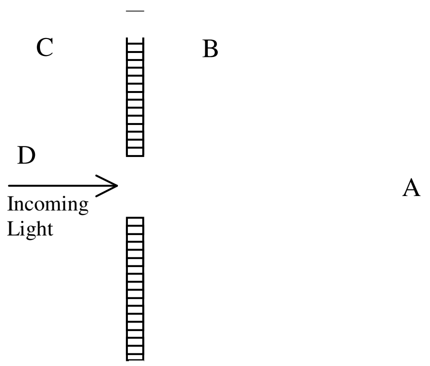


Figure F1 Diffraction by a slit

In fact this simple model must be corrected to take account of the fact that there is no wave in the ' backwards' direction. This is done by introducing a 'direction factor'. The amplitude of a secondary wave travelling in a direction making an angle F with the incident light is A(1 + cosF)/2. (In some books this is referred to as the Huygens obliquity factor).

F3 According to this formula, what is the amplitude:

a in the direction of the incident light (F=O)?
b at 90° ?
c at 180° (i.e. in the ' backwards' direction)?

When we do an experiment with light we are only concerned with diffraction through very small angles (because the slit is many wavelength wide), and so the direction factor can be safely ignored. But with 3 cm waves this may not be the case.

Of course if you are working with POINTS the direction factor does not apply; they are assumed to emit equally in all directions.

c Distance

In Figure F2 S_1 and S_2 are two equal sources.

F4 Which will be greater at P_0 – the amplitude due to S_1 or the amplitude due to S_2? Which will be greater at P_1? at P_2?

Figure F2

Remember that there are two conditions for a zero disturbance at a particular point: phase difference must be exactly ½, 1½, 2½ ... and the two amplitudes must be equal in magnitude. The amplitude of a wave varies as 1/d where d is the distance from the source. (It is the intensity that varies as l/d^2.)

F5 a In Young' s double slit experiment with light, what might be the maximum value of the ratio S_2P_2 / S_1P_2?

b What might this ratio be in an experiment with 3 cm waves?

The computer program allows you to investigate the effect of the three factors (distance, direction, number of secondary sources) – see Manual H. But first you should take some measurements on a real interference pattern using ' 3 cm' radiation – see Manual G.

STUDENTS' MANUAL G – MEASURING AN INTERFERENCE PATTERN

Now do a real experiment to measure the microwave radiation in a two slit interference pattern. Questions *F3*, *F4* and *F5* should have suggested conditions in which the DIRECTION and DISTANCE factors will be important

Figure G1 shows the arrangement suggested. Set it up in as open a space as possible: you do not want the pattern to be affected by reflections from the walls of the room etc.

The transmitting horn should be at least 1 m from the diffracting apertures. Use a microwave detector and light spot galvanometer to take measurements. It is better not to use a diode mounted in a horn, even though it may give a higher reading. Why?

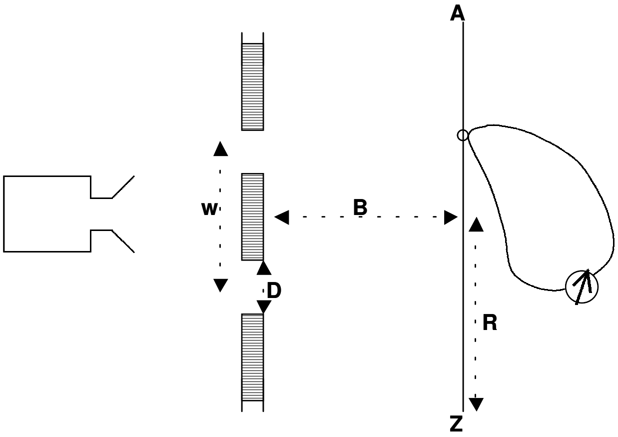


Figure G1 Investigating intensities in an interference pattern.

Move the detector along a line parallel with the screens. The distance B in Figure G1 is the DISTANCE you are asked to input to the program. SLIT WIDTH (D) should need no explaining. SEPARATION is the distance between slits, measured from centre to centre (W). RANGE is the distance R from the centre over which calculations are made. The program calculates the intensity at 25 equally spaced points in the range R.

Unwanted reflections

You must make sure that unwanted reflections are not affecting your measurements: you may find that the galvanometer reading changes as you move about. Stand well away from the apparatus when you actually take a reading.

You are advised to check, periodically, that the output of the transmitter has not changed. The simplest way to do this is to return to the first measurement you made, which will probably be in the centre of the pattern, every so often. (When you want to compare your measurements with the computer predictions you will need to express each value as a percentage of the central value).

Detectors

Because of doubts about the intensity of the response of microwave detectors (i.e. galvanometer reading may not increase linearly with signal strength) you cannot, unfortunately, expect very good agreement between the predicted and measured numerical values. Instead compare the gross features of the patterns: positions of maxima and minima; whether a minimum is actually a zero of intensity; the relative sizes of maxima; and so on.

STUDENTS' MANUAL H – TESTING THE MODEL

You can now use the COMPLEX model part of the program to explore the effect of each of the factors mentioned in Manual F. If you want to find the effect of DISTANCE from the slits on the calculated intensity pattern, rather than the effect of direction or of secondary sources, your responses to the questions should be:

Model
○ Simple
● Complex

Complex
☐ Direction
☑ Distance
☐ Secondary Sources (2-20)

You will have a chance to vary the model (e.g. to include the DIRECTION factor) while keeping the experimental conditions (wavelength, etc.) the same.

The program calculates the intensity at 25 equally spaced positions on either side of the centre of the superposition pattern. It does not give any information about intensity between these points, and interpolation may not be possible. The only way to be sure of the intensity at intermediate positions is to choose another RANGE so that calculations are done for a different set of 25 positions.

Note also that the COMPLEX model involves a very large number of calculations for each position - especially if a number of SECONDARY SOURCES are involved. The intensity of each point has to be calculated before any results can be given.

It is worthwhile investigating the effect that a small change in wavelength has on the predictions: your measurement of the wavelength of radiation used in your experiments (Manual D) may have an uncertainty of as much as 10%.

H1 *(For discussion). Which of the refinements to the model should be considered in accounting for the intensity distribution in a two slit interference experiment using ' 3 cm waves' taking measurements*

a *close to the slits (say 25 cm) ?*
b *far from the slits (1 m or more)?*

The model we adopt and the degree of sophistication needed obviously depend on the use we want to make of it.

H2 *Which factors do you think need to be considered in accounting for the results of a Young' s two slit experiment with light?*

This unit has concentrated on one particular phenomenon in physics and the model used to account for it. You will have seen that the simple model may need to be, modified if it is to give acceptable predictions. This is a fairly general point about the way in which physics works; and in this final question you are invited to think of similar instances. For example – the kinetic theory of the ' ideal gas' to explain the behaviour of the gases – the mass and spring analogue for electrical resonance in an LC circuit. In these and other examples, the simple model gives a useful way of thinking about the phenomena and is an essential first step; but because it is idealised, it may not account for the detailed observations of a real experiment.

H3 *What modifications are necessary in these cases? Can you think of similar examples?*