Telescopes

We want to: 1.) build the largest telescope we can afford (or can get someone else to buy for us), 2.) design it to be efficient and 3.) at the same time shield the signal from unwanted contamination, 4.) provide diffraction-limited images over as large an area in the image plane as we can cover with detectors, and 5.) adjust the final beam to match the signal optimally onto those detectors.

For now, we will concentrate on 4.), getting the best images. We want them to look like to one to the right, the Airy function. The derivation of this result is illustrated in 2.3.2 of the “book” notes.

To get there, we need to control a bunch of aberrations that degrade the wavefronts.
The six (plus one) deadly aberrations
The first five are the Seidel Aberrations

*spherical*, occurs when an off-axis input ray is directed in front of or behind the image position for an on-axis input ray, with rays at the same off-axis angle crossing the image plane symmetrically distributed around the on-axis image. Spherical aberration tends to yield a blurred halo around an image.

*coma* occurs when input rays arriving at an angle from the optical axis miss toward the same side of the on-axis image no matter where they enter the telescope aperture, and with a progressive increase in image diameter with increasing distance from the center of the field.
Astigmatism is a cylindrical wavefront distortion resulting from an optical system that has different focal planes for an off-axis object in one direction from the optical axis of the system compared with the orthogonal direction. It results in images that are elliptical on either side of best-focus, with the direction of the long axis of the ellipse changing by 90 degrees going from ahead to behind focus.

Spherical aberration, coma, and astigmatism are among the low-order Zernicke polynomials – functions that let you fit all the problems in your optical system if you wish. These three are the most relevant to telescope design.

curvature of field, which occurs when the best images are not formed at a plane but instead on a surface that is convex or concave toward the telescope entrance aperture
Low order Zernickes, from Wikipedia.


**distortion** arises when the image scale changes over the focal plane; that is, if a set of point sources placed on a uniform grid is observed, their relative image positions are displaced from the corresponding grid positions at the focal plane.

Field curvature and distortion do not actually degrade the images and can often be corrected virtually completely.

**chromatic aberration**, resulting when light of different colors is not brought to the same focus. Applies to refractive optics only.

**manufacturing errors** and **misalignments** are also sometimes called aberrations but are really a completely different kind of problem. Still, they must be carefully controlled – they are the real limit to achieving diffraction limited performance in most cases.
Seeing

The images can be further degraded by atmospheric seeing, resulting from atmospheric turbulence. A rough approximation of the behavior is that there are atmospheric bubbles with different refractive indices of size $r_0 = 5 – 15$ cm moving at wind velocities of 10 to 50 m/sec ($r_0$ is defined by the typical size effective at a wavelength of 0.5$\mu$m and called the Fried parameter). The time scale for variations over a typical size of $r_0$ at the telescope is therefore of order 10msec. For a telescope with aperture smaller than $r_0$, the effect is to cause the images formed by the telescope to move as the wavefronts are tilted to various angles by the passage of warmer and cooler air bubbles. If the telescope aperture is much larger than $r_0$, many different $r_0$-sized columns are sampled at once. Images taken over significantly longer than 10msec are called seeing-limited, and have typical sizes of $\lambda/r_0$, since the wavefront is preserved accurately only over a patch of diameter $\sim r_0$. These images may be 0.5 to 1 arcsec in diameter, or larger under poor conditions. However, since the phase of the light varies quickly over each $r_0$-diameter patch, a complex and variable interference pattern is formed at the focal plane due to the interference among these different patches. A fast exposure (e.g., $\sim$ 10msec) freezes this pattern and the image appears speckled, within the overall envelope of the seeing limit. This behavior is strongly wavelength-dependent. Because the refractive index of air decreases with increasing wavelength, $r_0$ increases roughly as $\lambda^{6/5}$, so, for example, the effect of seeing at 10$\mu$m is largely image motion even with a 10-m telescope.
Image Descriptions

- rms or peak-to-peak wavefront error
- Strehl – the ratio of the peak brightness in the image to the peak brightness of the image that would be delivered by a telescope of the same parameters but with perfect optics (this definition allows for telescopes with non-round primary mirrors, for example)
- encircled energy – the fraction of the total energy in an image contained within a circular aperture of a given angular diameter
- The Maréchal criterion says that a telescope can be considered diffraction limited if the rms wavefront errors are less than $\lambda/14$. This gives a Strehl $> 0.8$.
- An expansion is $S \approx e^{-(2\pi \sigma/\lambda)^2}$, which gives the Strehl as a function of the rms wavefront error, $\sigma$
Reflecting Telescope Types

A *prime focus* telescope has a paraboloidal primary mirror and forms images directly at the mirror focus. The paraboloid does not meet the Abbe Sine Condition.

A *Newtonian* telescope uses a flat mirror tilted at 45° to bring the focus to the side of the incoming beam of light.

A *Gregorian* telescope brings the light from its paraboloidal primary mirror to a focus, and then uses an ellipsoidal mirror beyond this focus to bring it to a second focus.

A *Cassegrain* telescope intercepts the light from its paraboloidal primary ahead of the focus with a convex hyperboloidal mirror. This mirror re-focuses the light from the virtual image formed by the primary to a second focus.

The image quality of these types is limited by the coma of their paraboloidal primary mirrors.

The *Ritchey-Cretién* telescope uses two hyperboloidal mirrors (so no images at the focus of the primary to compensate spherical and comatic aberrations and provide a larger field (until it is limited by astigmatism). It is designed to meet the Abbe Sine Condition.
A Prime Focus Telescope
Basic telescope types

These are all based on Fermat’s Principle.

The Ritchey-Cretien looks like the Cassegrain, but abandons the conic sections and instead is optimized around the Abbe Sine Condition:

\[
\frac{h}{\sin \alpha} = F
\]
Key terms and concepts to describe a telescope

- Focal length
- F/number – focal length divided by diameter (or equivalent measure of ray bundle)
- Plate scale – arcsec/mm or mm/arcsec at the focal plane
- Field of View (FOV)
- Stop – a baffle that limits the bundle of light that can pass through
- Aperture stop – aperture stop (e.g., edge of primary), field stop (e.g., edge of field of view at focal plane
- Pupil – entrance pupil, exit pupil
  The exit pupil in a telescope is an image of the aperture stop. Sometimes the aperture stop is called the entrance pupil.
- Why are pupils important?
Concept quiz: Where is the pupil?

If we put a lens behind the telescope focus, where does it form a pupil?
Resolution

Often characterized in line pairs per millimeter, or line pairs across the sensor (for cameras). Here is a standard test pattern for cameras, and below it the image one might get with a not-so-good lens. The resolution limit is where we can no longer distinguish the lines.

This approach falls short when we want to combine the effects of multiple optical elements. We use the modulation transfer function for this more complex situation.
Modulation Transfer Function (MTF)

As you increase the spatial frequency of an image (imaging a bar chart), the modulation in the output decreases. This is a more sophisticated measure than the “line pairs per millimeter” often quoted for the performance of a camera lens, for example.
The MTF is the amplitude as a function of spatial frequency. The OTF includes the phase behavior and is a more complete description, but for many purposes the MTF is adequate.

The MTF can be computed as the absolute value of the Fourier Transform of an image of a point source.

If we want to know the image resulting from a series of optical elements, we would have to convolve the individual ones – however, by the convolution theorem we can just multiply the MTFs to get the MTF of the resulting image!
Some specialized telescopes

Wide field: one classic approach is to avoid the coma associated with any paraboloidal primary and use a spherical one. The spherical aberration is then compensated by putting inverse spherical aberration into the beam with a thin corrector plate.

Larger telescopes (and ones working at wavelengths where a corrector might not transmit) can be made by using three mirrors. The secondary mirror corrects the acts like the corrector plate and the third, spherical, mirror finally brings the light to a focus. This design, originated by Baker and Paul, is the basis of LSST.

Reasonably large fields are also provided by sub-aperture refractive correctors patterned on a design by Wynne.
Infrared optimization

- In the thermal infrared, most of the foreground (as high as 95%) comes from emission by the telescope.
  - Minimize telescope emissivity by using special mirror coatings (silver, gold) and keeping them very clean
- We want to reduce the view the detector has of the telescope as much as possible without losing too much signal.
  - Form a pupil in a cryostat (needed anyway) and put a cold stop around it
  - Make the secondary mirror undersized and remove all baffles (the secondary is in the near field and thus one gets Fresnel rather than Fraunhofer diffraction, which provides much better baffling). The sky is far "colder" than the telescope.
- We want to detect signals as small as a millionth of this foreground. However, the part of the foreground associated with air moves and results in “sky noise” which can overwhelm our astronomical signals.
  - Chop rapidly (few Hz) between two spots on the sky
  - Doing this with the secondary mirror results in the two air paths being identical until high in the atmosphere
  - Move the telescope every minute or so to dither on the array, reverse the roles of the two chopper beams
  - This double differencing lets us work to the photon noise limit
- If we can, go to space and cool the telescope (can reduce foreground by more than a factor of a million)
Radio Telescopes

- Typically of conventional parabolic-primary-mirror, prime-focus design.
- The primary mirrors have short focal lengths, f-ratios ~ 0.5, to keep the telescope compact and help provide a rigid structure.
- Sometimes telescope is designed so flexure as it is pointed in different directions preserves the figure of the primary – these designs deform homologously.
  - For example, the 100-m aperture Effelsberg Telescope flexes by up to 6cm as it is pointed to different elevations, but maintains its paraboloid to an accuracy of ~ 4mm.
- Telescopes for the mm- and sub-mm wave regimes are smaller and are built in a Cassegrain configuration, often with secondary mirrors that can be chopped or nutated over small angles to help compensate for background emission.
- Radio receivers are of coherent detector design; all such receivers are limited by the antenna theorem, which states that they are sensitive only to the central peak of the diffraction pattern of the telescope.
  - This behavior modifies how the imaging properties of the telescope are described. The diffraction rings of the Airy pattern appear to radio astronomers as potential regions of unwanted sensitivity to sources away from the one at which the telescope is pointed, called sidelobes. Additional sidelobes are produced by imperfections in the mirror surface.
  - The primary measure of the quality of the telescope optics is beam efficiency, the ratio of the power from a point source in the central peak of the image to the power in the entire image.
The Greenbank Telescope eliminates some sidelobes with an off-axis primary that brings the focus to the side of the incoming beam.

The Jodrell Bank telescope was the first really large radio telescope.
X-ray Telescopes

- Reflection off a thin metal film ceases to be efficient in the hard UV and X-ray because of the large imaginary part of their refractive index (that is, they absorb strongly).
- Certain materials have indices of refraction in the 0.1 – 10 keV range that are slightly less than 1 (by ~ 0.01 at low energies and only ~ 0.0001 at high).
- At grazing angles these materials reflect X-rays by total external reflection; however, at the high energy end, the angle of incidence can be only of order 1°.
- The images formed by grazing incidence off a paraboloid have severe astigmatism off-axis, so two reflections are needed, one off a paraboloid and the other off a hyperboloid or ellipsoid.
- A paraboloid followed by a hyperboloid comprise a Wolter Type-1 geometry.
• The on-axis imaging quality of such telescopes is strongly dependent on the quality of the reflecting surfaces.
• The constraints in optical design already imposed by the grazing incidence reflection make it impossible even to give lip service to the Abbe Sine Condition, so the imaging quality degrades significantly for fields larger than a few arcminutes in radius.
• As an example, we consider Chandra. Its Wolter Type-1 telescope has a diameter of 1.2m, within which there are four nested optical trains, which together provide a total collecting area of 1100 cm² (i.e., ~10% of the total entrance aperture). The focal length is 10m, the angles of incidence onto the mirror surfaces range from 27 to 51 arcmin.
• The telescope efficiency is reasonably good from 0.1 to 7 keV. The on-axis images are 0.5” in diameter but degrade by more than an order of magnitude at an off-axis radius of 10’.
An example: Chandra images over the field of view of the telescope
The Chandra design can be compared with that of XMM-Newton, which emphasizes collecting area. It has three modules of 58 nested optical trains, each of diameter 70cm and with a collecting area of 2000cm$^2$ (~50% of the total entrance aperture). The total collecting area is 6000cm$^2$. The range of grazing angles, 18 – 40 arcmin, is smaller than for Chandra resulting in greater high energy (~10 keV) efficiency. The on-axis images are an order of magnitude larger in diameter.
Above about 10 kev, oblique reflection is very inefficient because the angles over which it can occur become very small (tens of arcmin). Similar telescope designs can use Bragg reflection in crystals. If layers are used with different crystal spacing, a range of X-ray energies are reflected.

This is the principle behind NuSTAR, about to become operational:

http://www.nustar.caltech.edu/
Modern Optical/Infrared Telescopes

- For many years, the Palomar 5-m telescope was considered the ultimate large ground-based telescope;
  - Flexure in the primary mirror was thought to be a serious obstacle to construction of larger ones.
  - The benefits from larger telescopes were also argued to be modest. If the image size remains the same (e.g., is set by a constant level of seeing), then the gain in sensitivity with a background limited detector goes only as the diameter of the telescope primary mirror.
- This situation changed with dual advances. The size limit implied by the 5-m primary mirror can be violated by application of a variety of techniques to hold the mirror figure in the face of flexure.
  - The images from the telescope can be analyzed to determine exactly what adjustments are needed to its primary.
  - In addition, it was realized that much of the degradation of images due to seeing was occurring within the telescope dome. By reducing the mass of the primary, the entire telescope could be made less massive, resulting in a faster approach to thermal equilibrium.
- Three basic approaches have been developed for large ground-based telescopes.
  - The Keck Telescopes, Gran Telescopio Canarias (GTC), Hobby–Everly Telescope (HET), and South African Large Telescope (SALT) use segmented primary mirrors. For Keck, the relative positions of the segments are sensed by capacitive sensors. A specialized alignment camera is used to set the segments in tip and tilt and then the mirror is locked under control of the edge sensors. The alignment camera also allows for adjustment in the z coordinate by interfering the light in a small aperture that straddles the edges of the segments.
  - The VLT, Subaru, and Gemini telescopes use a thin monolithic plate for the optical element of the primary mirror. A VLT telescope has a 8.2-meter primary mirror that is only 0.175 meters thick. It is supported against flexure by 150 actuators that are controlled by image analysis at an interval of a couple of times per minute.
  - The MMT, Magellan, and LBT Telescopes are based on a monolithic primary mirror design that is deeply relieved in the back to reduce the mass and thermal inertia. Use of a polishing lap with a computer-controlled shape allows manufacture of very fast mirrors, which allows an enclosure of minimum size. The mirrors are stiff enough to hold their figure for reasonably long times.
To make the adjustments that maintain their image quality, all of these telescopes depend on frequent and accurate measurement of the telescope aberrations from flexure and thermal drift.

- A common way to make these measurements is the Shack-Hartmann Sensor. We consider the light in terms of wavefronts – say the crests of the waves. A “perfect” optical system maintains wavefronts that are plane or spherical. In the Shack-Hartmann Sensor, the wavefront is divided by an array of small lenslets. The situation for a perfect plane wavefront is shown in dashed lines going into the lenslet array. Each lenslet images its piece of the wavefront onto the CCD. For the plane input wavefront, these images will form a grid that is uniformly spaced.

- Aberrations impose deviations on the wavefronts. An example is shown as a solid line. Each lenslet will see a locally tilted portion of the incoming wavefront. As a result, the images from the individual lenslets will be displaced when they reach the CCD. A simple measurement of the positions of these images can then be used to calculate the shape of the incoming wavefront, and hence to determine the aberrations in the optics from which it was delivered.
The methods developed for control of the figure of large primary mirrors on the ground have been adopted for the James Webb Space Telescope, in this case so the 6.5-m primary mirror can be folded to fit within the shroud of the launch rocket. After launch, the primary is unfolded and then a series of ever more demanding tests and adjustments will bring it into proper figure. The demands for very light weight have led to a primary mirror of 18 segments of beryllium, and very fast optically (but the telescope has a final f/ratio of about 20). Periodic measurements with the near infrared camera will be used to monitor the primary mirror figure and adjust it as necessary for optimum performance. The overall design is a three-mirror anastigmat (meaning it is corrected fully for spherical aberration, coma, and astigmatism), with a fourth mirror for fine steering of the images.
There are a number of proposals for 30-meter class ground-based telescopes. Given the slow gain in sensitivity with increasing aperture for constant image diameter, all of these proposals are based on the potential for further improvements in image quality to accompany the increase in size. These gains will be achieved with multi-conjugate adaptive optics (MCAO) – correcting the effects of atmospheric turbulence along multiple paths. MCAO is based on multiple wavefront-correcting mirrors, each mirror placed in the optics to work at a particular elevation in the atmosphere (or more accurately, at a given range from the telescope). Laser beacons are directed into the atmosphere and the returned signals (due, e.g., to scattering) along with those from natural guide stars are analyzed to determine the corrections to apply to these mirrors. Such a system achieves a three-dimensional correction of the atmospheric seeing and can 1.) extend the corrections to shorter wavelengths, i.e., the optical; 2.) increase the size of the compensated field of view; and 3.) improve the uniformity of the images over this field.

One proposal, the Thirty Meter Telescope (TMT), is from a partnership of Canada, CalTech, and the University of California. This telescope would build on the Keck Telescope approach. Its primary mirror would have 492 segments (up from 36 for Keck). The European Southern Observatory is proposing to build a 42-meter segmented telescope, once the Overwhelming Large Telescope (OWL) when it was 100 meters, not just the E-ELT that it has shrunk to 42 meters. The Giant Magellan Telescope (GMT) is being promoted by an international consortium, including the University of Arizona. Its design superficially resembles the original MMT more than the segmented telescopes. It will be based on a close-packed arrangement of seven 8.4-m mirrors, figured to provide one continuous primary mirror surface (unlike the MMT, which was like six individual telescopes). Its collecting area would be equivalent to 21-m single round primary.
All of these projects face a number of technical hurdles to work well enough to justify their cost (projected to exceed $1 Billion). We have already mentioned that their sensitivity gains are dependent on the success of Multi-Conjugate Adaptive Optics. Their large downward looking secondary mirrors are a challenge to mount, because they have to be “hung” against the pull of gravity, a much more difficult arrangement than is needed for the upward looking primary mirrors. For the segmented designs, the electronic control loop to maintain alignment will be very complex. All of them will be severely challenged by wind, which can exert huge forces on their immense primary mirrors and structures. Nonetheless, we can hope that the financial and technical problems will be surmounted and that they will become a reality.