

Reflecting Telescopes

All the earliest optical telescopes were REFRACTORS, using lenses to form an image; they date back to at least 1608. Since light of different wavelengths is bent or 'refracted' unequally as it passes through glass, a refractor always gives a certain amount of false color round an image such as that of a star. Light of whatever color is however reflected in the same direction, so a REFLECTOR does not suffer from this chromatic aberration. The first practical optical reflecting telescope was made by Isaac Newton around 1668.

In a Newtonian reflector, there is no lens to collect the light. The light passes down a tube and falls upon a concave mirror. The mirror sends the light back up the tube onto a smaller, flat mirror placed at an angle of 45° . The light is then directed into the side of the tube and is brought to focus. The image is formed outside the incoming light beam and is enlarged by an eyepiece lens—the observer's head does not obstruct the incoming beam (see NEWTONIAN TELESCOPE).

The Newtonian pattern is still widely used by amateur reflectors of the 6 inch to 20 inch (15 to 50 cm) class. The lower limit to the useful size range is set by the proportion of light to the main mirror which is obstructed by the flat mirror and its support. The upper limit is weaker and is set by the convenience of access to the eyepiece, say at the height of a standing man or woman, although larger telescopes may have a Newtonian focus accessed by ladders. The 72 inch (1.9 meter) Radcliffe Telescope, originally erected in 1948 at Pretoria in South Africa and later moved to Sutherland in 1974, was the largest Newtonian telescope constructed (equal to the size of the Rosse reflector of 1845). Its Newtonian focus is accessed from a cage attached to the dome shutter mechanism—this facility (intended for photography) is almost unused nowadays.

For larger apertures than, say, 50 cm, the CASSEGRAIN TELESCOPE, invented in 1673 is more convenient. Here the secondary mirror is convex and is placed between the main mirror and its prime focus, reflecting the light to the main focus of the telescope, through a hole in the main mirror. The combined action of the two mirrors lengthens the focal length of the telescope above the focal length of the primary mirror alone, but makes the telescope more compact. The combination of concave and convex mirrors also reduces the off-axis aberrations introduced by the primary mirror. The focus of a Cassegrain telescope is close to the observing floor, and as convenient to access as the telescope mounting will allow. The reduction in overall length of a Cassegrain telescope (compared to a Newtonian telescope) directly reduces the size of the building in which it is housed, with consequent saving of costs. Thus, Cassegrain telescopes quickly became popular for astronomical use, and still are, largely because they are much shorter and more compact than Newtonians and are therefore much easier to handle and less expensive.

The next major developments in making reflecting telescopes were due to William Herschel. He made his own mirrors and telescopes, of altazimuth design. With one of these, a reflector of 6.2 in (16 cm) aperture and 7 foot (2.1 m) focal length, he discovered the planet Uranus in 1781. His largest telescope had a mirror 49 in (1.5 m) across. It was not surpassed in size until 1845, when the third Earl of Rosse, in Ireland, produced a Newtonian telescope with a 72 in (1.9 m) mirror. Despite the limitations of its extraordinary mounting (it swung on ropes and chains between two massive stone walls on which the observing platform was mounted, to access the eyepiece), and its cylindrical tubular mounting (which trapped heat and, potentially, degraded seeing), the Rosse telescope discovered the spiral forms of the objects we now know to be external galaxies. The telescope was restored to working order (although not with its original mirror) in 1998.

The early reflectors had 'speculum' mirrors of low reflectivity and did not produce bright images. The metal mirrors tarnished quickly and had to be regularly re-polished, whereas refractors required practically no maintenance at all. It became possible to make glass mirrors, which could be coated with a highly reflective substance such as silver or aluminum. In modern times, the reflection coating can be optimized to the wavelength bands used by the telescope, e.g. the infrared.

As telescopes, whether refractors or reflectors, track a star, or point to different stars in the sky, their attitude changes relative to the vertical and thus to the direction of gravity. This produces mechanical flexure not only of the telescope structure but also of the glass lenses or mirrors, causing degradation of the images. The mechanical rigidity of glass held at the edges limits the size of lenses to about the 40 inch (1 m) size of the Yerkes refractor, made 1895. A mirror, on the other hand, can be supported over the whole of the back of the mirror. Supporting mechanisms or mirror mounts were developed to spread the support evenly and to be effective at all attitudes of the mirror.

Reflecting telescopes are typically made with a paraboloidal primary mirror, which, if perfectly formed, correctly focuses light from a star on its optical axis to a diffraction-limited point image. Off-axis, however, the images are aberrated by coma. A large reflecting telescope thus has a small field of view, perhaps only an arc minute or two, unless a correcting lens is used just ahead of the prime focus. A corrector lens combined with its 3.9 m hyperboloidal primary mirror enables the Anglo-Australian Telescope to have a field of view of up to 1° . The hyperboloidal primary mirror is combined with an ellipsoidal secondary mirror in the AAT's Ritchey-Chrétien optical design.

For survey purposes, such as to make a photographic atlas of the whole sky, an even larger field of view is a great advantage. In 1930, an entirely new optical system was developed by an Estonian researcher, Bernhard Schmidt, with a modified system invented in 1941 by Dmitri

Maksutov. In these reflecting telescopes, the incoming light is collected by a main mirror which is spherical rather than paraboloidal. Normally this would introduce serious image distortions, but these are removed by means of a glass corrector plate fixed at the upper end of the tube. The SCHMIDT TELESCOPE corrector has a complex aspheric profile, the Maksutov corrector has spherical surfaces. The detector, say a photographic plate, a photographic film, or a mosaic of CCDs, is situated at the prime focus. The main problem is that the focal plane is curved, and so the detector has to be shaped to the surface of a sphere. A special plate-holder has to be used to bend a glass photographic plate into the correct form, or the CCDs have to be mosaicked onto a spherical surface. The end result is that sharp star images can be obtained over very wide fields, often well over 10° across. The Oschin Schmidt telescope at Palomar, in California, has a 48 in (1.2 m) corrector plate feeding its 1.8 m primary mirror and was used to make the Palomar Observatory Sky Survey of the northern hemisphere. It is optically similar to the UK Schmidt Telescope in Siding Spring Observatory. The 1.35 m Schmidt at Tautenberg, in Germany, is the largest Schmidt telescope of classical design, whose size is limited by the same issue of support of the optical corrector lens as has restricted refractors to the 1 m class. However, a 4 m Schmidt telescope, LAMOST, is under construction near Beijing for multi-object spectroscopy. Its spherical mirror is fed by a celostat on whose almost flat reflecting surface the appropriate corrections are figured.

In 1908 George Ellery Hale masterminded a 60 in (1.5 m) reflector, which was set up on Mount Wilson in California. It was not so large as the Rosse 72 in, but had a silvered glass mirror and a fully maneuverable equatorial mounting. The tube was a structure of rigid, triangular, skeletal girderwork, rather than being solid walled tube. This reduced weight, improved air flow and seeing, but held all the optical components in exactly the right positions. Most modern reflectors have similar open support structures, which nevertheless are referred to as telescope 'tubes'.

Another design driver, for the tube of telescopes like the 4 m UK InfraRed Telescope on Mauna Kea, the largest designed specifically for infra-red use, is the desire to reduce the amount of structural material intruding into the infra-red beam, so as to limit the thermal radiation created as infra-red background in the telescope.

Hale made a 100 in (2.5 m) equatorially mounted reflector, again set up on Mount Wilson and financed mainly by a Los Angeles millionaire, John D Hooker, after whom it is named. Before he died, Hale planned the reflector with a 200 in (5 m) mirror on Mt Palomar named in his honor. The Hale telescope was completed in 1948 and was the largest telescope in the world for a generation, with epoch-making discoveries to its credit too many to list. The telescope incorporated the 'Serrurier Truss,' newly invented by Mark U. Serrurier of CalTech in Pasadena in 1935 as a way of controlling flexure in the tube of the telescope that he helped to design. Serrurier

conceived of a structure that bent as little as possible, but if it did deflect (as was inevitable to some extent), it kept the primary and secondary mirrors in the correct relative positions. The telescope tube includes a cubical section at its center of gravity where the declination axis is attached. Eight triangular trusses are fixed to the corners of the cube, four pointing up to the top end ring which supports the secondary mirror, and four to the primary mirror cell. Four opposite pairs of the triangular trusses oppose bending by gravity, while the four interposed pairs form a parallelogram with the end-rings such that motion of the end rings is of equal magnitude and in parallel, thus keeping the optical elements collimated in spite of flexure. The Gemini telescopes use a variant of this principle, with the large cubical sections at the center of gravity eliminated because of their effect on thermal input into the light beam of the telescopes.

A telescope has two principal degrees of freedom, the axes around which it rotates to point to and follow a star. To a first approximation, an equatorially mounted telescope tracks by rotation about one axis, at constant speed. However, mechanical flexure changes the optical axis of the telescope with two additional degrees of freedom. The change of focus, whether due to mechanical flexure or thermal expansion, is another. Although the telescope mounting structure will have been made to the highest standards, nevertheless the axes will not be exactly orthogonal, nor aligned exactly on the sky. Its bearings will not be exactly circular nor exactly centered, and the gears that drive the telescope will have periodic errors introduced in their manufacture. Refraction of starlight by the curvature of the atmosphere means that the sky does not appear to rotate uniformly. All these effects limit the accuracy of telescope performance.

With the development of computers, it was possible to coordinate the motions of the telescope structure at a high enough rate to compensate for these departures from ideal. In 1974, building on the experience of radio astronomers in controlling altazimuth radio telescopes, the 3.9 m Anglo-Australian Telescope successfully implemented computer control of its equatorially mounted structure at the arc second level. This paralleled the successful computer control of altazimuthally mounted optical NASMYTH TELESCOPES, like the 6 m Bolshoi Teleskop Azimutalnyi (BTA). Virtually all the current generation of large telescopes (over 4 m) are altazimuth designs. The BTA telescope, however, revealed just how important it was to control the thermal environment of a large mirror, otherwise diurnal changes of temperature propagate into the mirror, causing an ever-shifting pattern of thermal distortion.

Symmetrically oriented in gravity, altazimuth telescopes can be made stiffer, and hence could respond better to control. The dome can be fitted more symmetrically around an altazimuth telescope, made more compact and cheaper—the less money of a telescope project spent on a building, the more that can be spent on the telescope and its instrumentation.

Table 1. The 30 largest reflecting telescopes

Name and abbreviation	Location	Size (m)	Date	Website URL
Keck Telescope I	Mauna Kea, Hawaii	10.0	1991	astro.caltech.edu/observatories/keck
Keck Telescope II	Mauna Kea, Hawaii	10.0	1996	
Gran Telescopio de Canarias (GTC)	La Palma, Spain	10.0	2002	www.gtc.iac.es
Hobby-Eberly Telescope (HET)	Mt Fowlkes, Texas	9.2	1999	www.as.utexas.edu/mcdonald/het/het.html
South African Large Telescope (SALT)	Sutherland, S. Africa	9.2	2003	da.sao.ac.za/~salt/
Large Binocular Telescope (LBT)	Mt Graham, Arizona	8.4	2002/04	lbtwww.arcetri.astro.it/
Subaru	Mauna Kea, Hawaii	8.3	1999	www.naoj.org/
Antu (VLT 1)	Cerro Paranal, Chile	8.2	1998	www.eso.org/outreach/info-events/ut1fl/
Kueyen (VLT 2)	Cerro Paranal, Chile	8.2	1999	
Melipal (VLT 3)	Cerro Paranal, Chile	8.2	2000	
Yepun (VLT 4)	Cerro Paranal, Chile	8.2	2000	
Gemini North	Mauna Kea, Hawaii	8.1	1999	www.gemini.edu
Gemini South	Cerro Pachon, Chile	8.1	2000	www.gemini.edu
MMT	Mt Hopkins, Arizona	6.5	2000	sculptor.as.arizona.edu/foltz/www/mmt.html
Magellan Telescopes I and II	Las Campanas, Chile	6.5	2000	medusa.as.arizona.edu/mlab/mag.html
Large Zenith Telescope (LZT)	Vancouver, BC	6.1		www.astro.ubc.ca/LMT/lzt.html
Bolshoi Teleskop Azimutalnyi (BTA)	Mount Pastukhov, Russia	6.0	1975	www.sao.ru
200 in Hale Telescope	Mount Palomar, Ca	5.0	1948	astro.caltech.edu/observatories/palomar/
William Herschel Telescope (WHT)	La Palma, Spain	4.2	1987	ing.iac.es/WHT.html
SOAR	Cerro Pachon, Chile	4.2	2001	www.lna.br/soar/soar_e.html
Victor Blanco Telescope	Cerro Tololo, Chile	4.0	1976	www.ctio.noao.edu/telescopes/4m/base4m.html
Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST)	Xinglong Station, China	4.0	2004	159.226.88.56
Anglo-Australian Telescope (AAT)	Siding Spring, Australia	3.9	1975	www.aao.gov.au
Mayall Reflector	Kitt Peak, Arizona	3.8	1973	www.noao.edu/kpno/kpno.html
UK InfraRed Telescope (UKIRT)	Mauna Kea, Hawaii	3.8	1978	www.jach.hawaii.edu/UKIRT/home.html
3.6 m Telescope	La Silla, Chile	3.6	1977	www.ls.eso.org/lasilla/Telescopes/360cat/html/tel360.html
Canada-France-Hawaii Telescope (CFHT)	Mauna Kea, Hawaii	3.6	1979	www.cfht.hawaii.edu
Largest reflecting telescopes in space				
Next Generation Space Telescope (NGST)	Lagrangian point, L2	8	2007	ngst.gsfc.nasa.gov/index.html
Hubble Space Telescope (HST)	Low Earth orbit	2.4	1990	www.stsci.edu
Largest reflecting telescope for public education: Faulkes Telescope (FT)	Haleakala, Hawaii	2.0	2001	www.faulkes.com

The Gemini Telescopes at 8 m, the four telescopes of the VLT at 8.2 m and the Subaru Telescope at 8.3 m have probably reached the practical limit of a thin monolithic mirror, whose optical figure is computer controlled by actuator pads—the transportation of such a mirror from the factory to the site is a major issue, solved in the case of the BTA in the then Soviet Union by construction of a special railway. To transport the monolithic mirrors of the 8 m Gemini telescopes, roads were widened, the radius of curvature of bends reduced and detours constructed around low bridges.

To make larger aperture reflecting telescopes, the solution is to make a segmented mirror, in which the various smaller components are fitted together to make the correct optical curve. This technique was developed in reflecting telescopes working at wavelengths longer than light, such as the James Clerk Maxwell Telescope

on Mauna Kea for sub-millimeter wave astronomy, where 276 individual panels are assembled into a mosaic, each of which can be moved by 3 motorized adjusters. Its first realization for optical astronomy was in the original 4.5 m Multi-Mirror Telescope in Arizona, before its six mosaicked mirrors were replaced by a monolithic 6.5 m.

The Keck telescopes, also on Mauna Kea, have hexagonal reflecting mirrors 12 m across (10 m diameter effective circular area). Each hyperboloidal mirror is made up of 36 hexagonal segments, 1.8 m in diameter, fitted into a honey-comb pattern like tiles. Although each telescope is more than twice the aperture, and four times the area of the Palomar 200 in (5 m) telescope, the total mass of glass in each is little more than 14 tons—about the same as the Palomar mirror. The Gran Telescopio de Canarias, under construction for La Palma, also has a similarly segmented 12 m diameter mirror, essentially replicating the Keck

design. As the largest telescopes in the world, the Keck telescopes are setting the pace of discovery among optical observatories.

The overall mirror figure of a segmented mirror is typically maintained through active computer control of the mirror support system, referenced to laser beams. In active optics, the shape of the main mirror is continually modified by computer-controlled pads behind it, so that the shape can be maintained very precisely when the mirror is moved around to point to different directions in the sky. Acceptance that the mirror will bend and provision of a compensating control mechanism makes it possible to reduce the thickness of a mirror, reducing its weight and the strength of the telescope support, and the thermal inertia of the mirror, with benefits in thermal distortion and cost reduction. An alternative method to reduce mirror mass is through a hollow honeycomb construction of the mirror material, used in the two telescopes of the Large Binocular Telescope with 8.4 m mirrors.

With adaptive optics, a relatively bright star in the field of view is monitored, either a naturally occurring star or an artificial star generated in the upper atmosphere by a laser beam. Reacting to the degradation of the image of the monitor star, a flexible optical component in the telescope beam (a small mirror) is continuously modified in shape, to remove distortions due to turbulence in the Earth's air. This technique is more effective at infra-red wavelengths, as optimized in the design of the 8 m Gemini telescopes, which reach the diffraction limit of resolution.

An alternative approach with large reflectors to increase angular resolution is to combine beams from separate telescopes situated tens or hundreds of meters apart. The two Keck telescopes and the Large Binocular Telescope will be used this way, as will the world's greatest telescope at Paranal in Chile; this is the VLT (Very Large Telescope) which will use four mirrors, each 8 m across, working separately as four powerful 8 m telescopes or together as an interferometer.

Seeing conditions at Paranal and other mountain-top observatories, where large reflectors are nowadays constructed, are excellent, but of course for 'perfect' seeing it is necessary to be above the Earth's atmosphere, and this has been achieved with the Hubble Space Telescope, launched from the Shuttle on 25 April 1990. It has a 2.4 m mirror. The size of the monolithic reflecting mirror of the HST was limited by the capacity of the Space Shuttle's cargo bay. In spite of its relatively small size, the HST is the reflecting telescope with the most impact of modern times. The 8 m Next Generation Space Telescope (NGST) reflecting telescope, optimized as a successor to the HST for observations in the near infrared, will be made of segments which unfold like an umbrella. Thermal distortion of the mirror due to solar, terrestrial and lunar thermal radiation, will be controlled by sunshades and passive thermal radiators. In weightlessness, gravitational deflection will not be an issue!

A completely different approach to the provision of large reflecting telescopes is to make their mirrors of a rotating reflective liquid (mercury), spinning on a vibration-free bearing such that centrifugal force builds up the correct parabolic dish shape (as first proposed by Isaac Newton). The 3 m NASA Orbital Debris Observatory (NODO) telescope in New Mexico and 2.7 m Liquid Mirror Telescope of the University of British Columbia are as far as this technology has been proved, but a 6 m Large Zenith Telescope is under construction and a 42 m equivalent aperture array of 18 10 m telescopes with combined focus is planned. Such telescopes are restricted to staring at the zenith, and can be used to sample the sky, whether for space debris or for stars or galaxies.

Another large innovative reflecting telescopes is the Hobby-Eberly Telescope, a spherical reflector of 91 interchangeable segments forming an 11×10 meter hexagon. The telescope structure is tilted at a fixed angle of 55° above the horizon (35° zenith angle). The structure rotates 360° about a vertical axis. It can be rotated to catch stars and galaxies as they rise or set across the small circle centred on the zenith at 55° altitude, and track them via a moving instrument carriage for long enough for spectroscopy (up to 2.5 hours). The South African Large Telescope (SALT) destined for the observatory at Sutherland is a copy of this design.

It is believed that there are no theoretical limitations to the manufacture of ground based reflecting telescopes up to the 50 m to 100 m class. Design studies are in progress for the OWL (Overwhelmingly Large Telescope) or MaxAT (Maximum size Astronomical Telescope); they will surely be projects with global participation.

Ever since Galileo had such spectacular success in 1608 when he first turned a telescope to the sky, astronomers have been seeking ways to make larger and more accurate telescopes in their quest for more light. The present large telescopes of the 8 to 12 meter class are fine examples of what can be done. Engineers, technologists, scientists, administrators and politicians have been inspired to work together to address questions that, in the 21st century, are the modern equivalent of the questions tackled by Galileo in the 17th century. In the words of astronomer Fred Hoyle, put into the mouth of Britain's Prince Charles at the dedication of the Anglo-Australian Telescope in 1974, 'reflecting telescopes are examples of the sorts of things our civilization does well'.

The largest reflecting telescopes operating or under construction are listed in table 1.

Paul Murdin and Patrick Moore