Radio telescopes

Science content

Electromagnetic waves, reflection, converging mirror, wavelength, beamwidth, star, galaxy.

Science curriculum links
AT15 Using light and e/m radiation
AT16 The Earth in space

Syllabus links
○ GCSE Science, Physics

Lesson time
1–1½ hours

Links with other SATIS materials
1208 Are you made of Stardust?

NERIS
Search on
RADIOTELESCOPES or
TELESCOPES

SUMMARY

The unit uses radio waves to exemplify some of the properties of electromagnetic radiation. It considers the design of radio telescopes and the problems of obtaining good resolution, defining the 'beamwidth' of a radio telescope. Comparisons are made with other radio communication devices such as TV satellite dishes, microwave links etc.

STUDENT ACTIVITIES

☐ Interpreting photographs taken with optical and radio telescopes;

☐ Drawing a cross-section of a paraboloid, showing rays reflected by it;

☐ Calculating the beamwidth for a range of communication devices.

AIMS

☐ To link with work on electromagnetic radiation and astronomy

☐ To show some of the scientific principles involved in the design of radio telescopes

USING AND ADAPTING THE UNIT

☐ The unit in its entirety is suitable for more able students from the fourth to lower sixth forms. (Q7 requires an understanding of trigonometry.)

☐ Q1 and the 'Discussion activity' may be used with a wider range of students.

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Teaching notes

The resolving power of a telescope, its ability to distinguish between two objects close together, depends on the wavelength divided by the diameter of the aperture. To get the same resolution as an optical telescope, a radio telescope working at 1 metre wavelength would need to be a million times larger.

Beamwidth ($60\lambda/D$), the term used in the unit to describe the accuracy with which a radio telescope can be directed, is proportional to its *resolving power* (measured in degrees it is approximately $70\lambda/D$).

To make 'larger' radio telescopes, astronomers now use an array of radio telescopes and combine the data by interferometry.

Discussion activity

Good dictionaries and encyclopaedias may prove helpful, although students may compile their glossaries using the unit alone.

More detailed answers are provided here than would be expected from students themselves.

Radio waves Electromagnetic waves ranging in wavelength from millimetres to a few kilometres (frequencies of 10^{12} to 10^{4} hertz).

Radio telescope A special aerial/antenna for receiving radio waves from space.

Galaxy A system of stars.

Optical telescope Receives and focuses light.

Paraboloid A geometric surface with the shape of a parabola: $y^2 = 4ax$.

Focal length The distance from the base of the reflector to the focus.

Beamwidth A measure of the antenna's directivity; the angle between the two directions in the main beam at which the power response has fallen to half its maximum value.

Array of radio telescopes Several radio telescopes, pointing towards a single object and connected to a single receiver.

Acknowledgements
Figure 1 reproduced by permission of J. O. Burns.
Figures 5, 6, 7, 8 and 9 supplied by F. Graham-Smith.

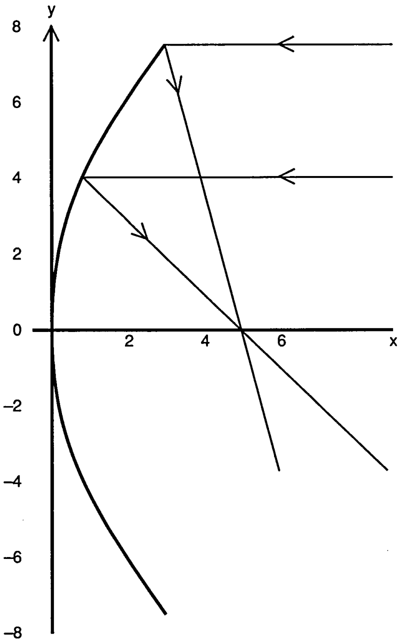
Answers to the questions

Q1 *Radio emission comes from outside the visible galaxy. (It is emitted by hot gas ejected from the central region in two oppositely directed jets.)*

Q2 *(a)* $y^2 = 20x$

(b) 0, (1.41) 2.00, 3.16, 4.47, 6.32, 7.74

(c) and (d) See diagram.



Q3 *(a) 0.27 cm (2.7 mm),*

(b) 0.1 mm.

Q4 *Beamwidth of the JCMT = 60 × 1/ (1000 × 15) = 0.004° = 14.4 seconds.*

Astra satellite dish = 60 × 2.7/60 = 2.7°

Lovell telescope = 60 × 0.21/(76.2 × 100) = 0.16°

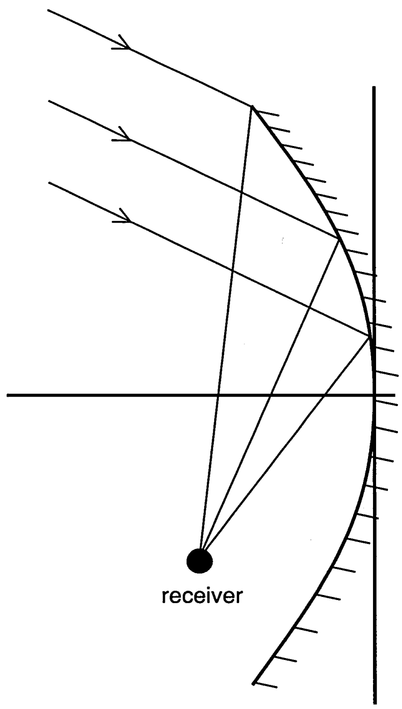
Microwave link = 60 × 3/ 200 = 0.9°

Airport radar = 60 × 10/(100 × 2) = 3° vertical,

60 × 10/ (100 × 5) = 1.2° horizontal.

Q5 *There is 4° between satellites. The beamwidth of a 40 cm dish = 4°. There will be no interference from Copernicus only if the dish is correctly aligned.*

Q6 *(a)*



(b) The dish may be mounted nearly vertically.

Q7 *Assuming a beamwidth of MERLIN of 0.1 second as given in the text (in practice considerably less), students will need to use* $s = r \sin \theta$ *or* $s = r\theta$, *(if* θ *is small and measured in rads) where s is the distance across beam, r is the distance from the radio telescope*

(a) s = 5000 km × sin (0.1/3600)°
= 0.00242 km = 2.42 m

(b) s = 400000 × sin (0.1/3600)°
= 0.194 km ≈ 200 m

(c) s = 1 000 000 × sin (0.1/3600)°
= 0.485 light years ≈ 0.5 light years

Radio telescopes

Reading, discussion, questions and calculations. A4 graph paper is needed for Q2.

Radio telescopes are really no different from the satellite dishes people use to watch TV programmes. This unit explains how they work.

Radio waves from space were discovered by an American, Karl Jansky, who published his discovery in 1932. However, **radio telescopes**, which are aerials (antennas) specially designed for studying radio waves from space, were not built until after the Second World War.

Discoveries made with radio telescopes have helped to revolutionise our understanding of the universe. Astronomers found **galaxies** so far away that they could not be seen with ordinary **optical telescopes**. Radio waves from these giant systems of stars take billions of years to reach the Earth. They give information about what the universe was like a very long time ago. Such infomation has led astronomers to believe that the universe began with a 'big bang'.

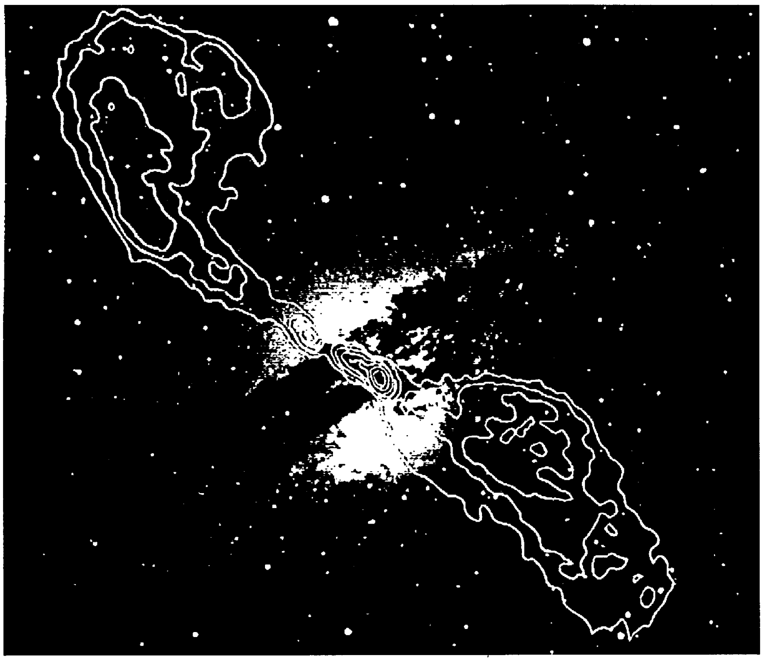


Figure 1 A galaxy, seen with an optical telescope and with a radio telescope. The contour lines show the strength of the radio emission

> ***Q1** Describe the differences you see between the shape of the galaxy seen by an optical telescope and a radio telescope in figure 1.*

An investigation with radio waves

- Try using a portable radio inside a cardboard box.
- Then cover the box with cooking (aluminium) foil.
- Try this with the radio tuned to long, medium, and short (VHF) wavelengths.

What do your observations tell you about the properties of radio waves compared with light waves?

Discussion activity

What do the following terms mean? Find where they are used in the unit. Work with a partner and decide on the best definitions you can. Then write them down.

radio waves
radio telescope
galaxy
optical telescope
paraboloid
focal length
beamwidth
array of radio telescopes

Telescopes – what do they do?

Optical telescopes collect light from distant objects and focus it, either within the eye or on to some recording instrument such as a camera.

Some stars, including our own Sun, emit radio waves as well as light. These radio waves can be collected by a radio telescope, which focuses them on to a radio receiver. Astronomers can then measure their strength and other characteristics.

Light and radio are both electromagnetic waves, but with different wavelengths.

Light

red	700 nanometres
yellow	600 nanometres
blue	400 nanometres

Radio

VHF	3 metres
TV	½ metre
microwaves	30 cm to 3 cm

(1 nanometre = 0.000 000 001 metre = 10^{-9} metre)

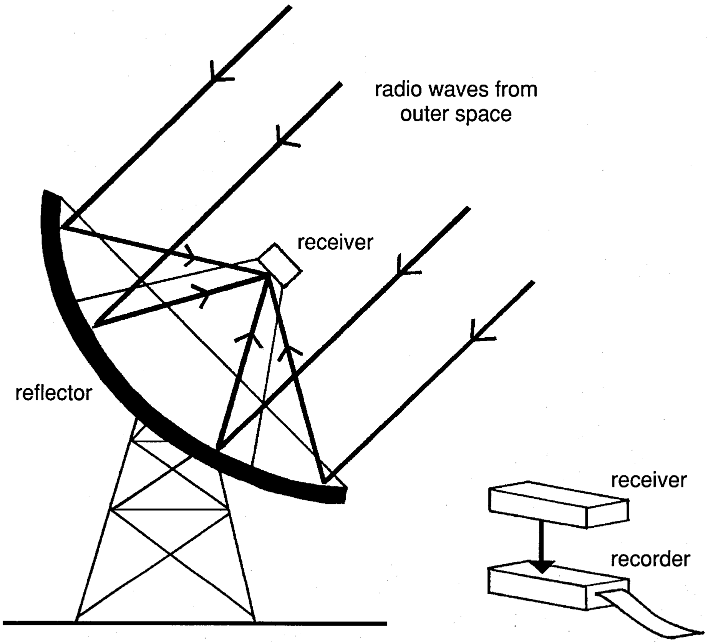


Figure 2 How a radio telescope works

How does a radio telescope work?

A radio telescope is a huge aerial for collecting weak radio signals from outer space. Radio telescopes and TV satellite dishes both use a large metal dish to reflect the radio waves onto the receiver. These dishes are made in the shape of **paraboloids**. The radio receiver is positioned at the **focus** of the paraboloid.

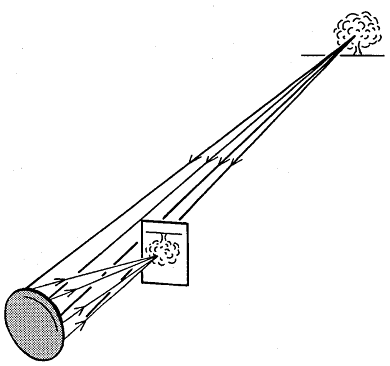


Figure 3 Projecting an image on a screen with a converging mirror

Have you tried using a converging (concave) mirror to focus an image from a distant point of light on a screen?

Reflector radio telescopes work in much the same way except the receiver replaces the screen.

The screen must be at the focus of the mirror to get a sharp image. The distance from the mirror to the screen is the focal length of the mirror.

The shape of the mirrors you use in school laboratories is part of the surface of a sphere. (They are known as spherical mirrors.) You can get a sharper image with a mirror curved in the shape of a paraboloid (a parabolic mirror). This is the shape used in reflector telescopes.

The **focal length** of the paraboloid is the distance from the base of the reflector to the **focus.** If this distance is written as ***a*** the shape of the paraboloid is described by the coordinates ***x*** and ***y***, which are related by:

$$y^2 = 4ax$$

Q2 *A paraboloid radio telescope has a focal length of 5 m.*

(a) What is the equation for this telescope?

x (m)	0	0.1	0.2	0.5	1.0	2.0	3.0
± y (m)		1.41					

(b) Copy the table and write in it the values of y.

(c) Draw a cross section of the paraboloid reflector with aperture 15 m (and focal length 5 m) using a scale of 1/100.

(d) Draw rays parallel to the axis and reflected at the surface. (All rays are reflected according to the simple law: angle of incidence equals angle of reflection.) All rays should then reach the focus.

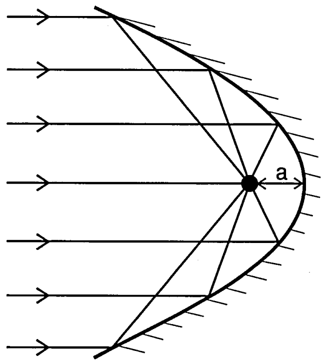


Figure 4 The shape of a paraboloid

The surface of a practical radio telescope must follow this shape with an accuracy depending on the radio wavelength being received. An accuracy of about *one tenth of the wavelength* is usually sufficient. The Lovell Telescope at Jodrell Bank in Cheshire works well at a 21 centimetre wavelength. Some radio telescopes can be used at wavelengths of less than one millimetre. These must have very accurate surfaces, and so they are comparatively small.

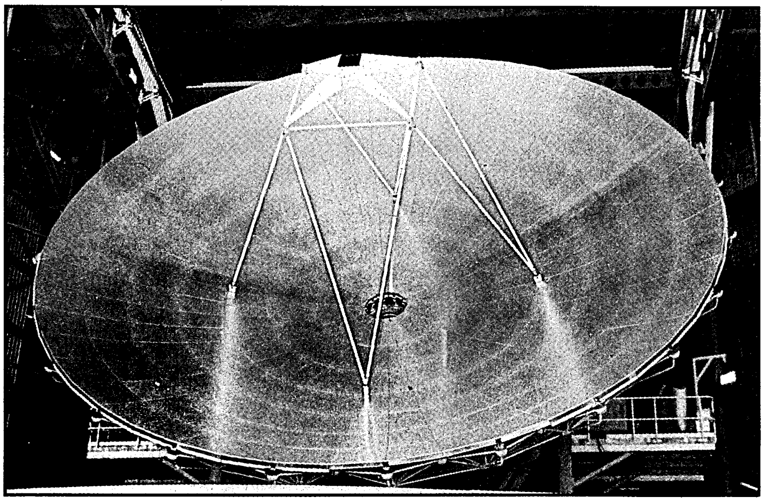


Figure 5 The 15 metre diameter James Clerk Maxwell Telescope on Mauna Kea, Hawaii completed in 1987. It is used to receive radio waves of millimetre wavelength. These waves are absorbed by water vapour, so the telescope is sited on a high mountain, above the lower atmosphere

Table 1 Diameters of some radio wave receiving dishes and typical wavelengths at which they work

Receiver	**Typical wavelength** λ	**Diameter** D
Astra TV satellite dish	2.7 cm	60 cm
Microwave link (Post Office Tower)	3 cm	2 m
Airport radar	10 cm	5 m × 2 m*
James Clerk Maxwell telescope in Hawaii	1 mm	15 m
Lovell telescope at Jodrell Bank	21cm	76 m

* Note that airport radar uses an elliptical reflector. The smaller vertical width gives a broader beam in this direction.

> *Q3 Look at table 1. How accurate must the surface of each of the following reflectors be? (The surface of a radio telescope reflector must be accurate to one tenth of a wavelength.)*
> *(a) An Astra TV satellite dish.*
> *(b) The James Clerk Maxwell telescope in Hawaii.*

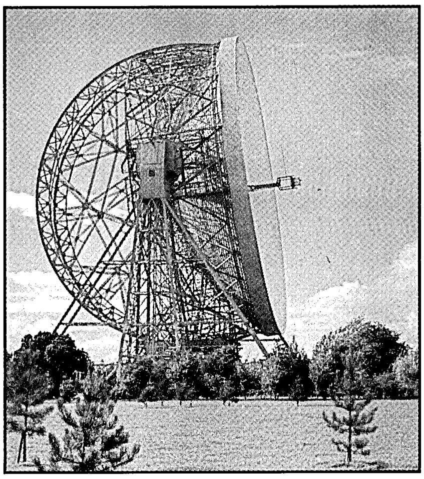


Figure 6 The Lovell radio telescope at Jodrell Bank, Cheshire

What is beamwidth?

A radio telescope is most efficient when it is pointing exactly in the direction of the source of the radio waves. This might be a star or a space probe. A small error in direction does not matter as long as it is within an angle called the **beamwidth**.

The beamwidth depends on the diameter (***D***) of the telescope and the wavelength (λ) of the radio waves.

This formula gives an estimate of the beamwidth

$$\textbf{beamwidth (degrees)} = \frac{60\,\lambda}{D}$$

(λ and D in the same units)

The bigger the radio telescope the smaller the beamwidth and the better it can separate radio sources that are close together in the sky.

> *Q4 Calculate the beamwidth of*
> *(a) the James Clerk Maxwell telescope,*
> *(b) one other receiver from table 1.*
>
> *Q5 Two TV satellites, Astra and Copernicus are at 19° east and 23° east respectively. Could viewers receive Astra programmes on a 40 cm dish without interference from programmes broadcast by Copernicus?*

Steering a radio telescope

An astronomer may need to study a series of objects in different parts of the sky and the telescope must move to point in any direction. Most are mounted on a circular track, for azimuth motion, while the reflector can move to any elevation.

Tracking a star

The Sun and the stars move across the sky as the Earth rotates. A radio telescope has to follow this movement. The pointing direction of the telescope is measured continuously. A computer checks the direction is the required one. Differences between measured and required directions are used to control the steering motors.

The bigger the better but . . . .

Radio waves are very much longer than light waves. Radio telescopes need to be much larger than optical telescopes to tell individual sources apart. The largest steerable radio telescope is in Germany and is 100 m across. A much bigger radio telescope would be impossible to steer. However, radio astronomers have devised some ingenious solutions to the problem!

The dish of the world's largest reflector telescope cannot be moved. It is built in a bowl-shaped valley at Arecibo, in Puerto Rico. Its reflector surface is part of a sphere rather than a paraboloid and points directly upwards. The telescope beam is directed over a range of angles by moving the receiver sideways, while the reflector stays still.

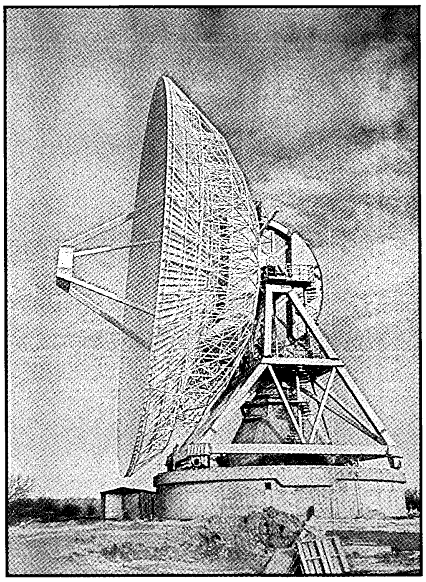


Figure 7 A 32 metre radio telescope at Cambridge. Electric motors drive the azimuth motion (round the azimuth track) and the elevation (through the vertical wheel)

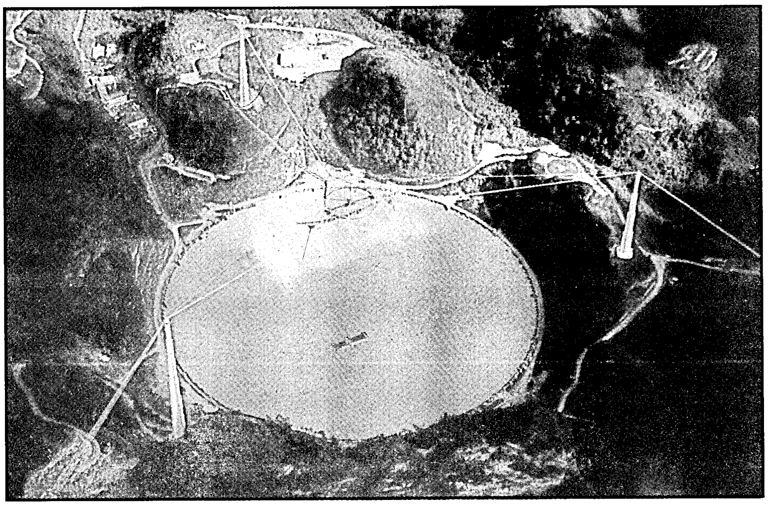
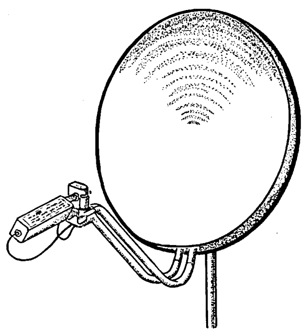


Figure 8 The Arecibo radio telescope

Q6 You may have seen TV satellite dishes with offset receivers.



(a) Draw a diagram to show how the radio waves reach the receiver.

(b) Suggest an advantage of this arrangement for mounting the dish on a wall.

Radio waves can be collected over a larger area with an array of antennas connected to a single radio receiver.

Another way of collecting radio waves falling on a large area is to use an **array of radio telescopes**. That means several radio telescopes, all pointing towards a single object, connected to a single receiver through microwave communication links. The beamwidth depends on the maximum spacing between the telescopes.

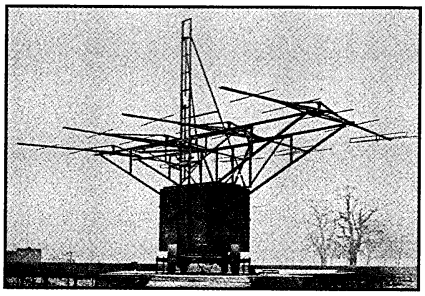


Figure 9 An array of antennas used in pioneering radio astronomical observations by J. S. Hey

A multiple telescope array called MERLIN extends from Jodrell Bank, near Manchester, to Cambridge, a distance of 220 kilometres. At a wavelength of 6 centimetres the beamwidth is less than 0.1 second. This array can be used to make maps of the radio emissions from galaxies and quasars with better detail than the largest optical telescopes.

Arrays of radio telescopes can be thousands of kilometres long. Each radio telescope records radio waves from the same object. These recordings are played into a single receiver.

MERLIN stands for Multi-Element Radio-Linked Interferometer Network.

Larger arrays of radio telescopes will have to extend into space. Astronomers would like to launch a series of radio telescopes into orbit around the Earth or even into orbit around the Sun. Such a telescope array would have a diameter of several hundred million kilometres across.

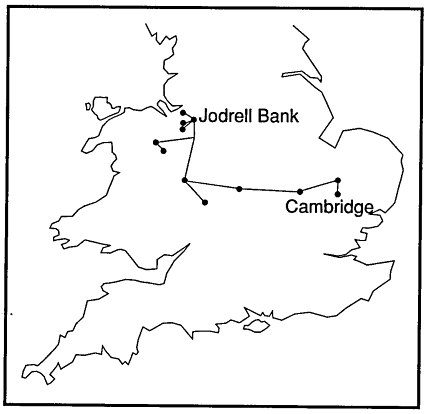
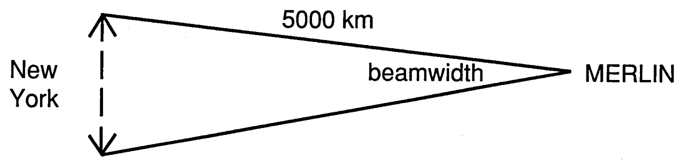


Figure 10 A map of MERLIN

A more challenging question

Q7 *How accurately would the beam of MERLIN (0.1 second) define the position of a radio emitter*
(a) over New York, 5000 km away,



(b) on the surface of the Moon, 400 000 km away,
(c) in a galaxy one million light years away?

Answers to the questions are given in the *Teachers' Notes.*