How to make a Herschelian ("Hersh~~ey Bar~~-Shelley-Ian") Telescope from an inexpensive shaving mirror

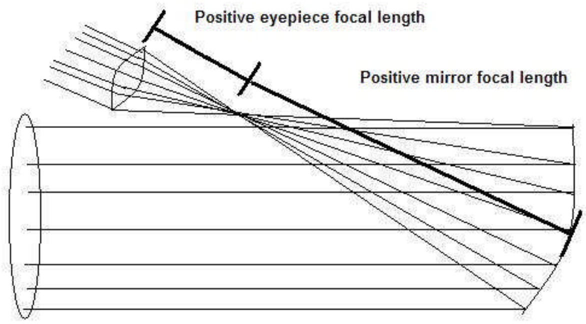

Figure 1 – Diagram of a Herschelian telescope – one positive reflecting lens-mirror and one positive lens – light enters from a beam at the left

- **Assumed knowledge**

  You have worked through the "How to make a Keplerian Telescope" or "How to make a Galilean Telescope" Handouts and the "Exploring hand magnifiers – a single positive lens" Handout.

- **Materials**

  A common shaving mirror purchased from a drug store for the telescope's objective. $4 U.S. in 2006.

  Any positive single lens for the eyepiece, preferably with a longer focal length between 30mm and 52mm. A telescope eyepiece is a good lens for this demonstration. Use the longest focal length eyepiece you have in your lens box. A 6x hand-magnifier will also work, but a 3x hand-magnifier is too weak a lens.

  A yardstick.

- **Positive lens also can be made from reflecting materials.**

  In prior handouts you worked with a single positive lens made of glass.

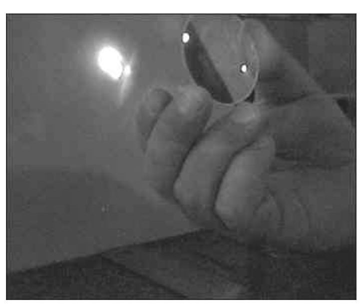

Figure 2 – A positive lens made of glass – one that *refracts* light

A glass positive lens works by bending or refracting light as it passes through the lens.

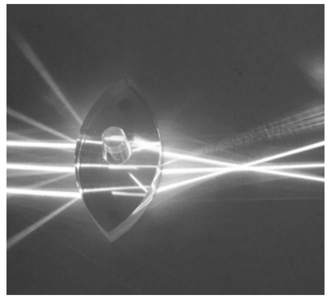

Figure 3 – Light moving through a positive refracting lens

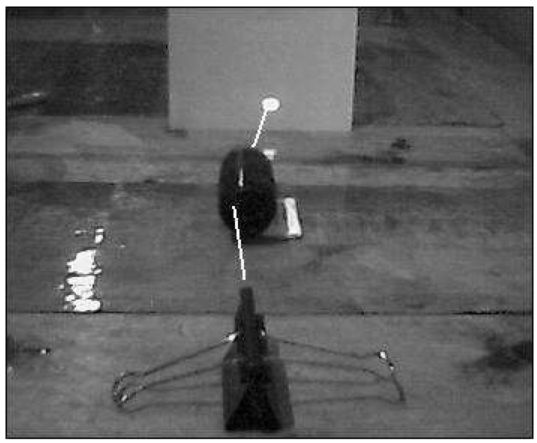

Figure 4 – A laser moving through the left side of the telescope eyepiece lens is *refracted*, bent and exits to the right

A positive lens can also be made from reflecting materials. A common reflecting material in your home is a mirror.

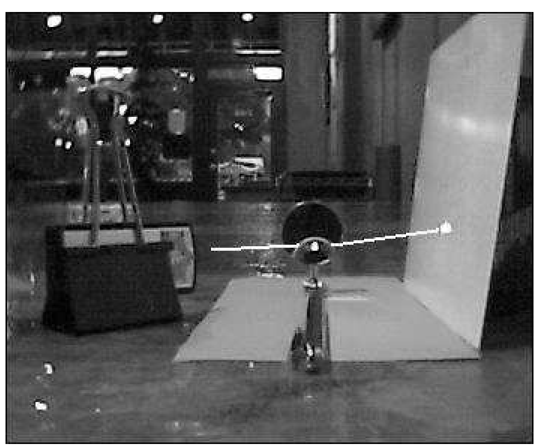

Figure 5 – The laser on the left *reflects* off a flat mirror and strikes the paper on right

If the flat mirror is curved, the reflected light will also bend. Common curved reflecting mirrors in your home is a shaving mirror and a woman's make-up compact.

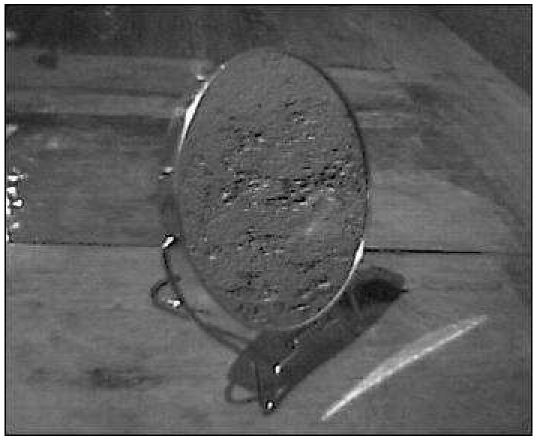

Figure 6 – A common curved shaving mirror

These mirrors are called *magnifying mirrors*. Like the positive glass refracting lens, they magnify images between zero and one focal length from the mirror-lens.

Shaving mirrors are inexpensive and can be purchased at a local drug or five-and-dime store for around $4 U.S. in 2006. Commonly, two varieties are available – a small 3x or 3 power shaving magnifier and a larger 5x vanity mirror magnifier.

A positive *reflecting* curved mirror acts like a positive single *refracting* glass lens.

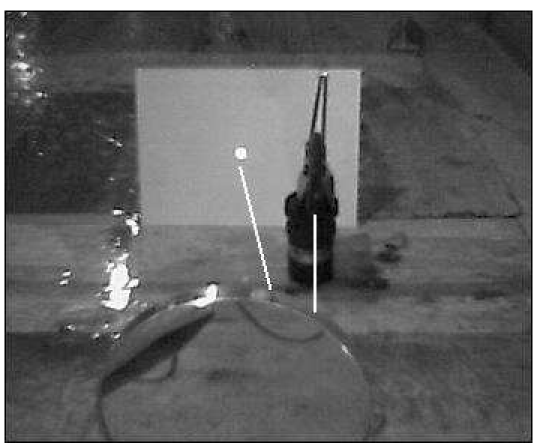

Figure 7 – A laser approaching from the right strikes the curved mirror, is *reflected* or bent and exits to the left – just as in a *refracting* glass positive lens

The glass *refracting* positive lens is called convex because it "sticks out".

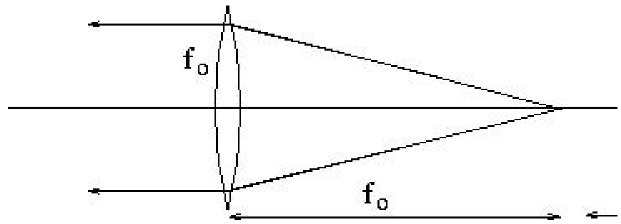

Figure 8 – A single positive refracting lens – curves out on both sides

A positive *reflecting* lens is called a "concave" mirror – it curves inward. A good way to remember the name for a positive reflecting mirror is that "There is a *cave* in a *concave* lens."

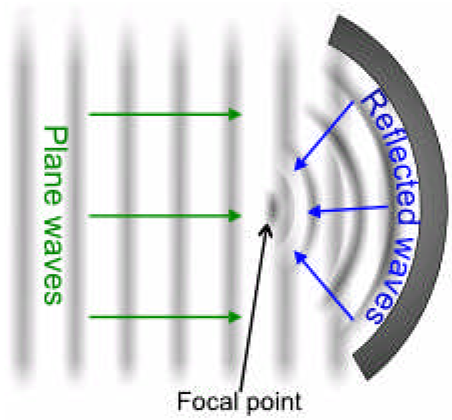

Figure 9 – A single positive *reflecting* lens – a *concave* lens curves inward to form a *cave* (Illustration by Theresa Knott, Wikipedia)

These curved reflecting lenses, depending on their shape, are also called *parabolic reflectors*.

- **A positive reflecting mirror acts similar like a positive refracting glass lens.**
  - **Case 1 magnification – looking at an object placed at less than one focal length from the mirror**

    When an object is placed next to the curved mirror, the mirror acts like a Case 1 glass lens – it magnifies objects – but the image is virtual. The image size does not change as you move your head back and forth.

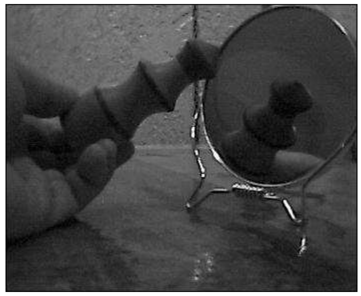

Figure 10 – A single positive *reflecting* lens mirror – a chess piece held close to the mirror is magnified, but the image is virtual

This is just what a positive glass lens does.

Figure 11 - Magnification where a positive glass lens is held less than 1 focal length from an object – a virtual erect image is created

Where a positive concave mirror differs is what occurs when the object moves more than one focal length from the mirror. The image becomes *real* but remains erect.

Figure 12 – When the chess piece is moved more than one focal length from the mirror, the magnified image in the mirror is *real*, but remains erect

With a positive *refracting* glass lens, the image becomes *real*, but is turned upside down, or *inverts*.

Figure 13 – A positive refracting lens moving past one focal length – the *real* image inverts – the picture on the wall is upside down

- **Case 2 magnification – looking at an object more than one focal length of the mirror distant**

  From one to two focal lengths, the mirror lens acts similar to a positive glass refracting lens between zero and one focal length when looking at distant objects more than one focal length away. Near one focal length in the mirror and zero focal lengths in a positive refracting lens, the image is unmagnified and erect.

Figure 14 – A single positive *reflecting* mirror (left) near one focal length and a positive *refracting* lens (right) at less than one focal length looking at a distant object more than one focal length away

In the mirror on the left is an image of a web camera looking at the mirror. The image of the web camera is erect – the light on the top of the web camera is at the top of the image, as occurs in the actual object. On the right, the glass lens shows the image of picture on a wall on the far side of a room.

In the "Exploring Hand-Magnifier" handout, when objects are further than one focal length distant – we called this "Case 1 magnification."

As the positive reflecting mirror moves form 1 focal length closer to 2 focal lengths and the positive refracting lens moves closer to one focal length, the image magnifies but remains erect.

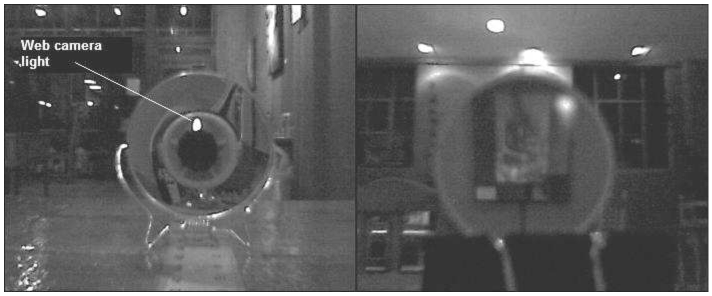

Figure 15 – A single positive *reflecting* mirror (left) moving towards two focal lengths and a positive refracting lens (right) moving towards one focal length – the image of the object magnifies

In the mirror at 2 focal lengths, the mirror image magnifies to infinity. That same occurs in the glass lens at one focal length.

Figure 16 – A single positive *reflecting* mirror at 2 focal lengths

At more than 2 focal lengths in the mirror and more than one focal length in the glass lens, the image inverts and is magnified.

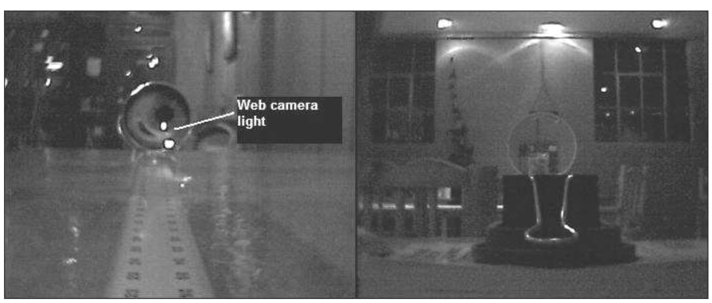

Figure 17 – A single positive *reflecting* mirror (left) moving past two focal lengths and a positive refracting lens (right) moving past one focal length – the image inverts

Here, the image in the mirror is inverted. The light on the top of the web camera now appears at the bottom of the image. The image of the picture on the wall, seen through the glass lens, is upside down.

As the mirror moves further than one focal length and the glass lens more than one focal length from the eye, the image becomes smaller than the apparent size of the object.

- **But in telescopic magnification, the real image in the mirror is at one focal length.**

To make a telescope from a positive-glass convex-refracting eyepiece and a positive-mirror concave-reflecting mirror, we will overlap the focal lengths of both lenses, just as when making a Galilean or a Keplerian telescope. In earlier handouts, we called this Case 4 magnification for Keplerian telescopes and Case 5 magnification for Galilean telescopes.

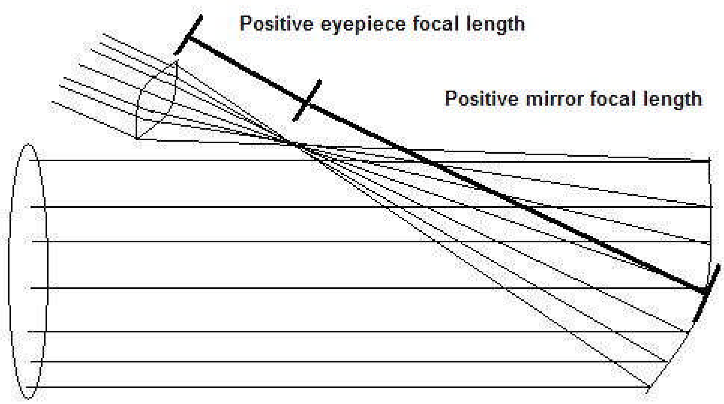

Figure 18 – Making a Herschelian telescope by overlapping the focal lengths of the lenses in Case 4 magnification

To build the Herschelian telescope, we will need to first find the focal length of the positive concave mirror.

- **Find the focal length of the single positive *reflecting* mirror – the telescope's objective lens**

Uses: Yardstick, shaving mirror, distant lamp in a darkened room, a white card, pen.

We will be using the reflecting method to find the positive mirror's focal length. This method involves projecting an image of a small object using the mirror. When the object is moved such that the image and object appear to be same apparent size, you are at 2 focal lengths from the mirror. The image that we will be projecting is a distant dim light bulb.

First, trace the outline of the mirror on the white cardstock.

Next, stand the shaving mirror at the end of the yardstick. Stand the white card up on the optical axis of the mirror.

Figure 19 – Setup to find the focal length of a positive mirror

The light from the distant bulb will reflect off the mirror and cast a circular outline on the white card stock.

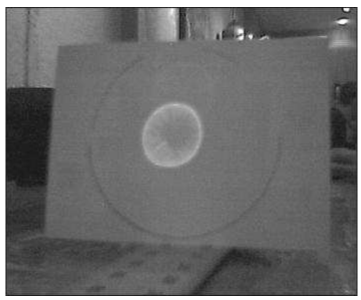

Figure 20 – Faint reflected light from the mirror casts a circular outline on the cardstock

Slowly move the card further from the mirror. When the circle of light is the same size as the outline of the mirror that you traced on the card, the card is 2 focal lengths from the mirror.

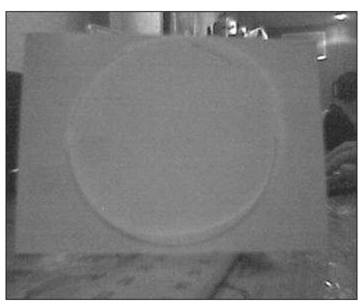

Figure 21 – A two focal lengths, the faint reflected light from the mirror casts a circular outline on the cardstock equal to the mirror size

The positive mirror focal length is ____________ inches or ______________ centimeters.

- **Find the focal length of the small lens – the eyepiece lens.**

  Find the focal length of the small positive lens using the techniques that you learned in the "Make a Keplerian telescope" or "Make a Galelian telescope" handouts. If the small lens that you are using is a telescope eyepiece, the focal length of the lens is marked on the side of the eyepiece.

  Small lens focal length is ____________ inches or ______________ centimeters.

  The small glass lens is also a positive lens. In this case, it is called a "convex" lens because it sticks "out" in the middle.

- **What is the sum of the two focal lengths?**

Lens	**Focal length**
Big lens	
Small lens	+
Sum of focal lengths	=

- **Make the Herschelian off-axis telescope**

  Materials: Yardstick, shaving mirror lens and the small lens.

  Gather everything you need. The telescope is best used during the daytime on terrestrial objects because it is harder to find the focus of the telescope at night.

  Put the yardstick on a table with one end at the edge of the table and the yardstick running along one edge of the table. Make sure you point the yardstick away from the Sun.

  Put the mirror at the other end of the yardstick pointing at an object of interest such as a car or tree across the street. The center or *axis* of the mirror runs down the centerline of the telescope.

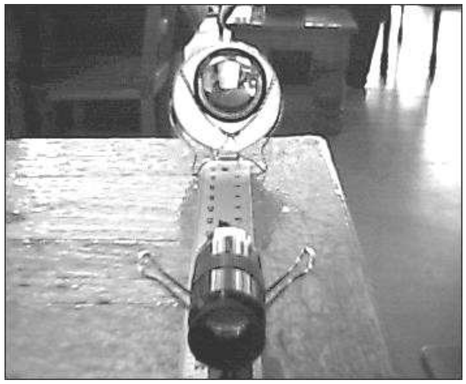

Figure 22 – Set up for making the Herschelian telescope

Measure off the focal length of the mirror lens on the yardstick. Now, imagine a circle with a center at the center of the mirror and its radius at the focal length of the mirror. Imagine a circular arc along this circle. About 3 to 5 degrees off of this centerline guess about where one focal length from the mirror is.

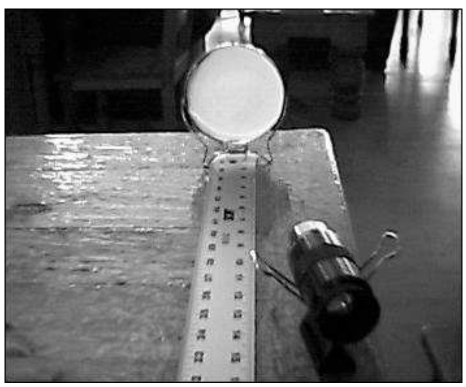

Figure 23 - The eyepiece is moved slighty off-axis to make the Herschelian telescope

Now hold the small lens in your hand. At your estimated off-axis focal point, direct the small lens at the center of the mirror and move the small lens back and forth until a magnified image comes into focus.

The telescope will come into focus, but be slightly distorted, when you are holding the two lenses apart as the same distance as the "Sum of the focal lengths."

Because the Herschelian telescope is off-axis, the images will have more distortion than seen in the Galilean or Keplerian telescopes. This is particularly noticeable if you focus your telescope on a street lamp at night. This distortion can be minimized by moving the eyepiece the smallest feasible angle off the axis of the primary mirror.

- **How much bigger is the image that you see in your telescope as compared to the actual object?**

Lens	**Focal length**
Big lens (divided by)	
Small lens	/
Magnification	=

- **The image you will see in the telescope is *virtual*.**

  While holding up your telescope, move your head backwards and forwards from the little or eyepiece lens. Notice that the magnified image does not, like most things in the world, get bigger and smaller as you move your head closer to further away from the eyepiece lens.

- **Other things to look for in the magnified telescope image.**

  You may see a fuzzy ring around a clear image in the middle. This is called “coma.”

  You may see color fringes – blue or yellow – around the object in the image. This is called “color aberration.”

- **If you drop your mirror or lens and the glass breaks, tell an adult and ask them to help sweep the glass up. Do not look at the Sun through a lens. You’ll go blind.**

- **Reference table – Inches, Centimeters and Millimeters**

Inches	**Centimeters**	**Millimeters**
1	2.5	25
2	5.1	51
3	7.6	76
4	10.2	102
5	12.7	127
6	15.2	152
7	17.8	178
10	25.4	254
20	50.8	508
30	76.2	762
40	101.6	1016

- **Who is Herschel that invented the Herschelian telescope?**

William Herschel (1738-1822) originally was a musician who became interested in telescope-making. He invented a unique off-axis telescope design, where the primary reflecting mirror was tilted slightly to project the real image of the primary positive lens to the side of the telescope tube.

To form his mirrors, Herschel used metal which was ground to shape. Then a layer of reflecting silver was applied. The reflecting silver had to be replaced every two or three months.

In 1781, using a 6.2 inch (~158 mm) mirror in a 7 foot (~2100 mm) tube, Herschel discovered the planet Uranus – the first new planet to be discovered since the ancient Greeks. External link to a picture of Herschel's 7 inch telescope from the British National Museum of Science and Industry: << http://www.scienceandsociety.co.uk/results.asp?image=10305266 >> accessed May 2006.

This drew the attention of the King of England, who appointed Herschel as a Royal Astronomer. The king financed Herschel's continually larger telescopes – ending with Herschel's 1787 40 foot (~12,000 mm focal length) long telescope with an aperture of 48 inches (~1220 mm).

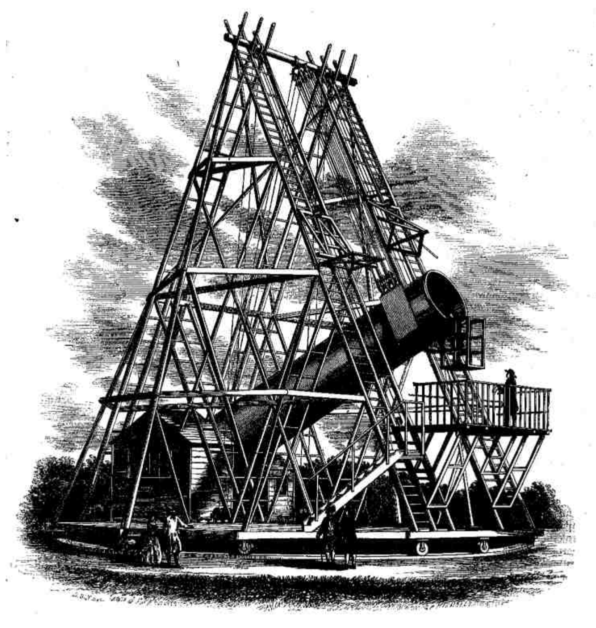

Figure 24 – Herschel's 40 foot telescope

In his 40 foot telescope, Herschel solved the problem of using his eyepiece off-axis (as we did with the shaving mirror) by simply positioning himself to one side of the tube-end.

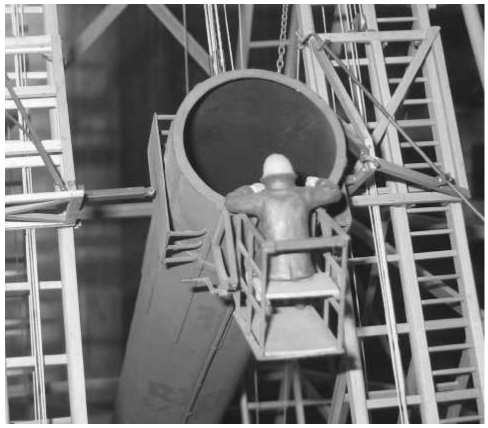

Figure 25 – Model of Herschel using his 40 foot telescope (courtesy of M. Tabb, The William Herschel Society)

Using this telescope and more often Herschel's smaller 20 foot long (~6000 mm focal length) telescope with an aperture of 18 inches (~475 mm), Herschel proceeded to systematically map the night sky visible from England – one degree at a time. The end result was Herschel's 1802 catalogue of approximately 2,514 deep sky objects (galaxies and nebula).

Today, amateur astronomers still use a subset of Herschel's catalogue – the Herschel 400 – as an observing list of interesting objects to look at with 6 inch to 10 inch telescopes. The Astronomical League Herschel 400 Observing Club << http://www.astroleague.org/al/obsclubs/herschel/hers400.html >> accessed May 2006.

Herschel's 20 foot telescope, which he used for finding most of the objects in his catalogue, is in the collection of the British National Maritime Museum, but is on permanent loan to the U.S. Smithsonian National Air and Space Museum. Photographs of Herschel's 20 foot telescope can be viewed on the internet at the Smithsonian National Air and Space Museum and its Herschel Telescope Online Exhibit.

The mirror housing of the 40 foot telescope is on display at the British National Museum at Greenwich.

Figure 26 – The mirror housing of Herschel's 40 foot telescope (courtesy of M. Tabb, The William Herschel Society)

Herschel's design is called an off-axis telescope. This means the primary mirror is tilted with respect to the central axis of the telescope.

Off-axis telescopes similar to Herschel's 7 inch telescope are still sold today by DGM Optics.

- **Further reading**

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- **Sources**

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Tabb, Michael (The William Herschel Society). 5/20-23/2006. Personal communication. (Current locations of Herschel's existing telescopes, their apertures, focal lengths and photographs)

- **Materials source**

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http://scientificsonline.com/
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Version: 5/23/2006