

Why Build Big Telescopes?

Ideas for Teaching Resolution, Sensitivity and Modern Telescope Design in the Astrophysics Option

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Introduction

The Astrophysics option of the Stage 6 Physics Syllabus states that “Our understanding of celestial objects depends upon observations made from Earth or space near the Earth” (Board of Studies, 1999). In addressing this point students need to specifically address the concepts of resolution and sensitivity and their impact on observations.

This paper aims to provide teachers with a range of ideas and activities plus some useful data with which to cover the syllabus requirements. It is not intended to provide a detailed theoretical background on the concepts as this is better covered in the various references but rather it aims to clarify some key teaching points and misconceptions about them.

Some emphasis is given to the Gemini Project telescopes for a couple of reasons. Firstly, it is the large optical telescope project with which Australia is most directly involved through a formal partnership with the consortium. As Australian astronomers make scientific discoveries with these telescopes, the profile and public awareness of this international collaboration will hopefully rise. It is important that Australian students are made aware of the collaborative nature of much of modern science and Australia's contribution to this. Secondly, the educational resources starting to become available from the Gemini Project are innovative, engaging and directly address several of the Syllabus dot points. Finally, the technologies applied to the Gemini telescopes directly relate to the key points of this paper.

Syllabus Requirements

The 1999 Board of studies Stage 6 physics Syllabus has recently been amended yet again. Some of these changes impact directly on the concepts covered here. Whilst these changes are not valid until the 2003 HSC, I have used the latest version in this paper. These are included below for ease of reference: (Board of Studies, 1999 and 2002)

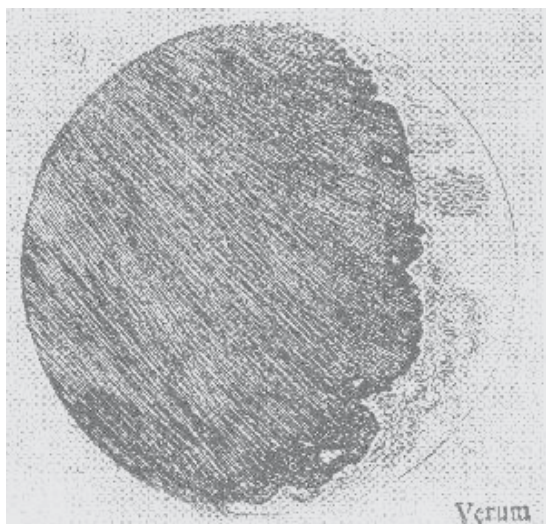
	<i>Students learn to:</i>	<i>Students:</i>
1. Our understanding of celestial objects depends upon observations made from Earth or space near the Earth	<ul style="list-style-type: none">• Recall the components of the electromagnetic spectrum and describe the properties of each component• Explain why some wavebands can only be detected from space• Define the terms resolution and sensitivity• Discuss the problems associated with ground-based astronomy in terms of resolution and atmospheric distortion• Outline methods by which the resolution and sensitivity of ground-based systems can be improved, including:<ul style="list-style-type: none">- adaptive optics- interferometry- active optics	<ul style="list-style-type: none">• process information to discuss Galileo's utilisation of the telescope to identify features of the moon• identify data sources, plan, choose equipment for, and perform an investigation to demonstrate why it is desirable for telescopes to have a large diameter objective lens or mirror in terms of both sensitivity and resolution• gather, process and present information on new generation optical telescopes



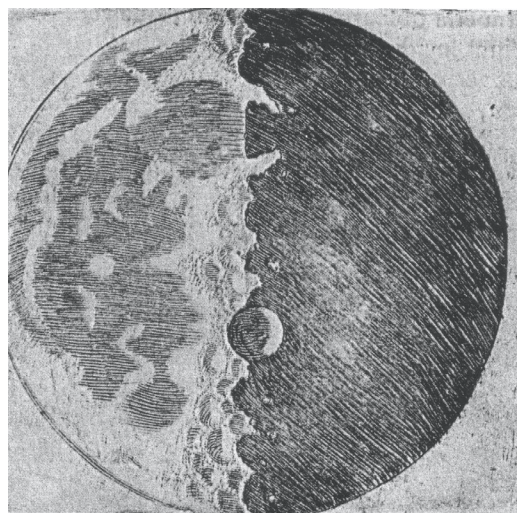
The first two dot points of the second column revisit material first covered in 8.2 *The World Communicates* and will not be directly addressed here (see *Useful Web Sites* at the end of the paper for additional information). Reading the rest of the section, however, shows that the key themes of *resolution* and *sensitivity* form the focus of the dot points. These, therefore, also form the focus of this paper. The first dot point of the third column requires a discussion of Galileo's use of the telescope, with specific reference to the Moon. This may, at first glance, seem out of place or tokenistic but it can serve as an effective introduction to the whole module and to the ideas of sensitivity and resolution in particular. The next section briefly addresses this point.

Galileo's Use of the Telescope

Galileo's systematic use of the refracting telescope, commencing in 1609, was a seminal moment in observational astronomy and the history of science. His publication of *Sidereus nuncius* or "The Starry Messenger" in the following year allowed his observations to be discussed and verified by others across Europe. Modern translations of this work are readily available (Galileo, 1989) and reproduce his drawings of the Moon (reproduced below), Jupiter's moons, Orion, the Pleiades, and the nebulas in Orion and Praesepe. These can form the basis of a simple observational exercise (available on request from the author) that students can do at home. Stores such as *Australian Geographic* sell cheap refractors for about \$20. I have one, which I issue to students for a few nights and also have available for viewing nights when larger, modern reflectors are used. The cheap refractors are remarkably similar in size, resolution and sensitivity to those used by Galileo. By using one of these small, hand-held telescopes, students sketch their observations and compare them with Galileo's. They soon learn to appreciate the care and skill needed for effective observations. Typically they get frustrated by the vibration from their hands and the difficulty in actually locating and holding the scope on an object. These points serve to introduce the need for rigid and effective telescope mounts and the concept of field-of-view. When resolution and sensitivity are formally introduced, students can calculate the theoretical values of each for a Galilean telescope and compare with more modern ones. A final mention needs to be made of *The Galileo Project* (<http://es.rice.edu/ES/humsoc/Galileo/>). This site contains a vast amount of material related to every aspect of Galileo's life and times. Source material could be incorporated into a range of tasks.



Galileo's drawing of a Crescent Moon



Galileo's drawing of a Quarter Moon

Picture credits: (Galileo, 1989)

Sensitivity and Resolution

What is sensitivity? This simple question can generate a range of responses from students. It serves as an effective opening question particularly as it soon leads to mention of telescopes. At this point the misconceptions normally start to arise. Follow-up questions such as *why are telescopes so large?*, or *what is the purpose of a telescope?* in turn should produce mention of *magnification* from one or more students. Ask your class how many of them have a telescope. Unless you have an amateur astronomy enthusiast within the class, the best you will find is one or more students who may have been given a telescope from a department store. Typically these are sold on the basis of their magnification, often claiming something like *see 500 x magnification!* Most students believe telescopes are devices for magnifying the night sky. The true roles of telescopes, to gather light from faint sources and resolve sources clearly, are not immediately apparent to most.

Essentially a telescope is used for one of two functions (Smith, 1995); *imaging* in which pictures of celestial objects are clearly resolved, requiring optics that produce a sharp image, or *photometry*, where the incoming radiation is measured either for brightness or split to obtain a spectrum. Photometry traditionally did not require the level of resolution necessary for effective imaging but modern multi-fibre spectroscopes such as 2dF (2 degree Field) instrument on the

Anglo-Australian telescope are only effective if numerous objects in a dense field (eg a star cluster or deep galaxy cluster) can be individually resolved.

Sensitivity is a measure of how much light a telescope can gather. All other things being equal, a telescope of larger primary mirror or lens is more sensitive than one with a smaller primary, that is, it can collect more light. The size of a primary mirror or lens is normally expressed in terms of its diameter. A simple phrase often used by astronomers is that of the *light bucket*. The bigger the bucket, the more light can be poured into it. The more sensitive a telescope, the more light it can gather from faint objects. The more light gathered, the fainter the object (or the more distant for a given class of object) that can be studied photometrically or imaged. Exercise 1 outlined overleaf suggests ways in which students can explore the idea of sensitivity and develop a mathematical relationship between mirror (or lens) diameter and the amount of light gathered.

Of itself, sensitivity is but one factor that makes an effective telescope. Equally important is the ability of a telescope to distinguish between, that is, *resolve*, close objects. For circular apertures, such as in telescopes, where the light rays from a source are parallel, as is the case for distant point sources of light such as stars, the light will be diffracted so as to form an Airy disc. The circular diffraction pattern formed contains 84% of the light in the central bright spot with decreasing percentages in the surrounding bright rings. It is the size of the Airy disc that imposes a limit on resolution. Two objects are said to be resolved if their Airy discs are sufficiently separated to be seen as distinct (Smith, 1995). Rayleigh proposed the criterion that two point objects are just resolved if their angular separation is such that the central maximum from one point source lies on the first minimum of the other (Muncaster, 1997). The theoretical resolving power of a telescope can be determined by the expression:

$$\theta = \frac{1.22\lambda}{D}$$

(Equation 1)

where θ is the angular separation (in radians),
 λ is the wavelength of the light being collected
and D is the diameter of the primary.

Both D and λ must be in the same units and it is only valid for $D \gg \lambda$.

Note this equation as it stands may pose a problem for students primarily due to the fact that it uses radians as a measure of angle. Whilst not specified in the syllabus, this expression is useful to discuss with students as it allows for several ideas to be subsequently developed from it. If you wish to avoid the added complexities of introducing the concept of radians (though some students may have covered it in their mathematics studies), the alternative form of the equation:

$$\theta = \frac{2.1 \times 10^5 \lambda}{D}$$

(Equation 2)

where θ is now in seconds of arc or arcseconds.

may be simpler. One problem with using this form, however, would be in trying to use it in a spreadsheet such as *Excel* as these typically calculate angles using radians.

Using this equation for visible light, students can easily calculate the theoretical resolution for a fully dilated human eye to be about 0.3 arc minutes. In practice, corneal imperfections reduce this further to only about 1 arc minute (<http://cfao.ucolick.org/AO/whatisao.html>). If an optical device such as an eye or telescope achieves its theoretical resolution in operation it is said to be *diffraction limited*.

Whilst not specified in the syllabus, a useful point worth mentioning that arises from the resolution equation is the effect of increasing wavelength on theoretical resolution. Students can calculate values for key wavebands such as radio, infrared, visible and UV and compare the resolutions for a specified size of telescope. The exercise could then be tackled again, this time asking the question; *what size telescope is needed at each waveband to achieve 1 arc second resolution?* From this, discussion on the similarities and differences between optical and radio telescopes can be developed. Higher frequency bands such as X-rays could be included in the exercise but the smaller wavelengths of these means that telescopes designed for them have to utilise *grazing* optics rather than the more traditional reflection methods.

In reality, many telescopes, particularly large ones, do not reach their theoretical limit for resolution. This is due to a number of factors, most of which are due to the effects of Earth's atmosphere, collectively referred to as *seeing*. They are discussed in the following section.

The Turbulent Atmosphere – *Seeing*, Refraction, Absorption and Scattering.

Our atmosphere is constantly in motion. It is a mixture of gases, water vapour, dust and other suspended particles. All these impact on the ability of a telescope to receive light and to clearly resolve an image.



The most obvious effect is that of absorption. Most radiation incident on the Earth's upper atmosphere does not reach the ground. The atmosphere is effectively opaque to all but some radio wavebands and light in the optical window. This includes the entire visible region (390 nm – 780 nm) plus the near ultraviolet, near infrared and some far infrared wavebands. Much of the infrared (21 μm to 1 mm) suffers absorption from water and carbon dioxide molecules whilst most ultraviolet undergoes absorption by ozone. Gas atoms and molecules absorb X-rays and γ -rays (Muncaster, 1997). Students have discussed the effects of these in Stage 5 so should be able to suggest reasons for selective transmission of wavebands through the atmosphere. This material is also covered in modules 8.2 and 8.5 of the Preliminary Course. A firm grasp of these concepts will help students develop effective responses to questions related to the location and limitations of modern telescopes. Examples are given in some of the activities that follow.

Scattering of light is strongest when the wavelength of the light is of the same order of magnitude as the diameter of the scattering particles. Visible light, therefore, is more readily scattered by dust and mist than infrared. This can be demonstrated by the use of a torch and an infrared remote control; visible light, from a bright, narrow torch beam for example, is readily scattered by fog or a cloud of fine particles such as talcum powder or chalk dust. By shining a torch beam on the cloud, students should be dazzled by the back-scattered light. In contrast, infrared radiation can pass through readily. Aiming an infrared remote control through the cloud should still enable the settings on a television or video to be controlled. Replacing the dust cloud with a beaker of water (or a suspended clear plastic bag of water to avoid disputes about the glass) should see the infrared remote control ineffective due to the absorption by the water. The light on the other hand should pass through unaffected. These simple demonstrations can be used to introduce discussion as to where to site infrared telescopes. They can also serve as starting points to show images of the galactic centre and various nebulae at different wavelengths, which in turn are important in developing a model for stellar formation.

Variations in density of the atmosphere in a line of sight with an object cause intensity fluctuations. The variations in the refractive index of a cell of air above a telescope will alter the apparent position of an object, normally over a range of a few arcseconds. Collectively these effects combine to make point sources such as stars appear to “dance” about. This rapid change in brightness and position is termed scintillation. Ask your students if they can distinguish between a star and a planet merely by observing the night sky. Stars “twinkle” more than the bright planets because they are so much more distant that they are effectively a point source. Their light gets smeared across a *seeing disc* a few arcseconds in diameter. Planets, with an angular diameter of $\sim 10\text{-}30$ arcsecs are extended sources and thus less affected. Turbulent cells of air in the atmosphere limit the actual resolution of telescopes in the optical wavebands to typically no better than that obtained by a 20-cm telescope. The seeing at any location depends upon many factors and changes due to temperature, weather, pollutants and local microclimate. Good locations may achieve a typical seeing of 1 arcsecond but most sites are worse than this. Even the best sites rarely achieve seeing of better than 0.5 arcseconds (O’Byrne 1996). If the resolution a telescope achieves is limited by the seeing rather than its diffraction limit it is said to be *seeing limited*.

Activities on Resolution, Sensitivity and Seeing

There are many simple and effective ways in to convey aspects of resolution, sensitivity and seeing. Several ideas and activities are presented here. In some cases it is hard to remember the original source of a demonstration or idea but others have been adapted from two key sources (Pompea 1994) and (Gibbs 1999). Both of these are excellent resource books and recommended for all teachers of physics. Others not discussed here are readily available in new texts (Andriessen *et al* 2001).

Exercises for Sensitivity

1. **Eyes and Pupils.** The simplest way to show sensitivity is for students to observe each other’s pupil diameters in dim light and then compare it with the diameter in bright light. If done the other way around, going from bright to low light, more time is needed for pupil dilation but some dim objects, previously set up behind the students can then be observed to see when they become visible. It takes about half an hour for the eye to become fully dark-adapted but once this is achieved the eye is about 2000 x more sensitive than in daylight. (Pompea 1994).
2. **Viewing Nights.** If you hold a viewing night as part of the module, allocate some of it to naked-eye astronomy. Ideally have students present before dusk. As twilight proceeds, have them sit down and gaze out into the distance. They will gradually lose the ability to distinguish colour. This is related to light intensity and the cone and rod receptors in the eye. The cones that detect colour require higher light levels, therefore are less sensitive (and abundant) than the rods responsible for gray scale vision. By also looking at the sky, students should also gradually see more and more stars become visible. Simple pre-prepared star charts of prominent constellations (Scorpius in winter and Orion in summer are easy to find) can be used to determine the limiting magnitude of the location and provide a measure of the seeing for that night. Competitions such as who can detect the faintest object can keep students occupied when telescopes are being used by others.
3. **Cardboard Cut-Outs.** Provide students with scale cut-outs of various telescope primaries (a list of examples is provided below in activity 4). These could range from small telescopes to large optical ones such as the 10-m Keck telescopes. The scale chosen will depend upon the size of the available paper but larger sheets such as A3 or even butcher’s paper give better results for the large primaries. Students simulate the light-gathering ability of each

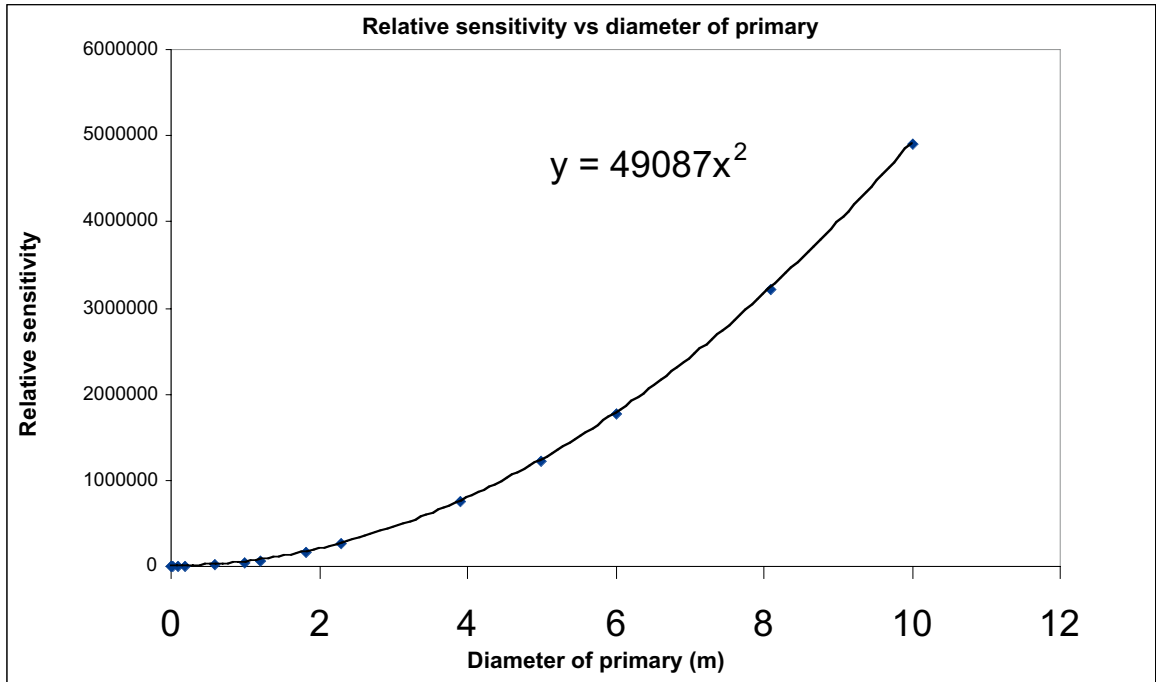


mirror or lens by placing small, regular-sized objects such as tiddly-winks or dried peas on the cut-outs and then counting the number that fit into the area. These tiddly-winks can represent "photons" or equal amounts of light. The students then tabulate the results and try and determine a mathematical relationship between size of the primary and the amount of light (ie tiddly-winks) collected. If they plot number of "photons" against primary diameter they should get a parabolic curve or close to it. To verify this they could then try "photons" against (diameter of primary)². The level of direction from the teacher will depend upon time available and student ability. If time is short, the task could be broken up, with small groups of students tackling one or two telescopes each and then collectively tabulating the class results. This option also allows a larger data range to be generated. Another variation is to make up templates for each from plywood. By surrounding the edge of each with a 1-cm high strip of cardboard or similar, the templates can be filled up with dried peas. These can then be weighed to provide the "number of photons" more quickly than counting objects on a flat sheet, albeit sometimes with greater range of uncertainty which in itself can provide a useful teaching point. Conceptually, this approach also underpins the "light-bucket" analogy.

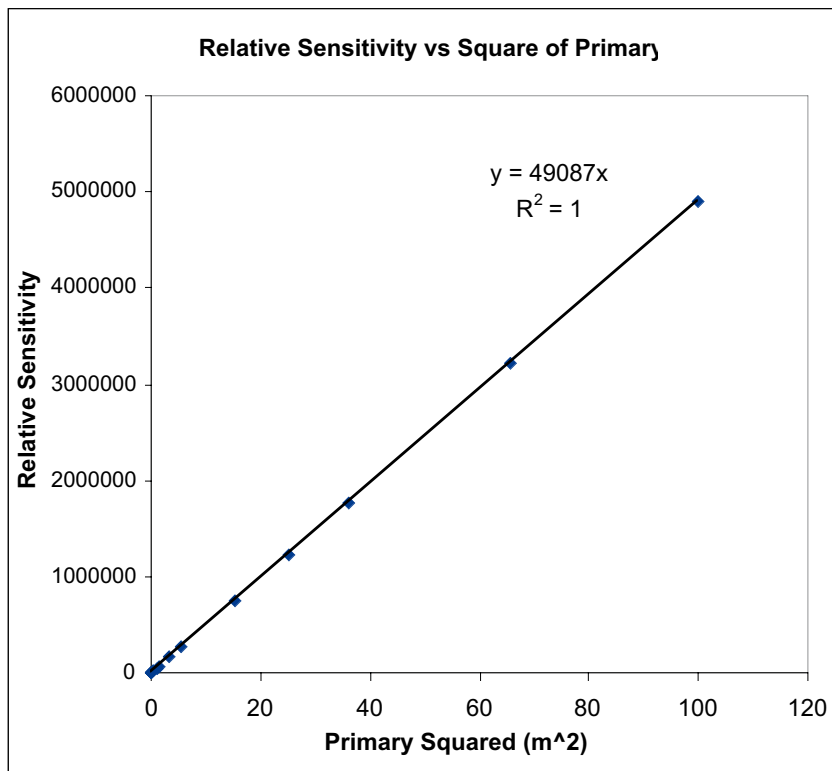
4. **Mathematical Modelling and Spreadsheets.** Many students will fairly quickly suggest a mathematical relationship based upon the diameter (or radius) of a collecting surface and its surface area. This idea can be efficiently examined using spreadsheets. The examples shown below give an *Excel* worksheet with data for a range of telescopes (contact the author for a copy). Numerical values for sensitivity and resolution have been calculated and sample plots generated. The amount of information and guidance given to a class again depends upon time available and experience.

(Resolution calculations for light at 550 nm)

Telescope	Diameter of Primary (m)	Radius (m)	Number of "photons"	Square of Primary (m ²)	Theoretical resolution (arcsec)	m arcsec	Resolution compared to eye
human eye	0.008	0.004	3	0.000064	1.44E-03	1.44375	1
Galilean refractor	0.03	0.015	44	0.0009	3.85E-04	0.385	4
4-inch refractor	0.1	0.05	491	0.01	1.16E-04	0.1155	13
8-inch Dobsonian	0.2	0.1	1963	0.04	5.78E-05	0.05775	25
60-cm reflector	0.6	0.3	17671	0.36	1.93E-05	0.01925	75
Yerkes Refractor	1	0.5	49087	1.00	1.16E-05	0.01155	125
Herschel's reflector	1.2	0.6	70686	1.44	9.63E-06	0.009625	150
Lord Rosse's	1.83	0.915	164389	3.3489	6.31E-06	0.006311	229
ANU 2.3m	2.3	1.15	259672	5.29	5.02E-06	0.005022	288
AAT	3.9	1.95	746619	15.21	2.96E-06	0.002962	488
Hale	5	2.5	1227185	25.00	2.31E-06	0.00231	625
Bolshoi Teleskop	6	3	1767146	36.00	1.93E-06	0.001925	750
Gemini	8.1	4.05	3220623	65.61	1.43E-06	0.001426	1013
Keck	10	5	4908739	100.00	1.16E-06	0.001155	1250
CELT	30	15	44178647	900.00	3.85E-07	0.000385	3750
Euro50	50	25	122718463	2500.00	2.31E-07	0.000231	6250
OWL	100	50	490873852	10000.00	1.16E-07	0.000116	12500



Note only telescopes up to Keck have been included in the plots. Plotting relative sensitivity against primary diameter² gives:



Exercises for Resolution

- Eyes.** Draw two dots about a millimetre apart on a piece of paper. Have this stuck up on a wall or on the edge of a board so that it is not immediately obvious. When appropriate, ask students to look at it and describe what they see. They can then move to the opposite side of the room. Ask them to walk slowly towards it and stop when they can resolve it into two dots (Gibbs 1999). This provides a quick and effective introduction to the concept of resolution. Numerous variations are possible. Print out copies of a message in different sized fonts or an image in different

sizes. Get students to see at what distance they can read the messages or describe the images. Another variation involves holding a coin up and asking students to identify the denomination or the image on it as they walk towards you along a corridor or across an oval.

6. **Lasers.** Two lasers or laser pointers can be set up pointing onto a piece of white paper taped onto a wall so that they converge, appearing as a single dot. As one of the lasers is moved slowly, two distinct points become visible (Pompea 1994). This can also be related to the resolution of visual binaries. Ensure you take appropriate safety precautions whenever using laser products. Another use of a laser is to produce Airy discs through a telescope. The laser is shone onto a steel ball bearing. The reflected light appears as an Airy disc when observed through a telescope set up many metres away (down the end of a corridor for example). The focus of the telescope can be adjusted to emphasise the effect. This demonstration needs to be strictly controlled, with the optical arrangement best set up and aligned before hand. Students should be kept well away from the ball bearing/laser region until after the effect has been observed and the laser switched off.
7. **Telescopes.** Apart from the demonstration outlined in the previous section there are several other ways in which resolution can be demonstrated using a telescope. Some but not all require night time viewing. The size of a telescope is not essential although if you have two or more of different sizes student can qualitatively investigate their differences.
 - a. **The effect of aperture on resolution.** Preparing masks of cardboard that fit over the front of the telescope can alter its aperture (Pompea 1994). These masks can be of decreasing aperture (the effect of shape can also be investigated). The effects are most noticeable when the aperture is not too large, the seeing is good and bright stars are observed at high magnification (if you have different eyepieces try those with the lowest number on them , eg 9-mm instead of 25-mm). Stars are so far away that even the largest, close ones at best subtend an angular diameter of a few milli-arcseconds, so rather than resolving their surfaces, they form an Airy disc. Diffraction images should be obvious when masks are used. Compare the image with and without masks. Then try the same sequence when observing the Moon or a planet. As these are extended sources their surface can be resolved so little, if any, effect should be apparent.
 - b. **Observing Visual Binaries.** A common challenge for amateur astronomers is to see which visual binaries can be resolved or “split” using a given optical configuration. Many popular astronomy magazines and observing manuals publish lists of suitable candidate stars that can be selected for comparison observations. More generally, the stars of Crux and the Pointers (actually part of Centaurus) provide easily located and resolved telescopic binaries. Many students have difficulty reconciling a telescopic view of the visual binary α Cen A and B with what they see with their naked eye. A significant number confuse the telescopic view with the pairing of α Cen and β Cen, the two bright naked eye stars of the Pointers.
 - c. **Aligning cards to show resolution.** (Pompea 1994) Construct a card with a narrow slot about one mm wide that cuts across the centre of the card and is as wide as the aperture of the telescope. With the card fixed on the front of the telescope, have students observe a brick wall at middle distance (across a quadrangle or playground for instance). When the slot is horizontal, the vertical mortar joints in the wall should be visible but not the horizontal ones. Rotating the slot so that is vertical makes the horizontal joints appear but the vertical ones disappear.

Exercises for *Seeing*

8. **Naked-Eye Observing.** The simplest way to observe the effect of seeing is to encourage students to view objects in the night sky. They should look at objects close to the horizon and compare them with others high overhead near the zenith. Most should detect that stars seem to “twinkle” more when close to the horizon. If a bright planet is up students should see if they can see any differences between it and stars in the same region of stars. By observing over several nights, students may appreciate that the seeing varies according to atmospheric conditions.
9. **Using a Telescope in Daytime.** Given the difficulty often encountered in arranging a viewing night and then actually getting clear skies, it is handy to have ways of demonstrating some atmospheric effects during the day. Any type of telescope can be used, as optical quality is not essential for demonstration purposes. This activity works best if you can place the telescope at one end of a dim corridor and place the other equipment at the far end, ideally in low light. “Stars” can be simulated by using a cheap fibre optic torch, which are readily available from toy shops or science shops at museums. Pass a few of the strands through a black piece of card so that the points of light face towards the telescope to form a constellation. Make sure that the distance between the points of light varies. When viewed through the telescope, ensure that at least two “stars” close together are visible in the same field of view. Placing a fan heater or other heat source just below and in front of the constellation card simulates thermal disturbance of the atmosphere. When turned on, the heater sets up convection cells that should distort the image in the eyepiece. Ideally the two stars merge into one extended, twinkling source.
10. **Telescopic Observation of Celestial Objects.** Use a high magnification eyepiece to observe and compare bright stars near the horizon and the zenith. Focus the telescope on a bright planet, preferably Jupiter or Saturn and let



students observe how the clarity of the image varies in real time. If you have a video camera you may be able to connect it to the telescope and a monitor so that more students can see it. The Moon is another object that is easy to observe and shows the effects of the atmosphere.

11. **Studying the Location of Modern, Large Optical telescopes.** Ask students to obtain and plot the locations of all optical telescopes larger than those in the 4-m class. This information is quickly obtained from the SEDS *Large Telescope* site at <http://www.seds.org/billa/bigeyes.html>. See if they can identify any trends in the locations. They should realise that the bulk of these modern instruments are built in only a handful of places, notably Mauna Kea in Hawaii and various regions of the Chilean Andes. Other large telescopes have also been built on mountains on the west coast of California and on the Canary Islands in the Atlantic Ocean. These sites share some common factors; most obviously they are at high altitude therefore above a lot of the local weather and atmosphere. The more astute students may realise that all these sites are either on the west coast of continents or on mid-ocean islands. This is no coincidence. Given that the typical weather patterns move from west to east it means that the air masses moving over the telescopes have traversed a broad expanse of ocean and so have not picked up much in the way of pollutants. As the air rises as it hits the coast and mountain it tends to lose any moisture low down. As it has not had time to be heated by large expanses of warm air it does not become too turbulent. The result is a laminar flow of air across the observatory. The lack of turbulence provides sub-arcsecond seeing whilst the absence of water vapour makes these sites ideal for infrared and millimetre wave observations.

Adaptive and Active Optics

As is evident from the earlier discussion of atmospheric effects, modern telescopes such as the 8.1-m Gemini telescopes in practice can not achieve their theoretical resolution limit. Instead they are not much better in resolution than a 20-cm telescope. Why then do astronomers spend millions of dollars building such instruments? One reason that students should offer in answer to this question is the improvement in sensitivity. Even without improved resolution, a large telescope can still gather more light than a small one. This is vital for tasks such as spectroscopy of faint galaxies and stars. Some students may offer the solution of placing telescopes above the atmosphere, as is the case for the Hubble Space Telescope, removes the problem of atmospheric turbulence altogether. This point is worth discussing with students. They should be asked to find out the cost of the HST program and the size of its primary mirror then reconsider their response (an 8-m class ground-based telescope such as Gemini can be built for about one thirtieth of the cost of the HST for example). Additional reasons are succinctly provided at *What is Gemini?* (<http://www.ausgo.unsw.edu.au/background.html>)

The development of new materials and computer control technologies allow telescopes to correct the effects of the atmosphere and build large, thin mirrors that are much lighter than those used in earlier generations of large telescopes such as the 200-inch Hale telescope on Mount Palomar. Using the techniques of *active* and *adaptive* optics, these large telescopes can overcome many of the effects of the atmosphere and obtain improved resolution. This section does not provide detailed theory as to how each of these works as this is available from a range of comprehensive sources. Dr John O'Byrne, from the University of Sydney, gives a useful overview of the issue with a local perspective in a *Sky & Space* article (O'Byrne 1996). This magazine may be available in school libraries. Similar, updated articles are likely to be found in periodicals such as *Sky & Telescope*, *Scientific American*, *Astronomy* and *Mercury*. Students must outline how these techniques can improve the resolution of ground-based systems hence must also be able to distinguish between them.

Active Optics: Overcoming Primary Mirror Distortion

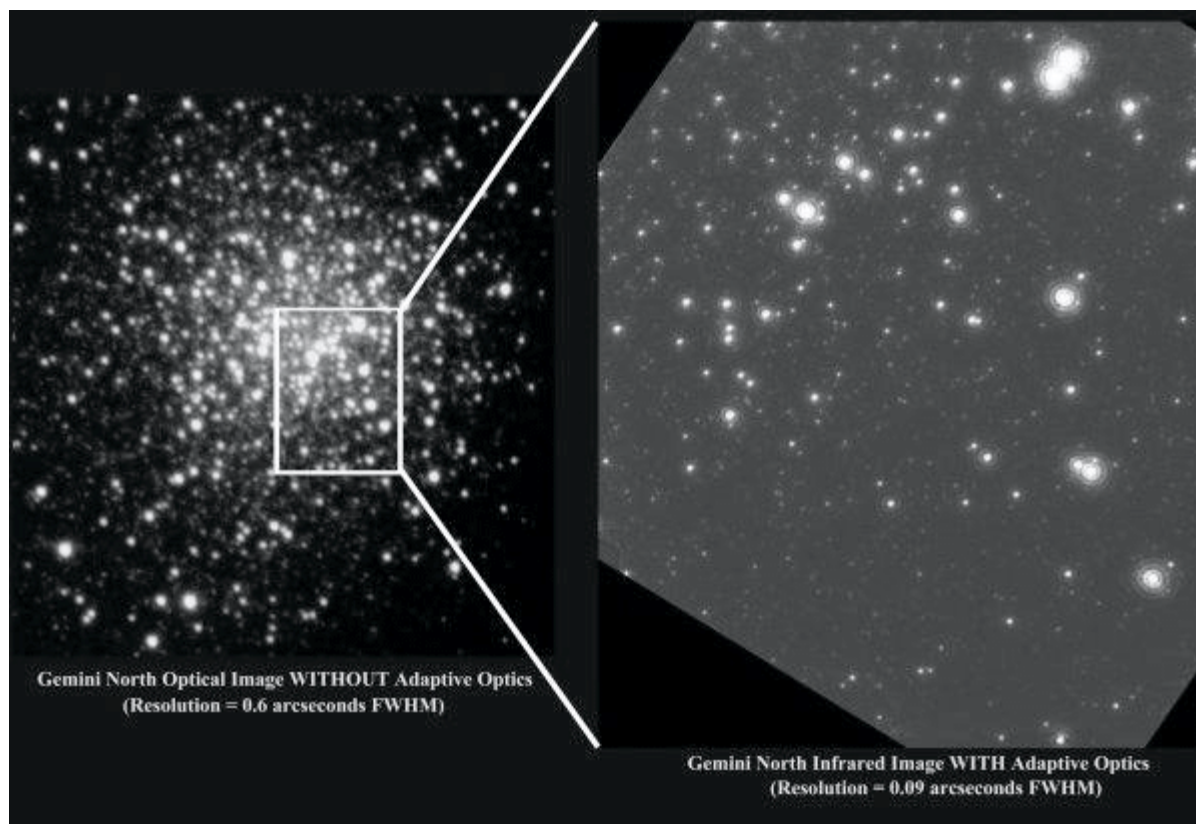
No mirror can be made perfectly smooth. Distortions in the reflecting surface reduce the quality of any image formed. Prior to the 1980s, primary mirrors were rigid with a thickness normally about one-sixth the diameter (O'Byrne 1996). This ensured that they did not flex when pointing to different regions of the sky. The weight of the primary required a strong mounting system that also added to the overall mass of the system. Thick mirrors also take longer to reach thermal equilibrium each night, reducing the achievable resolution and adding to *seeing* effects. Modern primaries, however, can be made very thin. Those for the Gemini telescopes are only 20-cm thick. The mounts for these therefore can be much lighter. The problem is that the mirrors sag under their own weight as they point to different parts of the sky. To produce any worthwhile image the primary must be *actively* corrected by continuous computer control. By measuring a reference star within the field of view, corrections are sent to electromechanical actuators on the back of the primary. These push or pull on a section of the primary to change its shape. Active optic systems correct the primary shape about once per minute.

Adaptive Optics: Correcting Atmospheric Effects

Whereas active optics corrects for the distortion of the thin primary as it moves around, *adaptive* optics corrects for the distortions in an image caused by atmospheric turbulence. Adaptive optics systems operate at high frequencies, typically about 1 000 Hz. This is too fast for altering a primary so adaptive optic systems are designed to act via the secondary mirror and additional optical elements placed in the light path. There are several different methods that can be used to monitor and correct the incoming wavefront of light but many use a tip-tilt mirror and a thin, deformable one



(see Junor *et al* 1998, O'Byrne 1996, and Schilling, 2001 for more detailed treatments and diagrams). Vital to all is the need for powerful, fast computer processing and modelling of the incoming waveforms. Systems either rely on a bright reference star within the field of view (which is surprisingly hard to find given the narrow field of view in many large telescopes) or they produce an artificial reference star using a laser. At present, adaptive optics is still a new technology and many systems are still in the developmental phase. Apart from the reference star problem, most systems also trade-off sensitivity for resolution as each additional optical element scatters some light and adds a small amount of heat, degrading infrared performance (Schilling, 2001).



This image shows the effect of adaptive optics operating at infrared waveband on a globular cluster

Photo courtesy of Gemini Observatory, National Science Foundation, and the University of Hawaii's Adaptive Optics Group (<http://www.gemini.anu.edu.au/public/adaptive.html>)

Activities for Active and Adaptive Optics

It is harder to demonstrate the concepts of active and adaptive optics than those of resolution and sensitivity. There are however, some useful sources of computer-generated imagery that can help convey the concepts.

12. **Gemini North Virtual Tour and Simulations CD-Rom.** The Gemini Observatory Image Gallery CD-ROM contains a beta version of a virtual tour of the Gemini North telescope. The virtual tour contains animated audiovisual explanations of the active and adaptive optics systems plus a couple of games that simulate how these systems work. Students can use actuators on the primary to match its shape with an incoming waveform and control an adaptive optics system to correct for atmospheric distortions. The tour also walks through the different parts of the telescope building, introduces you to some of the astronomers and engineers, shows the structure of the telescope and dome, discusses the science of the telescope, shows the other telescopes on Mauna Kea and discusses the indigenous cultural and archaeological significance of the mountain. It is a valuable resource that runs under QuickTime on both PC and Mac platforms. Currently it is still in a beta version and under development. Some copies are available from the paper's author but it is not formally distributed in Australia.
13. **Euro50 Web site.** This site discusses a Swedish proposal to build a 50-m optical telescope. Within the *Visualization of optical performance* frame is a series of simulated images of a stellar cluster showing the effect of different Strehl ratios on adaptive optical performance. The *Downloads* frame also contains these linked as a large (64 Mb) avi movie. Other comparable images and simulations are given in the Useful web sites section at the rear of this paper.

Interferometry

Astronomical optical interferometry may involve *intensity interferometry*, a process pioneered by Robert Hanbury Brown in Australia or *speckle interferometry* (Smith, 1995). In essence, optical intensity interferometry is the same technique that has been used for many years on radio interferometers such as the Australia Telescope Compact Array, ATCA (see the *ATCA Live!* Page at http://www.narrabri.atnf.csiro.au/public/atca_live/atca_live.html for real time information on what is being observed) and the Very Large Array at Socorro in New Mexico, famous in the film *Contact*. The key difference is that as the wavelength of the light is much smaller than that of radio waves, the precision required in the optical path is much higher. Cumulative errors of less than a micron can render observations useless (Jayawardhana, 2002). This is a key reason why it is only recently that large intensity optical interferometers have begun to be widely developed. The references and useful web sites listed at the end of the paper provide more detail on the theoretical aspects of optical interferometry and include a number of useful diagrams. It is worth stressing to students that Australian astronomers and engineers have had a key role in pioneering interferometric techniques. It is worth investigating the Sydney University Stellar Interferometer site for more details (<http://www.physics.usyd.edu.au/astron/susi/>).



The Sydney University Stellar Interferometer, Narrabri NSW

(<http://www.physics.usyd.edu.au/astron/susi/>)

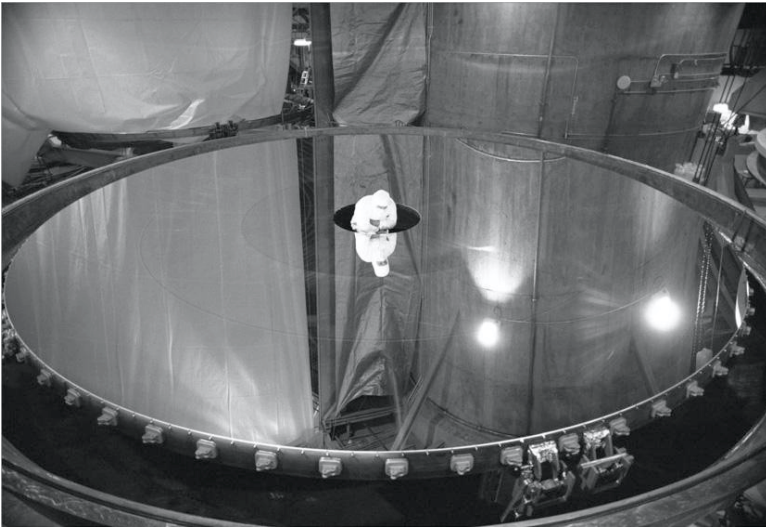
As the interferometers being developed for the twin 10-m Keck telescopes, the European Southern Observatory's four Very Large Telescope units and others such as at Mount Wilson come into everyday use, many exciting discoveries are expected. The predicted resolution of these will make them very powerful instruments.

Modern Large Optical Telescopes

A visit to *Large Telescopes* <http://www.seds.org/billa/bigeyes.html> provides an up-to-date list of all the large optical telescopes in the world with links to the relevant home pages for each. It is a useful starting place for information on them. Additional information can regularly be found in the popular astronomy magazines and other scientific periodicals (Jayawardhana, 2002, and Stix, 1999). The topic of new generation optical telescopes can form the focus of effective secondary research tasks. Given the number of telescopes available and depending upon class size, each student or small group can be allocated their own telescope to research. The author has run this as an oral presentation assessment task with success. Rather than provide an overview of all the telescopes that fit into this category, the Gemini Project will be examined briefly as an example below.

The Gemini Project

The Gemini Project (<http://www.gemini.edu/>) is a multi-national collaboration that has built two identical 8.1-m telescopes, one in the northern hemisphere atop Hawaii's Mauna Kea at 4 200 m and the other in the southern hemisphere in Chile on Cerro Pachón at 2 700 m. Australia currently has a 5% share in the project, which also includes the United States, United Kingdom, Canada, Chile, Brazil and Argentina. Having identical telescopes provides coverage of the whole sky and allows innovative observing programs to be undertaken. The Gemini telescopes are optimised for optical and infrared observations and incorporate adaptive and active optics technologies. One hundred and twenty actuators correct the distortions caused by gravity in the 20-cm thick mirror to preserve its precise shape. A typical adjustment is only about a thousandth the thickness of a human hair.



The image shows the Gemini North mirror receiving its first coating of aluminium. Eventually both Gemini mirrors will be coated with silver. This will improve the infrared capabilities of the telescopes.

(Photo Courtesy of Gemini Observatory)

It is not just the optical design and technology that makes the Gemini telescopes superb instruments. Unlike traditional telescope domes, the 45-m high Gemini domes open up at night to allow smooth air movement across the structure through 10-m wide vents. This reduces the effect of *dome-seeing* and along with the 20-cm thickness of the primary allows thermal equilibrium to be reached sooner.

Further details can be obtained from the Gemini home page (<http://www.gemini.edu.au>) and from the excellent *Gemini Observatory Image Gallery CD-Rom* that contains the Gemini North Virtual Tour discussed earlier.



This image shows the thermal vents fully open on Gemini North dome at sunset. The observing slit is partially open, revealing the truss and top end of the telescope.

(Copyright 1999, Neelon Crawford – Polar Fine Arts, courtesy of Gemini Observatory and National Science Foundation)

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Useful Web Sites

There is a wealth of information available on the web. These sites provide information at a range of depths. Some are more suited as general introductions whilst others provide detailed technical information. Many give links to other sites. They are arranged according to topic.

Galilean Telescopes and Observations

The Galileo Project <http://es.rice.edu/ES/humsoc/Galileo/> is an essential site at Rice University for all things to do with Galileo. It has a wealth of material including copies of his observations and a page, *Making a Galilean Telescope* http://es.rice.edu/ES/humsoc/Galileo/Student_Work/Astronomy96/mtelescope.html

Atmospheric Absorption

Observations at other Wavelengths <http://csep10.phys.utk.edu/astr162/lect/light/other.html> is part of a set of lecture notes that has a useful table showing what types of objects are observed at what wavelengths, a diagram showing the atmospheric windows and a link to SkyView at NASA from which views of the sky at different wavelengths can be generated.

Resolution, Sensitivity and Seeing

B.04 What is the resolution of a telescope? <http://www.faqs.org/faqs/astronomy/faq/part2/section-6.html> gives a concise answer to his question. It is part of large set of answers to frequently asked questions.

ASTR1020-002—LESSON 2 <http://cosmos.colorado.edu/astr1120/lesson2.html> provides a concise coverage of the key points related to sensitivity, resolution and interferometry as applied to telescopes on Earth and in space. It is part of an online hypertext course by Richard McCray at University of Colorado that also contains other useful pages.

M74—the Effects of Astronomical Seeing <http://www.astr.ua.edu/gifimages/m74seeing.html> provides a useful split-frame image of the galaxy M74 that shows the effect that atmospheric turbulence has in the resolution obtainable from ground-based observations.

The Purpose of a Telescope <http://astrosun.tn.cornell.edu/courses/astro201/purpose.htm> is a simple page that addresses seeing, resolution and diffraction limits for telescopes, linking to other pages in this set of lecture notes. The page on *seeing* has a nice set of four images showing the effects of seeing on an image of galaxy clusters.



Telescope Resolution <http://msowwww.anu.edu.au/~pfrancis/phys2023/notes/node15.html> by Australian astronomer Dr Paul Francis is concise, reasonably technical and discusses resolution of telescopes in different wavebands. It is part of his online course notes.

Adaptive and Active Optics

An introduction to active and adaptive optics <http://www.eso.org/projects/aot/introduction.html> from the European Southern Observatory provides a clear, authoritative introduction to these areas. The language is challenging but conveys the key points. Laser guide star and multi-conjugate adaptive optics techniques are discussed.

The Center for Adaptive Optics <http://cfao.ucolick.org/> at the University of California, Santa Cruz, contains a number of particularly useful pages including clear, concise descriptions on resolution, what adaptive optics is, why it is useful and how it works.

Euro50 <http://www.astro.lu.se/~torben/euro50/index.html> provides information on Swedish plans for a 50-m telescope. If you go to the *Downloads* frame you can obtain an avi movie file that models the effects of adaptive optics in resolving a star cluster. The file is about 64 Mb. The *Visualization of optical performance* frame provides similar images in a more compact format.

Gemini Adaptive Optics Home Page <http://www.gemini.edu/sciops/instruments/adaptiveOptics/AOIndex.html> is a technical site for scientists and engineers and hence may be too detailed for students but may serve as a source for very keen students.

The VLT Active Optics System <http://www.eso.org/projects/vlt/unit-tel/actopt.html> gives details on the system used for the four 8.2-m mirrors of the Very Large Telescope in Paranal, Chile.

Optical Interferometry

Astronomical Optical Interferometry http://www.cus.cam.ac.uk/~rnt20/interferometry/ast_opt_int/page1.html is a detailed site with numerous links to other interferometry pages. It provides some useful diagrams and a wealth of history and theory.

ATCA Live! http://www.narrabri.atnf.csiro.au/public/atca_live/atca_live.html provides real time updates about the six 22-m dishes of the Australia Telescope Compact Array radio telescope at Narrabri in northern NSW. Although a radio rather than an optical interferometer, it serves as a useful comparison.

Keck Interferometer <http://huey.jpl.nasa.gov/keck/> provides an overview and details about the plan to link the two 10-m Keck telescopes to together to form an optical interferometer

MWO – Education – Presentations – Interferometry <http://www.mtwilson.edu/Education/Presentations/Interferometry/> is a useful article from the Mount Wilson Observatory educational team covering the basic idea of wave interference, the Michelson-Morely experiment and the application of interferometry to astronomy. This brief article would also be useful for module 9.2 *Space*.

OLBIN Links <http://olbin.jpl.nasa.gov/links/> is a NASA site providing information on all optical long baseline interferometry projects, both ground-based and space-based.

Scientific American: Feature Article: A Sharper View of the Stars: March 2001 <http://www.sciam.com/2001/0301issue/0301armstrong.html> provides a clear, detailed overview of the theory and engineering behind optical interferometry and the scientific value of it. It is an excellent source that includes effective diagrams.

SUSI Home Page <http://www.physics.usyd.edu.au/astron/susi/> is the site for the Sydney University Stellar Interferometer, a 640 m baseline optical interferometer at Narrabri, NSW built and run by the Institute of Astronomy. The site has brief but clear pages such as *What is stellar interferometry?* that are at appropriate depth for students.

Modern Optical Telescopes

Large Telescopes <http://www.seds.org/billa/bigeyes.html> regularly updated site tabulating all the large optical telescopes in the world. It is organised according to operational status of telescopes and lists them by aperture, providing additional information on name, location, latitude and longitude and brief comments. Most telescopes are linked to their relevant homepages. This site is a valuable source of data and a good reference for students to commence any secondary research task.

Welcome to the Gemini Observatory Web site <http://www.gemini.edu/> is the home page for the Gemini telescope project. Links are provided to a range of pages including those dealing with the engineering and technology, observations, media releases and images. An Australian Mirror Site is also available at: <http://www.gemini.anu.edu.au/>

