Distortions of the Equatorial Coordinate Frame

- The Earth is a moving platform with an atmosphere. Our view of the celestial sphere from a ground based telescope is distorted due to two effects.
  - Aberration of starlight – A telescope must be “tipped” in order to catch the light coming down from a star due to the Earth's 30 km/s orbital velocity.
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**FIGURE 2.22** Telescopes must be tilted in the direction of the Earth’s motion by an angle \( \theta \approx v/c \) to assure that photons arrive at point \( P \) at the same time as the bottom of the telescope.
Refraction

- The apparent direction to astronomical sources is not the actual direction. At the zenith there is no effect. At the horizon the shift is more than $\frac{1}{2}$ degree.
Refraction is color dependent... more later
The Green Flash
Also Stellar Parallax....

- The positions of nearer stars shift more than those of more distant stars due to the annual motion of the Earth.
- The largest parallax is 0.75" - 1.5" annual motion, so it is a small effect. Most stellar parallaxes are unobservable (< 0.001")

**FIGURE 2.5** (a) Geocentric, or diurnal, parallax due to a change in position relative to the Earth’s center. (b) Heliocentric, or annual, parallax due to a change in position relative to the Sun.
Also Stellar Parallax....

- The positions of nearer stars shift more than those of more distant stars due to the annual motion of the Earth.

Fig. 3.12 The parallactic ellipse. The apparent position of the nearby star, S, as seen from Earth, traces out an elliptical path on the very distant celestial sphere as a result of the Earth’s orbital motion.
And, of course, Proper Motion

- All stars have **random velocities** relative to us. Some are close/fast enough to have significant annual “proper motion”
- Barnard's Star (17h57m +04 41) is the record holder at 10.3” per year.
Ephemerides

- Solar System objects can move substantially faster than the highest proper motion stars.
- Updated coordinates may be required hour-to-hour or even minute-to-minute (or sec-to-sec for near-Earth asteroids).
- The JPL Horizons system provides one of the most comprehensive and flexible ephemeris calculators.
- Alternatively, XEphem provides good coordinates and has the option of loading object files with the orbital elements of Solar System objects.
What Your Telescope Control System Does

- Calculates sidereal time and thus hour angle
  - Your UT clock had better be set right. 10 seconds off and you miss your target by 2.5 arcminutes at the equator
- Drives telescope to coordinates (possibly via alt/az calculation)
- To get there it must account for
  - precession (47 degrees in 13K years)
  - nutation + polar wander (10")
  - aberration (20")
  - refraction (up to ½ degree)
  - proper motion (arcsec/year at most)
  - parallax (< 1", usually undetectable)
  - mechanical flexure of the telescope
Telescope Mounts

- Telescopes can be oriented in the horizon system or the equatorial system.
  - Equatorial telescopes need be turned around only one axis to compensate for Earth rotation.
  - In the computer age, 2-axis tracking is no big deal. Alt-Az mounts are mechanically simpler (cheaper) due to the direction of gravity.
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Equatorial Mounts
Equatorial Mounts

THE 200 INCH Telescope
LOOKING EAST
Equatorial Mounts
Equatorial Telescope Configurations

(a) German Fork
(b) Polar Axis
(c) Declination Axis
(d) English Yoke

THE 200 INCH TELESCOPE
LOOKING EAST
The German Flip

- German equatorial mounts are common but have the annoying problem that they are configured so that the telescope can crash into (or track into) the pier.
- Just when your source gets to the meridian you have to flip.
- The McCormick 26 1/2” refractor and the Fan Mountain 31” are of this configuration.
- For most declinations crossing the meridian requires an elaborate flip of the telescope.
  1) With the telescope at 0 H.A. point at the pole.
  2) Flip the telescope over the top of the pier going 12 hours in H.A.
  3) Go to the declination of your choice.
- General guideline: The counterweight should never be higher than the telescope
Alt-Az Mounts
The Large Binocular Telescope
The Large Binocular Telescope
Field Rotation in Alt-Az Systems

- Equatorial telescope rotate around the same axis as the sky. Thus the orientation of the field of view remains fixed.
Field Rotation in Alt-Az Systems

- Alt-Az telescope's field of view remains fixed relative to the horizon. Stars rotate in the field of view over time.
- Images will be smeared unless a focal plane “rotator” undoes the sky rotation.

http://astronomyasylum.com/telescopemountstutorial.html
Parallactic Angle

- Parallactic Angle represents the angle between the zenith and the pole and thus the rotational offset between the Alt-Az and Equatorial views.
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Because atmospheric refraction elongates stars perpendicular to the horizon, spectroscopic observations rotate the slit to align with the zenith direction. The required rotation from North is the parallactic angle.
Parallactic Angle

Parallactic Angle represents the angle between the zenith and the pole and thus the rotational offset between the Alt-Az and Equatorial views.
Counterweights, Balance, and Preloads

- Since motor (and human) drives tend to be modest, telescopes are exquisitely balanced on their axes.
  - most (unclamped) telescopes can be swung on both axes with a finger.
  - movable counterweights adjust the balance.
  - every instrument change requires re-balance.

- An out of balance telescope is a hazard (a potentially fatal one).
  - Never disconnect an instrument from a telescope without considering the consequences of lost balance, especially the action of lever arms.
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  - Never disconnect an instrument from a telescope without considering the consequences of lost balance.

- Perfect balance is also not desirable as the telescope can “float” between gear teeth.
  - “preload” weights or motors provide a little force to keep the telescope tracking on the gear teeth.
Telescopes Without Balance Issues

• But with other related problems. Angular momentum is conserved....
Telescope/Lens Geometry

• The overall goal is to create an image of the sky on an, ideally, flat “focal plane”

• Start with a simple pinhole camera – in the end image sizes scale in the same way.

• Each point on the object forms a corresponding point on the image, simply via geometry.

• The blur is proportional to the size of the pinhole.

• The inverting property of an optic is evident.
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**FIGURE 6.1** A camera obscura, as used to project the image of a nearby church.

**FIGURE 6.2** A pinhole camera, which is simply a miniature camera obscura. Points on the object, to the left, map onto the image plane on the right. A long camera (a) produces a larger image than a short camera (b).
Telescope/Lens Geometry

Lenses collect light over a larger area, but the central ray is undeviated so the pinhole camera concept is still informative.

**FIGURE 6.1** A camera obscura, as used to project the image of a nearby church.

**FIGURE 6.2** A pinhole camera, which is simply a miniature camera obscura. Points on the object, to the left, map onto the image plane on the right. A long camera (a) produces a larger image than a short camera (b).

**FIGURE 6.3** By replacing the pinhole in Figure 6.2 with a convex lens, we can admit more light. The image plane is now fixed, and its location depends on the shape of the lens.
Refraction and Snell's Law

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

Note that the refractive index, n, is a \textit{wavelength dependent} quantity

http://www.haverford.edu/physics-astro/songs/snell.htm
The focal length, $F$, of a lens is the distance from the lens (actually its principal plane) to the lens' focus when imaging a point source on the optical axis.

For a "thin" lens the focal length is given by

$$\frac{1}{F} = (n_\lambda - 1) \left( \frac{1}{r_1} - \frac{1}{r_2} \right)$$

- This equation applies for a thin lens in vacuum (or air).
- $n_\lambda$ is the wavelength-dependent refractive index of the lens material.
- $r$ is the radius of curvature. $r_1$ is the first surface encountered, $r_2$ is the second.
  (convex to the left is positive curvature)
A Lens Primer

Focal Length
Distance from a lens to a point where it forms an image of a distant object. Usually midway between center of lens and object point.

Principal Planes
Imaginary planes from which exact focal length measurements are taken. If the lens is symmetrical, the PP's are symmetrical.

Finding F.L. of a Lens
Hold the lens in sunlight and, alongside a ruler, move lens up and down to form smallest image of sun. Read the F.L. on ruler.

White Light
White light is composed of all colors. A narrow beam of sunlight directed through a prism will emerge as a colored band: the spectrum.

Longitudinal Color
Simple lens breaks up white light into a series of colors. Blue bands focus closer than red. The prism is constant over whole field.

Lateral Color
Failure of the lens to form same image size in all colors. This fault increases with field angle... is not present on axis.

Spherical Aberration
As shown, a positive lens is spherically under-corrected. S.A. varies with f-value of lens and is less for a small aperture.

Achromatic Lens
Achromats are two-element lenses corrected for longitudinal color and spherical aberration for an axial object.
Focal Length and Focal Ratio \((f/#)\)

The focal length, \(F\), of a lens is the distance from the lens (actually from its principal plane) to the lens' focus when imaging a point source at infinite distance (parallel incident rays).

The f-number \((f/#\text{ or } f)\) is the ratio of the focal length to the lens diameter. \(F = f D\)
Focal Lengths

- The 6” Clark Refractor has a focal ratio of f/12 and a focal length of 1830mm
- The 26 ½” Clark has a focal length of 391” (9930 mm)
- The Fan Mountain 31” telescope has a focal length of 480” (12190 mm)
Plate scale

The plate scale derives from knowing that rays through the middle of a lens are undeviated. Consider an object subtending an angle of one arcsecond.

\[ \theta_{\text{arcsec}} = 206265 \times \frac{x}{F} \]

You can either set theta to 1 arcsec and solve for x – giving you millimeters per arcsecond (assuming you express F in millimeters). Or set x=1 and derive the number of arcseconds per millimeter.
**Plate scale**

An arcsecond of angle on the sky maps to some linear dimension at the focal plane of a lens. The “plate scale” is a number connecting the astronomical angular scale to the physical scale of the detector (in the old days photographic plates – thus the name).

Via the small angle equation, given the focal length $F$...

$$\frac{\text{mm}}{\text{arcsec}} = \frac{F (\text{mm})}{206265}$$

$$\text{arcsec/ mm} = \frac{206265}{F (\text{mm})}$$

Since lenses are often described by their “focal ratio”, $f$, which is their focal length divided by their diameter, $D$, so $F = fD$....

$$\text{arcsec/ mm} = \frac{206265}{fD (\text{mm})}$$
How a Telescope Works

An “objective” optic (lens or mirror) forms an image. The observer inspects the image formed with a small magnifying glass (the eyepiece).

Magnification = \( \frac{F_{objective}}{F_{eyepiece}} \)
How a Telescope Works

An “objective” optic (lens or mirror) forms an image. The observer inspects the image formed with a small magnifying glass (the eyepiece).

Note that in modern research usage (i.e. no eyepiece) a light sensitive plane (photographic plate (also arcane) or charge coupled device) is placed at the telescope focal plane and receives the image directly.

The eyepiece was just a means of relaying the image to the eye's retina. It's the eyepiece/eye interaction that makes telescopes more mysterious. If you just consider the objective and its primary image, things are simple.
Birney gives limiting magnitude as a function of aperture as

\[
\text{Limiting Mag} \approx 2.7 + 5 \log\left(\text{diam}_{\text{millimeters}}\right)
\]

- The result is approximate because it depends on the individual.
- You can derive the relationship by assuming a limiting magnitude (5.5 or 6) and the diameter of the dark-adapted human pupil (6 or 7 mm).
It's All Done With Mirrors

Although refraction and reflection are equally good ways to create an image, mechanical support of the primary optic favors reflectors.
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\[ \text{focal length} = \frac{\text{radius of curvature}}{2} \]
It's All Done With Mirrors

Although refraction and reflection are equally good ways to create an image, mechanical support of the primary optic favors reflectors.
Reflection

Reflection simply requires equal angles of incidence and emergence for a ray independent of material.

The only wavelength dependent quantity is reflection efficiency (which will not affect image shape).

7.4.4. Reflectors. Although in the infrared most metal mirror surfaces are better than at shorter wavelengths, the requirements are often very stringent. Representative spectral curves are given in Figure 7-43. The reader should be aware that oxidation, dust, and tarnish from other chemical reactions can reduce the reflectivity of the specified surfaces below that reported here.

The Infrared Handbook (Wolfe)

Fig. 7-43. The reflectance of various films of silver, gold, aluminum, copper, rhodium, and titanium [7-75].
**First Facts about Telescope Mirrors**

- **Focal Length**: Distance from surface of a mirror to the point where it forms an image of distant object.
- **Radius of Curvature**: The radius of a spherical mirror, or, radius of center zone of a parabolic mirror.

**Sagitta Formula**:

$$\text{Sag} = \frac{r^2}{2R}$$

**Sagitta**: The depth of a curve. The sagitta formula is used to calculate all telescope mirrors.

**Parabola**

A curve which reflects parallel light to a point. The parabola revolved forms a paraboloid.

**Where are you?**

**Spherical Mirror**

A mirror with a spherical surface. This shape makes a good telescope if f/value is f/10 or higher.

**Parabolic Mirror**

A mirror with a surface which is a revolution of a parabola. It is the perfect surface for telescopes.

**Wavelength of Light**

...is useful as a unit of measure to specify the surface accuracy of a lens or mirror.

- One wave (1) = 0.000022" (22 microinches)
- 1/4 wave (1/4) = 0.0000055" (5.5 microinches)
- 1/8 wave (1/8) = 0.00000275" (2.75 microinches)
**f/ Value**
The focal length of a lens or mirror divided by its diameter. f/8 is most common.

**Sagitta**
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**Parabola**
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**Spherical Mirror**
A mirror with a spherical surface. This shape makes a good telescope if f/ value is f/10 or higher.

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**Wavelength of Light**
Is useful as a unit of measure to specify the surface accuracy of a lens or mirror.

**¼-Wave Mirror**
A mirror will perform close to perfection if its curve is smooth and not over ¼-wave from the ideal parabolic shape.

**Spherical Aberration**
The variation in focus between edge rays and center rays. It is the only aberration you have to deal with in grinding your own mirror.

**The Shadow Test**
Shadow or knife-edge test originated by French physicist Jean Foucault, lets you see and measure shape of mirror to ¼ wave.
Telescope Precision

Mirrors can only deviate from the desired shape (usually a parabola) by a fraction of the shortest operating wavelength.

- Blue light has a wavelength of 400 nm, so 20 nm precision or better is desirable.

The mirror support structure must hold this precise shape as the telescope points around the sky.
Telescope Precision

Figure 5. Grayscale surface maps and synthetic interference patterns for the first Magellan mirror. Grayscale bars are labeled in nm of surface; interference patterns are calculated for 633 nm. Top: at completion of polishing, with mirror on passive polishing support; astigmatism and spherical aberration have been subtracted. Bottom: with mirror on active telescope support, after optimization of support forces; no aberrations have been subtracted.
Historic Monolithic Mirrors

- In the old days, mirrors had to be thick so that they could be stiff enough to avoid distortion. Thick = weight = bad.

Palomar Observatory 200” mirror
Modern Mirror Support (LBT)

- Computer control enables the use of thin, floppy mirrors.
Modern Mirror Support (LBT)

- Today mirrors can be thin with shape maintained by computer control.
Grinding a Mirror
Casting a Mirror

Spinning oven time lapse