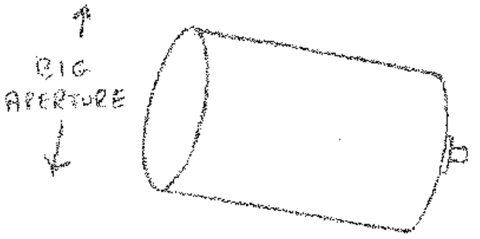
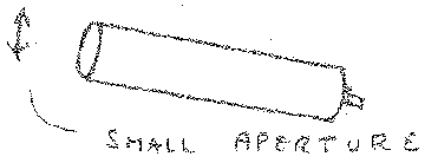
Tony Fairall - PART 2
TELESCOPES

Our knowledge and understanding of the universe around us made enormous advances with the work of Galileo and, somewhat later, William Herschel, because they made use of telescopes. Telescopes do two things: They let us see much fainter objects than the naked eye can detect (light gathering power). They also let us see greater detail than the naked eye can resolve (magnification).
In the same way that a large funnel would collect more falling raindrops than a small funnel, so a LARGE APERTURE telescope will collect more photons of light (from a distant object) than a small aperture telescope.

TELESCOPE FUNDAMENTALS

A telescope operates somewhat like a funnel - it channels the light into the observer's eye (or into a detector fitted to the telescope). At best the human eye has an aperture (diameter) of about 6 mm (with pupil dilated). Amateur astronomers may possess telescopes with apertures of 60 to 200 mm, while professional telescopes have apertures measured in metres, and the largest telescopes in the world have apertures of around 10 metres.

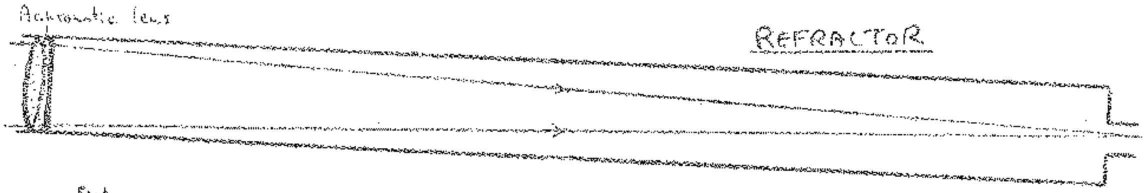


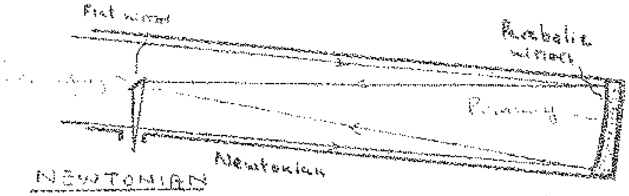


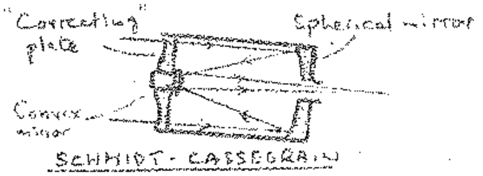
A telescope can also be used to magnify the image, to allow the eye (or camera) to record greater detail. Note however that all stars, other than the Sun, are so very distant that even seen through telescopes, they are still unresolved points of light. The magnification of a telescope can be changed simply by changing the eyepiece - most amateur telescopes come with a range of eyepieces. There is no point, in any case, magnifying the image too much - otherwise it simply becomes blurred and no further detail can be seen (like magnifying a newspaper photograph). Generally the blurring is caused by thermal irregularities in the Earth's atmosphere. Astronomers refer to this blurring as the 'seeing'. It varies like the weather. Sometimes it may be around 2 arc seconds (an angle of 1 arc second is 1/3600 of a degree) so that stars images look like blurry balls 2 arc seconds across. Excellent seeing (for example at Sutherland) may be down to 0.5 arc seconds.
Over and above seeing effects, students of physical optics will also know that a bigger aperture means increased resolution. For example, if a double star had its components separated by 2 arc seconds, then a minimum aperture of 60 mm would be required to separate them - or for a separation of 1 arc second, a minimum of 120 mm aperture.

DESIGNS OF OPTICAL TELESCOPES

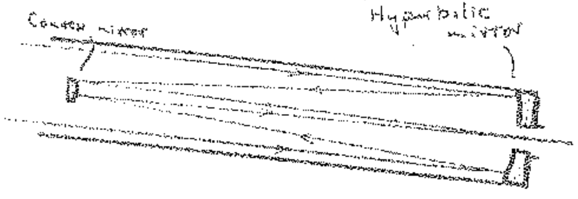
The accompanying diagrams show the most popular optical designs for small telescopes. Note that the three telescopes are equal in aperture - while the refractor is physically very long, the Schmidt Cassegrain is very compact (more portable and easier to mount).



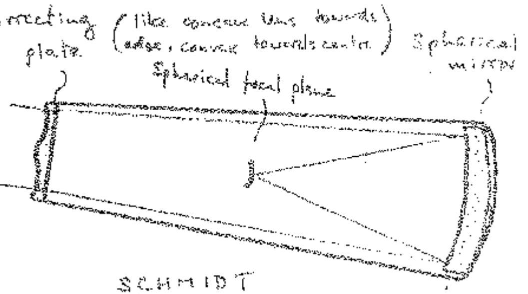




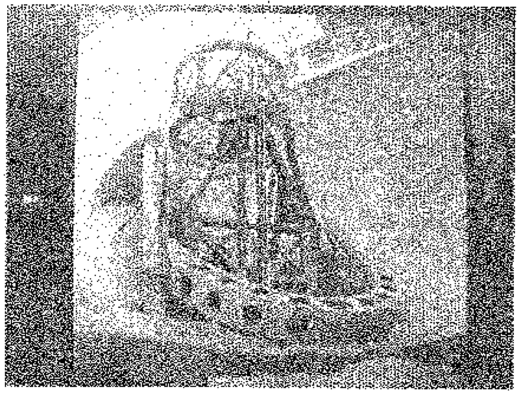
While giant refractors were built in Victorian times, almost all modern large professional telescopes are of Cassegrain design, while the Schmidt telescope serves as a wide-field camera with fast f-ratio.



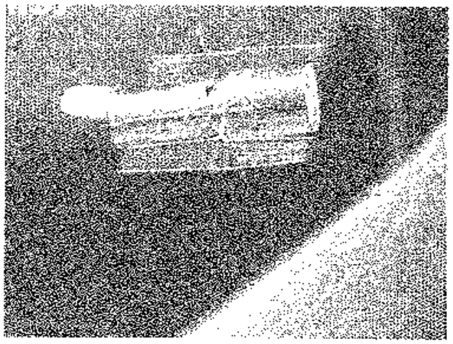
CASSEGRAIN



SCHMIDT

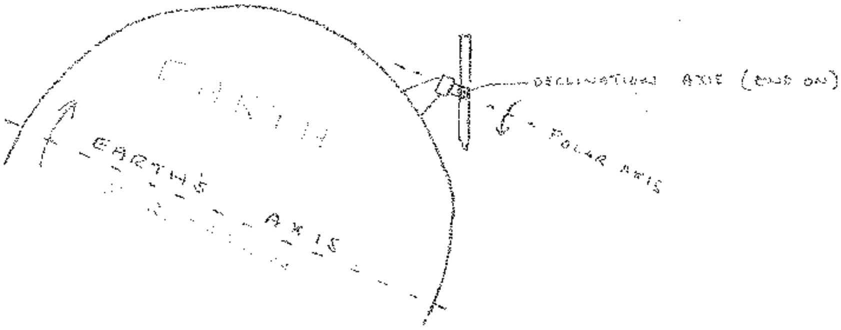


Building larger and larger primary mirrors for telescopes has been the challenge, since the optical surface has to be accurate to a fraction of the wavelength of light. Up until the early 1980s, the approach was to build mirrors as thick and rigid as possible, and to support them uniformly at many points so they did not deform. Given that that the mirror will be tipped over in various directions, as its telescope tracks the stars, this is not easy to achieve. The largest such mirror is 6m in diameter, built in the 1960s-80s for the Special Astrophysical Observatory in the then Soviet Union. The Hubble Space Telescope, designed in the 1970s, also has a lightweight but rigid mirror (and the advantage of absence of gravity when operating). This proved to be a major problem when it was found a mistake had been made in figuring its optical surface, and the telescope operated for almost four years with imperfect optics. Only when fitted with corrective 'spectacles' did it achieve its design specifications. Operating above the Earth's atmosphere is one way of overcoming the problems of the seeing.

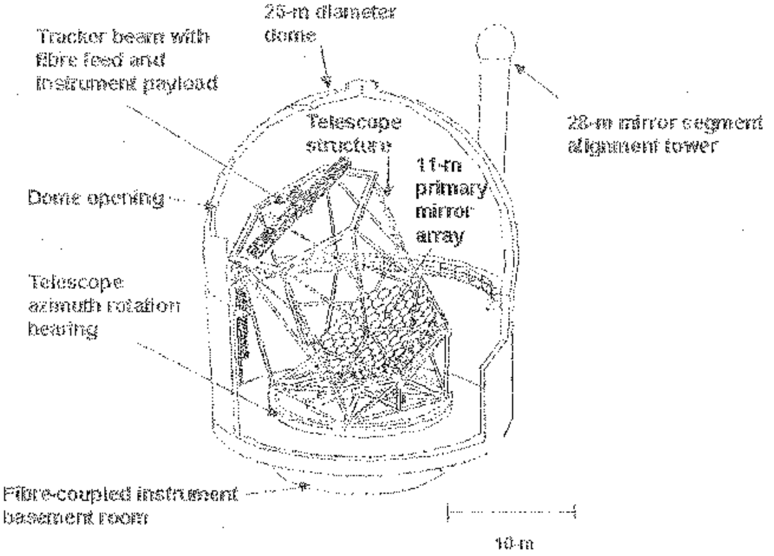


The modern method of building telescopes is to make the mirror thin, but to support it at many points with computer-controlled actuators that constantly adjust to hold the mirror in perfect shape. In this way, a number of 8m telescopes have been built. They include the four units of the 'Very Large Telescope' of the European Southern Observatory, the Gemini Telescopes (one in the Northern Hemisphere and one in the south) and the Japanese Subaru Telescope.

Alternatively, mirrors can be manufactured in segments and the segments aligned as a single reflecting surface by active control. The twin Keck Telescopes, each with 10m aperture, in this fashion operate. Similarly, the Hobby-Eberly Telescope (HET) and the Southern African Large Telescope (SALT) have mirrors of over 10m composed of 91 identical segments. A considerable cost saving with these last two telescopes comes about by making the primary mirror spherical, not hyperbolic, so all segments are identical and interchangeable. But a corrector to overcome 'spherical aberration' has to be employed.



Older and smaller telescopes are generally attached to an equatorial mounting: a 'clock' drive turns the telescope (once in 23h56m) about the polar axis so the telescope compensates for the Earth's rotation and remains aimed at the same star. Modern large telescopes (since the Soviet 6m) have altazimuth mountings (simple vertical and horizontal movement). Computer



controls take care of the tracking as the Earth rotates.

A great saving with both HET and SALT is that the telescopes themselves do not move. Instead, a small mobile tracker, mounted on the top end of the telescope does the work (positioning itself within a few thousandths of a millimetre). Further, the telescopes are aimed at an angle in the sky - and can be picked up, swivelled around and set looking into a different part of the sky.

DETECTORS

Up to the late 1800's all observations through telescopes were made by eye. The advent of photographic emulsion, with its ability to accumulate signal over long exposures, was a revolutionary breakthrough. Although modern emulsions still are used for wide field Schmidt cameras, photography today has gone digital using Charge Coupled Devices. CCDs (of superior quality to those used in TV cameras) are much more efficient than photographic emulsions (typically some 70% versus 10%) at registering photons. Unlike photographic emulsion, they are 'linear' devices, since they literally can count the number of photons per pixel (and cannot so easily saturate as photographic emulsion). To reduce background signals, CCDs on telescopes are often cooled to liquid nitrogen temperatures.

Photometry is the precise measurement of the apparent brightness of a star. For absolute measurement, the sky brightness must also be measured, and frequent standard stars. (Some members of the department at UCT specialise in photometry of stars that vary in brightness over a matter of minutes of time or less. Sometimes these variations are less than a one part in ten thousand). Multi-colour photometry measures apparent, brightness through different colour filters, especially U (Ultra-violet), B (Blue), V (Visual, i.e. yellow), R (Red) and I (very-near Infrared). Spectroscopy provides either the entire spectrum, or the enlargement of a portion of the spectrum, of an astronomical object. Modern spectrographs use reflection gratings and the image of the spectrum is recorded on an elongated CCD detector.

Most modern telescopes are controlled by computer, or multiple computers, taking care of data acquisition as well. The raw data is either immediately processed, or stored for later reduction of data.

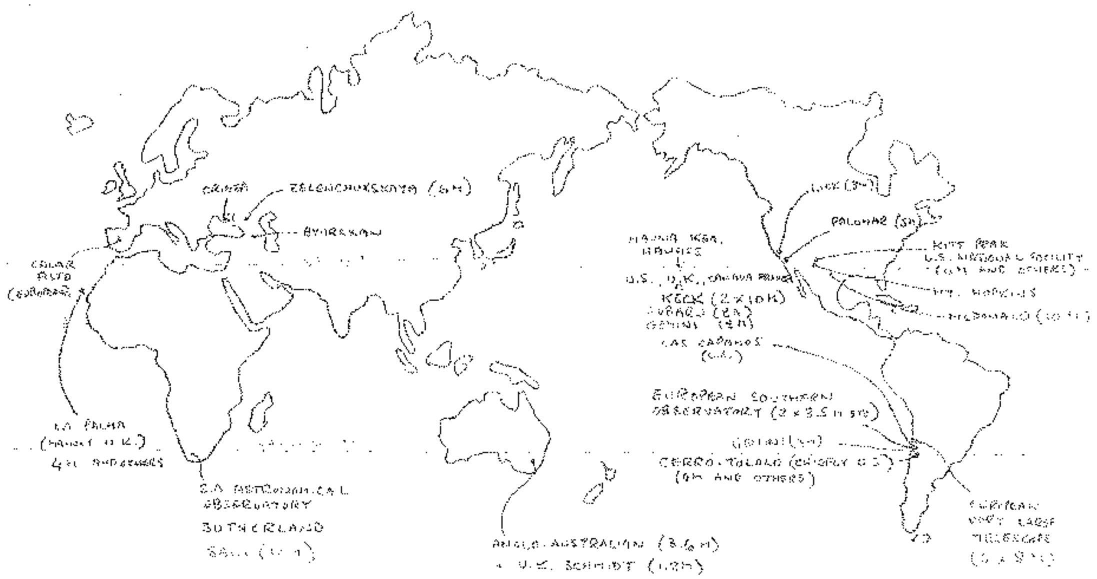
ACTIVE OPTICS

The problem of overcoming the blurring of the Earth's atmosphere (one of the main drivers for the Hubble Space Telescope) has made great advances in the past decade. The optical train from a telescope includes a small flexible mirror shaped by hundreds of computer-controlled actuators, with incredibly fast response times. By monitoring a bright star, or artificial star (produced by shining a laser beam to excite sodium ions in the Earth's upper atmosphere), atmospheric fluctuations are registered, analysed by the computer, and corrected by the active optics. As with the Space Telescope, resolutions approaching 0.1 arc seconds can then be achieved.

OBSERVING SITES

Years ago, many observatories were situated in cities (hence the suburbs of 'Observatory' in Cape Town and Johannesburg), but modern street lighting now makes the sky brightness above cities far too high. Much of the developed world is now faced with the problem of 'light pollution'. Telescopes are expensive investments so it makes sense to site them where skies are dark and the weather most conducive to clear skies and good seeing. Pure deserts tend to be too dusty, so semi-desert arid regions with high altitude are preferred. The accompanying map shows where the major observatories of the world are situated. In general, the best sites are near Latitude 30 degrees North and South. The Karoo is one of the best places in the world.

MAJOR OPTICAL OBSERVATORIES (AND OTHER TELESCOPES)



THE ELECTROMAGNETIC SPECTRUM

Visible light is only a small portion of the electromagnetic spectrum.

Most of the electromagnetic radiation received from space is thermal emission.

Like a conventional incandescent light bulb, it results from the temperature of the emitting surface. As temperatures increase, so the amount of radiation increases dramatically (by the 4th power of the absolute temperature), also the wavelength of peak emission becomes shorter, and the photon energy higher. In order of increasing photon energy, we get:

Thermal radiation	Characteristic temperature	Main emitters
Microwaves	A few degrees absolute	Cosmic Microwave Background
Radio	A few tens of degrees	
Infra-red	A few hundreds of degrees	Dust clouds
Visible	A few thousands of degrees	Stars
Ultra-violet	A few tens of thousands of degrees	Hot stars
X-ray	Millions of degrees	V. hot gas
Gamma ray	(Very high energy)	

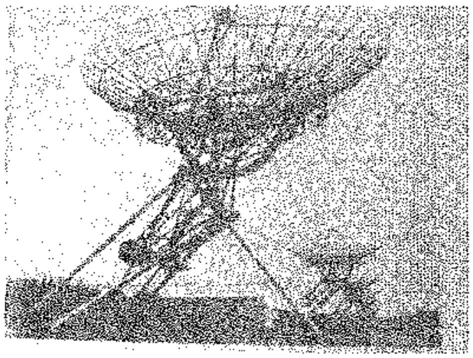
However, like fluorescent lights, it happens there are also non-thermal sources of electromagnetic radiation in space. The atmosphere of Earth, however, is opaque to all but visible, very near infrared and radio.

RADIO RADIATION

The science of radio astronomy was slow to take off because it was previously believed that the only major type of radiation in the universe was optical - due to stars. However a view of the radio sky shows this to be far from the case. There are a considerable number of non-thermal sources, usually emitting 'synchrotron' radiation sources (supernova remnants, active galactic nuclei and their ejecta, etc.) and a lot of 'line-emission' sources. Perhaps the most important of these is the 21 cm emission line of neutral hydrogen (abundant in our Galaxy and others), while carbon monoxide comes close behind. The great advantage of these emission lines is that they enable us to see cold gas - that would otherwise be invisible.

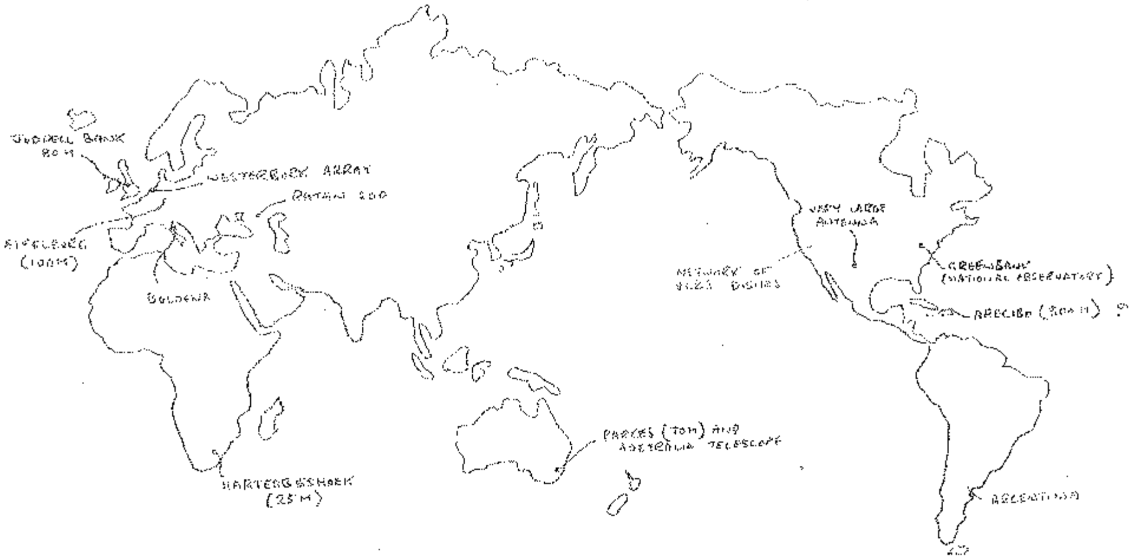
RADIO TELESCOPES

Like their optical counterparts, most modern radio telescopes are of Cassegrain design. However their apertures are very much larger (largest single aperture 300 metres) and the mirrors have reflecting surfaces of metal plate or mesh. Radio wavelengths are a hundred thousand times longer than optical wavelengths so the accuracy with which the reflecting surface is shaped can be a hundred thousand times less than the surface of an optical mirror.



Unlike the dark sites and dark nights of optical astronomy, the radio environment has abundant thermal radiation. It is therefore always necessary to subtract background noise from the signal. A single dish, however, has very poor resolution (e.g. a 20 metre radio telescope would be the equivalent of an biggest radio telescopes are still far short of the resolution of the human eye) but this can be overcome by coupling a number of radio telescopes together as an 'interferometer array'. The further apart the telescopes, the better the resolution. Resolution, comparable to optical telescopes can be achieved by arrays such as the VLA (Very Large Antenna, about 20 telescopes spread apart by up to 30 km in New Mexico), Merlin (Various telescopes in the U.K. linked by microwave transmission), and the new Australia Telescope (Various telescopes in NSW). A array of very long baseline inferometry (VLBI) telescopes is spread right across the United States. Superior resolution (to 0.001 arcsec) is achieved when telescopes on different continents all observe together. The data is recorded at each site against an accurate clock, and later merged to produce the high resolution.

MAJOR RADIO OBSERVATORIES



Starting around 2010, radio astronomers hope to build a 'Square Kilometre Array' with superior sensitivity (it will have a square kilometre of collecting array) and resolution (with antennas spread wide). South Africa and Australia are amongst the countries bidding to host the most powerful radio telescope ever.

INFRA-RED

Special telescopes can be built (or optical telescopes adapted) to work in the near infra-red. Since any object at room temperature (including the telescope and housing) emits infra-red, special procedures are employed to subtract radiation due to the environment. The detector is usually cooled with liquid helium.
The Earth's atmosphere is totally opaque to far infra-red radiation and spacecraft have to be used, including the recently launched Spitzer telescope.

MICROWAVE

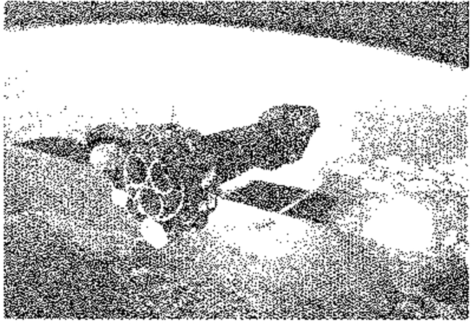
Only certain microwave wavelengths can make it through a dry atmosphere (e.g. above Antarctica), otherwise microwave telescopes can fly on balloons or spacecraft. The Wilkinson Microwave Anisotropy Probe is the most up to date spacecraft exploring the Cosmic Microwave Background.

ULTRA-VIOLET

Can only be observed from space (as the protective ozone layer shields the surface of the Earth from harmful ultra-violet from the Sun). The Hubble Space Telescope is able to explore ultra-violet as well as optical.

X-RAY

A large number of spacecraft have been used to explore the X-ray sky, which abounds with sources (interacting binary stars in our galaxy, active galactic nuclei. The European "XMM-Newton" satellite (left) has been most active lately.



GAMMA-RAY

Lower energy gamma rays are observed by various spacecraft. However, highly energetic gamma-rays can be detected indirectly from the ground. An incoming gamma-ray creates a shower of particles in the Earth's atmosphere, which generates a light pulse. The duration of the pulse is too short for the eye to register, but can be recorded by special detectors, employing large mirror arrays. The difference in arrival times at different detectors allows the direction of the incoming gamma-ray to be determined. Various gamma-ray sources have been identified, as well as "gamma-ray bursters". The University of Potchefstroom pioneered this work in the Southern Hemisphere, and the High Energy Stereoscopic System (HESS), a joint collaboration with Germany, operates in Namibia.