# Building your own telescopes

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1. Introduction.

In these pages of text we are going to describe the types of glass lenses that you would most frequently encounter and we will explain how they affect light that shines through them.

We shall describe how to design and build a REFRACTING telescope – one that gathers light by means of a lens at its front end. We shall not describe the REFLECTING telescope because that type of telescope gathers light by means of a hollow-curved mirror. We do not sell such mirrors.

We will describe how to design and build an ASTRONOMICAL telescope, which is the simplest type of telescope to build; it gives a view that is upside down and back-to-front. We shall describe first the straight-through astronomical telescope and then we shall describe briefly how to build a right-angle telescope (an elbow telescope) which can be more convenient for looking at objects that are high in the sky.

Once we have dealt with the astronomical telescope we shall describe the theory and practice of building a TERRESTRIAL telescope – a telescope that gives a view that is the right way up and the right way round. You can ignore this long section of text if your interest is confined to astronomy.

2. The shapes of lenses.

All the lenses that you are likely to need are circular. The amount of light that passes through them depends on the diameter of the lenses, so larger lenses tend to give a brighter view than smaller lenses.

The amount of light that passes through a lens is directly proportional to the area of the lens. A lens that has double the diameter will allow FOUR TIMES the amount of light to pass through it; this is because the lens is not only twice as wide but it is also twice as high, so its area is four times the area of the smaller lens.

What happens to the light once it has passed through the lens will depend upon how the front and rear surfaces of the lens are curved. Figure 1 shows the cross-section of the five most common types of lens. (The cross-section is how each of these types of lens would look if you sawed it in half across its diameter then looked at the sawn edge.)

![Types of Lenses Diagram](image)

Lenses that are thicker at the middle than at the edge can be used as magnifying glasses. If you look at a page of text through such a lens the text will appear bigger and closer than
without the lens. Such lenses are called POSITIVE LENSES because they have a positive effect upon the size of text seen through them.

In figure 1 you can see that the biconvex lens is a positive lens. Its name derives from the fact that both faces of the lens have been ground and polished to give a convex shape. In the diagram we have shown the curvature of both faces as being equal, so such a lens would be described as being an ‘equal biconvex’ lens. In real life it is often the case that the two faces have different degrees of curvature, so the lens would be described as an ‘unequal biconvex’ lens.

You can see that the plano-convex lens is also a positive lens. The ‘plano’ refers to the fact that one surface is accurately flat. (In optics the word ‘plane’ as an adjective means ‘it is flat’. The word ‘plane’ as a noun means ‘an accurately flat surface’. ) You can use a plano convex lens as a magnifying glass.

Lenses that are thinner in the middle than at the edge cannot be used as magnifying glasses. If you look at a page of text through such a lens the text will appear smaller and farther away than without the lens. Such lenses are called NEGATIVE LENSES because they have a negative effect upon the size of the text seen through them.

In figure 1 the biconcave lens is a negative lens. It is shown as having both surfaces equally curved. Again, biconcave lenses more frequently have a different curvature on their two faces. Such lenses would be known as ‘unequal biconcave’ lenses.

The plano-concave lens is also a negative lens.

The meniscus lens is a mongrel version of the positive and negative lenses. If the meniscus lens is thicker at the middle than at the edges then it will be a positive lens and so it could be used as a magnifying glass. This is because the degree of curvature is greater on the convex face than on the concave face.

If the meniscus lens is thinner at the middle than at the edges then it will be a negative lens and so it cannot be used as a magnifying glass. This is because the degree of curvature is greater on the concave surface than on the convex surface, so the concave effect wins.

(You may guess that meniscus lenses are the sort of lenses that are most frequently used in spectacles. Positive meniscus lenses are used to correct long-sightedness – hypermetropia – while negative meniscus lenses are used to correct the condition of short-sightedness – myopia.)

3. Does it matter which way round I use a lens?

Yes it does.

Whatever optical device you are building it is vitally important to install the lenses the right way round. The only time that it would not matter is if you were using an equal biconvex lens or an equal biconcave lens, and it is very unlikely that you would ever encounter one of those. In all other circumstances the way that the light behaves as it passes through the lens depends vitally upon which direction the light passes through the lens. If you install the lens the wrong way round your telescope will not give a clear, well-focused view.
4. Refraction as light passes between air and glass – a change in direction.

When light passes from air, which is a transparent medium of low density, into glass, which is a transparent medium of much greater density, it alters the direction in which the light is travelling. You can see this if you look at figure 2.

In figure 2 you can see that the light that reaches the lens near the edges is bent inwards, which causes it to be brought to a focus some distance behind the lens. The degree of bending of the light path gets less, the nearer to the centre of the lens the light strikes the lens.

Figure 2 shows that the light that strikes the lens at its exact centre is not deviated at all – it passes straight through. This is because the light is striking the glass surface at an exact right-angle. It is a fact that whenever light strikes, or leaves, glass at an exact right-angle its direction of travel is not altered.

If you look at figure 2 you will see that the light that strikes the lens at its edge is not hitting the glass at a right angle, but at an angle that is less than 90 degrees. At places nearer to the centre of the diameter of the lens the angle at which the light strikes the surface of the glass becomes greater – nearer to 90 degrees – so the amount of bending of the light becomes less.

This process of light bending as it passes from air into glass is called REFRACTION.

You should also understand that the refraction also happens as the light leaves the glass and passes into air; this is also shown in figure 2.
5. Rays of light and ray diagrams.

Whenever diagrams are used to describe the passage of light through lenses or prisms the accompanying text will use the word ‘rays’ to describe the path that the light follows. In the diagrams, such as our figure 2, the ‘rays’ of light are shown as straight lines that are bent as they pass in and out of the lenses and prisms.

These straight-line diagrams that illustrate how the light travels are called RAY DIAGRAMS, but science books never explain what these ‘rays’ of light really are, so here is that explanation:

Light ‘rays’ are lines drawn on a diagram to show the direction in which the light waves are travelling.

Light travels through space as WAVES of light. These light waves start at the source of the light (perhaps the tip of a leaf on a distant bush, or a distant electric light or a star) and they spread out from that source in all directions, much as the ripples on a calm pond radiate outward from the point where a tiny pebble is dropped into the pond. All the ripples are curved and they are circles that have as their centre the source of their energy.

If you look at the waves on a calm pond you can see that the diameter of these ripples increases as they travel away from the point where the pebble was dropped into the water; as they travel, the WAVE-FRONT becomes less curved. At a very great distance from its source the wave has such a huge radius that, for all practical purposes, the wave front is straight, rather like the waves that you see lapping at the sea shore.

| The direction in which any wave is travelling is always a straight line drawn at right-angles to the front of the wave. |
| This imaginary straight line is the line that is shown on a ray diagram, so light ‘rays’ are the directions in which the waves of light are travelling. |

As light waves radiate out from their source the curvature of the light waves becomes less pronounced. If we observe the source of that light (perhaps the tip of the leaf on the bush) using a pair of binoculars we need to adjust our binoculars so that the view is in focus. As we move farther away from the object we will need to re-focus to give us our new view.

The reason that we need to re-focus our binoculars is that the wave-front of the light reaching the front lens of the binocular is less curved because we have moved farther away. If we move far enough away from the object which we are viewing the wave-front of the light will have such a tiny degree of curvature (as seen across the width of the binocular lens) that the wave-front will be, for all practical purposes, flat.

Beyond that distance from the object that we are viewing we will not need to re-focus the binocular if we move farther away because the wave-front will continue to be flat. In technical jargon we say that the object that we are viewing is ‘at infinity’ because the light coming from it, and into our binocular, behaves as though it were coming from an infinitely huge distance away. For a pair of binoculars the distance beyond which everything seems the same distance away is about 1000 metres – once you have focused the binoculars on an object at that distance you will not require to alter the focus for an object 5000 metres away – it will be, in effect, at INFINITY.

The same effect is seen when you focus a camera. If the camera has a focus ring on its lens it will be marked in terms of distance. The focus ring has the infinity symbol (∞) when the lens will be adjusted to focus scenes that are more than, say, 1000 metres distant.

If light is arriving at a lens from a great distance away it follows that the wave-front of the light will be going in exactly the same direction right across the width of the lens. The ‘rays’ of light (i.e. imaginary lines drawn at right-angles to the wave-front) will all be PARALLEL for light that strikes the lens. This is the situation in fig.2A and fig.2B.
7. White light and dispersion - chromatic aberration.

Sunlight and the light that comes from the filament of an electric light bulb can be split into rainbow colours if it passes through a suitable prism. The reason that this happens is because the light is made-up of all the colours of the rainbow. Sunlight, and the light from a light bulb, is called WHITE LIGHT.

Look at figure 2A, which shows the front part of a telescope.

In fig.2A white light from a very distant object that is somewhere to the left of the diagram passes into the glass lens and is bent (refracted) so that it is brought to a focus some distance away from the rear surface of the lens.

The degree of bending of the white light depends upon the degree of curvature of the glass lens; a chubby lens will bring the light to a focus close to the lens because the glass surfaces are strongly curved, whereas a lens that has only a slight degree of curvature will cause less bending (refraction) so the light will be focused a much greater distance from the lens.

Unfortunately there is another, more subtle effect at work. The degree to which light is bent also depends upon the wavelength (the colour) of the light that is passing through the glass lens. Blue light (shorter wavelength light) is bent the most, while red light (longer wavelength light) is bent the least. All the other colours are bent at differing amounts between the two extremes of blue and red.

As you can see in figure 2A the blue component of white light is brought to a focus slightly nearer to the lens than the green component. The red component of the white light is brought to another focus, slightly farther away still from the lens.

This separation of the colours in white light is called DISPERSION. The verb ‘to disperse’ means ‘to spread apart’, or ‘to separate’ (Example: “The mob was dispersed by a water cannon” or “The seeds of a dandelion are dispersed by the wind”.)

What this means in practical terms is that it would not be possible to bring this telescope to a sharp focus. If you were observing, say, a distant tree you would see the tree surrounded by rainbow colours. Worse still, if you were looking at a star in a clear night sky you would see the star as a coloured blob, surrounded by rainbow colours.
The effect of false colours spoiling the sharpness and purity of the view through the telescope is called CHROMATIC ABERRATION and it was the bane of the life of early astronomers, who just could not get a clear view of stars or planets.

Another factor that has a subtle effect upon the way that light is focused by a lens is, of course, the nature of the glass itself – to be precise it is the DENSITY of the glass that also decides the degree of bending of the light for a given curvature of the lens.

Glass that is of high density, such as the so-called FLINT glass bends the light more than a lower density glass, such as CROWN glass.
8. Glasses of varying dispersive power – a solution to chromatic aberration at last.

Flint glass is a dense glass so it has a high dispersive power. This means that when white light (daylight, starlight) passes through a prism made of flint glass the light is separated into its individual colours. This display of rainbow colours is called a SPECTRUM. Using a prism made of flint glass is ideal if you want to have a spectrum where the colours are well spread-out.

Crown glass is less dense than flint glass, so its dispersive power is less than that of flint glass. Crown glass would be a bad choice if you wanted to make a prism that was intended for producing a spectrum from white light.

The problem of chromatic aberration in a lens arose because, even if crown glass were used to make the lens, there would still be significant dispersion when the light was brought to a focus by the lens. This always resulted in a rainbow hue being present around a star when it was viewed through the telescope and a poorly focused view.

The problem was solved with the invention of the ACHROMATIC lens.

Figure 2B shows an achromatic lens and it shows, diagrammatically, how the lens works.

As you can see, the lens is made of two elements.

The front element, which is nearest to the object of interest (a distant tree or a star) is just the sort of lens that you would expect, it is a POSITIVE (biconvex) lens nicely made of crown glass, to minimize dispersion.

The rear element (the element that is always hidden inside the telescope) is made of the more dispersive flint glass. You can see that the shape of this rear element is the opposite sort – it is a NEGATIVE lens, which means that it will still produce rainbow colours, but these rainbow colours will be the opposite way round to the rainbow colours produced by the front element.

You can see from the diagram that the front element will have a much more powerful bending effect on the light because it has TWO highly curved surfaces, whereas the rear element has only one highly curved surface, so it does not undo the good work done by the front element in focusing the light.
The fact that the rear element is made of a more dispersive glass means that this lens can undo the chromatic aberration caused by the front element because the chromatic aberration caused by the rear element is in the opposite sense to that caused by the front element, even though the rear element does not bend the light so strongly.

The overall effect of all these shenanigans is that all the colours of the spectrum eventually re-combine at the place where the light comes to a focus (the FOCAL POINT), so there is no dispersion when the telescope is brought to a focus, so those nasty rainbow colours have disappeared and the observer can see a crisply focused view through the telescope.

It has to be admitted that there are still some tiny traces of false colour when you use an achromatic lens. It turns out that you can only bring TWO colours to an exact focus with a two element lens (known as a DOUBLET LENS). The lens designer usually chooses to bring blue and yellow together at the same focus, which leaves red and green very slightly out of focus. This effect is so tiny that it is invisible for all practical purposes.

If it is essential to bring THREE colours together at precisely the same focus the lens designer must produce a lens with THREE elements (a TRIPLET LENS). These lenses are known as APOCHROMATIC lenses.

As you can imagine, a triplet lens is a much more expensive item, because three different types of glass must be used and the lens has six different surfaces that must all be accurately ground and polished, rather than the four surfaces involved in making an achromatic (doublet) lens.

If you are going to make your own telescope then you will have to acquire an achromatic lens as the OBJECTIVE lens of your telescope (that is, the lens that gathers light from the OBJECT of interest that you are viewing). The objective lens is the big lens at the front of a telescope or binocular.

It is easy to tell if a lens is an achromatic doublet just by looking at it. As you can see in fig.2B the edge of the lens is thicker that a singlet lens because the rear element is thick at its edge, so an achromatic doublet is always a thick and heavy lens. Also looking at the edge of the lens, you can clearly see the join between the crown element and the flint element.

Achromatic doublets come in two formats – cemented and air-spaced.

A cemented doublet has the crown and flint elements glued together, which makes the lens relatively easy to handle. The glue (the ‘cement’) is transparent and the thickness of the glue is just about zero, so the glue does not spoil the performance of the lens.

Traditionally the glue was CANADA BALSAM, which was a natural resin that had been decolourised then dissolved in an organic solvent such as toluene. Canada balsam had two major advantages: it would soften when you heated it gently, so you could separate the two elements of the lens if the balsam showed signs of getting old.

The other major advantage of Canada balsam was that it never really set hard; it was forgiving of changes in temperature and consequent differential expansion and contraction of the crown and flint elements.

Nowadays Canada balsam has sadly given way to modern adhesives that set by the application of UV light. These adhesives are colourless and very good, but they seem to be less tolerant of differential expansion, with the result that peculiar, fractal-like patterns can occur within the adhesive, where it has started to crack-away from the two mating glass surfaces. Unfortunately these modern adhesives cannot be undone by heating, so it is impossible to separate the crown and flint. Once the adhesive has developed a flaw you need to replace the lens.

An air-spaced doublet does not have any adhesive between the two elements, so you can take them apart. This is both a blessing and a curse, because if you clean the lens you need to take great care, when you re-assemble the lens, not to leave any specks of dust or lint between the mating surfaces.

Another factor which is important with the larger air-spaced doublets is that you must have the two elements in the same relative positions when you put them back together again. When the manufacturers test the lens they will rotate the two elements relative to one another until the lens gives its optimum performance. Be aware of this and mark the edges of the doublet with a pencil, so that you know how to re-assemble it.

Objective lenses are usually cemented up to a diameter of, say, three or four inches. Larger doublets are air-spaced to allow for differential expansion and contraction.

Small air-spaced doublets are usually assembled in a metal cell with their mating surfaces touching – the layer of air between the two glass surfaces is microscopically thin. The larger achromatic doublets have three small metal spacers arranged equally at the edges to prevent the crown and flint elements from grinding against each other. These little spacers are usually made of thin aluminium or lead foil. The thickness of these spacers does matter because they influence the thickness of the air gap between the two elements, so don’t be tempted to replace them.
10. Problems in handling your achromatic objective lens.

We want you to have a happy time when you are making your telescope, so we need to warn you about the possibility of wrecking your achromatic objective lens.

As we told you earlier, flint glass is denser than crown glass; it is also much more fragile. Flint glass is crumbly and it is very easy to scratch it or to crack it.

A major problem can arise when you are putting your new achromatic doublet into the metal lens cell that you have made for your home-grown telescope. The lens cell needs to be large enough inside so that the objective lens will slip into it easily and not be 'pinched' on cold nights, when the metal cell contracts due to the cold. The danger is that the doublet lens will turn slightly sideways as you slide it into its cell, then jam against the sides of the cell.

Once the lens has become jammed into the cell it is all too easy to flake a large scab of glass off the flint element as you try to get the lens out of the cell. If that happens then (costly) replacement of the objective lens is the only remedy.

The way to overcome this problem requires an extra day's machining at the lathe.

Make a thin, light-weight capsule for the objective lens, probably machined from thick-walled alloy tube. This capsule needs to have two components: a thin, inner sleeve that is open at one end so that you can fit it around the lens, with a slight lip at the other end, so that the lens cannot fall out.

Also make an equally thin outer sleeve that slides over the open end of the inner sleeve, with a lip at the end, so that the lens cannot fall out of that end either. By that means the glass lens is safely stored in a metal capsule, which will stop the lens from jamming as you slide this assembly into the lens cell.

The extra day or two spent making a lens capsule for your objective lens is well-worth the time and effort – having to replace your wrecked and expensive objective lens is a bitter experience.
11. Starting to build your astronomical telescope.

Technical point: ‘Object’ and ‘Image’:
In this document the words ‘object’ and ‘image’ are in use when describing the way that lenses work.

An object is something that is viewed by a lens. Once the light from this object has passed through the objective lens it is brought to a focus by the lens to produce an image of the distant object at the focal point of the lens. (If you were to hold a piece of white card at the focal point you would see, on the card, an inverted, coloured picture of the object that is being viewed by the lens.)

The image that is produced by the objective lens becomes, in turn, the object that is viewed by the eyepiece lenses. The light from this object is transmitted through the eyepiece lenses and becomes the image that is viewed by the observer’s eye.

Introduction.

In the following article we describe how to make the various parts of an astronomical telescope and we imply that the telescope will be made of metal tube and that you, the constructor, have access to a well-equipped workshop, complete with a centre lathe.

Certainly it is true that if you plan to make a polished brass telescope such as those that we make then you will need a lot of equipment, but there is no optical or practical reason why a telescope has to be made of metal or, indeed, have round tubes.

If you are keen to make a telescope then it is perfectly alright to make the telescope out of timber and have a square-section main tube, indeed there are powerful advantages in going down the timber route.

If you do not have the facilities necessary to work with metal tubes then your materials of choice include thin plywood sheet. Good quality 3-ply is what we would recommend; avoid the scabby stuff that D.I.Y. superstores have the effrontery to offer.

The long, narrow strips of 3-ply, necessary to construct the sides of the main tube of your telescope, will be very flexible individually, but when they are combined to form a tube the complete structure has remarkable rigidity – just what is required for the job.

Thin ply is easy to cut to shape, using a sheet saw or a fret saw, depending upon whether you are making a straight cut or a curved cut. It is also a strong but lightweight material that glues beautifully. Also it has the major advantage for the astronomer that it does not have a shiny surface; once the interior surface of a plywood tube has been painted with matt black paint, such as blackboard paint, it has low reflectivity.

A telescope tube with flat sides makes it particularly easy to mount a finder telescope and to set the eyepiece and draw-tube at right-angles to the body. Also, the flat sides of the tube make it easy to attach the stubby axles that you will need to mount the telescope on a tripod. These tasks are not so easy for the engineer who is constructing his telescope of round-section metal tube.
To make the baffles for the inside of a wooden telescope you can use very thin modelling plywood, which is one sixteenth of an inch thick (1.5 mm) and which is supplied in A4 size sheets.

The material to totally avoid is plastic pipe – it is too shiny on the inside and it lacks rigidity. As time goes by a telescope constructed from plastic pipe will bend under its own weight and the optical components will no longer be aligned.

Finally, if you are making a telescope that is going to be too heavy to hold in the hand, be it of timber or metal, you need to realize that the telescope is going to be only half of the job – you must also plan the design of a tripod that is tall enough and sturdy enough to support the telescope without wobbling.

Now we will leave you to read how a telescope can be constructed.

(i) The components of the telescope.

The component parts of a straight-through astronomical telescope are shown in fig 3.

This design works just as well for any size of telescope, whether it is a tiny telescope that you can hold in one hand or a large, tripod-mounted instrument, such as those that we make.

The eyepiece (e) is fitted inside the draw-tube (d). Usually the end of the draw-tube has a small clamp-screw to hold the eyepiece safely in place. The purpose of the draw-tube is to allow the observer to alter the distance between the objective lens and the eyepiece, so that the telescope can be brought to a sharp focus.

The draw-tube should be a smooth sliding fit inside a plug ‘p’ fitted in the rear end of the main tube, shown as ‘m’ in figure 3.

You may wish to provide this plug with a clamp-bolt so you can hold the draw-tube in a fixed position once you have focused the telescope.
(ii) The length of the telescope.

You need to know the length of the telescope that you are going to make, so that you can select the tubes that you will need in order to make it.

The factor that decides the length of the telescope is the FOCAL LENGTH of its objective lens. In fig. 2B you can see that the focal length of the objective lens is the distance from the lens to the point where it brings the light to a focus. The finished telescope will be just a little longer than this because of the length of the eyepiece at the rear and the amount that the objective lens is recessed into the main tube, to form a SHADE.

The first job is to measure the focal length of the lens or, to be more accurate, the distance from the rear (flint) surface of the lens to the place where the objective lens forms a sharp image. This distance is the BACK FOCAL LENGTH (b.f.l.) of the lens and it may be slightly different from the focal length of the lens, as given by the manufacturer.

(iii) Measuring the b.f.l. of the objective lens.

To do this job accurately, and to minimize the possibility of your dropping the lens, you will need an assistant to do the measuring.

During the daytime stand indoors opposite a window. Hold the lens against the wall opposite the window and make sure that the front of the lens (the most curved surface of the lens) faces the world outside the window.

Gradually move the lens away from the wall until it produces, on the wall, a sharply focused image of the outside world. Measure the distance from the lens to the wall. That distance is the back focal length of the lens. Do this experiment several times, just to make sure that you get an accurate assessment of the b.f.l.

The sharply-focused image of the outside world that you saw on the wall was upside-down and, surprisingly, larger than the diameter of your objective lens.

The objective lens at the front of your telescope behaves like the lens of a film projector: it takes the light from the outside world and projects it on to an invisible screen called the FOCAL PLANE. The focal plane is the two-dimensional version of the focal point and the distance from the rear of the objective lens to the focal plane is called the back focal length (b.f.l.).

Ray diagrams can be misleading; they give the impression that a positive lens brings all the light to a focus at a brilliant point of light. Well, as you saw when you did this experiment, no such thing happens.

In this entire scene that is projected on to the focal plane, the only part that is ever going to be used is that part of the scene that will just fill the size of the eyepiece lens. All the rest of that light will miss the eyepiece altogether and just go around inside the telescope, causing a nuisance.
(iv) Why does the lens give an inverted image?

Your objective lens gives an image that is upside down and back to front. You can see why this happens if you take the simpler example of a pinhole camera.

You can make yourself a pinhole camera using a small cardboard box; something with sides about 4” (10 cm) long would be ideal - a shoe box is too large.

Cut a hole about the size of a 50p piece in the middle of one side of the box and glue over it a piece of thick aluminium foil, such as the bottom of the cake case around a fruit pie. Use a sharp pin or needle to prick a hole in the middle of the foil.

Cut a much bigger hole in the opposite face of the box and glue a piece of greaseproof paper over the hole, taking great care to ensure that the greaseproof paper is stretched flat and tight over the hole. This piece of greaseproof paper is the screen upon which the pinhole will project an image.

Stand indoors with your pinhole camera and point it out of the window on a bright day. If you hold the box at arm’s length you will be able to see a full-colour, upside down view of the world outside projected on to the greaseproof paper screen. Sometimes it is worthwhile to make a hood around the outside of the greaseproof paper screen to keep side-light off the screen, which makes the rather faint image difficult to see.

Here is a diagram that shows how the pinhole camera works:

As you can see, the pinhole aperture in the metal disc (your piece of aluminium foil) acts to constrict the light from different parts of the object, so that the top right of the scene becomes the bottom left of the image, while the bottom left of the scene becomes the top right of its image on the screen.

A lens behaves in exactly the same way; you can think of the lens as being a very large number of pinhole apertures.
(v) Doing the scale drawing of the telescope.

Measure the diameter of the objective lens and measure the diameter of the eyepiece lens and make written note of these measurements. Make allowance for the fact that you will not be able to use the full diameter of either lens, because each will be held in some sort of cell or capsule, which will have a lip that retains the lens within the cell.

Now you are ready to start designing your telescope.

Make a scale drawing of the telescope; it will look very much like fig.3. The very best idea is to make the drawing a full-scale drawing. If you are making a large telescope, as we do, you will need a long piece of paper. The paper only needs to be wide enough to take the full width of the objective lens, with a margin of an inch or so (30 mm) on either side.

You can either tape lots of sheets of A4 paper together to give you a long enough sheet of drawing paper OR you can use a spare piece of plain lining paper that you bought once from the wallpaper shop when you were re-decorating.

Begin by drawing an optic axis (an accurately straight line) along the mid line of the sheet of drawing paper, just as in fig. 2A and fig. 2B. All the lenses will lie symmetrically along this line.

Draw the objective lens near one end of the optic axis, making the diameter of the lens the same as you plan the clear aperture to be in the real telescope. Draw the clear diameter of the eyepiece lens on the optic axis, having regard to the back focal length of the objective lens plus about 1 cm, to allow for the focal length of the eyepiece lens (important). At this stage in the drawing you will have the objective lens and the first of the two eyepiece lenses accurately positioned, more or less as they will be when your telescope is in use.

Here is fig.3 again:

![Diagram of Astronomical Telescope](fig3)

Using an accurately straight edge, draw your own dotted lines to show the cone of light that will eventually be projected by the objective lens on to the surface of the first eyepiece lens. This cone of light contains only the light that will eventually reach your eye from the eyepiece lenses. All the rest of the light that fans outward from the objective lens is just wasted light and, given the chance, it will reflect off the inside of the main tube (marked as ‘m’) and off the inside of the draw-tube (marked as ‘d’).
Designing the telescope parts.

(i) Designing the lens cell.

The purpose of the lens cell is to hold the objective lens on the optic axis and to clamp it securely to the main tube of the telescope.

It is worthwhile making the lens cell a chunky item because that will have the dual benefits of protecting the objective lens from being broken if the telescope is knocked and adding weight to the front end of the telescope to counterbalance the weight of the finder telescope (if fitted), the focus mechanism and the eyepiece which all add weight to the rear of the main tube.

Figure 4A shows the cross-section through a simple lens cell, while figure 4B shows the individual components that you will need to make.
In fig. 4A you can see that the lens cell has a flange that will be bolted to a similar flange on the front of the main tube of the telescope. You should provide the flange with three, equi-spaced holes to take bolts that are sufficiently strong the clamp the lens cell firmly to the main tube. Once you have made the flange you can join it permanently to the lens cell body by soldering or by gluing.

The lens is safely stored within two thin-wall capsules – the innermost is a loose fit around the glass lens, while the outer capsule is a neat sliding fit over the inner capsule. Make the depth of each capsule slightly shallower than the thickness of the glass lens – this is so that the lens can be squeezed firmly against the back of the lens cell body when the threaded retaining ring is gently tightened against the front of the lens.

When the retaining ring is threaded into place it should press the lens gently but firmly against the rear of the lens cell – this ensures that the lens is always square-on to the telescope and is accurately aligned with the optic axis (the centre line) of the telescope and the eyepiece.

Very slight sideways movement of the lens within its thin-wall capsule is fine – it ensures that the lens will not get pinched when the lens cell contracts on a cold night. If the lens is pinched it will give distorted images of stars; in a bad case each star will have three spikes radiating from it.

This style of lens cell will work with any diameter objective lens.

If it is intended for a small (up to, say, 2" diameter) objective lens you can join the lens cell body to the main tube of the telescope by screwing it to the threaded front of the main tube. For larger diameters the flange method is best.

Again, for small diameter cemented doublets you can dispense with the thin-wall capsules, but they are essential for larger diameters and for all air-spaced doublets.

You will notice in fig.4B that we have marked a dimension called ‘x’. This diameter is slightly smaller than the diameter of the objective lens; ‘x’ is the clear diameter of the alloy lens capsules that house the objective lens and prevent it from jamming in the body of the lens cell. Each of these two capsules has a lip that stops the objective lens from falling out, so the diameter ‘x’ is the distance across the internal diameter of the lip.

It is sensible to also make ‘x’ the inner diameter of the threaded retaining ring and the inside diameter at the rear of the lens cell body, as we have shown in fig. 4B.
(ii) Designing the telescope baffles.

We mentioned earlier that the light gathered by the objective lens is projected by the lens in an expanding cone of light towards the rear of the telescope. The only part of that cone of light that will ever be used is that part that is projected on to the eyepiece lenses. All the rest of that cone of light is stray light that will reflect off anything shiny within the telescope.

This stray light will spoil the quality of the view seen through the telescope by destroying the CONTRAST of the image. You can prevent this stray light from getting anywhere near the eyepiece by fitting BAFFLES inside the telescope main tube and inside the draw-tube.

The baffles choke-off the stray light from the objective lens and keep the inside of the telescope nice and dark. Figure 3 shows THREE such baffles, marked ‘a’, ‘b’ and ‘c’.

The baffles are circular screens that fit neatly inside the main tube (marked ‘m’). They are ideally made of thin metal, but sturdy plastic or card or very thin ply would do almost as well. The baffles will be held in place by sleeves in front and behind.

Each baffle has a circular hole at its centre and the purpose of the baffles is to guide the cone of light to exactly the whole of the first eyepiece lens. Once you have decided upon the position of the baffles you can draw them in place on your scale drawing, such that the hole in each baffle comes just to the edge of the cone of light.

Important: Whatever material you choose for the baffles, take trouble to make the edge of the aperture razor sharp, so that light cannot reflect off the edge.

Now you can measure the diameter of the hole in each baffle using a ruler on your scale drawing.

You can have as many baffles as you like, but three would normally be enough. When you come to design the draw-tube, make sure that the inner end of the draw-tube cannot collide with one of your baffles, such as ‘b’.
(iii) Designing the draw-tube and plug.

The purpose of the draw-tube is to:
(1) Hold the eyepiece exactly on the optic axis and
(2) Adjust the distance of the eyepiece from the objective lens, within narrow limits.

There is going to be a compromise between the length of the main tube of your telescope ('m' in fig.3) and the length of the draw-tube ('d' in fig.3).

The draw-tube must not be too long and narrow otherwise its inner end will cut-off valuable light from the edge of the objective lens; doing that would, in effect, reduce the working diameter of the objective lens and thus give a dimmer image at the eyepiece.

The inside diameter of the draw tube must be significantly greater than the diameter of the eyepiece lenses, so that light which is reflected off the inside of the drawtube at a grazing angle, does not enter the eyepiece and spoil the contrast of the view. For a small, hand-held telescope we would use a thin-wall draw-tube that had an outside diameter of 1¾" (45 mm) while for our big brass refractors we use a thin-wall draw-tube with an outside diameter of 2" (50 mm).

The plug in which the draw-tube slides (shown as 'p' in fig.3) must allow the draw-tube to slide in and out smoothly, but with some slight resistance. The plug must be of sufficient length that the draw-tube does not wobble out of alignment when the telescope is being focused.

We recommend that the plug should have the same length as the diameter of the draw-tube that is sliding within it. Our large brass refractors have a 2" diameter draw-tube, so the plug at the rear of the main tube has a length of 2".

The amount of forward and backward movement of the draw-tube needs not be very great. This free movement needs to be sufficient to allow for the various focal planes of the different makes of eyepieces that you might buy and it should allow you to de-focus the telescope slightly when you are making adjustments.

Taking the case of a 2" diameter draw-tube, we would recommend 1½" inward movement from the focused position and 1½" outward movement from the focused position.

These suggestions give a total free movement of the draw-tube of 3"; the thickness of the plug is 2", so the total length of the draw-tube needs to be 5". Allow an extra inch for slight inaccuracies in the scale drawing and cut the draw-tube metal to a length of 6" (150mm).

Add all this information to your scale drawing and it will automatically give you the length of the main tube of your telescope, when you take into account the length of the lens cell that will hold the objective lens.

However...
(iv) Incorporating a star diagonal into your design.

You need to think ahead about how you intend to use this telescope. If you are building an astronomical telescope it is going to spend its working life pointing upwards, sometimes at a steep angle. This means that you will need to spend your observing time with your head under the telescope, which can be uncomfortable and wearisome.

The solution to this is to employ a little adapter called a star diagonal, or just ‘diagonal’, which diverts the light that comes out of the draw-tube through an angle of 90°. This adapter fits in the outer end of the draw-tube, where the eyepiece would normally go. The eyepiece fits into the socket of the star diagonal.

When you are using the telescope fitted with its star diagonal you look downwards into the eyepiece while the telescope is pointing steeply upwards.

The star diagonal contains a right-angled prism or a front-surface mirror, which is set at an angle of 45°. These adapters are supplied as either 1¼” fitting or 2” fitting. Their price depends upon how optically accurate they are – it can vary from a few pounds up to a quite significant investment. If possible, choose the 1¼” version because they are less heavy than the larger version and they are significantly cheaper.

If you are going to build an astronomical telescope you may as well adjust the design so as to use a diagonal. The diagonal bends the light through 90° but the path length from objective lens to eyepiece will remain the same – that length is just bent round a corner. This means that the total length of the telescope body will need to be shorter by about 3” (75 mm) to allow for the path-length through a 1¼”star diagonal or about 4” (100 mm) for a 2” diagonal.

When you make your telescope so that it will receive a star diagonal you will not be able to bring the telescope to a focus if the star diagonal is not in place – the body of the telescope will be too short for that.

(v) Making a draw-tube extension tube.

There will be times when the amateur astronomer will need to have the telescope working in the ‘straight through’ format. This might be when the telescope is going to be used for photography and the astronomer just wants to hang a camera on the end of the draw-tube.

If you are building the telescope to be used mostly with a star diagonal you will need to make an extender to increase the length of the draw-tube when the diagonal is not in place; if you are using 1¼” fittings then the extender will need to be about 3” long, to give the same path-length as would be used by the star diagonal.

Here is the best way to do this:

Make the draw-tube so that the outer end (where the eyepiece goes) is threaded on the inside, with a threaded eyepiece holder (complete with eyepiece clamp screw) threaded into it. Make the extension tube with a male thread at one end (so that it will screw into the open end of the draw-tube) and with a female thread at the other end (so that the eyepiece holder can screw into it).
(vi) Making the draw-tube baffle.

Figure 3 shows that the inner end of the draw-tube contains a light baffle in the form of a plug. This baffle/plug serves the purpose of defining the cone of light that is allowed to reach the eyepiece and thus prevents reflections off the inner surface of the draw-tube. The hole through this baffle needs to have a razor-sharp rim to minimize reflection from it.

In fig.3 you can see that we use this plug as a safety feature – it prevents the draw-tube from falling out of the back of the telescope when the telescope is pointing upwards. This plug needs to be either screwed or glued in place.

(vii) Finishing the baffles.

When you have assembled your telescope you can tell if the baffles are correct by looking into the telescope from the front, with the objective lens in place. When your eye is right at the edge of the objective lens you should just be able to see the entire eyepiece.

(viii) Inhibiting internal reflections.

The inside of the telescope must behave as though it is completely non-reflective. An obvious way to do this is to paint all the interior components with matt black paint.

However

You need to be aware that even matt black paint is reflective when the surface is viewed at a grazing angle, so there are some surfaces, such as the inside surfaces of the draw-tube and the inside surfaces of the lens cell, that are going to merit some extra treatment.

A good trick is to machine a thread on such interior surfaces, then paint them black. The thread gives the surface a zigzag nature which is almost completely non-reflective at a grazing angle.

The interior of the front portion of the main tube (before the first baffle) can also cause problems, so one solution is to cover that part of the tube with black velour. Some firms advertise this black velour as an especially non-reflective variety that also does not shed fluff during its life.

An alternative is to buy self-adhesive velour that is intended for the bottom of items such as table-lamps, table mats and wooden bowls. This velour is available in many colours including black and its adhesive is very effective, which is both a blessing and a curse. It is easy to apply this self-adhesive velour to the front few inches of your telescope main tube and it provides an excellently non-reflective surface.

The problem arises when you have to get the material farther down inside the tube because it is almost impossible to get the self-adhesive material all the way inside the tube without its touching, and sticking to, the front of the tube, where it gets stuck fast. Also, it cockles-up during handling and becomes stuck to itself when you try to place it deep inside the main tube.

You can overcome these problems by lining the main tube with cylinders of rough-textured paper, such as the woodchip paper used for wallpapering, which you have painted with black emulsion paint. These cylinders of paper can be slid inside the main tube and pushed down inside, with the pre-painted baffles put in at the same time.
Lots of amateur telescope makers have their own, favourite ways of blackening the insides of their telescopes, so it pays to listen to the experience of others, but a good compromise is to use velour on the first part of the main tube with cylinders of black-painted wood-chip paper farther down, black paint on both sides of the baffles and black-painted threaded surfaces inside the lens cell.

The draw-tube presents a unique problem because it is too narrow to get velour inside it and too long to be threaded in the lathe. A good solution is line it with a cylinder of black-painted woodchip paper or black cartridge paper that you have coated with black emulsion paint.

The more care you have taken with the design and layout of the baffles, the less you will need to rely on these nostrums and the better that your telescope will perform.

Small metal components, such as the interiors of eyepieces and the spacers used between eyepiece lenses can be rendered less reflective by painting with, or immersing in, blackening fluid. This is a pale blue liquid, whose ingredients seem to include copper selenate. You can find suppliers of this rather expensive fluid if you search the Web for ‘blackening fluid’.

What you will find is that the components take-on a black coating but it will rub-off on handling. The final, durable surface that you will achieve will probably be brown, but it will have a less reflective surface than the original metal so it is ideal for surfaces that have been threaded.

Another advantage of using this liquid on aluminium and its alloys is that it provides a porous surface to which paint will adhere; aluminium alloys are difficult to paint because the paint just does not bind well to them.

A final point: do not forget to check that the edge of your objective lens is also black. If it has not been black-painted by its manufacturer you can black the edge using a thick black felt-tip pen.

The advantage of an angled telescope is that you do not have to get your head under the telescope when you are observing objects that are at a high angle, such as the stars that are nearly overhead. There is another advantage: the telescope is more compact.

This diagram shows the layout of a right-angled telescope.

As you can see the telescope has the same components with which you are already familiar: an objective lens in its cell, several baffles to eliminate internal reflections, a draw-tube and an eyepiece. The additional component is a means of diverting the light from the objective lens through a right-angle.

Just as we mentioned when we described a star diagonal, the path-length of light from the objective lens to the eyepiece will remain unaltered but the length of the telescope will be reduced. The dotted lines show where the objective lens would have formed its image if the light were not diverted.

There are several ways to divert the light through a right-angle.

These are:
(i) Using a front-aluminised mirror;
(ii) Using a right-angled prism;
(iii) Using a pentaprism;
(iv) Using an Amici prism.

(i) Using a front-aluminised mirror.

Using a mirror will give an image that is the right way up but laterally inverted (back to front). That is fine for astronomy but inconvenient if you wish to use your telescope for observing terrestrial objects.

The plane (flat) mirror is fixed directly under the draw-tube so that the centre point of the mirror lies on the both the centre line of the draw-tube and the centre line of the main tube of the telescope. The mirror is fixed at an angle of 45 degrees to these centre lines.

The mirror is special in that it must be aluminised (‘silvered’) on its front surface, rather than (as with domestic mirrors and car mirrors) on its rear surface. This is so that you do not get a
double reflection – a main reflection from the rear, aluminised surface and a fainter, but very noticeable, reflection from the front surface of the glass. These double reflections would give rise to double images in the eyepiece, which would ruin the telescope’s performance.

Take care to use a mirror that is just the right size. If you choose a mirror that is too large you will need to have a larger diameter main tube to hold it. If you have a mirror that is too small the eyepiece will not receive all the light from the objective lens. As with the straight-through telescope you must make a scale drawing of the telescope and measure the size mirror that will be needed.

If you elect to use a rectangular front-aluminised mirror (the cheaper option) the length of the mirror will need to be 1½ times the width of the mirror, because the light will be striking the mirror at a grazing angle. If you elect to use an elliptical mirror (the dearer but better solution) the proportions of the mirror will be correct anyway.

You mount the mirror in its correct position by fixing it to a flat block that is cut at an angle of 45 degrees. This block can be supported on the back-plate of the telescope.

(ii) Using a right-angled prism.

The right-angled prism behaves in exactly the same way as the plane mirror and also gives an image that is erect but laterally inverted. Like the mirror you require the width to be slightly greater than the diameter of the eyepiece lenses.

Fixing the right-angled prism in place needs care because (unlike the mirror) you must not fix it by gluing the support to the inclined surface (the hypotenuse) of the prism. The hypotenuse of the prism allows the light to be bent through a right-angle and so behaves exactly like a mirror, due to an effect called total internal reflection – the hypotenuse is not ‘silvered’.

Total internal reflection arises because the light strikes the hypotenuse of the prism at an angle of about 45 degrees, which is too small an angle for the light to pass out through the glass/air interface. If you attach anything to the hypotenuse of the prism that glass/air interface is replaced by another interface, such as a glass/glue or glass/cork interface, which destroys the conditions necessary for total internal reflection and so the prism can no longer behave as a mirror and reflect the light into the eyepiece.

You will need to support the right-angled prism by a bracket that is glued to the triangular side of the prism.

(iii) Using a pentaprism.

The advantage of a pentaprism is that it reflects the light through a right-angle but it does so without any inversion of the image. This means that the astronomical image of a straight-through telescope (upside down and back to front) is retained after the light has been reflected by the pentaprism – the image seen in the eyepiece of the right-angled telescope is still upside down and back to front.

A pentaprism is a five-sided prism, two of whose sides are ‘silvered’ because total internal reflection is not possible for such a prism. The pentaprism is a bulkier and heavier prism than the right-angled prism. It is also much more expensive.
Again, you must support the pentaprism by means of a bracket that you attach to the side of the prism.

(iv) Using an Amici prism.

An Amici prism diverts the light through a right-angle with total inversion. This means that the astronomical image is converted into an image that is the right way up and the right way round; the astronomical image is converted into a terrestrial image.

By using an Amici prism (it is also known as a ‘roof prism’) you can construct your own right-angled terrestrial telescope. If you use a top-quality Amici prism, such as our PR.6, the image is so good that you can use it for astronomy also.

Again, you must support the Amici prism by a bracket that you attach to the side of the prism.

There are many designs of eyepiece – dozens, in fact – but one of the commonest eyepieces used in astronomy, and certainly the easiest to make, is called the Plössl eyepiece, which was designed in 1860 by Georg Simon Plössl.

It consists of two, identical achromatic lenses placed with their most curved surfaces (the crown elements) facing each other. The lenses are positioned so that these surfaces are almost (but not quite!) touching. The same design is also called the symmetrical or dial sight eyepiece.

It is obvious why it is called a symmetrical eyepiece when you look at a diagram of its construction – the two lenses are placed symmetrically on each side of the metal spacer ring that holds them apart. It follows from this that it does not matter which way the light passes through this type of eyepiece, the performance will be the same. The Plössl design is also known as the dial sight eyepiece because it is the style of eyepiece that was always used in a dial sight, which was the optical aiming sight on artillery pieces.

The Plössl eyepiece is especially suitable for astronomy because it has a large eye-relief, which allows those who wear spectacles to wear them while they are looking into the eyepiece. The eyepiece has a crisp image right to the edge of the field; its apparent field of view is $50^\circ$ to $55^\circ$.

The focal length of the Plossl eyepiece is about HALF of the focal length of each of its lenses.

The diagram shows the components that you will have to make or acquire: The eyepiece body; a lens holder; a threaded ring to hold all the components inside the body; a spacer ring to prevent the two lenses from grinding against each other and two, identical achromatic doublets.
Making the eyepiece.

(a) Make the **lens spacer** first, preferable from metal. It must be exactly the same diameter as the lenses and thin enough not to obscure the view through the lenses. The **width** of the spacer needs to be sufficient to prevent the two lenses from touching each other. A good trick is to thread the inside of the spacer with a nice fine thread (say, 48 t.p.i.) to make the inside surface of the spacer non-reflective. Paint the inside surface and the edges of the spacer with matt black paint. Brass is the favourite material for making the spacer.

(b) Make the **lens holder** next; this is the component whose design needs a lot of care. As you can see from the diagram it has a recess that is just the right diameter to receive the two lenses with their spacer. They need to be a smooth, sliding fit inside this recess in the lens holder so that they do not rattle from side to side when the eyepiece is in use.

The **depth** of the recess needs to be very slightly **less** than the front-to-back length of the two lenses with their spacer. What is needed is that the lens protrudes very slightly (about 0.020” or 0.5 mm) from the lens holder. This is so that the lenses and spacer are compressed when the eyepiece is assembled, so that they cannot rattle forwards or backwards when the eyepiece is in use.

The **total length** of the lens holder is of critical importance; it needs to be of such a length that its narrower end is exactly in focus when you look through the eyepiece. The edge of this narrower end must form the crisp edge of the field of view through the eyepiece. (If you are going to have cross-hairs in the eyepiece they will be glued to that edge of the lens holder and they will be in exact focus when you look through the eyepiece.)

As you can see from the diagram the inside of the lens holder needs to be threaded, like the lens spacer, with a good, fine thread to provide a non-reflective surface. Paint this threaded section and the ends of the lens holder with matt black paint. Aluminium alloy is the favourite material for making the lens holder, to minimize weight.

(c) The **eyepiece body** needs an internal diameter such that the lens holder is a smooth sliding fit inside it. As you can see from the diagram the eye-end of the body has a lip to prevent the lenses from falling out. The hole at the eye-end needs to be as large as you can make it, so that you have access to almost the total diameter of the lenses. A nice, wide diameter view will make the eyepiece comfortable to use.

The focal plane of the eyepiece, i.e. the inner end of the threaded lens holder, needs to coincide with the end of the body and the start of the **1¼” (31.7 mm) diameter barrel of the eyepiece.**

The length of the barrel should be about **¾” (20 mm) long.** This is the part of the eyepiece that goes inside the draw-tube. The barrel must be accurately threaded on its inner surface to receive the threaded retaining ring. This retaining ring will be screwed into the eyepiece body so that it pushes gently against the eyepiece holder and keeps all the components in place.

Paint the inner surface of the lip at the eye end of the body with matt black paint.

(d) Make the threaded **retaining ring.** It must be accurately threaded so that this ring will screw smoothly into the body of the eyepiece. Give the inside of the ring a fine thread to provide a non-reflective surface. Paint this inner threaded surface and the ends of the retaining ring with matt black paint.
(e) Paint the ground-glass edges of both lenses with matt black paint, so that they become non-reflective. If you get any paint on the faces of the lenses (and you will) leave the paint to dry overnight then gently wipe this excess paint off the faces of the lenses with a soft cloth slightly moistened with white spirit.

If you wish to make a very fine eyepiece you should choose our lens 5293.

A pair of the 5293 lenses will give a Plössl eyepiece with a focal length of approx. 35 mm. This eyepiece is the standard item that we supply with our large brass refractors and we fit it to our brass star-finder telescopes. It performs superbly.

In the next section we are going to describe how to build a terrestrial telescope, which works by means of additional lenses within the telescope.

This description includes a long section on the theory and practice of relay lenses. There is no point in studying this long section if you are not planning to make a terrestrial telescope.

However...

The practical issues of using relay lenses will be useful to you if you plan to convert one of your camera telephoto lenses into a telescope. You cannot usually put an eyepiece directly to a camera lens because there is not enough distance from the lens body to its focal plane for you to be able to insert an eyepiece into that space. Relay lenses allow you to reach into the camera body and acquire the image for your eyepiece.
15. Constructing a terrestrial telescope.

Earlier we described the astronomical telescope, in which light is gathered by an objective lens at the front of the telescope and the light is viewed through an eyepiece, which is an arrangement of two or more lenses bunched together at the rear of the telescope. The astronomical telescope gives an inverted image i.e. the view is upside down and back to front.

Now we are going to describe how to make a terrestrial telescope, which gives an image that is the right way up and the right way round.

The terrestrial telescope is just like the astronomical telescope except that it has extra lenses between the objective lens and the eyepiece. These extra lenses, called relay lenses, completely invert the astronomical image, so the observer sees a view that is the right way up and the right way round.

(i) The difference between a terrestrial telescope and an astronomical telescope.

Relay lenses are used in telescopes to give an erect image i.e. the view is the right way up and the right way round. The purpose of this document is to describe how they work within the telescope.

Look at these two sketches, which show the lens layout in the astronomical telescope and then the terrestrial telescope. Both telescopes use the same objective lens and same eyepiece.

In the terrestrial version, an additional lens – the relay lens – has been added to produce a view that is laterally and vertically erect.
By looking at the sketch (above) of the terrestrial telescope you can see that the objective lens produces an image of the distant object that is being viewed, such as a ship or a hill.

This image is formed at the focal point of the objective lens and it becomes the object that is viewed by the relay lens.

The relay lens transmits the light and forms an image some distance behind the relay lens. This image, in turn, becomes the object that is viewed by the eyepiece.

(ii) The simplest relay system.

Diagram 1 contains a great deal of information about distances; you will need to take time to understand it and the text that goes with it.

The simplest relay system employs a single lens that is placed between the objective lens of the telescope and the eyepiece at the rear of the telescope. Diagram 1 shows how the light travels through this relay lens in a terrestrial telescope.

This diagram shows the relay lens, seen from the side. At the extreme left-hand side of the diagram is an upside-down arrow that represents an inverted object, such as the inverted image produced by the objective lens of a telescope. The objective lens of the telescope brings its view of the world to a focus at the place shown in the diagram by the upside-down arrow.

In the diagram you can see that the focal length of the relay lens has been marked by a dot. Since light travels just as easily either way through a lens you will see that there are two dots,
at equal distances either side of the centre of the lens. These distances from the lens are marked with the letter ‘f’, to show the focal length of the lens, seen from either direction. When you position the relay lens such that it is twice its focal length from the inverted object, (shown in this diagram as ‘2f’) the relay lens produces an erect image at precisely the same distance behind the relay lens (also a distance of ‘2f’). This is shown at the extreme right-hand-side of the diagram. In optics books the distance from the inverted object to the relay lens is conventionally called ‘u’, while the distance from the relay lens to the erect image is conventionally called ‘v’. You can see the distances ‘u’ and ‘v’ along the top of diagram 1.

In the diagram you can see that the distances ‘u’ and ‘v’ are exactly the same; ‘u’ is twice the focal length of the relay lens and ‘v’ is also twice the focal length of the relay lens. Since the inverted object and the erect image are equi-distant from the relay lens it follows that the erect image produced by the relay lens is exactly the same size as the inverted object. The happy effect of this is that the relay lens does not alter the magnification of the telescope; the relay lens just turns the view up the right way and round the right way.

Now that we have established that the relay lens has not caused any change in the magnification of the telescope you will notice in diagram 1 that the distance between the image produced by the objective lens of the telescope and the image produced by the relay lens is four times the focal length of the relay lens. You can see along the bottom of diagram 1 that the distance from the inverted object to the erect image is 4f, i.e. four times the focal length (‘f’) of the relay lens. This value of four times the focal length of the relay lens is the shortest distance that there can be between the inverted object and the erect image and it occurs only when the values of ‘u’ and ‘v’ are identical.

(iii) Increasing the magnification.

Look at Diagram 2 to see the effect when ‘u’ and ‘v’ are not identical:

In this diagram the layout of the lenses in the terrestrial telescope has changed. The relay lens has been moved slightly closer to the objective lens of the telescope, so the value of ‘u’ is smaller than it was previously. In response to this the value of ‘v’ has increased considerably i.e. the erect image formed by the relay lens is now a lot farther away from the relay lens. The inverted object viewed by the relay lens is still the same size, but the erect image that the relay lens has produced is much bigger.

You will also notice that the overall length of this part of the optical system of the terrestrial telescope is greater than it was previously; a small decrease in the distance ‘u’ (the distance of the relay lens from the inverted image produced by the telescope’s objective lens) causes
a disproportionate increase in the value of ‘v’ (the distance from the relay lens to the erect image that it produces).

The effect of moving the relay lens slightly closer to the objective lens is to increase the magnification of the telescope, because the erect image produced by the relay lens, and viewed by the eyepiece is bigger than previously.

**Technical point:**

The increase in magnification of the terrestrial telescope depends upon the ratio of the distance ‘v’ to distance ‘u’. If ‘u’ and ‘v’ are identical then the increase in magnification is $x \times 1$ i.e. the overall magnification is not changed by the presence of the relay lens.

If, as in diagram 2, the value of length ‘v’ is double that of length ‘u’ then the increase in magnification is length ‘v’ $\div$ length ‘u’ which gives a result of $x \times 2$ i.e. the magnification produced by the telescope has been doubled by moving the relay lens a small distance towards the objective lens of the telescope.

Using just one lens in the relay system greatly increases the length of the telescope, because the total distance from the image produced by the objective lens of the telescope to the focal point of the telescope’s eyepiece is at least four times the focal length of the relay lens. You can, of course use a relay lens of much shorter focal length, but that creates all sorts of problems. The practical solution to keeping the terrestrial telescope as short as possible is to use two lenses as the relay system. **Look at Diagram 3.**

**(iv) A practical relay lens system.**

![Diagram 3](image)

In practice the relay system in a terrestrial telescope uses two lenses. To keep the explanation simple we will only consider the case where both relay lenses are identical.

As you can see from diagram 3 the two relay lenses are spaced some distance apart. The great advantage of using two lenses is that the distance from the inverted object viewed by the relay system to the erect image produced by the relay system is smaller than would be possible using just one relay lens. From diagram 3 you can see that the distance from relay lens 1 to the inverted object is equal to the focal length of relay lens 1 (unlike in diagram 1, where the distance had to be twice the focal length of the lens).
Similarly in diagram 3 you can see that the distance from relay lens 2 to the erect image that it produces is equal to the focal length of that lens, not double the focal length of the lens, as shown in diagram 1. Therefore the length of the terrestrial telescope that is required for the relay lens system is smaller when two lenses are used, provided the distance between the two relay lenses is kept to a sensible value.

Here are diagrams 1, 2 and 3 again, so you can compare overall lengths of the relay system.
(v) The problems that relay lenses can cause and how to resolve them.

The astronomical telescope uses the minimum number of lenses so the view through the telescope is as pure as possible; each additional optical component added to the telescope will degrade the final image. When light passes through a lens some of that precious light is lost due to absorption by the glass and, more especially, by reflection at the front and rear surfaces of the glass. No lens is optically perfect, so every additional lens added to the system will cause additional distortion of the final image. This is why astronomers do not bother with having the view turned up the right way in their astronomical telescope – the extra lenses would cause unnecessary light loss and image degradation.

The great advantage of an astronomical telescope is that it has a particularly simple design; there is an objective lens at the front of the telescope whose function is to gather the light from the object of interest and there is an eyepiece at the rear of the telescope whose function is to magnify the image produced by the objective lens and project this magnified image into the eye of the observer as a pencil of parallel light rays. The rest of the telescope is full of nothing but fresh air.

The design of modern telescope eyepieces is such that they give a wide, flat field of view with the outer parts of the field in as sharp a focus as the centre of the field of view. In addition the eyepiece is comfortable to use because the observer positions his eye close to the eyepiece and can usually rest the eyepiece against his cheek.

Once a relay lens has been added to the optical system, however, all those benefits can disappear.

The distortions that you can notice, once you have inserted a couple of relay lenses between the objective lens and the eyepiece of your telescope, are as follows:

1. The image shows chromatic aberration; any high-contrast object, such as a television aerial viewed against the sky, is surrounded by a border of rainbow colours.

2. The image shows spherical aberration; a rectangular object, such as a brick wall, will appear bulged in the middle and all straight lines will appear curved. This is called ‘barrel distortion’

3. The image will suffer from flare; a white object against a dark background will show the white as being smeared-out across the background, especially if your eye is not exactly in line with the centre of the eyepiece lenses.

4. The eye-relief of the eyepiece will be increased, so the observer will have to position his eye much farther away from the telescope which will make it more difficult to acquire the view through the telescope. Also, the field of view of the telescope will be much reduced because the observer is looking into the eyepiece from farther away.

These problems can be overcome by paying attention to:

(a) The distance of separation between the two relay lenses;
(b) The distance between the rear relay lens and the eyepiece;
(c) The focal length of the relay lenses;
(d) The direction in which each of the two relay lenses faces;
(e) The design of the lenses that are to be used in the relay system.
Choosing relay lenses – keeping it simple.

In order to obtain the best optical performance for your terrestrial telescope it is best to choose achromatic lenses as the relay lenses, rather than the much less expensive simple lenses, which are made of a single piece of curved glass.

As shown in diagram 4 below, one element (usually the double-convex element) of the achromatic lens is made of crown glass, while the other element (usually the concave element) is made of the denser and more fragile flint glass.

Diagram 4.

For the sake of simplicity it is best to make the relay lens system of two identical lenses. When you use a pair of identical lenses to make the telescope relay lens system there are four possible ways to arrange which way the lenses face. All four are shown in diagram 5 below.

Diagram 5.

If the two lenses are not identical then there are eight different ways in which they can be arranged. Given that the lens spacing is also a variable, you can see why it is best to keep the design as simple as possible, by choosing a pair of identical lenses.
(vii) The real-life terrestrial telescope.

Diagram 6 is a repeat of the diagram of the terrestrial telescope that was at the beginning of this document. You will notice that each of the lenses is shown as a simple lens.

This was a schematic diagram whose purpose was only to show how the rays of light passed through a terrestrial telescope. It showed that the rays of light crossed-over twice: first at the focal plane of the objective lens, to give an inverted image, then at the focal plane of the eyepiece, to give an erect image. By making the rays of light cross-over a second time the relay lens restored the view seen in the eyepiece to an image that was the right way up and the right way round.

Diagram 6.

In practice, the lenses that are used are achromatic lenses and the relay lens is really a pair of lenses (as was shown in diagram 3). Diagram 7 shows the layout of a practical telescope.

Diagram 7.

The objective lens of the terrestrial telescope is an achromatic doublet, as are the two relay lenses and the two eyepiece lenses. Note the direction in which each lens is facing.

To give a nice, crisp border to the field of view seen through the telescope an aperture stop is placed just in front of the eyepiece lens at the focal plane of the eyepiece. This is shown in diagram 7. The aperture stop consists of a circular metal plate with a circular hole in it. It is the edge of this circular hole that forms the border to the field of view; the aperture stop is positioned in front of the eyepiece so that the edge of the circular hole is exactly in focus.

(If you wanted your terrestrial telescope to have cross-hairs in the eyepiece then you would glue the cross-hairs to this aperture stop. In that way the cross-hairs would be nicely in focus when you looked through the telescope and would be superimposed on the view seen through the telescope.)
You would have cross-hairs in the eyepiece if the telescope were being used as part of a measuring instrument, such as a theodolite or a sextant or if it were to be a finder-scope.

(viii) How to make a terrestrial telescope – our recipe.

If you wanted to make a small terrestrial telescope, perhaps for use as a measuring instrument, you could use our lens 5500 as the objective lens. This lens has a diameter of 25 mm and a focal length of 157 mm. Its optical performance is excellent.

The relay lenses are a pair of our lens 1114.

The eyepiece lenses are a pair of our lens 5293.

The total length of this little telescope is about 366 mm (14½”) and it would give a magnification of about x 4½.

Diagram 8 shows the distances between the various components of this terrestrial telescope.

Diagram 8.

The spacings given in diagram 8, and the best way round to place the relay lenses were found by experiment. We did the work so that you do not have to.
Making a larger terrestrial telescope.

If you want your terrestrial telescope to be larger, then all you have to do is change the objective lens. You could keep the eyepiece and relay lenses the same as shown in diagram 8, because that arrangement will work with any objective lens.

(a) Making a hand-held nautical telescope.

If you wanted to make, say, a nautical telescope you could use one of our 50 mm or 60 mm diameter objective lenses. Such a telescope would usually have a main tube that holds the objective lens and a drawtube that contains the relay lenses and the eyepiece. Traditionally the drawtube is almost as long as the main tube and it slides away into the main tube when the telescope is not in use.

If you choose to use an objective lens that has a particularly long focal length then the whole telescope will be much longer when it is in use. Under those circumstances you may wish to be bold and have two, or even three, drawtubes that all slide within each other. These ‘two draw’ or ‘three draw’ telescopes were traditionally used by deer stalkers in Scotland.

(b) Making a tripod-mounted terrestrial telescope.

If you wanted to make an even larger terrestrial telescope then you could use one of our larger diameter objective lenses, with a focal length of, say, 1000 mm and mount your magnificent creation on a beautiful timber and brass tripod.

Whatever size terrestrial telescope you decide to make it is important to note that you should not attempt to alter the distances between the two relay lenses, once you have built the telescope. Also, you cannot focus the telescope by altering the distance between the relay lens system and the eyepiece – that just does not work.

The relay lens system and the eyepiece must be mounted within the same (the rear-most) drawtube, so that they move as one when the drawtube is moved.

You alter the focus of the whole telescope by slightly adjusting the position of the eyepiece drawtube, which contains the relay lenses as well.

The telescopes that we have described so far have all had a fixed magnification. The magnification is given by the focal lengths of the objective lens and the eyepiece lenses if you have elected to use the relay lens system that gives a x1 magnification (which is really the best way).

The magnification of the telescope will be the focal length of the objective lens DIVIDED BY the focal length of the eyepiece. If you want to change the magnification of the telescope the best way to do that is the change the focal length of the eyepiece.

If you are absolutely determined to make a terrestrial telescope that has a variable magnification, you can read how to do it in the next section.
(c) Varying the magnification - making a pancratic telescope.

As you saw in diagrams 1 and 2, the magnification of the whole telescope can be altered by increasing the distance between the relay lens system and the eyepiece. You can think of the relay lens system as behaving like a film projector, casting its image upon a screen. If you move the projector farther away from the screen, the picture on the screen becomes larger and you need to make an adjustment to the focus, so that the image on the screen becomes sharp again.

Here, in the terrestrial telescope, the relay lens system casts its image upon the focal plane of the eyepiece.

It is possible to construct a telescope in which the eyepiece and the relay lens system are held in different drawtubes of the telescope; the relay lenses are held in the penultimate drawtube of the telescope, while the eyepiece is, of course, at the rear of the final drawtube. The magnification of the telescope can be varied, within small limits, by moving the eyepiece drawtube in or out of the relay lens drawtube. A telescope that works like this is called a pancratic telescope.

The main factor that decides the magnification is the focal length of the objective lens; the greater the focal length of the objective lens, the greater will be the magnification of the telescope, for a given eyepiece.

In a pancratic telescope you can only alter that magnification within narrow limits. By repositioning the eyepiece relative to the relay lens system you can increase the magnification factor of the relay lens system from $x1$ to $x3$ at the most. If you try to be too ambitious the final image will be too dark and fuzzy to be useful. To preserve a bright, crisp image it is best to be prudent and restrict the movement such that the maximum magnification factor is kept to $x 2\frac{1}{2}$.

Another factor that is important, and related to the magnification, is the brightness of the telescope image; if you double the magnification of the image, its brightness reduces by a factor of four. This arises from the example of the film projector: if you move the projector to double the distance from the screen the picture thrown on the screen will be double its previous width and double its previous height. This means that the projected image will have four times its previous area, but the total light available from the projector’s lamp remains the same, with the result that each part of the picture is now only a quarter of its previous brilliance.

Technical point:
In any telescope, the brightness of the view through that telescope will depend upon the magnification. As you increase the magnification of the telescope the brightness of the image will diminish in proportion to the square of the magnification increase.

Double the magnification, and the brightness will diminish by a factor of four; Triple the magnification and the brightness will diminish by a factor of nine.

An engineering difficulty that you will encounter in making the pancratic telescope is that the final drawtube, which holds the eyepiece, will need to slide in and out of the drawtube that holds the relay lenses without bumping into the relay lenses. The implication of this is that there must be sufficient distance between the rear of the relay lens system and the eyepiece to accommodate the length of the eyepiece drawtube.
That needs some careful thought because the distance between the rear relay lens and the aperture stop of the eyepiece is usually too small to allow the pancreatic tube to slide in or out. One possible solution is to use a relay lens system that has a very long back focal length, but that makes the complete telescope disproportionately long and it degrades the image seen through the telescope.

A more practical solution is to mount the relay lenses in a cell that is fixed in the front end of the penultimate drawtube of the telescope but which projects backwards so that it protrudes well inside the final draw tube. In this way you can get sufficient room for the final drawtube to slide inside the drawtube that houses the relay lens system.

This photograph shows a pancreatic telescope that we made many years ago. The eyepiece lenses were held (obviously) in the final, short, drawtube while the relay lenses were held in the middle drawtube.

This was a pancreatic telescope. Its magnification could be altered by moving the last drawtube.

A pair of standard terrestrial telescopes; their magnifications were not variable, because the relay lens system and the eyepiece were both held in the (single) drawtube.

This photograph shows a pair of naval telescopes (Officer of the Watch telescopes) that we made for use on a couple of naval vessels. These used exactly the same combination of relay lenses and eyepiece lenses that are described in diagram 8. The objective lenses were 50 mm diameter, 330 mm focal length. These telescopes had superb optical quality.
(x) Experimenting with relay lenses.

If you wish to use your own choice of achromatic doublets to make a relay lens system you will have to be prepared to undertake your own experiments to find the best distances between the lenses and the best arrangement of those lenses. That experimentation will require time, patience and careful written records of the measurements and observations that you make.

Here are a few practical tips:

1. Set aside the achromatic objective lens that you plan to use in your finished telescope and use instead a small achromat which is the same sort of diameter as your relay lenses and eyepiece lenses.

The great advantage of using a small, high-quality objective lens, such as our lens 5500, is that you can mount all of the lenses in the same diameter lens cells. The fact that all the lenses are in the same diameter lens cells (probably machined from solid metal bar) is that all their centres will lie on the same optic axis.

2. Mount the objective lens in a cell; mount each of the relay lenses in its own cell, so that you can vary the distance between the relay lenses by simple moving these two cells relative to one another. Mount the eyepiece lenses in a single cell, just as they will be used in your finished telescope.

3. Make all the lens cells out of the same diameter metal, then place the lens cells, with their lenses fitted, in a piece of metal or wooden channel, supported on a sturdy camera tripod. By this means you ensure that all the lenses have their optical centres exactly in line and you can vary the distances between the lenses. By experimenting with the distances between lenses you can find the very best arrangement for the telescope that you are making.

By mounting the channel on a camera tripod you can turn the channel so that it points to a convenient high-contrast object, such as a television aerial against the sky, or a distant chimney seen against the sky.

4. Start your experiments without the relay lenses. Arrange the eyepiece lenses in their cell at the rear of the piece of channel and put the objective lens, in its cell, some distance away in the channel.

Move the objective lens until the view through the eyepiece comes into sharp focus. Observe the image carefully and make a written note of how sharp the image is. Measure the diameter of the disc of light seen in the eyepiece, when you look at the eyepiece from some distance away. This diameter is the diameter of the pencil of light that is coming out of the eyepiece and into your eye.

You can calculate the magnification of this optical system by DIVIDING the clear diameter of your objective lens by the diameter of the pencil of light that is coming out of the eyepiece. You will notice that the view, seen through the eyepiece, is upside down and back-to-front.

5. Put the two relay lenses, in their separate cells, between the objective lens cell and the eyepiece lens cell. Start with the relay lenses separated by, say, 1¼ times the focal length of the relay lenses. (If each relay lens has a focal length of 48 mm, separate the two lenses by 60 mm.) Move the objective lens cell farther away from the eyepiece lens cell, to allow room for the two relay lens cells. Patiently vary the distances in the system until you get a sharply...
focused view through the telescope. This time the view will be up the right way and round the right way. Adjust the distance from the relay lenses to the eyepiece until the same magnification is achieved as previously.

6. Try all four possible arrangements of the way the relay lenses can face, to see which arrangement gives the most sharply defined view through the telescope. During this experiment it is important to keep the same spacing between the two relay lenses. Keep written notes of your observations.

7. Once you have found the best way round to have the two relay lenses you can try altering the spacing between the two relay lenses, to see what spacing gives the most sharply defined view through the telescope. Again, keep written notes.

8. When you have found the best arrangement of the relay lenses you can vary the distance from the relay lenses to the eyepiece, to give you the most satisfying magnification through the telescope. At all stages of this entire experiment you must be scrupulous in keeping written note of distances and your estimate of the quality of the image that you are seeing through the telescope.

9. Once you have completed your series of experiments and you have established the optimum distance between the two relay lenses as well as the optimum distance between the relay lenses and the eyepiece lenses, you can replace the objective lens that you used in the experiment with the objective lens that you are planning to use in your finished telescope. You must now mock-up the final telescope by using, say, cardboard tubes and masking tape, to check that the whole system works to your satisfaction.

All this experimentation is demanding and time-consuming, but it is the process that we have to use when we are designing a terrestrial telescope for a client.

Returning to the topic of the best choice of relay lenses, it should be mentioned that the diameter of the relay lenses is a consideration, because the diameter of those lenses decides the amount of light that can pass through them. The amount of light that passes through the relay system will affect the brightness of the view seen through the finished telescope.

It is bad practice to use very short focal length lenses in a relay system because the extreme curvature of the glass surfaces in such lenses gives rise to distortions in the view seen through the telescope. Further, very short focal length lenses will also have small diameters, which will restrict the amount of light that can pass through them, thus making the view through the telescope murky and unsatisfying.

Take time to consider how to get the best compromise between large diameter relay lenses, which will help give the telescope a good bright image, and smaller, shorter focal length lenses that will help to keep the telescope shorter and easier to handle.
GLOSSARY OF COMMON ASTRONOMICAL TERMS

**Achromatic:** Literally, "without colour"

**Achromatic lens:** A lens designed to produce an image that has true colour and is free of the rainbow colours that border the images produced by simple lenses. An achromatic lens consists of two layers, made of different glasses, fitted together. One lens is convex, while the other is concave so that it fits closely against the first. The lens is designed so that the colour distortion produced by one element of the lens is corrected by opposite distortions produced by the other element.

**Air-spaced:** Sometimes the elements of an achromatic lens are not cemented together but are separated by a thin film of air, which can be so thin that the two elements are in contact. Large objective lenses for telescopes are almost always air-spaced.

**Altazimuth:** A mounting for a telescope or camera, which has two mutually perpendicular axes, one horizontal and the other vertical. This permits movement both horizontally and vertically. A camera tripod is an example of an altazimuth mount.

**Anti-reflection coating:** See 'coating'.

**Astronomical telescope:** A telescope that produces an inverted image.

**Balsam:** Canada balsam is a colourless, transparent resin that is used to glue optical components together.

**Bloomed:** See 'coating'.

**Cemented:** The two glass elements of most achromatic lenses are held together by transparent cement. Canada balsam was the traditional material but this has been superseded by modern adhesives. Canada balsam has the advantage that it can be melted over a hot-water bath, so the two components of the lens can be separated later if necessary. Modern adhesives tend to form a permanent bond.

**Coating:** Some lenses have a thin, transparent and colourless coating applied to their surfaces to minimise reflection of light. This enables more of the light to pass through the lens. Such coatings often appear coloured when viewed by reflected light. The blue or purple tinge of binocular lenses is due to this anti-reflection coating.

**Diagonal:** See 'star diagonal'.

**Doublet:** A lens made from two layers, one of crown glass, the other of flint glass. Doublets are thicker than simple lenses and the join between the two elements is visible at the edge. All achromatic lenses are doublets, but not all doublets are achromatic!

**Draw-tube:** The sliding tube of a telescope that permits the eyepiece to be moved to such a position that the telescope is in focus.

**Equatorial:** A mounting for a telescope which has two mutually perpendicular axes, one of which can be pointed to the celestial pole. This type of mount permits the movement of a star across the sky to be more easily followed than with an altazimuth mount.
**Eyepiece:** A lens or, more usually, a combination of lenses, whose function is to magnify the image produced by the primary lens or mirror of a telescope. There are many patterns of eyepiece, ranging from one element, such as the Tolles, two elements, as in the Ramsden, through four elements as in the Plossl and Orthoscopic, to six elements as in the Erfle.

**Eye-relief:** The distance from the surface of an eyepiece to the position where the observer's eye sees the greatest field of view. A too-short eye-relief makes the eyepiece uncomfortable to use because the observer's eye has to be pressed against the eyepiece. A long eye-relief permits an observer to wear spectacles whilst looking through the eyepiece.

**Focal length:** This is the distance from the edge of a lens to the point at which light from a very distant object is focused. The focal length of a complex system of lenses, such as an eyepiece, is the focal length of the single lens that would produce the same degree of magnification.

**Focal plane:** The imaginary surface on which a lens projects a focused image. It is separated from the lens by a distance equal to the focal length.

**Focal ratio:** The diameter of a lens expressed as the focal length divided by a suitable number. For example a lens 4" in diameter with a focal length of 60" is said to be a f/15 lens, because 60/15 = 4. Focal ratio is a useful way of describing the 'speed' of a lens. Lenses of low focal ratio (say f/2) when used for photography require shorter exposure times, and are thus 'faster' than lenses of high focal ratio (say f/15). Higher focal ratios, however, permit greater magnification and usually cause less distortion of the image.

**Finder:** More usually called a star-finder. It is a small telescope of low magnification whose eyepiece is fitted with a pointer or cross-hair. This auxiliary telescope is mounted on a larger astronomical telescope and is used to help point the larger telescope to the desired astronomical object.

**Graticule:** A thin disc of glass on which a cross or a scale is engraved. This is fixed inside an eyepiece (as in a rifle sight) and enables the optical system to be lined-up on a target, such as a star. A star finder eyepiece usually contains a graticule.

**Guide-scope:** A very high magnification telescope fixed to an astronomical telescope. It is used to keep the main telescope fixed on some astronomical object while the main telescope is being used for photography.

**Objective:** The large lens at the front of a telescope. It is usually achromatic and is fixed with its most curved surface facing outward from the telescope. It is often called an O. G. (Objective Glass).

**Ocular:** Another name for eyepiece.

**Orthoscopic:** A type of 4-element eyepiece which consists of a triplet lens with a singlet eye lens.

**Plössl:** A type of 4-element eyepiece in which two achromatic doublets are disposed with their most curved surfaces facing towards one another, and almost touching. This four-element ocular is characterised by a flat field of view and a long eye-relief. It is also called the symmetrical, or dial sight eyepiece. It was designed by Georg Simon Plössl in 1860.
**Ramsden:** A type of eyepiece in which two identical plano-convex lenses are disposed with their curved surfaces towards one another, separated by a distance equal to the focal length of each lens. It is named after Jesse Ramsden.

**Refractor:** A telescope in which the light from a distant object is gathered and focused by a lens.

**Reflector:** A telescope (almost always astronomical) in which the light is gathered and focused by a concave mirror.

**Star diagonal:** A device that contains a mirror or right-angle prism whose purpose is to turn the path of the light, from the objective lens of a refractor, through a right-angle. This makes the telescope more comfortable to use when it is pointed upwards because the observer looks downward into the eyepiece, instead of having to crouch under the telescope and look upward into the eyepiece.

**Star-finder:** See ‘Finder’.

**Terrestrial:** A telescope that produces an erect image. This is achieved by the use of extra lenses inside the telescope, which unfortunately also absorb some of the light. To avoid light-loss astronomical telescopes (q.v.) do not have these lenses.

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**Experimental work: Measuring the Magnification of a Telescope**

**Method 1:** By calculation.
If you know the focal lengths of the objective lens and the eyepiece the magnification can be found by dividing the focal length of the objective lens by the focal length of the eyepiece.

**Method 2:** By measurement.
Point the telescope at a bright surface, such as the daylight sky, and look into the eyepiece from a distance of a few centimetres. Use a ruler to measure the diameter of the spot of light seen through the eyepiece. Now measure the diameter of the objective lens. The magnification is found by dividing the diameter of the objective lens by the diameter of the light spot.

**Method 3:** By eye.
This method is only practical for low power telescopes, say up to X 10.
Focus the telescope on a brick wall about 30 yards distant. Observe this wall through the telescope and with your other eye open. You will notice that one brick, seen through the telescope, is the same size as several bricks seen with the unaided eye. The magnification is the number of bricks seen with the unaided eye contained within one brick seen through the telescope.