Swinburne Astronomy Online

Major Project Cover Sheet

Telescopes in all Shapes and Sizes – the Right Optics for the Job

ABSTRACT

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Farmers have tractors. Astronomers have telescopes. The astronomers' tool-of-trade was invented over 400 years ago and evolved with the science it serves, a plethora of architectures and functions reflecting a multitude of cosmic interrogations. I review a range of telescope features including mounts, light paths and optics, and describe their purpose. Terms of telescope categorisation aren't mutually exclusive so this project is in a self-referring format for clearer understanding. Assuming a telescope is a ground-based optical tube assembly plus its mount, focussing radiation from 100-1000 nm and employing dioptrics and/or catoptrics then there are two types by virtue of mount: equatorial and altazimuth. Light paths are broadly grouped into prime, Newtonian, Cassegrain and Nasmyth/coudé depending on where they direct incident light with respect to the tube assembly. Location of the focal plane either constrains or anticipates the instrumentation placed at that plane. Optical aberrations are discussed with respect to design and fabrication choices. The science performed by using each type of telescope is delineated by all these considerations. Illustrating the match of design and science, I provide scaled, light path diagrams and physical and optical specifications for four telescopes at the Perth Observatory. To perform frontier astrometry, a Repsold Meridian Transit Circle used state-of-the-art digital technology on a prime focus, refracting telescope. This telescope provided fundamental star positions for a Grubb astrograph to further the Carte du Ceil and to discover/image comets, asteroids and minor planets. An extraordinary telescope, the Catts/University was transformed many times since its original size, mount and light path. It ended life as a hybrid Cassegrain/Newtonian having travelled the world for research and teaching purposes. The Perth-Lowell multi-F ratio, RC-Cassegrain was retired in 2013 after being used to characterise the Martian surface for Viking landers and discovering exoplanets and the rings of Uranus

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1. Introduction

Over six thousand years ago, the Proto-Indo-European (PIE) languages used 'kwel' to mean 'distant' in either space or time, and 'spek' to 'observe' (Archeoweb). This evolved through the Greek 'tele'(distant) and 'skopos' (watcher), to the first recorded usage of the word 'telescopio' by the founder of The Accademia dei Lincei in Rome when Galileo's watershed technological step was taken at the start of the seventeenth century (Etyweb).

Contemporary telescopes range from cheap hand-held toys for children (see Spaceweb) to multi-billion dollar spacecraft employing cutting edge engineering and computing, with extraordinary resolution and look-back time. Research telescopes can be generally defined as those engineered to significantly ameliorate physical forces and systemic noise that would exacerbate the resolution of a target. They are employed to observe in every wavelength band from high energy gamma to long wave radio (EELTweb1).

The scope of this subject is problematic due to the vagaries of two words and the overlap of classifications. First, the word 'telescope' can be used to refer to a number of things:

- the Optical Tube Assembly (OTA) containing the mirror/lens system, for example Galileo's hand-held, or
- the [OTA + mount], for example my 40 cm reflector on its Dobsonian mount, or
- the [OTA+mount+housing], for example the Musk telescope at the Utah Mars Desert Research Station, or even
- the entire [OTA+mount+housing+facility], usually called an observatory, for example the European Southern Observatory's Very Large Telescope in Chile.

Secondly, 'optical' (again from the PIE root 'okw' – to see (Etyweb)) has several meanings in science, but for astronomers the optical part of the electromagnetic spectrum includes the ultra-violet (UV), visible and infra-red (IR) bands. Optical radiation then, is from 100 - 1000 nm (Gigaweb) and contains the visible at about 400 - 800 nm (ISOweb). Atmospheric absorption requires that UV and IR astronomy are done from the air (eg IR by SOFIAweb) or space (eg UV by Hisakiweb) respectively, so ground-based telescopes can typically only access the visible part of the spectrum.

'Optics' is even less well defined. It is a broad field of study in physics that examines the characteristics and behaviours of light as well as the instruments for examining, receiving and recording light (ISOweb). 'Optics' can be used to describe the properties of those components that reflect, refract and/or diffuse light, or used as a noun for those actual components (Halliday 2005). This report will take the middle ground and describe the arrangement of components, light paths and physics of imperfections, as they relate to the general architecture of telescope design and the desire for various science outcomes.

Terrestrial telescopes are tailor-made to match performance and aesthetic outcomes as well as employing new technologies like, for instance, liquid mirrors and adaptive optics. However, both amateur and professional telescope structures can be classified in two general pointing modes: equatorial and altazimuth. Multiple architectures have emerged around each mode, with features designed to satisfy a range of utilities. The optical path of incident light can also vary greatly depending on the architecture, practicalities and science of attached instrumentation. The combinations and permutations of telescope design and optics has therefore resulted in a plethora of physical outcomes.

The larger the aperture of a telescope, the more substantial must be the foundations, housing, pier and mount. If the telescope is recording high resolution data, then the mechanical engineering of the moving components must be high grade, and high-fidelity electronics must be used to drive it.

Instrumentation is another surprisingly unclear aspect. What it does, how and where it is mounted, all vary greatly. Sometimes there is just a provision for attachment and other times the imager/recorder is integral to the physical telescope. Here, an optical telescope will be defined as a ground-based OTA+mount observing from 100 - 1000 nm, with the potential to have observations recorded in some way.

"*Looking around the astronomical community, one finds telescopes in all shapes and sizes.*" This essay looks at design aspects that result in this variety of morphology: mounts, light paths, focal planes, imperfections and instruments. These categories are not mutually exclusive, so there is some cross-referencing throughout the essay. All figures and ray diagrams have been consolidated in a series of single-page Plates at the end of the document.

Contemporary and/or historical examples are mentioned throughout the text, then I present an expose of four diverse, historical examples that illustrate how science outcomes drive telescope design. Spanning the years 1898 - 2013, these four examples performed important science at the Perth Observatory (PO) in Western Australia. Specifications collected for the telescopes is incomplete, but sufficient to draw ray diagrams in some detail, and to say something about their contributions to science.

2. Telescope Architectures

2.1 Mounts

Though not strictly considered part of the optics of a telescope, mounts may determine the choice of OTA, light path, focal plane and subsequent design of instrumentation. Large research telescopes can incorporate instrument rooms and platforms into the mount design to allow for these and deliver appropriate pointing functionality to serve the desired science outcomes.

2.1.1 Equatorial Mounts (Plate 1)

An OTA can be attached to a latitude-specific supporting member that is longitudinally aligned parallel to the Earth's rotational axis, pointing to the local celestial pole. It is attached to, and driven (manually or by a drive) around this fixed axis so as to follow the apparent movement of the night sky, and target. This mode is known as an equatorial mount.

Large or small, equatorial mounts rely on their polar axis member being accurately and rigidly in place. This member must support the attached and cantilevered OTA as it is made to move around the polar axis. The OTA is itself on a swivel mechanism, allowing the target declination to be set for the viewing period. There are several foundational designs for equatorials:

2.1.1.1 German Equatorial

The German equatorial, named for Joseph van Franchiser (Waaland 1967) is a 'T' shaped mount with the OTA opposite a counterbalance with respect to the polar axis. A disadvantage of this arrangement is the inherent weight of the counterbalance and the consequent need to transport this if the telescope is a portable device. German equatorials are popular with amateur astronomers, but since the mid 1970s, (Leverington 2016) and the advent of accurate electronic tracking, research telescopes tend to be the more cost-effective and stable altazimuth type described later.

2.1.1.2 Fork Equatorial

As the name suggests, this arrangement consists of an OTA suspended between the tines of a supporting fork. The base of the fork attaches to a rotating plate that is offset at an angle equal to the local latitude, acting as the right ascension drive plane. The tilting of the OTA within the tines sets the declination. This design eliminates the need for counterweights (Byers 1983) because the OTA is mounted near its centre of gravity. The 152 cm telescope at Mt Wilson Observatory is an example. Edwin Hubble was using this to "*Explore the depths of Space*" in 1927 (Hubble 1927). More recently, lunar observation data recorded by this telescope prior to 2003 has been mined and extensions discovered to the s-solar index catalogue that appears in the VizieR catalogue (England et al 2017).

2.1.1.3 English/Yoke Equatorial

Here, the OTA is supported within a hollow rectangular member that is fixed at both ends to foundations and inclined to the local celestial pole. Though the OTA cannot point close to the pole, this is a very sturdy architecture (Orchiston 2001). The 254 cm Hooker telescope at Mt Wilson was a good example of this mount. In 1926, the Hooker was used in conjunction with the 152 cm mentioned above to take photographs of over 400 deep space nebulae and thereby estimate the size of the observable universe as being around 10^{10} parsecs and that the universe was expanding (Hubble, 1926).

2.1.1.4 Horseshoe Equatorial

This mount is a modification of the yoke. It has one end cut out and gives better access to circumpolar targets. A well known example of this mode is the 3.9 m Anglo-Australian Telescope in New South Wales (Gascoigne et al 1990). It is used for a wide range of observations from stars to galaxies as well as wide field surveys and exoplanet searches. It has an instrument called IRIS2 for IR spectroscopy and is still doing great science (see Simpson 2017).

2.1.1.5 English/Cross-axis Equatorial

This form of the English equatorial type has both ends of the polar axis member firmly supported, with a counterbalanced OTA (Orchiston 2001). A most famous example of this mount is the Great Melbourne Telescope, the largest steerable telescope in the world at the time, which had a 122 cm speculum mirror. It was originally designed to observe changes in nebulae that Herschel observed in the 1930s and note the recording device was pencil sketches made over many nights! In 1944, it was relocated to Canberra as a 127 cm with F/4.5 or F/3.8 and nearly 6 m focal length (Hart et al 1996). With a tortured history of fires and renovations, the GMT can nonetheless claim fame as the telescope used to first observe Massive Compact Halo Objects (MACHOs) with digital cameras in the 1990s (GMTweb).

2.1.2 Altazimuth Mounts (Plate 2)

The altitude-azimuth (altazimuth) mount was first conceived by Rømer in 1690 (Colby & Sandeman 1913), and encompasses any arrangement of a telescope's OTA/mount that allows for vertical movement only of the objective end (altitude), with horizontal rotation of the support structure (azimuth). Many architectures exist for this mode, the well known Dobsonian being popular with many amateur users (SWAweb).

The first modern research telescope to use this mount (the BTA in Russia) set the trend for altazimuth mounts because of the stability, economy and ability to very accurately point to a moving sky. The 3.5 m WIYN telescope at Kitt Peak National Observatory (KPNO) is a good example of a modern altazimuth with Nasmyth platform, integral field spectrometer, optical imager and modern drive (WIYNweb). It recently attempted to observe Rayleigh scattering in the atmosphere of exoplanet WASP-12b, some 900 light years away in Auriga (Luchsinger et al 2017).

2.2 Optics (Plate 3)

Telescopes can also be categorised by the type of 'glassware' they employ. Dioptrics is the usage and investigation of optical systems that have only lenses through which light passes. Catoptrics is the related science of reflecting surfaces. Catadioptrics is the study and functioning of mixed systems of mirrors and lenses. Applying this to telescopes, it is evident that pure dioptric telescopes have a refracting lens at the objective and eyepiece ends, and that catoptric telescopes have a reflecting surface (usually a curved, solid mirror) as an objective focuser (Weasnerweb). Catadioptric hybrids exist that combine the technology and science of both, such as the Maksutov corrector lens on a Cassegrain reflector (Archiveweb), and infact most new research telescopes are based on catoptric primaries and subsequent catadioptric systems.

2.2.1 Dioptric

Refrangents (old English), better known simply as refractors, were the first telescopes fabricated – Galileo's famous 93 cm long instrument was a simple dioptric tool invented by Dutch optician Lippershey (King 1955). Consisting of an objective lens and an eyepiece lens, refractors ushered in a new era in astronomy and for many years the glassware and mounts simply grew in size and power, the ultimate construction being the Great Paris Exhibition Telescope of 1900 which was a huge horizontal tube fixed in place (Launay 2007) for the exhibition but never used as an astronomical telescope. It had a 125 cm objective lens and a 57 m focal length. The Yerkes Observatory currently has the largest functional refractor with its 102 cm aperture (Yerkesweb).

Since refractors only use lenses, the light paths typically enter through the positively curved objective lens and are refracted towards a focal point beyond which is another lens that reforms the image at a detecting focal plane.

Light passing through a solid medium like glass loses some wavelengths to absorption (King 1955), and results in various aberrations at the focal plane (see §2.4 Imperfections). These problems can be somewhat ameliorated with a combination of precision lens systems, but historically the sheer mass of lenses became prohibitive for astronomers.

2.2.2 Catoptric

Better known simply as reflectors, and notwithstanding modern liquid mirrors, these telescopes usually use curved solid mirrors and have a mass advantage over refractors that makes them cheaper and more versatile. First conceived by Gregory in 1664 and first constructed by Newton in 1670 (Simpson 1992), they obviate the inevitable manufacturing flaws and chromatic aberrations of large lenses, though they do have their own optical problems as discussed later.

Reflectors come in a multitude of configurations with various combinations of spherical, parabolic, hyperbolic, flat and segmented mirrors. A mirror over about 8 m diameter becomes prohibitively expensive to construct, install and maintain, so about 30 years ago, segmented mirror technology began. Although segments must be precisely shaped to match the desired conic section of the overall primary surface, thus introducing imperfections, these can be largely corrected by modern adaptive and active optics (Keckweb1).

2.2.3 Catadioptric

The first time a lens and mirror were used together may have been in the early 17th century when Niccolo Zucchi apparently described his experiments in the Optica Philosophica (Galileoweb), but generally speaking, refractors ruled the skies for many years until reflectors took over, and then modern lens optics began to complement mirror optics.

A logical development, the combinations of lenses and mirrors, each with a range of optical properties, results in a catadioptric system. Common contemporary amateur telescopes often use a Cassegrain design that has been modified to remove optical aberrations by the addition of lenses. The Schmidt-Cassegrain and Maksutov-Cassegrain are two such designs discussed in §2.3.3.

The complexity of eyepieces, objective, primary, secondary, tertiary and combination lens systems, as well as imagers, detectors and science instruments in modern telescopes has contributed to the aforementioned range of telescopes, a few of which are mentioned here.

2.3 Light Paths

The reflections and refractions that incident light takes through an OTA/mount and consequently where it comes to focus, determine its light path. These paths result in different end points where the image appears at a focal plane and these focal planes determine the placement and operation of astronomical instruments such as imagers and spectrometers.

The aperture of a telescope is a measure of the effective area of the objective end of the OTA and since most telescopes have circular cross-sections, the aperture is usually recorded as a diameter. A 10 cm aperture therefore, has a light-collecting area of 25π cm^2 and a 20 cm aperture has an area of 100π cm^2 – larger apertures collect more light as a function of the square of the radius, and so produce relatively brighter images.

The focal length of a lens or mirror is the distance between the primary optics and the point at which it focuses the incident light. Shallow curved optics produce long focal lengths and deeper curves are ‘faster’ or ‘stronger’ and focus at shorter lengths. Of course, the specific mathematical type of curvature has a direct effect on the focal length as well as the sharpness of the focus.

The focal or ‘F’ ratio of a telescope is a fundamental description of the focussing ability because it relates the aperture to the focal length. F ratio (speed) is the strength and light capture expressed in one number as (focal length) / (aperture). The larger an F number, the longer the focal length for a fixed aperture, so this directly relates to the light-bending ability of the primary optics. High F ratios (eg F/10) result in relatively dimmer images and narrower fields of view, whereas low F ratios (eg F/2) result in relatively brighter images and wider fields of view.

The detailed physics of optics is beyond the brief of this project, suffice to say that when a telescope employs a combination of mirrors and lenses of various curvatures and/or complex correcting systems, the mathematics becomes important. Fundamentally, a system’s focal length varies in the form:

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} \text{ .... } 1$$

where: f is the system focal length, f_1 and f_2 are component focal lengths.

This becomes slightly different if the light path folds on itself as in a Cassegrain design, the initial formulae for which were calculated 120 years ago (Schaeberle 1896). The geometry of the OTA must be considered, resulting in a general form:

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2} \quad \ldots\ldots\ldots 2$$

where: d is the separation distance of the primary and secondary mirrors.

The diagram at top, right on Plate 4 shows the dimensions needed for a geometric calculation, but to fully specify a Cassegrain, knowledge of conic constants is also needed.

2.3.1 Prime (Plate 4)

The prime focus of an optical system refers to the plane where redirected incident light would come to focus if it was not diverted by any intervening optics. In diagrams on Plate 4, it is at the orange detectors. When a telescope has its detector at this plane, it is referred to as a prime focus telescope, the main optical problem being their limited distortion-free field of view (FoV) close to the optical axis (Cheng 2009). Coma is the main off-axis problem for prime focus telescopes and is directly proportional to the Petzval curvature (see §2.4) (Wilson 2013).

Early refractors were prime focus telescopes because the light path ran straight through the OTA and onto a primary focal plane at either a human retina or an imager's detection surface. Lippershey's invention, small, hand-held telescopes, spyglasses and binoculars are prime focus, as are many older refractors including Meridian Transit telescopes and astrographs, both of which are discussed later.

Large research telescopes such as the 8.2 m Subaru on Hawaii (Miyazaki et al 2002), and the 229 cm Steward at KPNO (Williams et al 2004) can have a platform at the prime focus (even though it may not be a prime focus telescope, it does have a prime focus for the primary mirror) so as to allow access for calibration and also to place cameras.

A Meridian Transit Circle (MTC) is the descendant of Ptolemy's and Brahe's quadrant concept for measuring the declination of objects as they pass across the local meridian. One was first built in the late 17th century as a fixed-RA declination telescope by Rømer (Rømer 1690). It is a simple prime focus refractor that requires the observer to take precise readings off a graduated wheel (the circle) when the target crosses the local meridian. MTCs marked the beginning of astrometry, a field that has continued to improve in accuracy since Hipparchus (Plate 5) (Høg 2017b).

MTCs were widely used to determine time with reasonable accuracy, Royal Astronomer Flamsteed being the first to reduce MTC data to also calculate right ascension (Blitzstein 1997). Rømer's data was mostly lost but what is left has been found to be within 4" (Høg 2017b) or 10" (Fabricius 2011 in Høg 2017b) of modern astrometric values, accuracy being lost in the precision with which the graduations are marked on the circles.

Astrometry became very precise in the second half of the 20th century, with the advent of photoelectric detectors and digital control of the MTC's micrometer and telescope, followed by the CCD revolution and modern additions and expansions of catalogues by the European Space Agency's (ESA) Hipparcos and Gaia space telescope missions and the Tycho catalogues (Høg 2017b).

As well as existing MTCs such as the 20 cm Flagstaff Astrometric Scanning Transit Telescope (FASTT) helping to determine the size and shape of asteroids (Waring-Dunham 2015), data have also been mined for discoveries such as a proposed 76 year cycle in the Sun's radius and its relationship to Sun spot activity (Gilliland 1981).

An astrograph is any instrument designed to take images of objects in the sky. Leaving aside modern telescopes and setups available for amateur astrophotography, this term is often used to refer to a large refracting telescope that has an associated imager. An active research astrograph is the Russian Academy of Science's Pulkova Normal Astrograph which has produced a catalogue of 100,000 stellar proper motions and 73 extragalactic radio sources (Pulkovaweb). Also, the Yale Southern Observatory has a twin 51 cm astrograph mounted in a fork. Each imager has a guide telescope and CCD detector optimised for a particular wavelength (one blue at 4358Å, one yellow at 5300Å) (YSOweb).

Since the 19th century, prime focus observations using MTCs and astrographs lead the way into modern photographic and spectroscopic astronomy at the Greenwich Observatory. Names like Troughton, Simms, Pond, Ransomes, May, Airey, Grubb and Christie were all destined to be significant influencers (King 1976). For example, Christie became Astronomer Royal and directed the Carte du Ciel with astrographs built by Grubb.

2.3.2 Newtonian (Plate 3)

The next level of complexity of reflector is the Newtonian (see Newton 1672), whereby a light collecting primary mirror located at the back end of the OTA delivers a beam to a flat mirror towards the front which in turn deflects the image perpendicularly outside the OTA, through an eyepiece and onto a detector. It was the go-to telescope after refractors and is still favoured by many for reasons of cost and operability. Because they employ parabolic mirrors, coma is the main off-axis problem for Newtonians and is directly proportional to the Petzval curvature (see §2.4) (Wilson 2013).

Newtonians of old had speculum reflectors, that is, made from a polished copper and tin alloy and were often quite long instruments because a large F ratio can give good results over their relatively small FoV. The 65 cm Baker Newtonian at the Ballarat Observatory (BOweb) was one of a generation of grand old Newtonians that rode the wave of enthusiasm for astronomy in the late 19th century (Orchiston 1989).

Newtonians are still in use by the research community, for example the 60 cm at Masaryk University in the Czech Republic was recently used in a study of magnetic flares around a White Dwarf binary (Qian 2017). Aside from school and enthusiast level astronomy, Newtonians are sometimes also used as receivers for such things as LIDAR signals during atmospheric studies (Mole et al 2017).

The eyepiece of small Newtonians is easily accessed by an observer but compared to other designs, a Newtonian focal plane has two obvious disadvantages. On large telescopes, the location of the eyepiece means that the human and/or detector must observe from a point far removed from the telescope's centre of gravity and often at a height from the floor, thus causing access issues and also restricting the weight of instruments that can be effectively attached.

The Newtonian design is still very common especially for telescopes on small mounts – tripod or Dobsonian, and the historical example described later in this report illustrates the scientific desire to have a Newtonian functionality designed into telescope architectures, thereby taking advantage of the attributes of a longer focal length without intervening optics.

2.3.3 Cassegrain (Plate 4)

The name sake of this telescope design is Laurent Cassegrain, born circa 1629 in northern France. A contemporary of Newton and Huygens (Launay 2016), Cassegrain is usually described suspiciously as a character who nonetheless developed a unique telescope design (before the Newtonian) whereby the incident light is bent back on itself and exits the OTA through a small aperture in the primary mirror (Newton et al 1672). Newton and others criticised it, and the design lay dormant for many years, but Cassegrain's original drawing is now an iconic scientific image (Launay 2016).

The Cassegrain focus also has an inherent physical access issue because it directs light straight out the back of the OTA. For viewer comfort today, smaller Cassegrains employ an eyepiece mounted in a 90^0 elbow, and larger research telescopes generally attach an instrument at the Cassegrain focus anyway. Nonetheless, similarly to historical prime focus refractors, designing safe, comfortable observing platforms for human operators was an issue for some time (see Farrell 1972).

Advantages of the Cassegrain design are their compact size and convenient location of the focal plane for instruments to be attached. Effective focal lengths of many meters are achieved by folding the light on itself and subsequent technological improvements have resulted in a common solution with hyperbolic mirrors at both primary and secondary positions – the Ritchey–Chrétien (RC) design. For reasons discussed later, the RC Cassegrain has become a favoured design for large research telescopes such as the 4.2 m William Herschel (WHTweb) and 10.4 m Gran Telescopio Canarias (GTCweb) on La Palma, Spain, and the 8.2 m Very Large Telescopes (VLT) in the Atacama Desert, Chile (VLTweb).

Cassegrain light paths exist in many optical formats, each addressing coma, astigmatism and field curvature with combinations of mirrors and lenses. The catadioptric versions locate a corrector lens at various positions with respect to the primary focus and each has its own advantages and disadvantages although some are far more popular than others. Designs are typically named for their particular developers:

Primary	**Secondary**	**Lens**	**Name**
spherical	spherical	-	original
parabolic	hyperbolic	± near focus corrector	standard
hyperbolic	hyperbolic	± near focus corrector	Ritchey–Chrétien
elliptical	spherical	± near focus corrector	Dall-Kirkham
spherical	oblate spherical	± near focus corrector	Pressman-Carmichael
parabolic	elliptical	± near focus corrector	Gregorian
aspherical	spherical	aperture corrector	Schmidt
spherical	spherical	aperture corrector	Maksutov
oblate spherical	spherical	aperture corrector var.	Wright
oblate spherical	spherical	aperture corrector var.	Houghton

Maksutov-Cassegrains are corrected for coma, spherical aberration and chromatic aberrations, and Schmidt-Cassegrains are corrected for spherical aberration (Cheng 2009). There are many books and web sites devoted to Cassegrain design and construction and the information in the table above is distilled from the site of a private company, R.F. Royce: Precision Optical Components in Connecticut, USA (RFRweb). It is provided to illustrate the multiplicity of Cassegrain design.

Designing and constructing a Cassegrain telescope requires an understanding of geometry and the physics of optics, and given the additions of post-secondary optical systems that may be catadioptric, the formulae to specify particular telescopes can be complex.

2.3.4 Nasmyth and Coudé (Plates 2 - 4)

James Nasmyth (1808 - 1890) was a Scottish engineer with a passion for astronomy that led him to construct his own 51 cm telescope with a novel manner of exiting the Cassegrain light path through the telescope mount bearings, before it reached the standard primary mirror. He fabricated the primary mirror using a steam engine to drive short, curved grindings (Andrews 1994).

Known as a Nasmyth focus, the term is usually applied to such a configuration that results in a focal plane just outside the OTA on a dedicated instrument platform. Nasmyth instrument platforms (including a coudé function) are integral to the design of the latest generation of large research telescopes such as the European Extremely Large Telescope (EELT).

French for 'elbow', a coudé (koo-day) arrangement also intercepts the light of a standard Cassegrain design before it exits through the primary. Uniquely though, this Nasmyth-type design directs the post-secondary light (out of the OTA through the polar axis) (UCOLickweb) to instrumentation at a physically removed location – often a coudé room.

Before the advent of Nasmyth platforms, large modern research telescopes often employed the coudé arrangement to obviate the heavy physical tracking requirements with an attached, large spectrograph or imager. Modern designs still include coudé functionality to take advantage of the extreme stability of the output light required for high resolution spectrographs (EELTweb2).

An interesting example, the EELT optical path design is complex and customised to the proposed instrumentation. The primary mirror is a 39 m, fast F/0.93 elliptical, secondary is a 4.2 m convex that directs light axially through a fourth mirror to the 3.8 m third, aspheric mirror. The fourth mirror is a large deformable, adaptive mirror with 8,000 points of actuated correction. The fifth mirror is an off-axis flat that sends light to either a Nasmyth platform instrument or a coudé-train constructed on the stable ground level. The resultant F/17.48 output at the Nasmyth focal plane is constrained by the size of the aperture in the fourth mirror, and will be diffraction limited over 10 arcminutes (EELTweb2).

With large collecting capacity and state-of-the-art optics and technology, the EELT expects to probe the universe at unprecedented resolution and to fine tune the red-shifted cosmological expansion (Liske et al 2008).

Another interesting coudé example is the off-axis, Gregorian design, Multi Application Solar Telescope (MAST) brought on line in 2015. It is owned by the Indian Institute of Astrophysics and is a 50 cm aperture, solar telescope that uses imagers, spectrometers and adaptive optics to collect observations that will inform solar weather theory (Venkatakrishnan et al 2017).

Illustrating the 'multi-messenger' nature of modern astronomy, Torres et al (2017) have recently published in the VizieR Online Catalog, results of nearly two decades of observations of V530 Ori. They used data from a Cassegrain-mounted, echelle spectrograph at the F. L. Whipple Observatory and the coudé-mounted spectrometer at the KPNO.

2.4 Imperfections (Plate 5)

Modern optics is based on the fundamental description of light rays traveling in straight lines of least distance (Schuster 1904). From a point light source such as a star, a telescope can only recreate the point to the extent that its optics will allow – perfect reproduction would be known as stigmatism (Poggiani 2016). Fundamental wave physics tells us that incident telescope light is usually composed of multiple wavelengths and that refracting and reflecting materials redirect light according to the incident wavelength as well as the engineered properties of the medium.

The cumulative effect of these systematic and physical imperfections is an image that resembles the source as much as possible by virtue of the telescope design. The degree of diffusion of a point source image from perfect, is called the Point Spread Function (PSF) and directly effects resolution (Geary 1993). For circular aperture telescopes, the PSF takes the form of a wave function with a strong central core surrounded by subsequent-order interference rings. This so-named Airy Pattern is the limiting attribute for improving resolution. The radial size (R_A) of the central core (Airy Disk) is given by:

$$R_A \approx \frac{1.2\,\lambda\,f}{D} \quad \text{.......... 3}$$

where: λ is wavelength, f is focal length, D is telescope aperture

It is clear from Eq. 3 that for any given wavelength and aperture, longer focal lengths produce larger Airy Disks and therefore less resolved images. It is also clear that for any particular wavelength and focal length (generally fixed for a particular telescope set-up), the Airy Disk size is smaller for larger apertures. Several systems have attempted to define exactly when two Airy Disks are deemed to be separate and therefore when resolution is achieved. Not described here, quoting a Rayleigh, Dawes or Sparrow resolution criterion informs a telescope user of the way resolution was calculated (Cheng 2009).

Of particular interest is the fact that designing a setup of focal length and aperture determines the best wavelength for a small Airey Disk. In general, the larger the aperture the better, the shorter the focal length the better, and the smaller the wavelength the better.

For precision output at an astronomical instrument then, certain system imperfections must be addressed by the optical design of the telescope. As a system approaches nill contributions to the image from these imperfections, it is described as diffraction limited. Also note that a telescope can be designed with an f/D ratio (simply the F ratio) to deliberately leverage desired wavelength observations.

The ideal mirror section is parabolic because all parallel incident rays will reflect to the mathematical focus. However, for a range of curvatures, a conic vertex polynomial describes the cylindrical coordinate (p) in terms of the optical axis (z), the radius of curvature (r) and the conic constant (K) the latter being a measure of the eccentricity of the primary mirror curvature (Poggiani 2016):

$$p^2 - 2rz + (1 + K)z^2 = 0 \quad \text{.......... 4}$$

- if $K = 0$, the curve is spherical,
- if $K = -1$, the curve is parabolic,
- if $K < -1$, the curve is hyperbolic,
- if $K > 0$, the curve is prolate ellipse,
- if $-1 < K < 0$, the curve is oblate ellipse.

Eq. 4 can be expanded into a Taylor Series to reveal multiple orders of various aberrations that rapidly diminish in significance after a few orders (Poggiani 2016, Geary 1993). There are five broad types of mono-chromatic aberration that emerge from the series (based on Seidel 1856). Non-axial aberrations (A) are described in a Cartesian coordinate (θ, y) system for incident light at θ degrees to the main axis (Schroeder 1999):

$$A = 3a_1 \frac{y^2\theta}{r^2} + 2a_2 \frac{y\theta^2}{r} + a3\theta^3 \text{ .... } 5$$

2.4.1 Field Curvature

Lenses and mirrors produce an axially symmetrical image on a *spherical* surface but detectors are usually (but not always) flat, so a distortion occurs at greater distances from the axis. The radius of this sphere is the Petzval curvature and its deviation from the flat detector can be absorbed to a small extent by CCDs, effectively addressed with negative (concave) corrector lenses (McLeodweb) and/or a slightly aspherical primary (Wilson 2013).

2.4.2 Field Distortion

Distortion is a second-order aberration of field curvature – it varies as the cube of the Petzval curvature. It is related to field curvature in that the separation of two points on a curved field will vary non-linearly depending on their position in the FoV (Wilson 2013). This becomes an issue when correcting mechanisms are used close to the image plane.

2.4.3 Spherical Aberration

This occurs when consecutive concentric rings of the incident light focus at different lengths, producing circular effects outwards from the primary axis. There is no spherical aberration with parabolic optics and in fact spherical aberration can be corrected with the addition of parabolizing optics.

At the third order level of Petzval curvature, spherical aberration is unaffected by the field curvature (Wilson 2013), but as witnessed by the Hubble Space Telescope incident, machining the conic section of the mirror incorrectly can have serious performance outcomes.

2.4.4 Coma

Objects in the outer part of the FoV can assume a comet or teardrop shape if the primary isn't perfectly spherical, as for a parabola. Mathematically, coma is comprised of concentric rings with displaced centres in a 60^0 arc from the core (Cheng 2009) and is more of a problem at faster (low F ratio) speeds (Schroeder 1999). It is the first term in Eq. 5.

The direction of the coma aberration is along the line between the true image and the y-axis point of zero coma. Parabolic mirrors suffer most from coma but poorly aligned secondary mirrors are also a common cause.

2.4.5 Astigmatism

Dependent on the square of the Petzval curvature (Wilson 2013), astigmatism results from the object coming to focus on different planes and appears as an elongated image with sharp features (Cheng 2009). It is the second term in Eq. 5 and is also worse in faster systems (Poggiani 2016).

2.4.6 Chromatic Aberrations

Refraction of light is wavelength dependent (Halliday 2005), so uncorrected dioptric and catadioptric systems produce a sharp focus only for a specific wavelength, surrounded by slightly out-of-focus coloured rings – chromatic aberration (Poggiani 2016). A wave aberration equation accounts for chromatic refraction in two dimensions, longitudinal and radial. Mirrors don't show this type of imperfection because reflection is not wavelength dependent (Cheng 2009).

Correction of chromatic aberration is by the addition of correcting lenses each of different refractive index. Correctors that focus red and blue to the same focal plane are known as achromatic and those that focus three (red, green and blue) are called apochromatic (Cheng 2009). Schmidt Cassegrains use a corrector lens to correct for aberrations of the spherical primary but this lens introduces chromatic aberrations that require a further, expensive corrector lens. Maksutov Cassegrains address this flaw with a thick corrector lens which nonetheless limits the size of the aperture (Cheng 2009).

2.4.7 Adaptive and Active Optics (Plate 5)

In order to leverage the great light collecting power of large telescopes, and approach the diffraction limit of the primary, two particular sources of error have been addressed since the late 80s (Wilson et al 1986). Mechanical stresses on the body of the primary can distort its shape from the manufacturers specifications, so an Active Optics system of actuators directly under the mirror cell is installed and computer controlled to make rapid, small adjustments to its shape. Wind loads, mass sagging, pointing activity and temperature all effect the shape of the dish which needs to be kept as close as possible to the desired shape, be it parabolic and spherical.

The column density of any telescope is a measure of the amount of atoms, molecules and dust in the path between the target and the primary. It plays an important role in the eventual seeing quality, and for ground-based telescopes, Earth's atmosphere is by far the largest contributor (Birney et al 2006).

The otherwise perfectly spherical wavefront approaching from the target is distorted by the atmosphere (Hardy 1977) such that the arriving wavefront can be out of phase by a few microns across a large mirror. Adaptive Optics measures this discrepancy against a reference star that is sometimes deliberately created (Keckweb2) with a laser exciting sodium atoms in the atmosphere (Foy & Labeyrie 1985). This sends adjustments of around 0.02 micron to a small, deformable mirror every millisecond. The true wavefront is then sent out from the deformable to the telescope detectors (ESOweb1).

A relatively new and rapidly growing field, much work is being done on getting the technology working well, but results are nonetheless starting to appear. For instance, quasar lensing was found in AO-aided SDSS data (Williams et al 2017), and stellar disks were characterised around M-dwarfs in Taurus (Ward-Duong et al 2017).

Multi-Conjugate Adaptive Optics (MCAO) uses multiple deformable mirrors and fully integrated Active/Adaptive Optics will be designed into future research telescopes at a very early stage so that all observations are done through these systems and extraordinary near-diffraction limit astronomy can be achieved (ESOweb1).

2.5 Resolution

Informing and constraining all areas of observational astronomy is done with a telescope, so a vast array of recording devices have been designed. Imagers, photometers, spectroscopes and CCDs each have an enormous variety of functions and designs, all employed for specific tasks to provide data for pleasure or science. The basic function of an astronomical recorder is to measure light. Early detectors relied on chemical, then photoelectric physics while today the CCD is preferred for research telescopes (Birney et al 2006). However, photometry and photography still have a crucial role in astronomy so imaging is an important science in itself.

Modern prime focus/Newtonian telescopes may have small F ratios to keep the OTA length smaller, and because of their small FoV, limit the type and size of instruments that can be used at the focus. Cassegrain light paths with Nasmyth/coudé trains are much more accessible and flexible in terms of instrumentation. These are considerations during the design phase of large research telescopes (Bely 2003).

In any remote sensing device, there are four fundamental types of resolution: temporal (over time), spatial (over distance), spectral (over wavelength) and radiometric (bit data) (Pelton & Buckley 2010). Temporal resolution incorporates a wide range of factors from scheduling to slew rates, detection times, re-set times and electronics. Spatial resolution is considered with respect to FoV, Airy Disks, aberrations and optics as described earlier. Spectral resolution, $\Delta\lambda$ is defined by the fidelity with which a specific wavelength is discernible in a spectrograph output and resolving power (R) can be calculated as $\Delta\lambda/\lambda$. Values of R=100,000+ are very high and currently achieved on telescopes like the VLT in Chile (VLTweb).

Detector responsivity and atmospheric noise determine the overall radiometric resolution of instrumentation (Brandl 2012). Contributing factors are synthesis of 16-bit pixel resolution at Full Well Capacity (FWC) specific to wavelength (Ryder 2012), Data Number (Seppo 2012), CCD size and gain (SpecInstweb 2012), and signal-to-noise-ratio (SNR) (Smith 2012). The latter is the largest component and may be addressed with frequent, short observations (Glazebrook 1998), frequent comparisons to blank/dark fields and physically ameliorating heat signatures, scintillation sources and using appropriate fabrication materials and optical coatings (Ryder 2012). Some of these factors are addressed with AO systems.

Mirror coatings deserve special mention. Speculum reflects about half the incident light when new but rapidly tarnishes over time. Silver-coated mirrors first appeared in 1856 and raised the reflectivity to 95% (Cheng 2009) but these surfaces also tarnish when exposed to sulphur in the atmosphere. Silver was superseded by aluminium coatings in 1934 (Cheng 2009) and today most mirrors are aluminium coated under low vacuum to a thickness of half the wavelength of yellow light. They have reflectivities around 90% varying with wavelength and need to be re-surfaced every few years. Wavelength/reflectivity profiles and budget inform the choice of coating, with gold, platinum and indium providing the best reflectivity (Cheng 2009).

3. Historical Examples

3.1 The Repsold Meridian Transit Circle (Plates 6 & 7)

On museum display from 1989 - 1992, item catalogue #1989-786 is a 1909 Repsold & Söhne, MTC currently languishing in storage at the Deutsches Museum in München, Germany. With funding from the Volkswagen Foundation, this 19 cm aperture telescope was shipped to the PO in 1969 (Sicka 2017) for use by the visiting Bergedorf (Hamburg) astronomical survey team. Rather than be upgraded and used for a proposed Japanese astrometry program, and to conserve its historical value, the MTC was returned to Germany around 1988 (Bowers 2016).

During negotiations in the late 1960s for a new PO site, and with parallel conversations with US, German and Australian astronomers, a new building for the MTC was constructed with precise location and altitude specifications (Bowers 2016). The telescope arrived with its own Danish GIER computer, recommended to work with the Repsold and the new photon counting method that complemented MTCs of the day (Høg 2017a). Photon counting is a technique invented by Høg whilst in Hamburg in 1960 (Høg 2012).

Foundation astronomical theory describes celestial coordinates and mapping, so a Fundamental Catalogue (FK) of 1,535 star positions was published in 1963 and periodically revised (McNally 2012). The current FK6 contains over 4,000 star positions incorporating astrometry from ESA's Hipparcos mission (Wielen et al 1999).

Also during the 1960s, and at the request of the International Astronomical Union (IAU) (Bowers 2016), the US Naval Observatory (USNO) and the Russian Pulkova Observatory (Rafferty & Klock 1986), initiated a 20 year survey of stars based on FK4. Conducted in southern skies up to declination $+5^0$, it would be used as reference locations for subsequent astrographic work. This Southern Reference Star (SRS) catalogue was completed in 1988 and contains over 20,000 star positions with 0.1 arcsec accuracy (1968 epoch) (McNally 2012).

The Bergedorf team used their Repsold MTC with an attached photoelectric micrometer (Høg 1976, Sicka 2017) to work on the SRS and eventually publish positions of 201,000 faint, and 4,800 bright star positions as the Perth70 Meridian Catalogue (Høg et al 1976). Two operators could record RA and Dec for 400 stars in one night (Høg 1976).

In 1966, this telescope was the first MTC to use a multi-slit, visual micrometer and it produced output via 5-channel punched tapes (4 bits + parity per row) that indicated position in the reticule as well as circle readouts. It was rated for magnitude 10 but was effective only to mag 9 stars (Bowers 2017). 110,000 observations of 26,000 star positions were set in the years to 1972 (Høg 1976, Høg & Nikoloff 1974).

To reduce thermal expansion and contraction, the MTC is made mostly of a nickel alloy steel and iron. Read errors were minimised (see Loibl 1978) by using large, 74 cm diameter circles with 3 arcminute grating marks of silver. The lensware was also designed for minimum thermal movement and is made of borosilicate and flint glass (Sicka 2017). The OTA measures 277 cm overall and the width of the declination axis is 240 cm. Its focal length is 2298 mm, with F/12.1 and it has a FoV of 89 arcseconds/mm (Sicka 2017).

Plate 8 is a schematic representation of the light path for this telescope with specifications gleaned from the literature. Since its raison d'être is to observe point sources as they cross the meridian, off-axis aberrations are largely moot, but it probably suffered a degree of coma and chromatic aberration although it is assumed that the borosilicate/flint objective is an achromatic corrector.

It is clearly a prime focus, dioptric telescope designed for purpose with leading technology of the time but had instrumentation modified and updated with respect to temporal and radiometric resolution. It was retired for its heritage value when electronic and digital technologies were beginning to exceed its optical capacity.

3.2 The Grubb Astrograph (Plates 8 & 9)

The Cartes du Ciel program was an outcome of the 1887, Paris International Astrographic Congress. A hole-sky Astrographic Catalogue down to mag 14 was to be created by enlisting the help of observatories around the world (Carte du Ciel 1889, ROGweb). The program required all participants to use an astrograph of the same specifications and it observed over 4.6 million stars, a million of which were recently used by the USNO to update the Tycho catalogue (Darlingweb). The Astrographic Catalogue was not completed but those ephemera that were recorded are highly regarded, and have been incorporated into modern catalogues such as Tycho (Høg et al 1998).

The Congress had released specifications for an equatorial mounted, standardised astrographic telescope which was later built by Howard Grubb of Ireland (Sisson 1992). Grubb was a leader in his field, in particular designing a new movement control that relied on mechanically engaging signals of 1 second from a mercury contact on a pendulum drive that produced very constant mechanism speed without slowing down the pendulum.

The 1895 Grubb astrograph consists of a dioptric imager connected to a dioptric guide telescope and was moved from its original city-side site to the new PO site in 1968, but not before some re-engineering of crucial drive components (Bowers 2016). Calibration at the new site was accomplished using Canopus and Neptune as a targets and it produced some 30,000 photographic plates during the same astrometric surveys as the MTC described above, and using its derived reference star positions (Bowers 2016).

The photographic plates had to be blue-sensitive to match the imager, so Kodak II-0 plates and 103A-O developing emulsion were chosen. To subsequently improve resolution from magnitude 11 to 14, these plates were baked by on-site staff before use (Bowers 2017). The Zeiss-Jena 3030 plate reader in the administration building was mounted on a dedicated concrete slab for vibration protection and the entire building was air-conditioned to reduce humidity and temperature fluctuations (Bowers 2017).

The imager has a 330 mm aperture, F/10.4 with focal length of 3,440 mm (Glass 1991). Its FoV was 1 arcminute/mm and it had a limiting magnitude around 14 after the aforementioned baking procedure (Bowers 2016). The 254 mm, F/13.5 guide telescope has the same focal length as the imager and is rigidly fixed in parallel is an integrated OTA. The astrograph was used to discover and image comets to magnitude 16 and reductions were performed originally on an IBM 1620, then a DEC PDP 11/10 computer at the University of Western Australia (UWA). The objective lens is an achromatic doublet (Lowe 2017) eliminating spherical and chromatic aberration, as well as coma, at 430.8 nm (Wayman 1988).

Successful production of glass photographic plates involved working in a red-lit darkened dome to manually clamp the photographic glass plate into its holder, slide it into the focal plane, retract the cover slide from the eyepiece, pull a string attached to the butterfly-cover on the objective, wait the desired time (often around 10 - 20 minutes) then repeat these steps in reverse. Plates were chemically developed in a darkened, adjacent room (Lowe 2017).

An important function of the astrograph was to collect time ephemeris with a Markowitz Moon camera as part of a USNO program performed by observatories around the world. Other programs focussed on external galaxies, minor planets, many comet discoveries (eg Jekabsons et al 1978), Pluto and on proper motions of stars (Bowers 2016).

For this astrograph, the connection between design, instrumentation and science could not be clearer. It was a bespoke imager, telescope and mount before fabrication even began and whilst later improvements were made to allow better temporal and spatial resolution, eventually the optical capability was superseded by technology and it became a public outreach display.

3.3 The Catts/University Telescope (Plates 10 - 12)

This most extraordinary, retired telescope has had many lives and as a result of impetus from this project, most of its components were found and rescued from multiple sub-standard storage locations. The history of its ownership, refurbishments and science is outlined by Orchiston (2010) and although some telescope details are still within unopened files in Thailand (Orchiston 2017), enough was discovered to construct light paths.

The Catts first appeared in the hands of Royal Society Fellow, Henry Ellis in the late 1890s, as a 508 mm, F/4.5 Cassegrain on a German equatorial mount, with a 152 mm refracting guide telescope. The next owner, Australian Walter Gale identified performance issues with the primary mirror, nonetheless observing Jupiter, Saturn and Mars, commenting on the "…*race of sentient beings*…" that probably inhabited the latter (Gale 1921).

After changing hands a few more times, the next significant owner was Director of the Planetary Section of the New South Wales Branch of the British Astronomical Association, Dr Con Tenukest who had the primary mirror renovated so as to continue planetary observations. J. H. Catts was a Sydney astronomer who bought the telescope from Tenukest in 1951. He is known to have displayed photographs of several comets taken with it. Catts then sold it to the Mt Stromlo Observatory (MSO) in 1952 (Orchiston 2010).

The MSO was moving from primarily solar, to galactic and extra-galactic astronomy and investing in new telescopes so the Catts was a temporary solution until delivery of same. It was used particularly for photometric work on eclipsing variables to about mag 13 (Wooley 1954, Eggen 1956, Wood 1959). An EMI 5060 photomultiplier was attached, and isophot plots constructed of both Magellanic clouds (Hogg 1955).

The Catts was relocated away from MSO's deteriorating seeing conditions and used as a site testing telescope at Mt Bingar field station in central, south New South Wales but not before a major overhaul. Converting to an F/12, the primary mirror was changed to a 660 mm US-made "…*thick-ribbed, honeycomb disk of Pyrex*…" (Bok 1960), a new 254 mm secondary ground, and the appropriate OTA and mount renovations made. A UBV photometer was attached and staff and post-doctoral students used the telescope for publications such as "Structure of the Southern Milky Way" (Whiteoak 1961). Stellar, cluster and galactic photometry continued to evolve as the EMI 5060 was superseded by a cooled RCA P2P photo-multiplier, then by an RCA 7102 tube.

Around 1966 and minus its primary mirror, the Catts was donated to the UWA and refurbished as a 406 mm Cassegrain/Newtonian hybrid used on-and-off at the PO site to observe variables photometrically (Burman et al 1990), including flares on Proxima Centauri using a new Gencom Starlight Photometer (Bowers 2017). It was thenceforth known as the University Telescope.

Whilst at the PO, the University telescope was also used to study double stars and planets, notably using a 'chopper' mechanism in a spectrograph for observations of Uranus' rings. An attached micrometer required the use of spider webs to construct a reticule, so a Red back spider 'farm' was managed onsite, the web being harvested and glued to the micrometer with nail polish (Bowers 2017). An attached Zeiss camera was also used to take 25^0 images of comets over four hour exposures (Bowers 2017).

1969 plans for a systematic supernova search with the University telescope was deferred when a larger telescope appeared on the PO horizon. The Perth-Lowell (PL) 61 cm stole this program from the University telescope which was consequently placed in storage in 1999, to be resurrected by this project in 2017.

The optics of the University telescope is interesting. The Cassegrain arrangement has a 9 m focal length and includes a tertiary dioptric system of unknown specification. The upper section of the OTA is replaceable with a Newtonian secondary module providing a 2 m focal length. Little was discoverable about the use of the Newtonian mode, suffice to say it is not mentioned in Orchiston (2010). This may be an oversight because it was most likely fabricated in the UWA workshop when the OTA was renovated with a 406 mm primary. A detailed search of the SAO/NASA ADS returned no hits.

The following Cassegrain specifications were discovered from the literature (Kroupa c1970), PO documentation, or calculated from measured, derived and estimated quantities, and using online formulae (BMweb, Konkolyweb, Lockwoodweb) in conjunction with Eq. 2. All lengths are in mm and are regarded as nominal because the telescope was in a disassembled state.

Of interest to come from these calculations is the high F ratio and 9 m focal length of the Cassegrain mode. If these numbers are correct, they illustrate the space-saving nature and slow speeds achievable with this design.

Specifications for the F/22.3 Cassegrain mode:

- Primary conic constant (parabolic) = -1
- Secondary conic constant (hyperbolic) = < -1
- Primary aperture = 406
- Secondary mirror diameter = 95
- System focal length = 9,000
- Primary focal length = 2,030
- Secondary system focal length = -554
- Secondary system magnification = 4.4
- System back focus = 355
- Secondary separation = 1,601
- Back focal length = 1,956

Specifications for the F/5 Newtonian mode:

- Primary conic constant (parabolic) = -1
- Primary aperture = 406
- Secondary mirror dimensions = 105 x 75
- System focal length = 2,030

Though the original design criteria for this telescope are unknown, its life history suggests that it was used opportunistically and renovated as and when science/teaching needs dictated.

3.4 The Perth-Lowell Telescope (Plates 13 - 15)

The NASA funded PL telescope was one of eight purpose-built in California and used specifically in global network of planetary studies preceeding NASA's Mars Viking landings. This telescope has a Ritchey-Chrétien Cassegrain light path. It has an F/3.5, 610 mm primary mirror that has been cooled by various technologies over its lifetime. It was essentially retired in 2013 when the state government astronomer's position was abolished.

On a motorised, German equatorial mount atop a 15 m concrete pillar, it is within a unique tower and under a motorised dome. Design of the OTA was set by the Lowell Observatory in the USA, but installation onsite was designed and fabricated entirely from scratch and resulted in some unique engineering and aesthetic outcomes (Hunt, 2017). The PL has undergone many modifications over its 40+ years of service. The OTA has a modular design, the objective end able to accept one of two secondary mirror sections – one to provide F/13 and another to provide F/75 (Bowers 2016).

It currently has multiple primary mirror coatings, a motorised secondary focuser, and CCD with computer controlled focuser (Atlas FLI) (Williams 1991). The main areas of research were planets (Baum et al 1970, Williams 1991), binaries, supernovae (Burman et al 1990) and exoplanets

(ESOweb2). A list of solo and collaborative highlights serves to illustrate the variety of science performed on the PL:

- Planetary Patrol Program observing bulk features of Mars, Jupiter and Venus from 1969 (Harris 1969)
- many minor planets during Near Earth Asteroid Tracking program 1970-1999 (eg Birch & Drenth 1970)
- Rings of Uranus in 1977 (Millis et al 1977)
- Asteroid topography of 44Nysa in 1981
- Installation of a nitrogen-cooled CCD (1985)
- Cryogenic jets in comet Halley (Ahearn et al 1986)
- Automated supernova search by Perth Astronomical Research Group from 1990 (Burman et al 1990)
- exo-planet OGLE-2005-BLG-390Lb in 2006 (Beaulieu et al 2006)

First light for the PL was imaged with a 35 mm film-based Planetary Camera supplied by NASA in 1970. It had two film cartridges to facilitate continuous imaging, the results of which were mailed to the USA for analysis (Bowers 2016). It used Kodak 2498 film for its colour response and superior grain definition. Photometers supplied by NASA used an EMI 6256 photo-multiplier and a Fabrey filter wheel so that backgrounds could be measured without taking the telescope off-target. These were used for observations of Jovian occultations and eclipses as well as comet Kohoutek (Bowers 2016).

In 1985, the University of Maryland sent a team to observe comet Halley with PO staff and also brought with them the latest technology in detectors – a CCD cooled with liquid nitrogen that would record through various filters selected for continuum and for molecular emissions: "…*Continuum 3650, CN 3870,* C_2 *5140,* C_3 *4060 and Continuum 4845*…" (Bowers 2016).

The following specifications were discovered from the literature (B&Cweb), PO documentation or calculated from measured, derived and estimated quantities, and using online formulae (BMweb, Konkolyweb, Lockwoodweb) in conjunction with Eq. 2. All lengths are in mm and are regarded as nominal because access to the telescope and its documentation was limited or non-existent.

Specifications for the F/13.5 mode:

- Primary conic constant (hyperbolic) = -1.083
- Secondary conic constant (hyperbolic) = -3.325
- Primary aperture = 610
- Secondary mirror diameter = 178
- System focal length = 8,205
- Primary focal length = 2,135
- Secondary focal length = -588
- Secondary magnification = 3.84
- System back focus = 700
- Secondary separation = 1,700
- Back focal length = 2,400
- Astigmatism Seidel coefficient = 4.71

Specifications for the F/75 mode:

- Primary conic constant (hyperbolic) = -0.94
- Secondary conic constant (hyperbolic) = -1.215

- Primary aperture = 610
- Secondary mirror diameter = 178 (assumed)
- System focal length = 44,790
- Primary focal length = 2,135
- Secondary focal length = -150
- Secondary magnification = 21
- System back focus = 700
- Secondary separation = 2,300
- Back focal length = 3,000
- Astigmatism Seidel coefficient = -3.76

As for the preceding historical examples of research telescopes, the PL was specifically designed for its initial astronomical program, then allowed to stay onsite and upgraded as and when science outcomes were determined by staff.

4. Conclusions

The main purpose of this review was to demonstrate the variety of telescope designs and to exemplify this with four historical case studies. The first tasks were to define terminology and then present and expand on the various characterising features of a telescope, citing real-world instances along the way. The discussion was limited to ground-based telescopes observing from 100 - 1,000 nm and excluded amateur astrophotography and advanced technologies like liquid mirrors and colour augmented consumer telescopes. The internal workings of instruments were not discussed, suffice to say they are specific to the science, designed for the science or determine the science of an observation run.

Broadly speaking, the type of i) mount, ii) optics, iii) light path, iv) imperfections and v) instrumentation are the areas to consider when designing a telescope. Each area is richly diverse with options and notwithstanding budget, if for instance, I wanted to observe the helium mixing ratio in the atmosphere of Sirius B, my thought process might go something like this:

1. Mount
   Altazimuth because they're cheaper and lighter than equatorial and modern electronics can locate and track them with precision,

2. Optics
   Catadioptric to accrue the mass and light capture benefits of large aperture mirrors and the aberration-correction of lenses,

3. Light path
   RC Cassegrain for compact OTA size, balance and optically matched mirrors. Nasmyth deck for spectrograph,

4. Imperfections
   MCAO to ameliorate telluric signals as well as local physical affects on the hardware, and

5. Resolution
   Spectrograph on Nasmyth platform to detect 10 - 124 nm (see Holberg et al 1998) and onsite synthetic spectrum analysis. High grade engineering and drive mechanism for slew rates and fidelity, high grade mirrors and lenses for diffraction limited observations. The largest aperture possible and the longest focal length for narrow FoV. The highest R value for spectral resolution requires echelle gratings. High grade electronics to maximise radiometric resolution.

Four historical examples each of a different design class, were presented, and scaled ray diagrams produced along with a brief history of the architecture and observing successes. The Repsold MTC is an early 20th century prime focus refractor that travelled across the world and back in order to do fundamental astrometry in the southern hemisphere. During its use, it underwent micrometer and photo-multiplier upgrades and furthered the established reference star catalogue. It now sleeps in a German museum.

The Grubb astrograph is also a late 19th century prime focus refractor that was design-for-task, travelling across the world to be at the PO where it stands today for the public to enjoy. After its primary function of using the Repsold MTC data to extend the mapped sky for the Astrographic Catalogue, it discovered many minor planets and asteroids. The clock drive was improved, the photographic plates were enhanced for better spatial resolution and additional cameras were attached for photometry programs.

The Catts/University telescope is another late 19th century product that found its way via many owners, functions and re-builds to end up in pieces under a damp stairwell. It had apertures from 406 - 660 mm and light paths of standard and non-standard Cassegrain as well as Newtonian. In its various incarnations it performed a huge variety of astronomical roles from spectroscopy to photometry, planetary to stellar and educational.

The Perth-Lowell telescope was also rigidly specified for its initial planetary work as a RC Cassegrain, but with a swappable OTA module to quadruple its F ratio. It became the central research telescope for the PO for four decades and made very significant contributions to science. Again, this telescope was also maintained, upgraded and accessorised as needed.

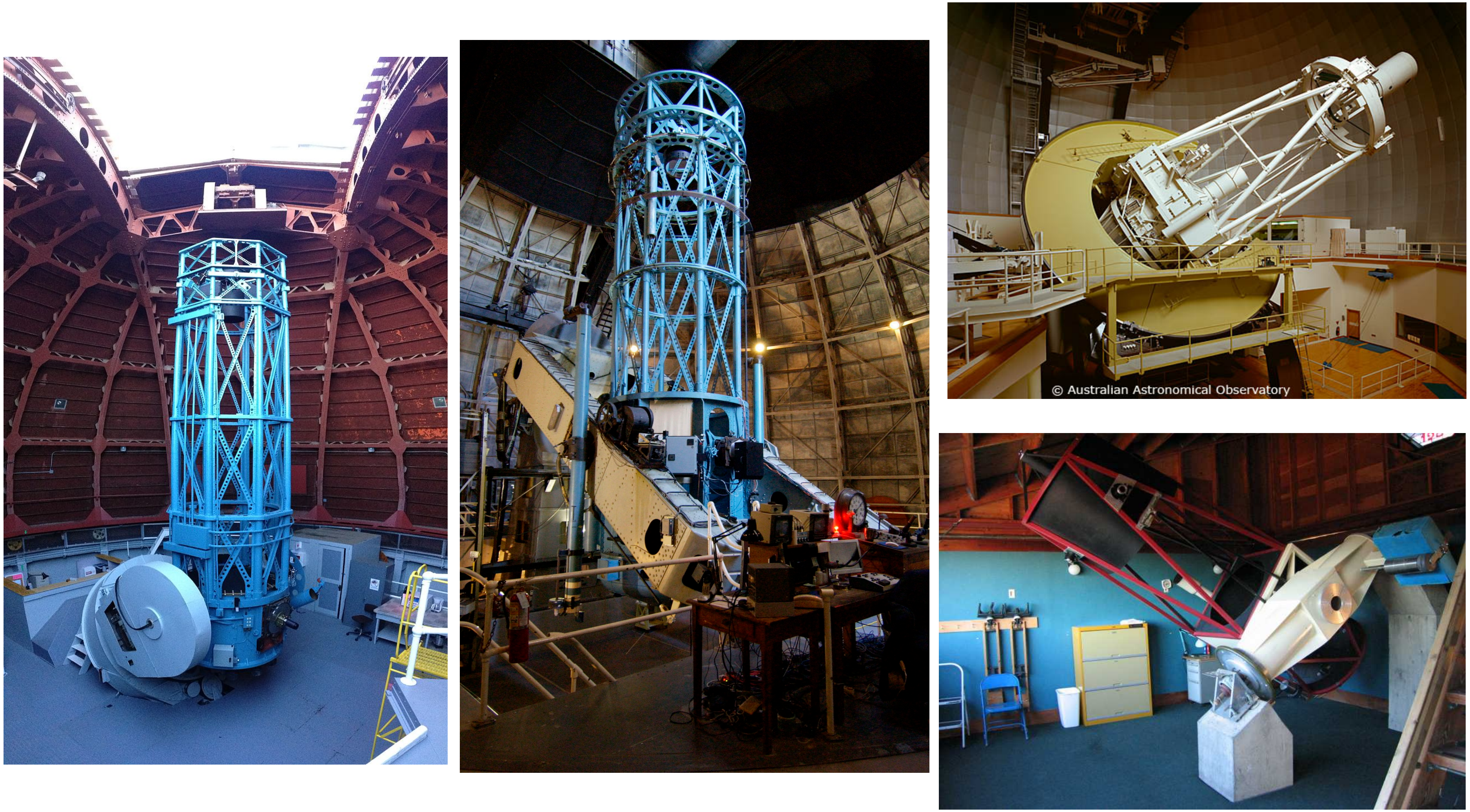


Plate 1 Equatorial mounts. Left: Mt Wilson 152 cm on fork equatorial, started operation in 1908 (Credit: MWO). Centre: Mt Wilson 254 cm Hooker is a Yoke/English equatorial but this prevents pointing near the pole (Credit: MWO). Top, Right: The Anglo-Australian Telescope is a solid horseshoe equatorial design. One end of a yolk mount is fabricated in a 'U' shape to give pointing access to the pole (Credit: AAT). The 76 cm Challenger with cross-axis equatorial firmly supported at both ends of the polar axis (Credit: Medlock

Plate 2 Altazimuth mounts. Clockwise from top, left: The simplicity of a tripod altazimuth (Credit: Tring). A commercial amateur telescope on a fork altazimuth mount (Credit: Teleskop). Sketch of the 4.2m William Herschel Telescope on the Canary Islands – a common large research telescope design (Credit: RGO). The author's personal Newtonian on a Dobsonian altazimuth mount (Hunt). The largest telescope in the world in the 1960s was an altazimuth built in Russia, the 6m BTA (Leverington 2016) (Credit: BTA).

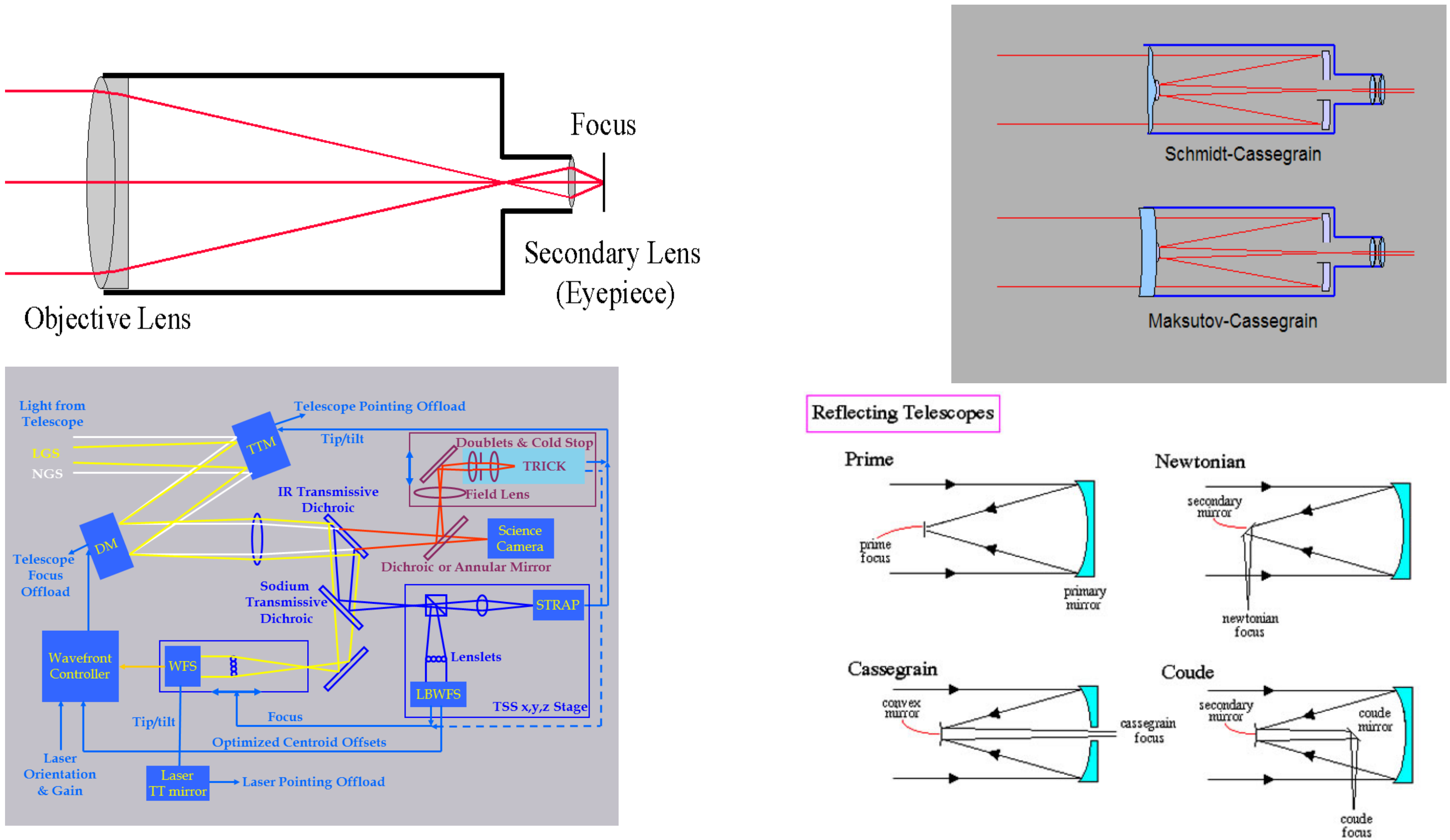


Plate 3 Light Paths. Clockwise from top, left: Basic light path of a dioptric telescope uses only lenses but notice that the lenses can be convex (positive), concave (negative) or compound, and that the focus is a plane at which an instrument (or eye) can be placed (Credit: Ohio). Combining lenses and mirrors results in a catadioptric system that can remove some of the chromatic and spherical aberrations as well as coma discussed later (Credit: Ed). From prime to Newtonian to Cassegrain to coude, reflectors bend the incident light towards various focal planes. Add in some adaptive optics, active optics, imagers and spectrographs, and the overall light paths become more and more complex (Credit: Keck).

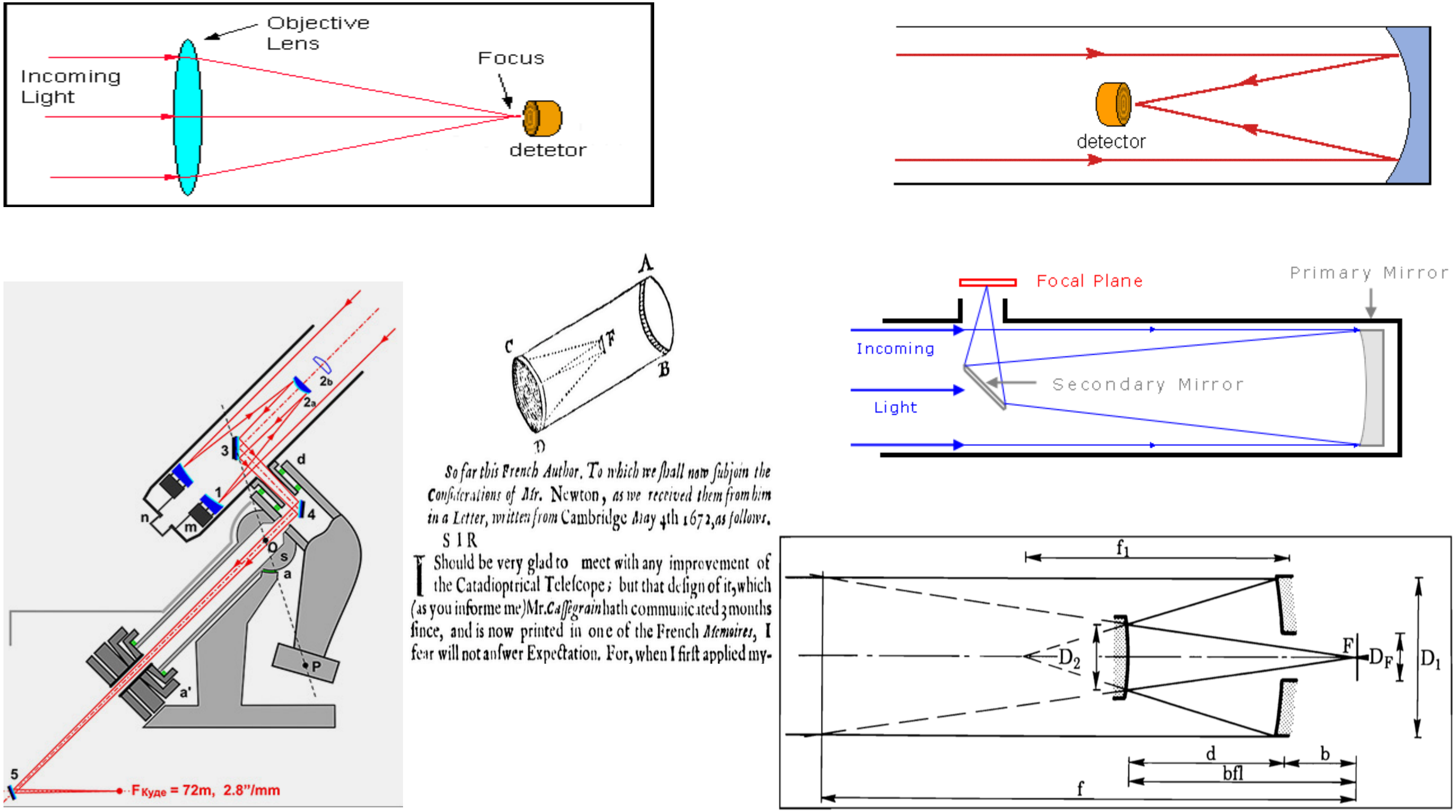


Plate 4 Focal Planes. Clockwise from top, left: Prime focus, showing refracted rays converging on a focal point, and a simple Cassegrain focus (Credit: Dhilon). A Newtonian light path showing the focal plane (Credit: Astropix). Geometric dimensions used to calculate focal length for a standard Cassegrian (Kolkonkyweb) An exerpt from the 'discussion' between Newton and Cassegrain regarding the latter's invention – sketch of the original Cassegrain (Credit: Newton et al). Incident light that is directed to a focal plane well outside the telescope and independent of the telescope motion, is called a coudé focus (Credit: Rozhen).

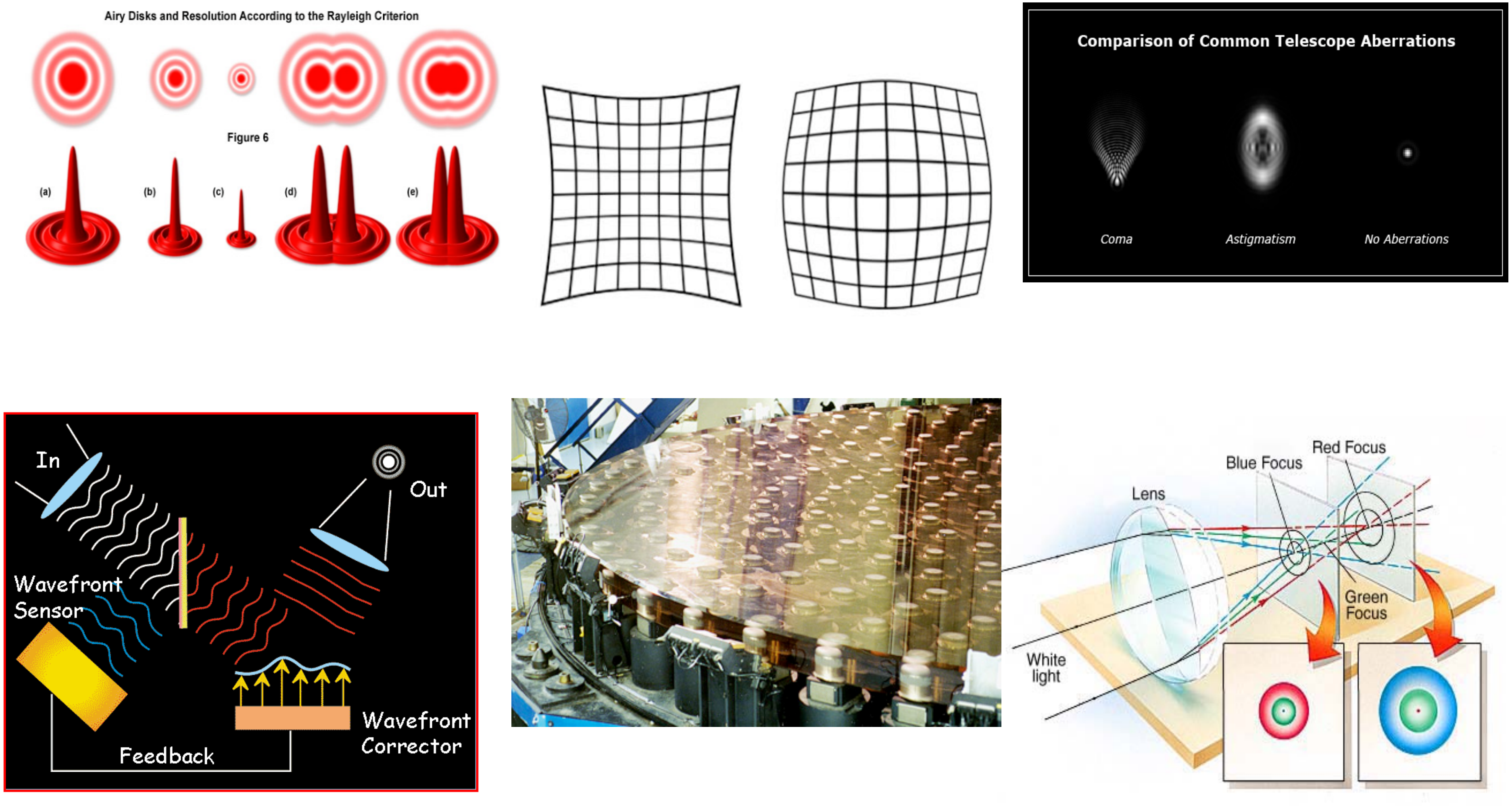


Plate 5. Clockwise from top, left: The Point Spread Function (PSF) of interacting waves creates an Airy disk. The spatial resolution of a telescope depends on how close the two central peaks can be and still discern two images (Credit: Zeissweb). Field cuvatire can be represented as a pincuchion or barrel effect of the focal plane as it arrives with the incident light. Points on these surfaces vary in their separation and produce field distortion (Credit: Starzonaweb). Coma ans astigmatism is seen through a telescope (Starizonaweb). Geometric representation of how light of differing wavelngths (colours) comes to focus at different planes, creating chromatic aberration (Credit: Kohlweb). Active Optics actuators under the Subaru telescope mirror (Credit: Subaruweb). Adaptice Optics employs a deformable mirror that responds to correcting signals from a sensor that measures atmospheric phase shifts in the incident light (Credit: Cambridge U)

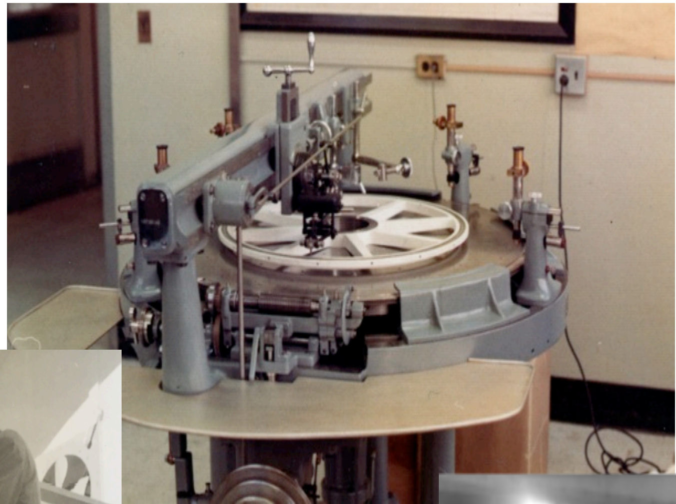


Plate 6 Repsold Meridian Transit Circle. Clockwise from top left: Meridian Transit Cirles were most often graduated on precise instrumentation at the USNO (Credit: USNO). A newly invented digital photometer attached to the Repsold MTC in Germany (Credit: Deutches Museum). The Repsold MTC in operation in Germany. The seated operator would call out when the target crossed to reticule and the other operator would record the micrometer reading at the same time. (Credit: Deutches Museum). The Repsold MTC being prepared for observations at the Perth Observatory (Credit: Perth Observatory)

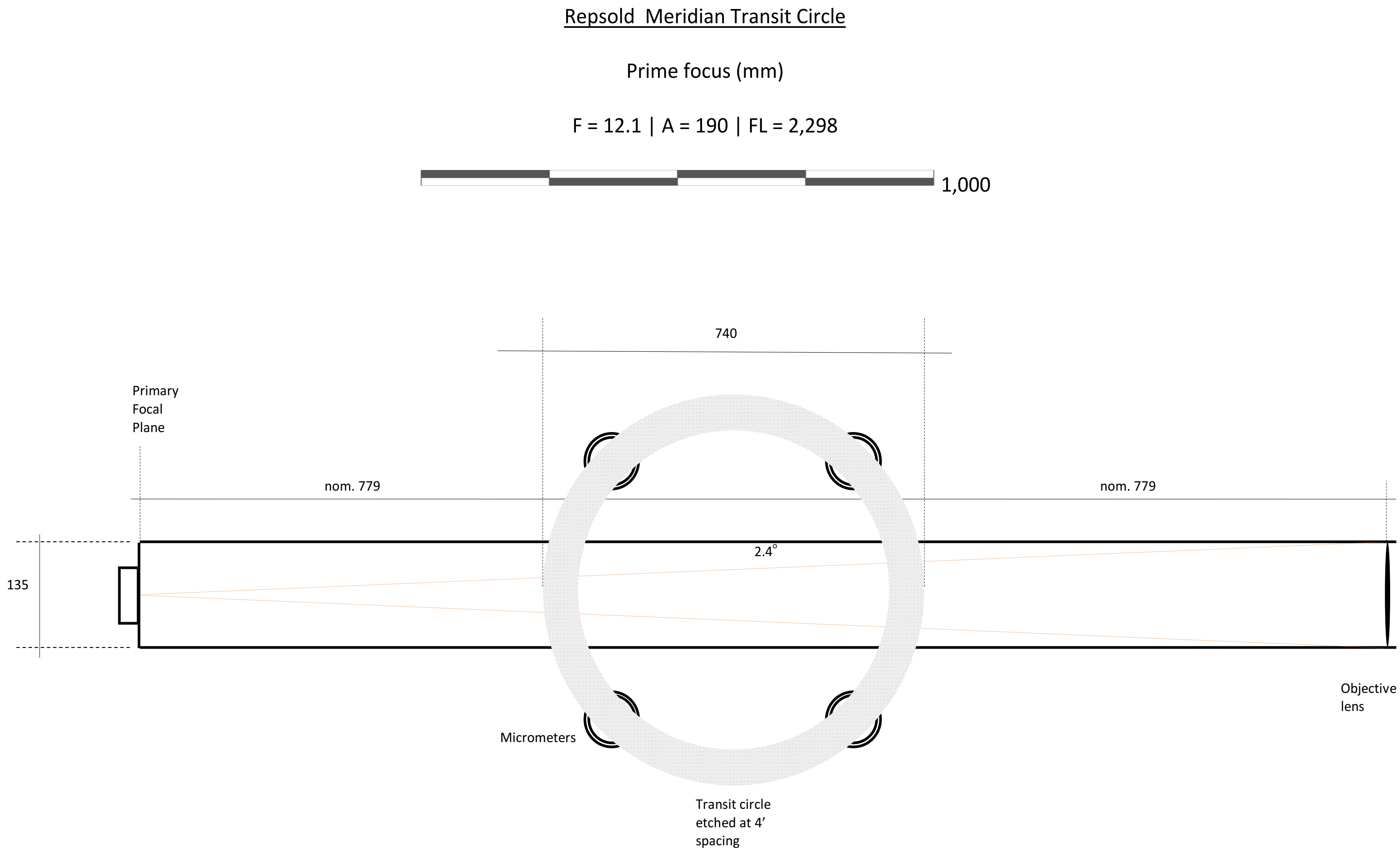
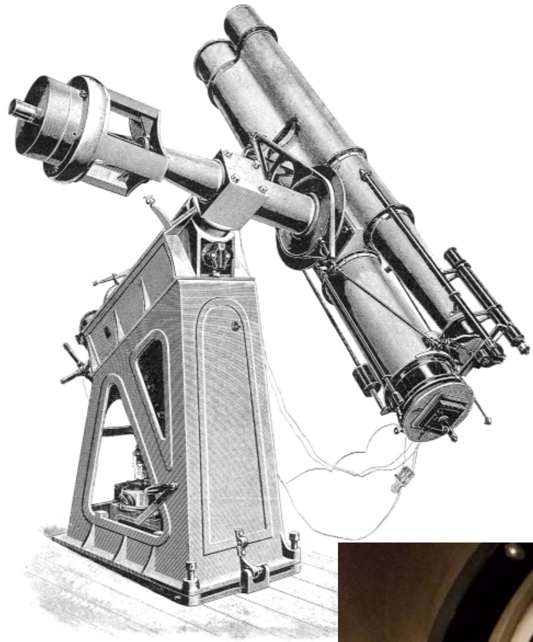
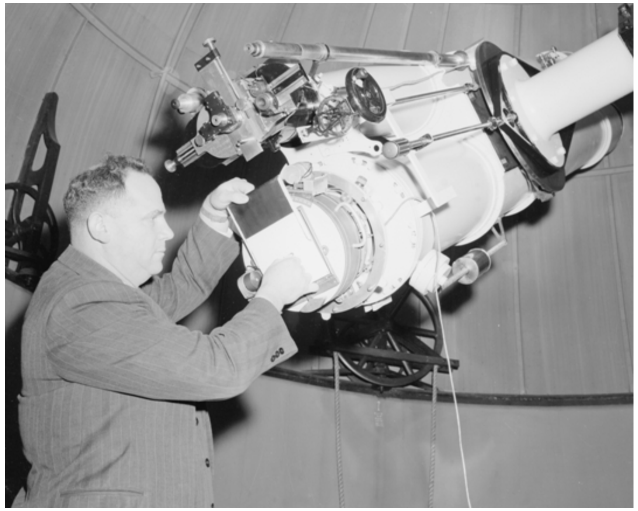


Plate 7 Schematic light path of the Rerpsold Meridian Transit Circle. All measurements are approximate (Credit: Hunt)





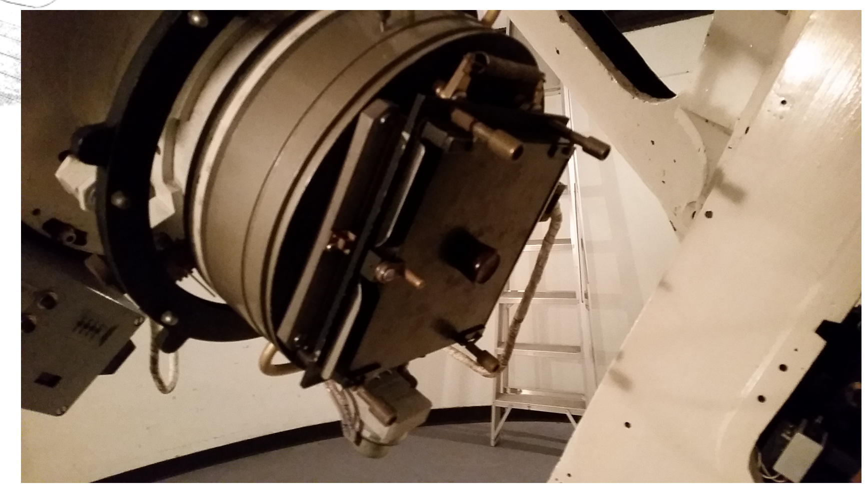


Plate 8 Grubb Astrograph. From left: The astrograph today – used for public outreach and attracting well known science outreach personalities (Credit: Perth Observatory). The original design of the Grubb astrograph (Credit: unknown). WA Government Astronomer Hyman Spigl operating the Markowitz Moon camera on the astrographc. 1955 (Credit: Perth Observatory). The glass photographic plate holder at the prime focus of the astrograph (Credit: Hunt).

Astrographic Imager & Guide Telescope

Prime focus (mm)

$F_i = 10.4$ | $F_g = 13.5$ | $A_i = 330$ | $A_g = 254$ | FL = 3,440

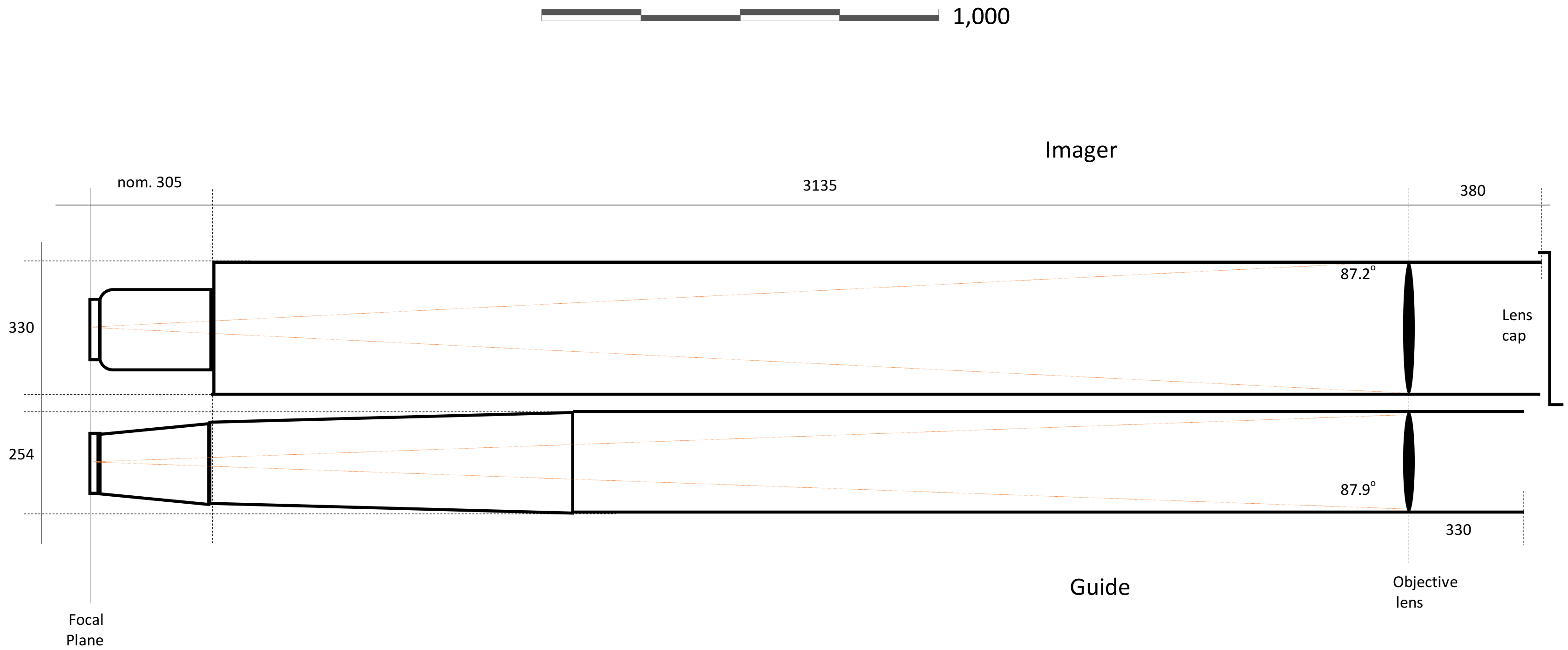


Plate 9 Schematic light path of the Grubb Astrographic telescope. All measurements are approximate (Credit: Hunt)

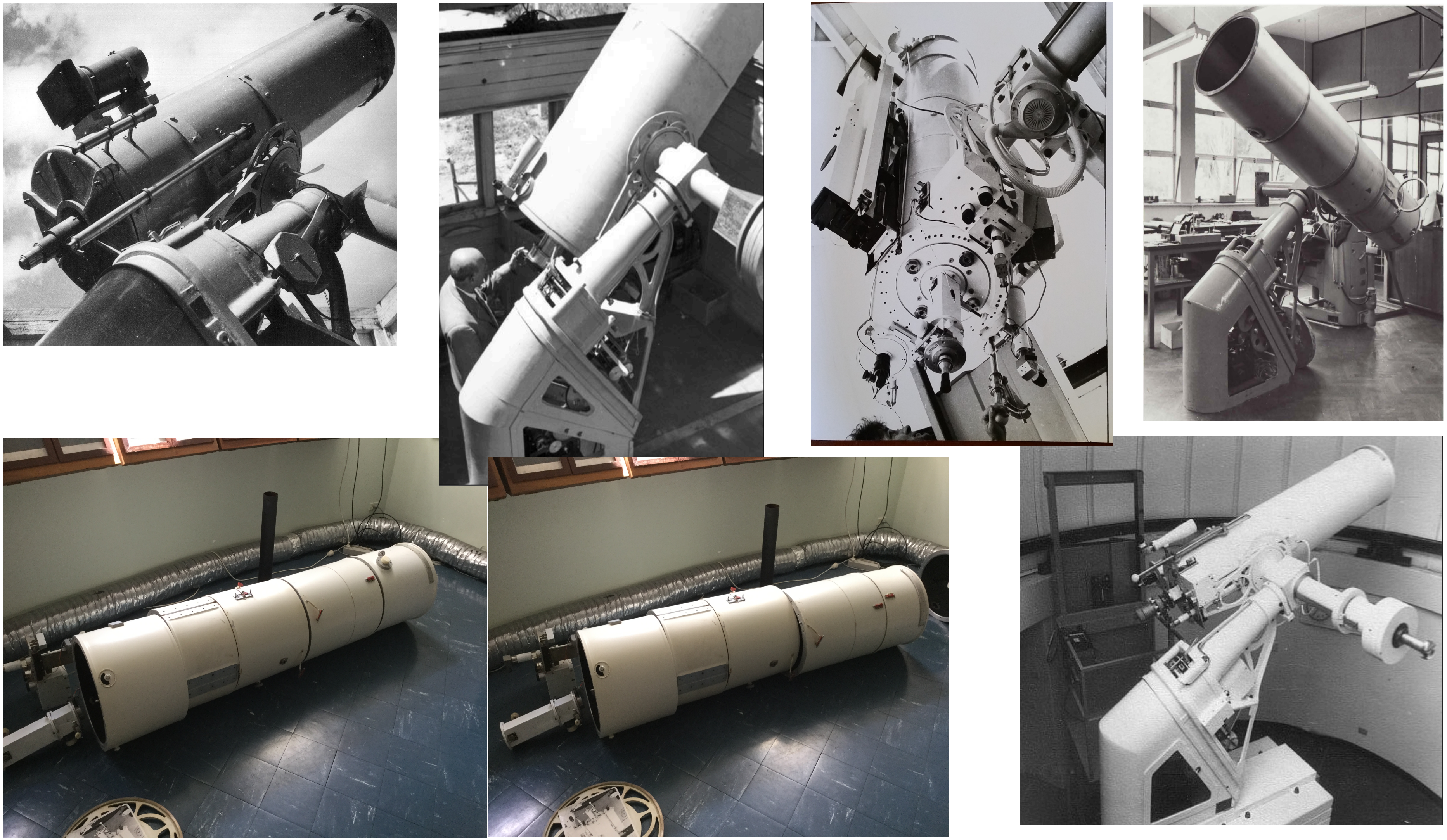


Plate 10 Catts/University telescope. Clockwise from top left: The original configuration with 51 cm OTA (Credit: Orchiston). The Catts at MSO (Credit: MSO). In Cassegrain mode with a rectangular spectroscope at the Perth Observatory (Credit: Perth Observatory. The renovations in UWA Physics workshop (Credit: UWA). The re-renovated Universitytelescope as a 406 mm (Credit: Perth Observatory). The 2017 pices: Cassegrain layout and Newtonian layout (Credit: Perth Observatory.

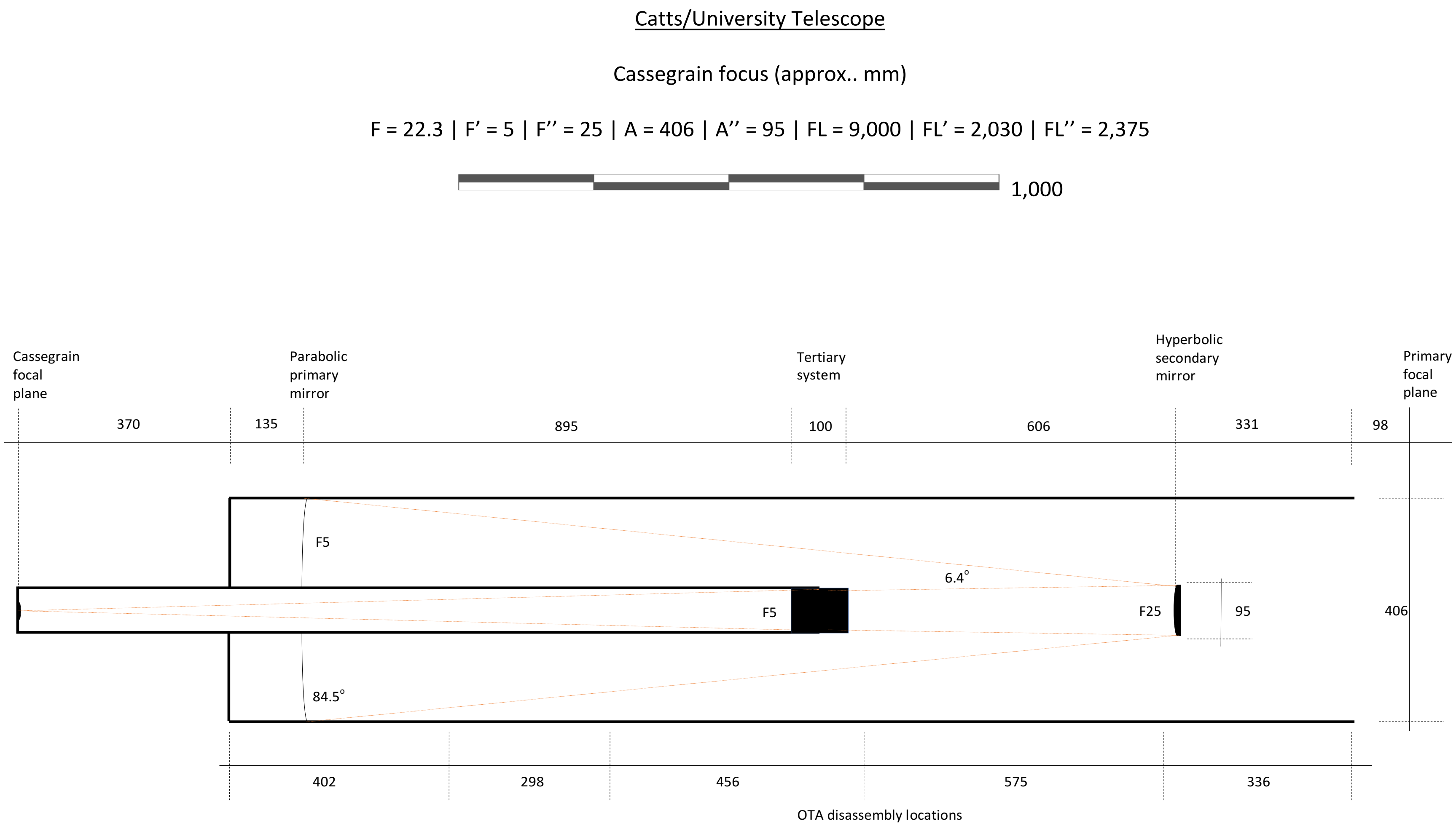


Plate 11 Schematic light path of the Catts/University Cassegrain telescope. All measurements are approximate (Credit: Hunt)

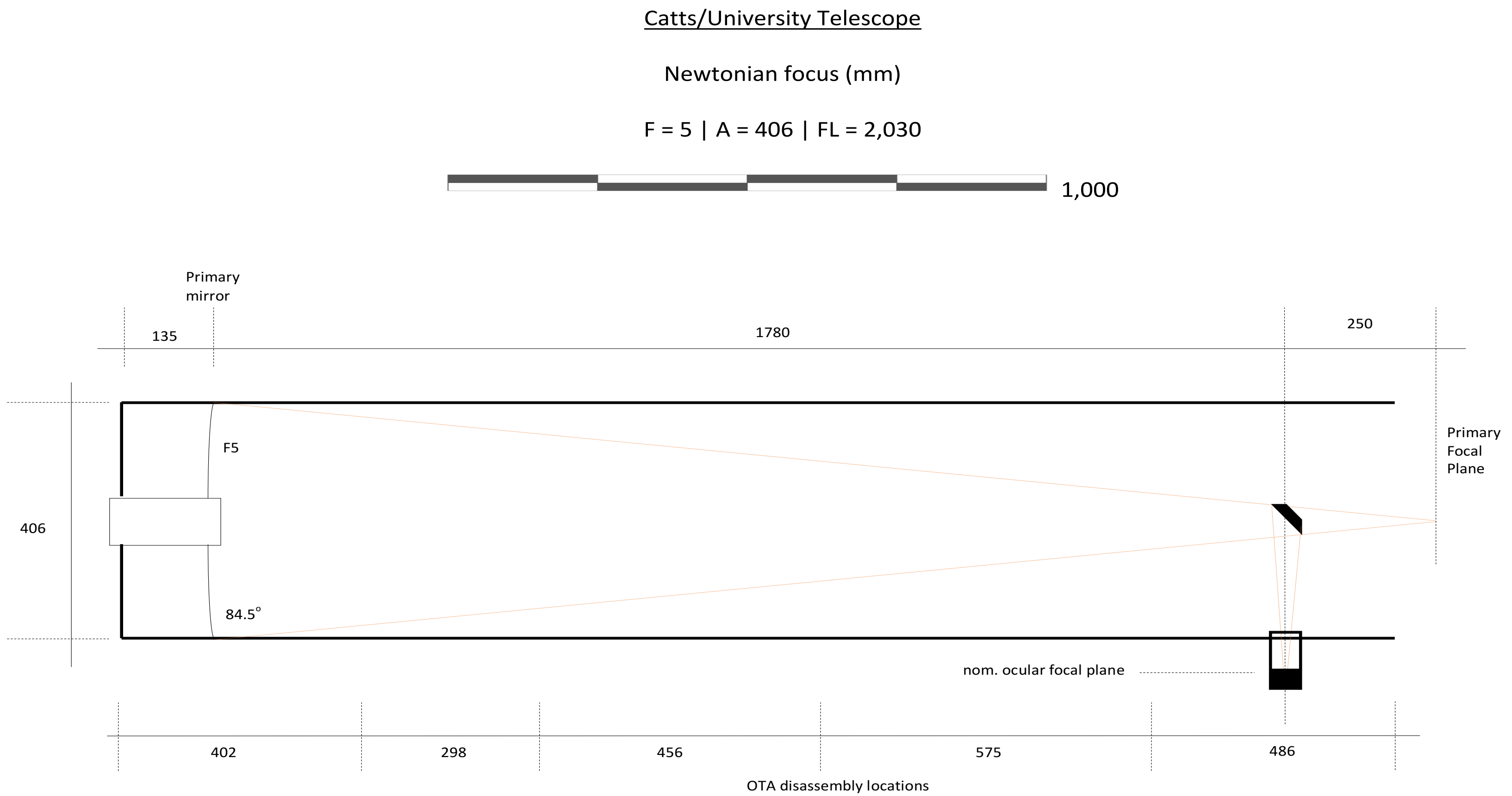
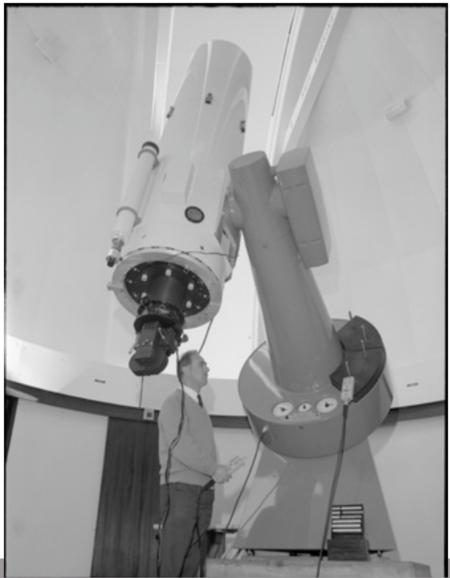
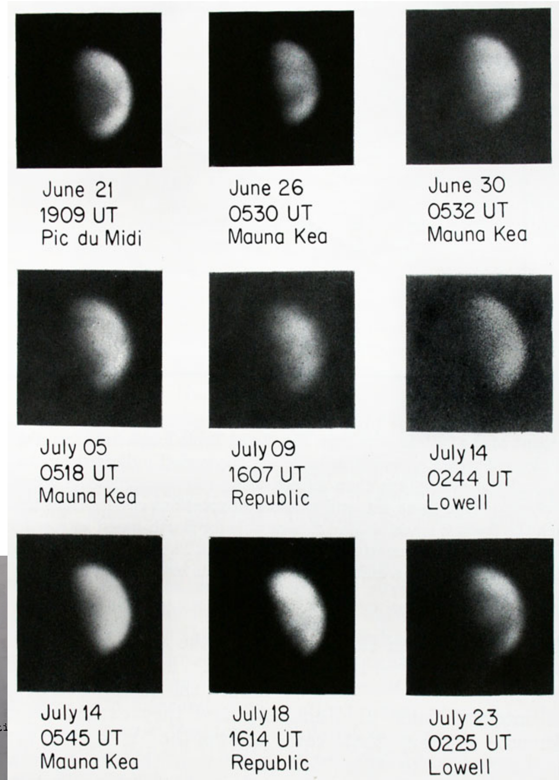


Plate 12 Schematic light path of the Catts/University Newtonian telescope. All measurements are approximate (Credit: Hunt)





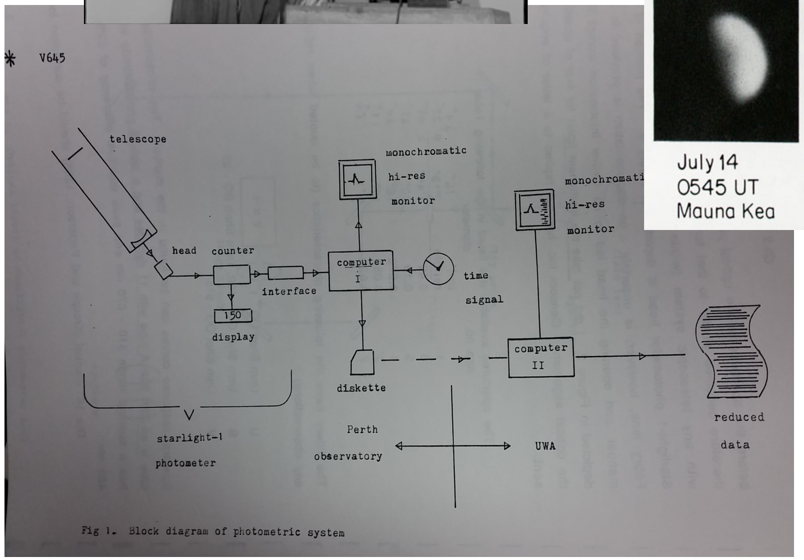


Plate 13 Boller & Chivens Perth Lowell telescope. Clockwise from top left: The Perth-Lowell in operation in 1970s showing the 35 mm Planetary Camera attached to the Cassegrain focus (Credit: Perth Observatory). Results of observations of the Martian atmosphere/surface (Credit: Perth Observatory). The Perth-Lowell telescope today. Notice the F/13.5 top module, the CCD at Cassegrain focus and the air-cooling system hoses (Credit: Hunt). Sketch of the photometry layout c. 1990 (Credit: A. Williams).

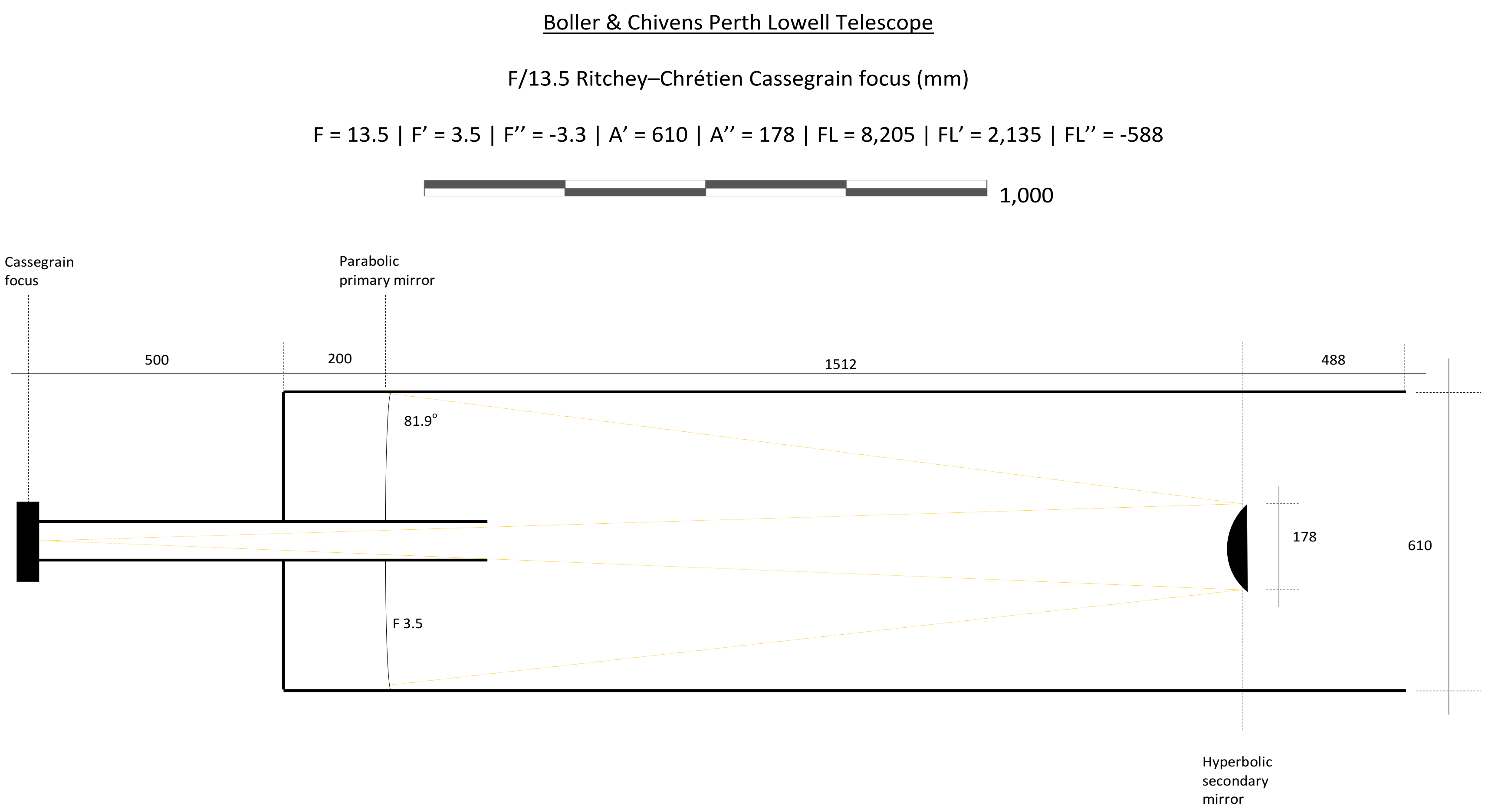


Plate 14 Schematic light path of the Boller & Chivens Perth Lowell F/13.5 telescope. All measurements are approximate (Credit: Hunt)

Figure 1

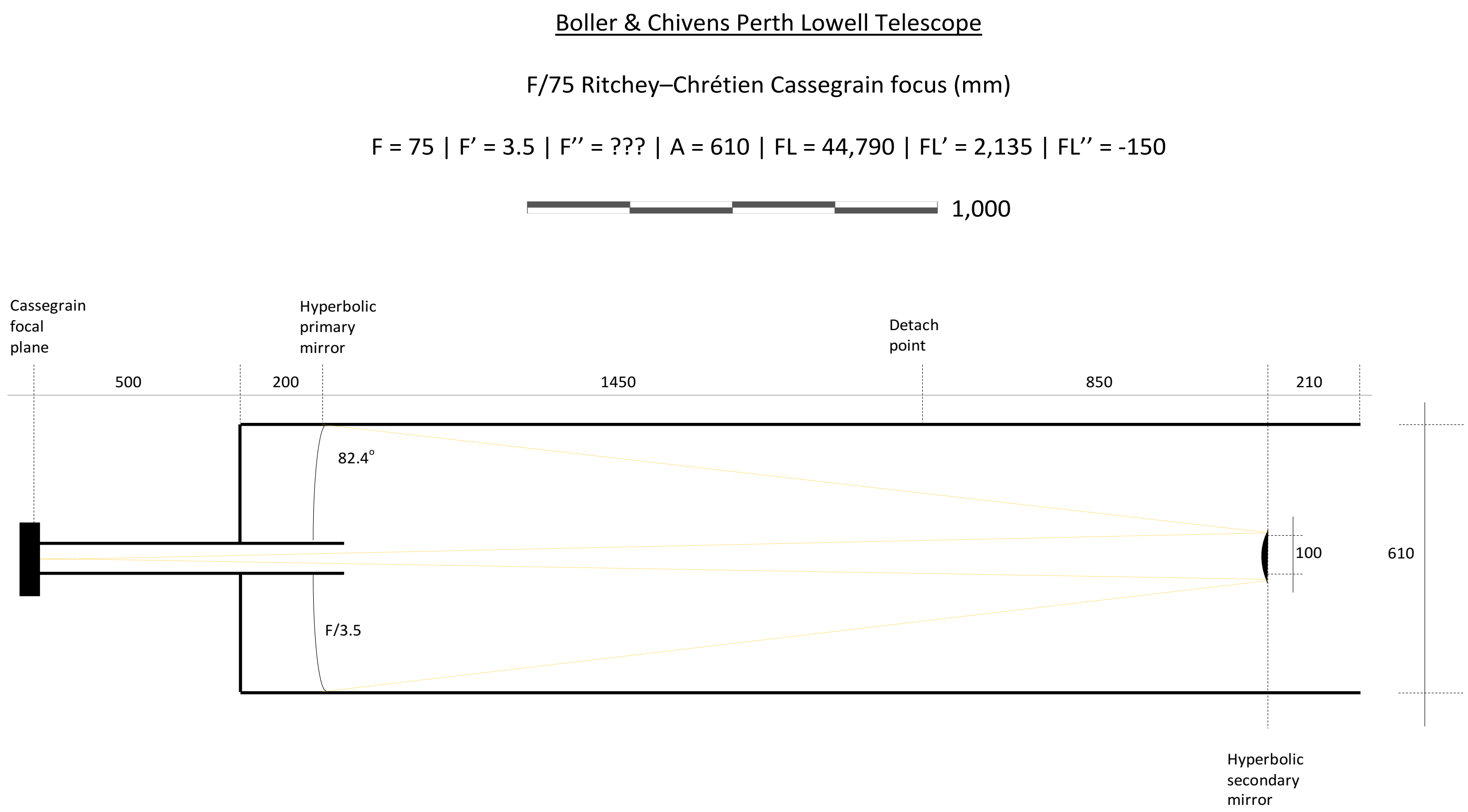


Plate 15 Schematic light path of the Boller & Chivens Perth Lowell F/75 telescope. All measurements are approximate (Credit: Hunt)

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