CHAPTER 1  Optical Telescope

I. Reflective and Refractive Telescopes
II. Telescope Optics
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Telescopes serve three main functions: (1) they are light collectors. The simplest telescopes simply focus light rays to a small area.; (2) Resolve light so that finer details can be seen; (3) Magnification: making objects look bigger (closer)

Two main types: refractive and reflective

As we are observing objects at very large distances, light can be assumed to come from infinity and can be represented as parallel rays
Basic Refractor

$$f_o = \text{focal length of objective}$$

real image formed here

Basic Reflector

$$f_o = \text{focal length of primary}$$
For research telescopes or for astrophotography, we will place the analyzer (e.g. photometer, spectrometer) at the location of the focal plane.

For visual observations, we need an eyepiece to properly collect the light through the objective lens or the primary mirror into the eye.

Note: Focal point of objective and eyepiece coincide.
✓ **Lens Formula:** \( \frac{1}{o} + \frac{1}{i} = \frac{1}{f} \)

where \( o \) = object distance from lens, \( i \) = images distance from lens, \( f \) = focal length of lens

✓ **Linear magnification** \( m \): \( m = -\frac{i}{o} \)

where \( m > 0 \) if the image is erect, \( |m| > 1 \) if enlarged

Reference: *Optics* by Hecht and Zajac (Addison-Wesley)
One of the most important number that characterize a telescope is its focal ratio (or, f/ number)

\[
\text{focal ratio} = \frac{\text{Focal length of primary}}{\text{Aperture diameter of primary}}
\]

E.g. Telescope’s aperture diameter = 5 cm
Focal length of primary = 25 cm
Focal ratio = 25 cm/5 cm = 5 (a f/5 telescope)
FAST telescope (or, fast scope, $\sim 6$)

1. Small focal ratio (or, small f/ number)
2. So, short telescope for fixed aperture
3. Wide field of view (with same eyepiece)
4. Excel at low power (low magnification) views of deep sky objects, e.g. galaxies, nebula, or open clusters
SLOW telescope (or, slow scope, >~ 8)

1. Large focal number
2. Narrow field of field (with same eyepiece)
3. Good for high power (magnification), small field observing, e.g. planets, double stars
4. Most large research telescopes are slow, e.g. Hubble Space Telescope (f/24)

Adapted from:
http://www.absolutebeginnersastronomy.com/
Magnification

\[ f_o = F \text{ and } f = f_e \]

\[ M = \frac{\beta}{\alpha} = \frac{f_o}{f_e} \]

Adapted from: Observational Astrophysics by Robert C. Smith

Note: Negative sign in formula dropped
The size of image of objective lens as seen by the eyepiece is called the **Exit Pupil**

All light passing through the objective must also pass through the exit pupil

**Eye Relief**: distance between eyepiece and exit pupil
Adapted from:
Optics by Hecht and Zajac

Exit pupil
Eye relief
Exit pupil plane

Chief ray

Adapted from:
Optics by Hecht and Zajac
✓ Suppose $D =$ diameter of primary/objective
   $d =$ diameter of exit pupil

\[
\frac{d}{D} = \frac{i}{o} = \frac{f_e}{f_o + f_e} \approx \frac{f_e}{f_o} = \frac{1}{M}
\]

because usually $f_o >> f_e$, and we have

\[
\therefore d = \frac{D}{M}
\]

Practical Information:
Diameter of human pupil $\sim 7 \text{ mm}$
Comfortable eye relief $\sim 6 - 10 \text{ mm}$
Any deviation from perfection of an image not due to diffraction are known as **aberrations**

There are **six** primary aberrations: Spherical aberration, Coma, Astigmatism, Distortion, Field Curvature, Chromatic aberration

All, except the last one, affect both refractive and reflective telescopes. **Chromatic aberration affects only refractive telescopes.**
For lenses and mirrors made with spherical surfaces, rays which are parallel to the optic axis but at different distances from the center fail to converge to the same point.

Effect is usually a 1%, or larger, difference in focal length.

For mirrors, effect can be totally removed if the mirror is parabolic instead of spherical (However, it is difficult to grind parabolic shape!)
Demonstration of Spherical Aberration
2. Coma

- For light rays entering the lens at an angle (off-axis)

- Coma is an effect where images of off-axis objects are displaced by increasing amount away from optical axis.

- Create trailing "comet-like" blur directed away from axis.

- May produce a sharp image in the center of the field, but become increasingly blurred toward the edges.

Adapted from: Observational Astrophysics by Robert C. Smith
Demonstration of Coma Aberration

Circular stars

Comet-shaped stars
3. Astigmatism

- Different curvature in horizontal and vertical planes
- Only important for wide-field imaging

Adapted from:
Hyper Physics concepts
http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html

Adapted from:
Telescope and Techniques by C. R. Kitchin
Demonstration of Astigmatism
4. Distortion

- Usually seen in thick double convex lenses
- Differential transverse magnification for different distances of image away from optical axis
- Explain why there is a practical limitation in the magnification achievable from a simple magnifier.

Adapted from: Hyper Physics concepts: http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html
The focal plane is not a plane, but a curved surface.

Flat detectors, e.g. CCD, will not be in focus over its entire region.
First, recall the physics of refraction (Snell’s Law):

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

where \( n_1, n_2 \) are the index of refraction of the two media.
✓ Index of refraction for most transparent materials are wavelength dependent, i.e. $n$ is a function of $\lambda$

$q_{2,\text{blue}} < q_{2,\text{green}} < q_{2,\text{red}} < q_1$

$n_{2,\text{blue}} > n_{2,\text{green}} > n_{2,\text{red}} > n_1$

✓ Chromatic aberration is the visual effect of the wavelength dependent refraction

✓ BUT, light reflects all wavelengths of light identically
Demonstration of Cromatic Aberration

Figure 1

Longitudinal and Transverse Spherical Aberration

- Peripheral Rays
- Paraxial Rays
- Simple Lens

Circle of Least Confusion

Paraxial Focus (3)

Transverse Spherical Aberration

Longitudinal Spherical Aberration

red image plane

green image plane

blue image plane
✓ Chromatic aberration greatly reduced (~10 times) by multiple lens system, e.g. achromatic doublet

✓ Usually, two lens have same curvature and are cemented together

✓ Note: Same focal length for two wavelengths so that they can be corrected simultaneously
### Summary of aberrations

<table>
<thead>
<tr>
<th>Aberration</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical</td>
<td>Mono-chromatic (affects single wavelength light), on- and off-axis</td>
</tr>
<tr>
<td>Coma</td>
<td>Mono-chromatic, off-axis only</td>
</tr>
<tr>
<td>Astigmatism</td>
<td>Mono-chromatic, off-axis only</td>
</tr>
<tr>
<td>Distortion</td>
<td>Mono-chromatic, off-axis only</td>
</tr>
<tr>
<td>Field Curvature</td>
<td>Mono-chromatic, off-axis only</td>
</tr>
<tr>
<td>Chromatic</td>
<td>Hetero-chromatic (affect multiple wavelength light), on- and off- axis</td>
</tr>
</tbody>
</table>

**Corrections:** Most of the aberrations can be reduced (but never totally removed) by using multi-lens system.
Here’s a stack of several calibrated images of NGC 6992 (the Veil nebula):

References

http://www.princeton.edu/~rvdb/images/deconv/deconv.html
The image appears soft because it is slightly out of focus (the temperature dropped significantly over the time frame during which the individual exposures were taken).
With these values, the PSFs for 100 bright stars in the raw image are modeled as follows:
Point spread function - PSF

Sketches illustrating a point spread function (A) and a line spread function (B).

Adapted from Smith (1966)
Typical ALIS background image with a few selected stars magnified, showing the variation of the PSF with image location.

Variation in widths of stars in ALIS images taken with an optics with 90 degrees field-of-view.
Implemented the Richardson - Lucy deconvolution algorithm using this non constant model for the PSF. The resulting image after 10 iterations of the algorithm is shown here:
More iterations gives even tighter stars but also begins to look over processed. Here's the result after 25 iterations:
A better approach is to break the problem into two parts: (a) first, make the stars round, and then (b) make the image sharper. The "rounding" step can be done, for example, by doing 10 iterations with minor radius = 0.9,

Then, the "sharpening" step can be accomplished by doing another 5 iterations with the suggested settings minor radius = 0.9,

Here's the result:
Aberration overcome by having achromatic objective lens and multi-lens eyepiece

Biggest refractor built: 1 m diameter (Yerkes)

Limitations for building bigger refractors:

1. Light absorption and chromatic aberration
2. Objective lens has to be supported at the edges and they sag under their own weight (glass is a fluid!)
3. To achieve large f/ number, telescope will be long and requires massive support and domes
The biggest optical telescopes (~10 m diameter, Keck) built in the world are reflectors.

Major advantages:
1. No chromatic aberration
2. No spherical aberration (parabolic mirrors)
3. Mirror can be supported at the back, no huge support structure needed
4. Improved technique on making big mirrors (Aluminium-on-glass, recoating needed)
The first working reflector (1668, 1 inch diameter)

Eyepiece moved to the side of the telescope
Cassegrain

- Basic configuration for most large research telescopes (e.g. Hubble, Keck 10m, VLT 8.2m)
- Secondary mirror produces narrow cone of light
- Can have large focal length compared to the physical length of telescope (telephoto advantage)
- Small field of sharp focus (few arcminutes)
Ritchey-Chretien

- Variation of the Cassegrain
- Remove coma aberration
- Good quality images over a larger field-of-view (10-20 arcminutes)

Adapted from Tumbling Stone general dictionary http://spaceguard.ias.rm.cnr.it/tumblingstone/dict.htm
Combined Refractor and Reflector: Schmidt Camera

- Advantage: Wide field-of-view (6-10 degree), good for sky surveying work
- Two major ones: Palomar, Siding Spring (1.2m)
- Disadvantage: telephoto disadvantage (long telescope length versus focal length)

Adapted from Tumbling Stone general dictionary http://spaceguard.ias.rm.cnr.it/tumblingstone/dict.htm
Compact design: compromise of large field-of-view and long focal length

Popular design for small telescopes, especially for astro-photography

Adapted from Tumbling Stone general dictionary http://spaceguard.ias.rm.cnr.it/tumblingstone/dict.htm
<table>
<thead>
<tr>
<th>Type</th>
<th>Primary Optics</th>
<th>Secondary Optic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keplerian</td>
<td>Sphere or parabola</td>
<td>None</td>
</tr>
<tr>
<td>Herschelian</td>
<td>Off-axis parabola</td>
<td>None</td>
</tr>
<tr>
<td>Newtonian</td>
<td>Parabola</td>
<td>Diagonal Flat</td>
</tr>
<tr>
<td>Gregorian</td>
<td>Parabola</td>
<td>Ellipse</td>
</tr>
<tr>
<td>Mersenne</td>
<td>Parabola</td>
<td>Parabola</td>
</tr>
<tr>
<td>Cassegrain</td>
<td>Parabola</td>
<td>Hyperbola</td>
</tr>
<tr>
<td>Ritchey-Chrétien</td>
<td>Modified parabola</td>
<td>Modified hyperbola</td>
</tr>
<tr>
<td>Dall-Kirkham</td>
<td>Ellipse</td>
<td>Sphere</td>
</tr>
<tr>
<td>Schmidt</td>
<td>Aspheric refractor</td>
<td>Sphere</td>
</tr>
<tr>
<td>Bouwers-Maksutov</td>
<td>Refractive meniscus</td>
<td>Sphere</td>
</tr>
</tbody>
</table>
New developments of optical telescopes

Segmented primary mirrors:
Large equivalent light collecting area

36 mirror segment (1.8m) equivalent of a single 10m mirror

Adapted from: Telescope and Technique by C.R Kitchin
Adaptive Optics:

Telescope can correct for any deviation from its desired shape by active real-time mechanical control from behind the mirror.

A total of 175 controlled actuators
Liquid Mirror:

- Spin up liquid Mercury on parabolic surface.
- Advantage: ~10 times cheaper than conventional mirror.
- Disadvantage: 1. Can only point straight up! (that explains the name); 2. Mercury is toxic.

Rotate at period of ~8.5 second to get a thin (~2mm) layer of Mercury.
The LZT is located at the Liquid Mirror Observatory in the UBC Malcolm Knapp Research Forest in Maple Ridge, British Columbia.

Design of the telescope

View of the primary mirror undergoing initial tests using water.
V. Telescope Mount

✓ Function: Support the optical components, point them to a required position, and track the object as it moves.

✓ Two components: telescope tube, support for the tube (mounting).

✓ Actually, most research telescopes contain no tube (open frame).
A stable and rigid mounting is very important for observations.

Two main types: equatorial and alt-azimuth.

**Mounting**

- Equatorial Mount
  - Coordenadas ecuatoriales: Eje polar y eje de declinación

- Altazimut Mount
  - Coordenadas horizontales: acimut y altura.
Equatorial Mounting

- Two axes: Polar axis (parallel to Earth’s rotation axis) and Declination axis (perpendicular to polar axis)
- Star tracking can be done with only one constant-speed motor rotating in opposite direction of earth’s rotation along polar axis
- Disadvantage: expensive to build, asymmetry gravity effects

Adapted from: Telescope and Technique by C.R Kitchin
Alt-azimuth mounting

- Used by all big (>4m) telescopes recently built
- Symmetric gravity effects, cheaper to build
- Disadvantages:
  1. To track objects in the sky, need two axes rotating at different speed;
  2. Rotation of image during tracking need to be overcome (by rotating cameras!);
  3. “Dead-zone” near zenith

Adapted from: Telescope and Technique by C.R Kitchin
Montura tipo alemán

Montura tipo inglés

Montura tipo americano

Montura con el armazón
VI. Observatory and Observatory site

✓ All telescope can be benefited by placing in an observatory (sometimes known as “the dome”)

✓ Classic design: a hemispherical roof with a open slot, rotating on a circular wall

✓ Choosing “good sites” means that majority of world’s largest telescopes are located in a few places, e.g. Hawaii, Chile, Arizona, Canary Island, Mexico (OAN-SPM)

✓ Criteria: away from light pollution, “clean” atmosphere (low dust and water), height, accessibility, steady atmosphere, ......
This is what the Earth looks like at night

Finding map (for a place away from light pollution)