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*ASTR 2401*

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# Telescopes II

Observational Astronomy

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# Telescopes

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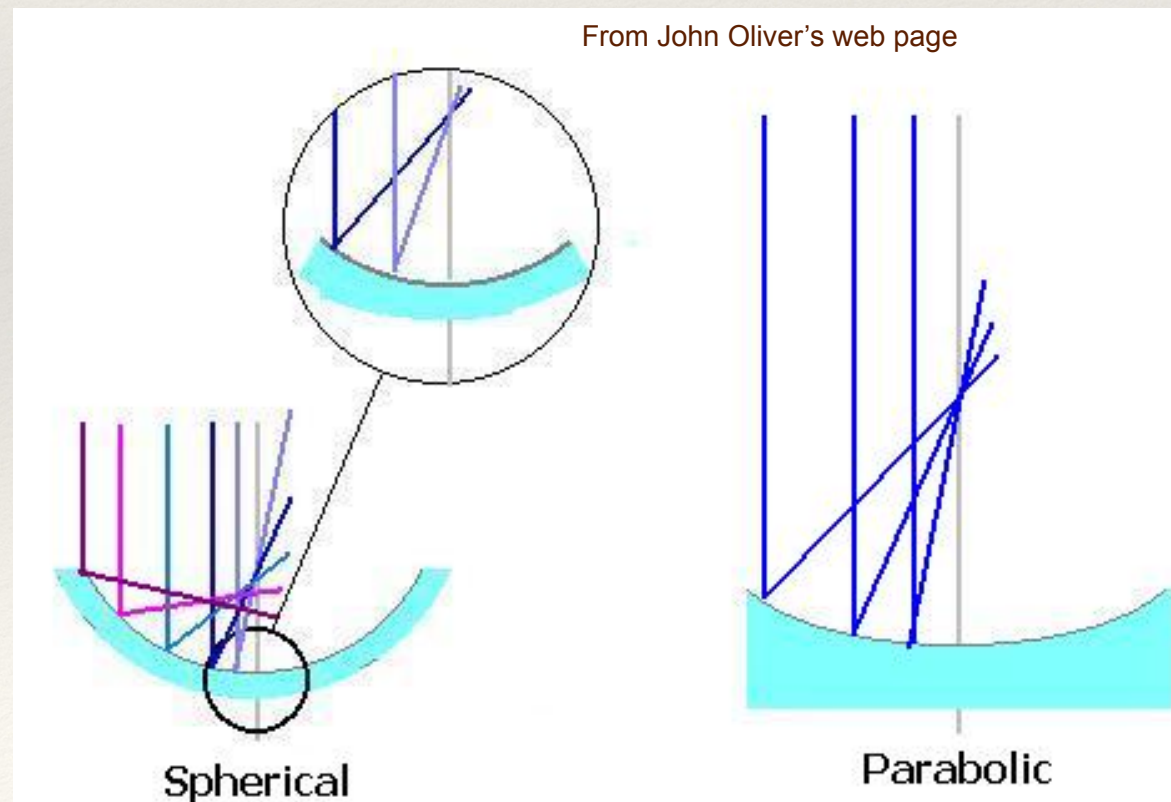
There are several basic features of optical telescopes that impact their performance and practicality for different applications. The main ones that we are going to discuss right now are

- ❖ The optical path design (e.g. Reflector, Prime Focus, Newtonian, Cassegrain)
- ❖ The curvature of the mirrors for reflectors (parabolic, spherical, hyperboloid)

# Mirror Curvature

There are four curvatures that are commonly used in astronomical mirror designs:

1. Spherical - Spherical mirrors are easy to build, but have some problems. Foremost, parallel light rays from an object (star) at infinity do not all pass through a common focus. This is called *spherical aberration*. This aberration can be corrected using *aspheric lenses*.

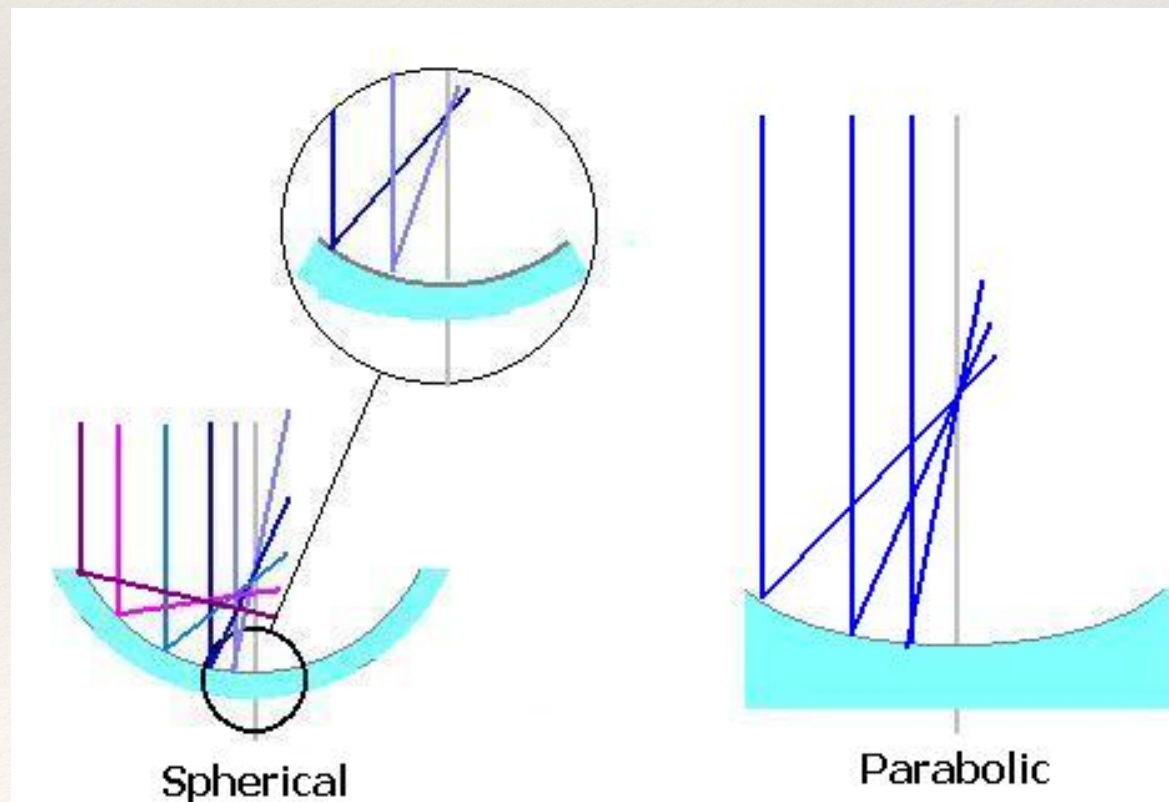




# Mirror Curvature

There are four curvatures that are commonly used in astronomical mirror designs:

2. Parabolic - Light rays parallel to central axis of parabola all pass through the focus. This isn't true though for light rays coming in at an angle. Thus, with a parabolic mirror you get good image quality over a small field, but *comatic aberration* off-axis.



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# Mirror Curvature

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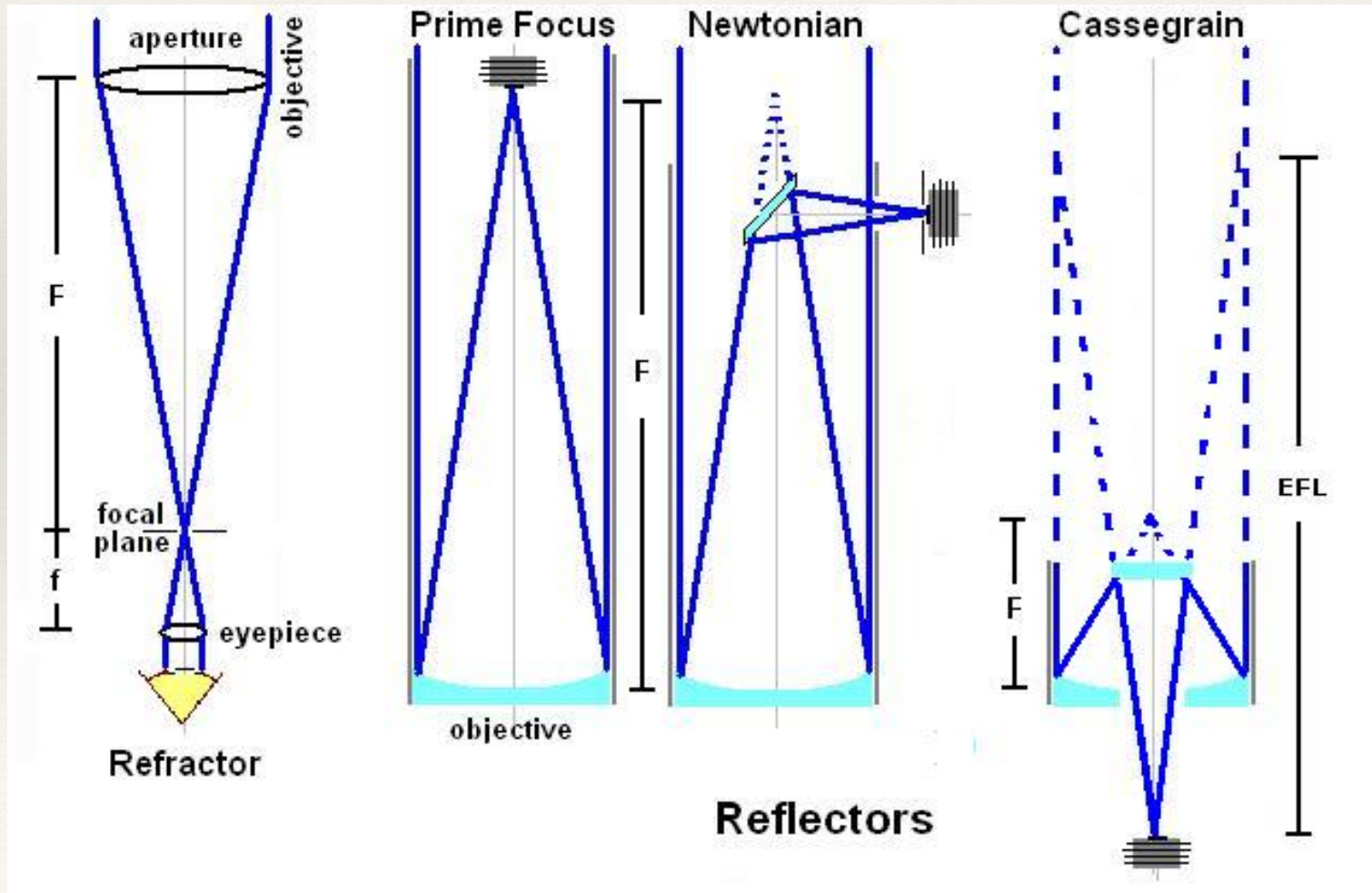
There are four curvatures that are commonly used in astronomical mirror designs:

3. Hyperbolic - Hyperbolic mirrors, while not used as monolithic primaries, have various applications in telescope design... we'll see a few.
4. Flat - The common flat mirror is often used to re-direct the optical path.



# Telescopes Types

The basic objective of any telescope is to collect incident light and bring it to a focus. There is, of course, more than one way to do this...



# Refractors

## Refracting telescope

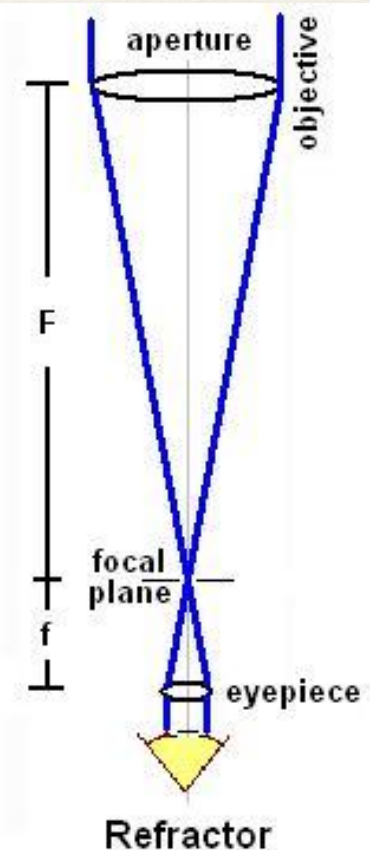
An objective lens brings light to a focus. Similar design to microscopes.

**Objective lens:** Focuses the light

**Eyepiece lens:** Determines the magnification and acts as an aperture stop.

## Disadvantages:

- ❖ Size: Because there are no reflections, the length of the telescope is set by the focal length of the objective lens. Hence, Refractors are *long*.
- ❖ Chromatic Aberration: Refractors are subject to chromatic aberration caused by dispersion in the glass of the objective. Chromatic aberration can be compensated with a lens of several elements of differing materials.





# Refractors

## Refracting telescope

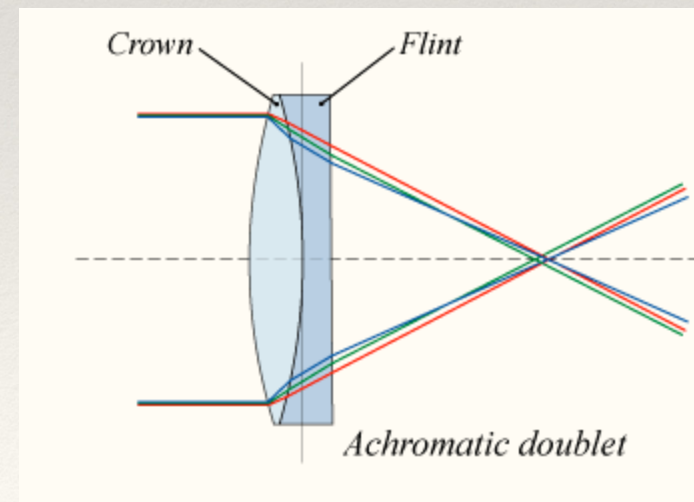
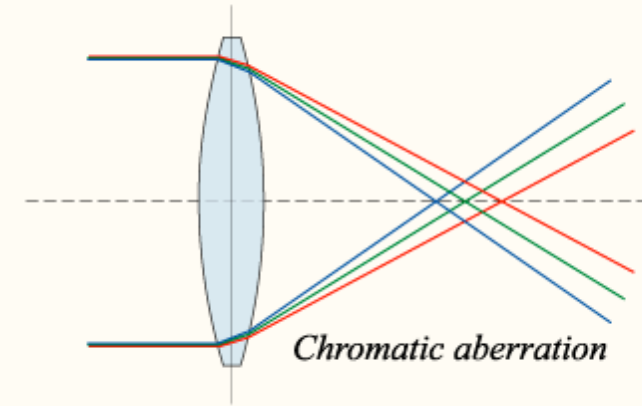
An objective lens brings light to a focus. Similar design to microscopes.

**Objective lens:** Focuses the light

**Eyepiece lens:** Determines the magnification and acts as an aperture stop.

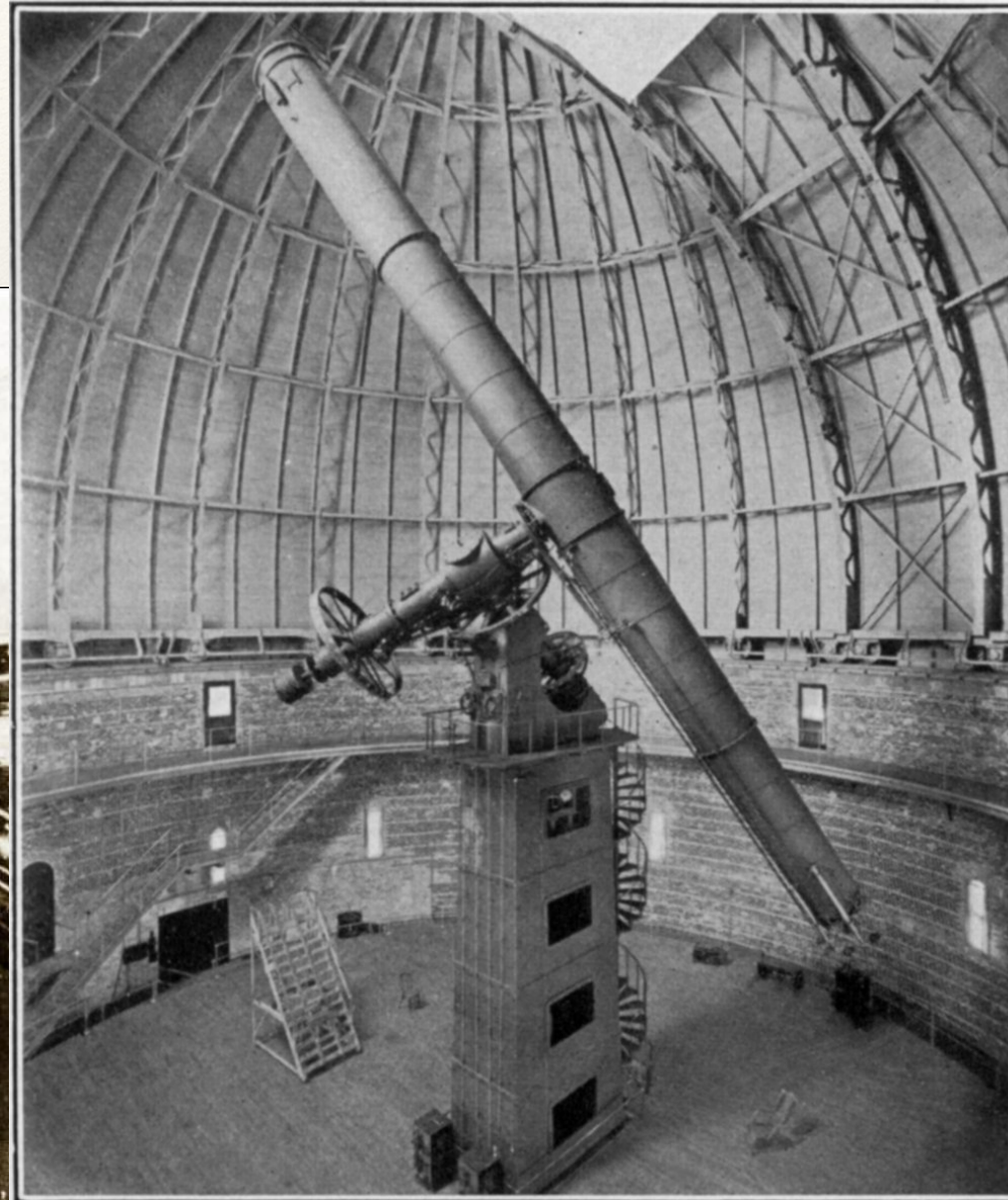
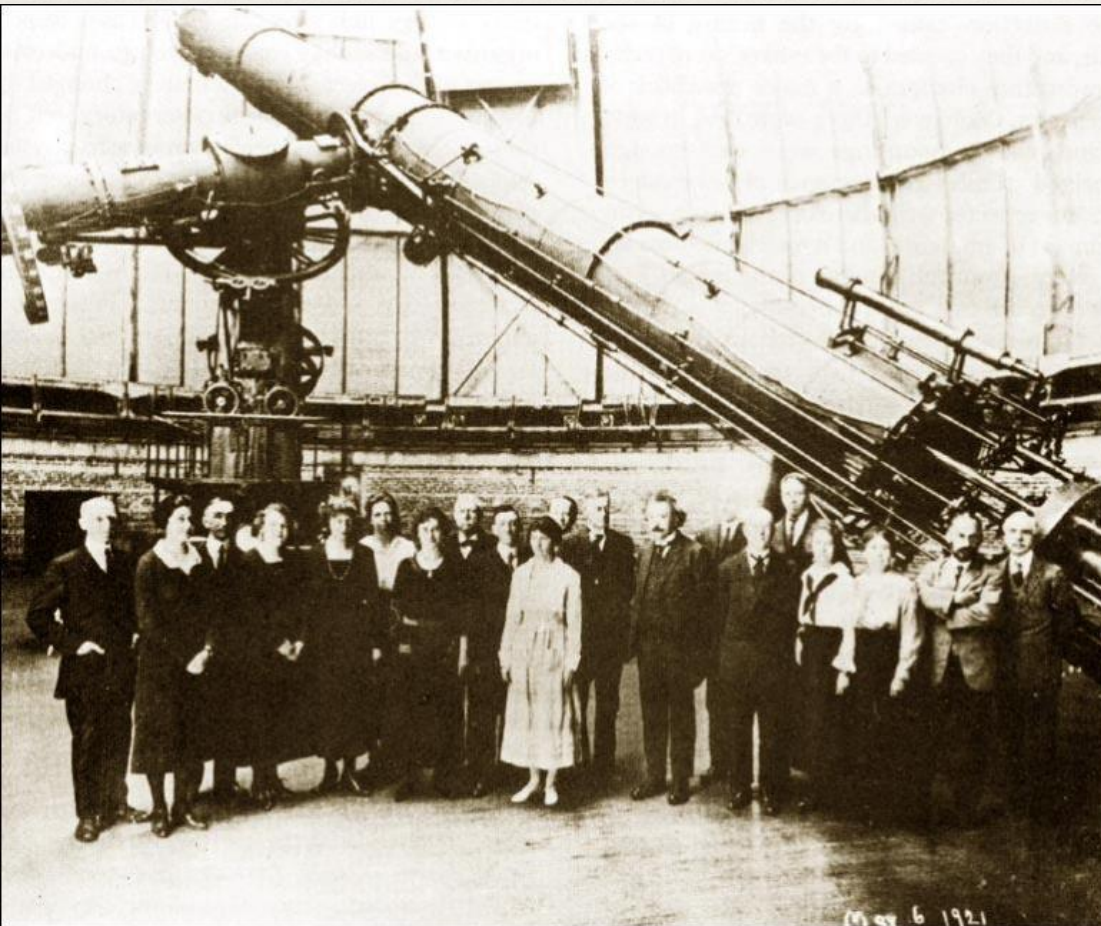
## Disadvantages:

- **Size:** Because there are no reflections, the length of the telescope is set by the focal length of the objective lens. Hence, Refractors are *long*.
- **Chromatic Aberration:** Refractors are subject to chromatic aberration caused by dispersion in the glass of the objective. Chromatic aberration can be compensated with a lens of several elements of differing materials.





# Examples of Refractors

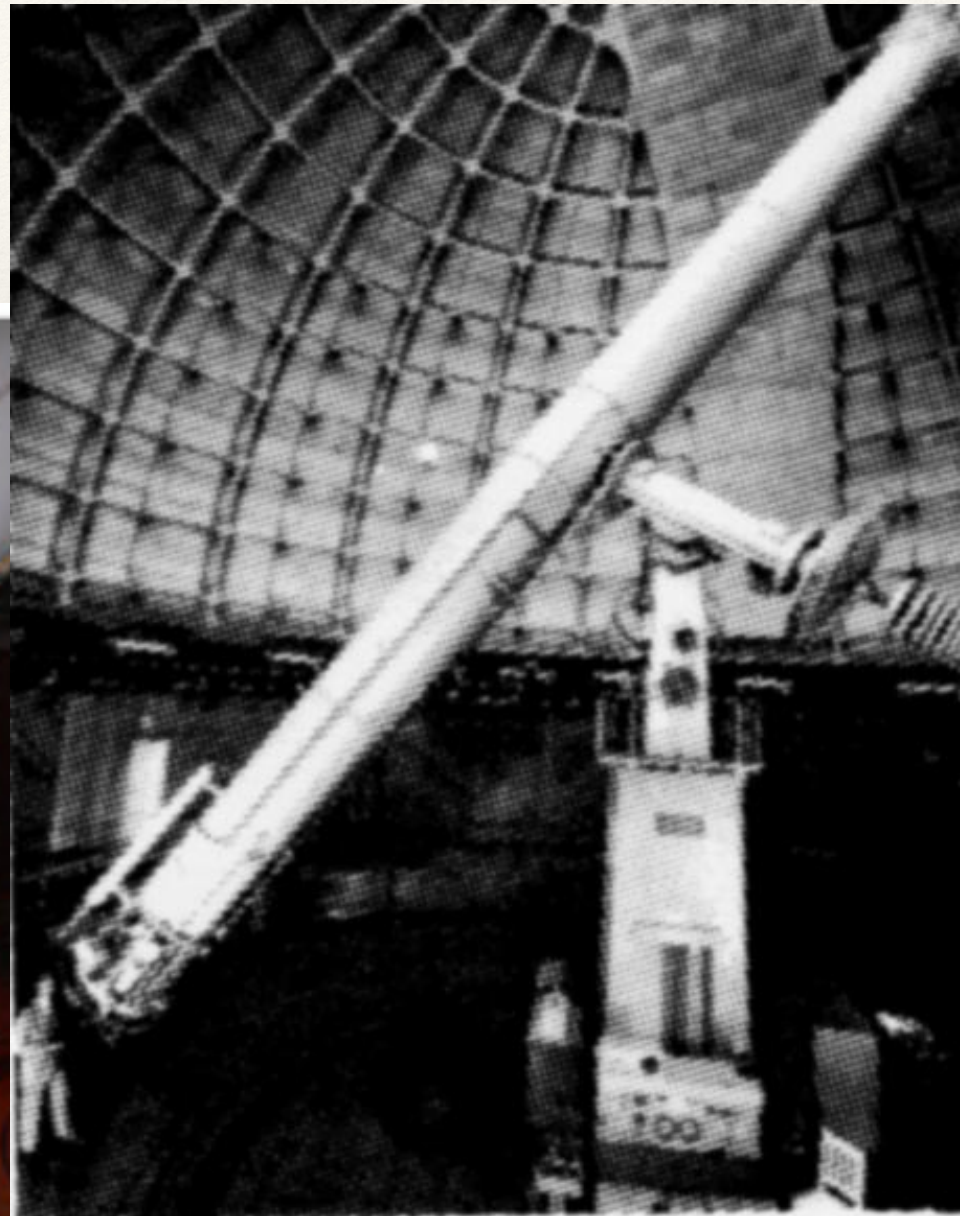




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# Examples of Refractors

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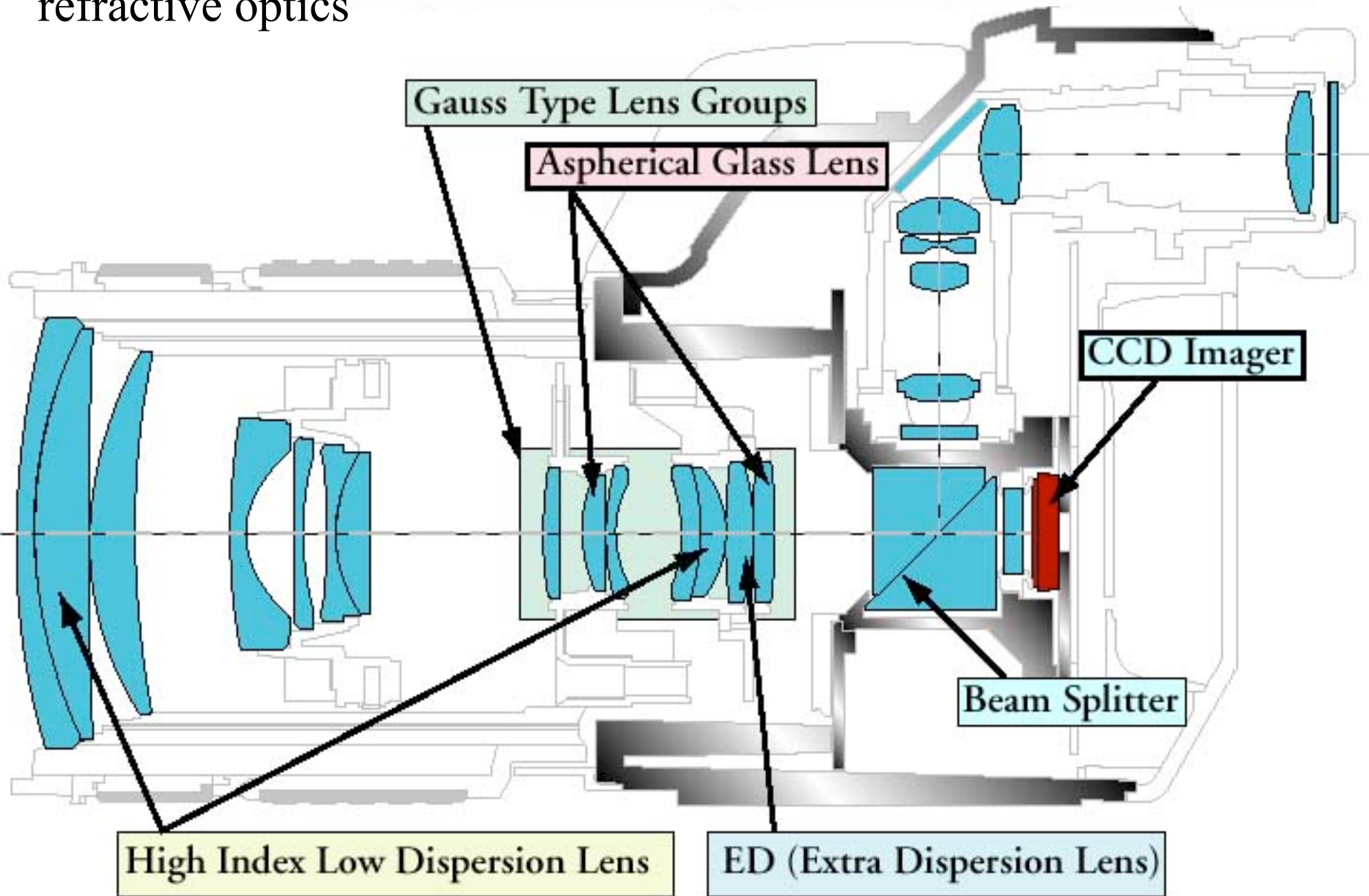






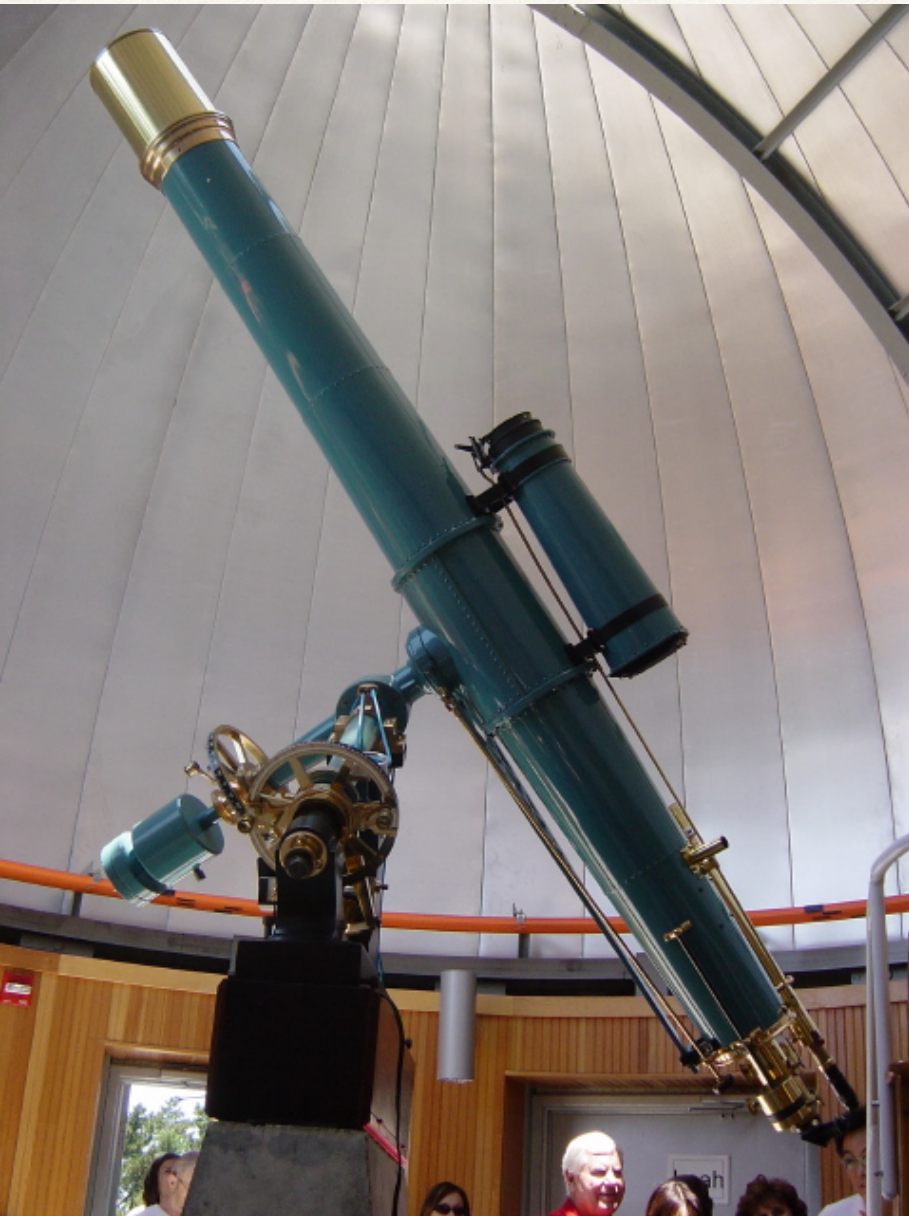


# Another example of refractive optics





# Reflector vs. Refractor



Left - 8" refractor at the Observatories at Chabot Space and Science Center in Oakland, California.

Below - 8" Celestron Schmidt-Cassegrain Telescope (company7.com/celestron)





# Prime Focus

A telescope configured for prime focus uses only the primary mirror to bring the light to focus, which means that *the focal plane is inside the telescope*. Consequently, the instrument (or observer) must ride along in a prime focus “cage”.

## Advantages:

- ❖ Moves optics to bottom of telescope
- ❖ Single reflection
  - ❖ Minimizes throughput losses
  - ❖ Simple optical path
- ❖ In IR, you don't have a glowing secondary
- ❖ No chromatic aberration (true for all reflectors)

## Disadvantages

- ❖ Observer riding in the cage not the most comfortable
  - ❖ Won't work for smaller telescopes
- ❖ Prime focus cage will obstruct incoming light
- ❖ Can't put large instruments at prime focus
  - ❖ Obstructs incoming light
  - ❖ Flexure in telescope
- ❖ Telescope is still long



Image of Jesse Greenstein at prime focus of the Palomar 200" (<http://www.astro.caltech.edu/palomar/prime/pf6.html>)



# Newtonian

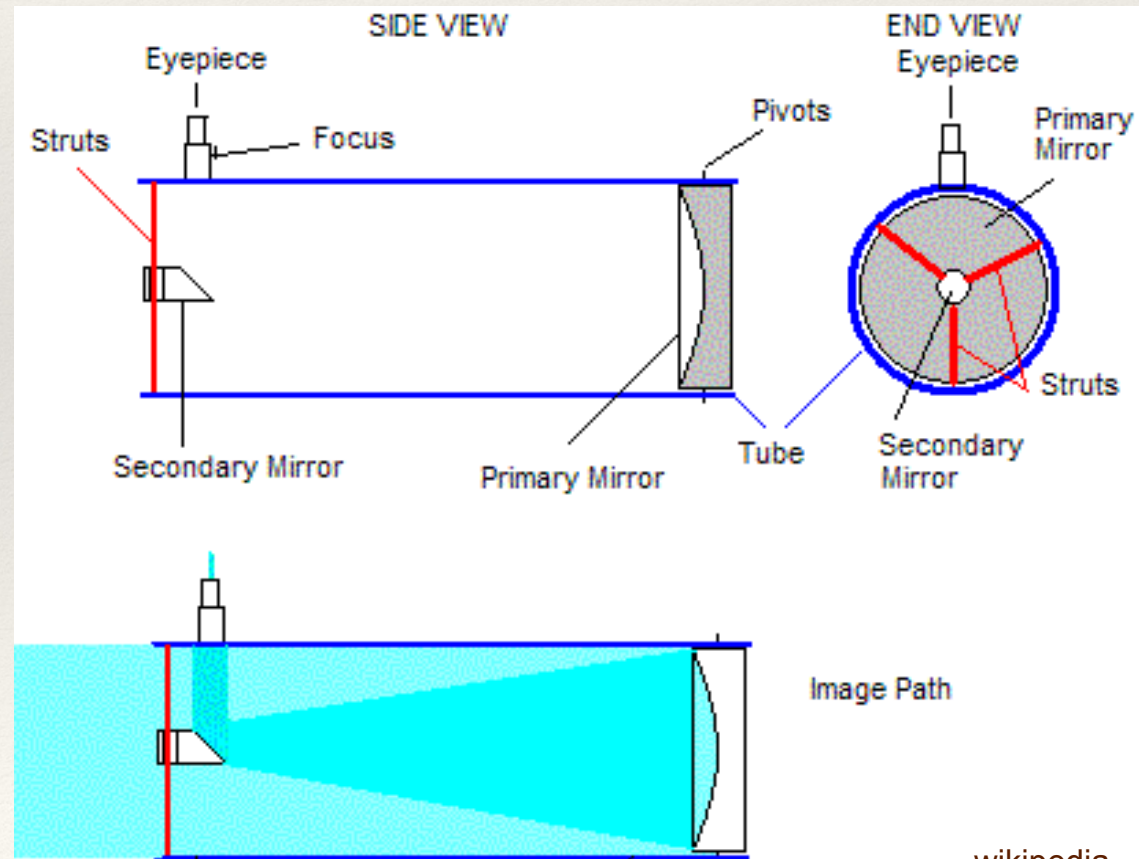
Newtonian telescopes add a flat, diagonal *secondary* mirror to the optical path to move the focal plane out of the telescope. These are popular for amateur astronomy because they are easy to use.

## Advantages

- ❖ Shortens telescope
- ❖ Focal plane out of telescope
- ❖ Inexpensive, relatively easy to make
- ❖ Collimation is relatively easy
- ❖ Instruments can (depending upon telescope mounting) be placed on fixed external platform

## Disadvantages:

- ❖ Central obscuration
- ❖ Diffraction spikes from supports
- ❖ Comatic aberration





# Cassegrain

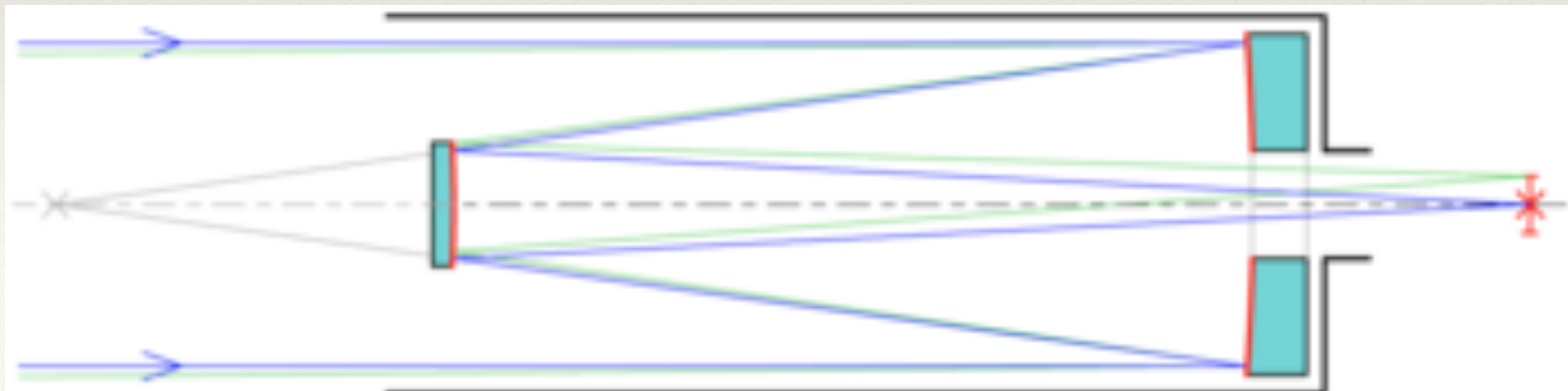
The defining feature of Cassegrain telescopes is that the convex secondary mirror redirects the light back down through a hole in the concave primary. For the “classic” Cassegrain, the primary is parabolic and the secondary is hyperbolic.

Advantages:

- ❖ Very compact telescope. The secondary mirror has a magnification factor  $m$  yielding an effective focal length which is  $m$  times the focal length of the primary mirror. This allows a much shorter overall telescope tube length than for the other types of telescopes for the same effective focal length.

Disadvantages

- ❖ Central obscuration and diffraction spikes
- ❖ Cassegrain design suffers from astigmatic and comatic aberrations
  - ❖ Trade-offs can be made between two effects depending upon whether you want to do high-resolution in a small field (classical Cassegrain, large f-ratio) or wide-field with lower resolution (Ritchey-Cretien)





# Cassegrain

The defining feature of Cassegrain telescopes is that the convex secondary mirror redirects the light back down through a hole in the concave primary. For the “classic” Cassegrain, the primary is parabolic and the secondary is hyperbolic.

Classical Cassegrain: Parabolic Primary, Hyperbolic Secondary

Ritchey-Cretien: Hyperbolic Primary, Hyperbolic Secondary

***Most large telescopes employ a Ritchey-Cretien design***

Advantages of Ritchey-Cretien: Free low order coma and spherical aberration.

(Does have ff-axis astigmatism and field of curvature distortions.)

Examples:

10m Keck Telescopes

4m Mayall (KPNO)

10.4m GTC

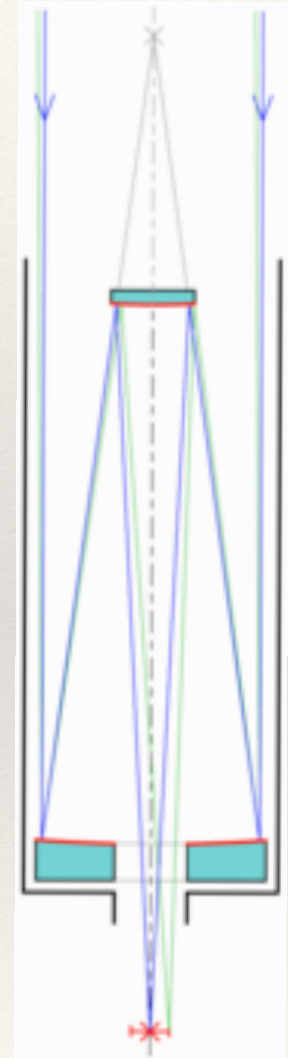
8m Geminis

8.2m VLTs

2.4m HST

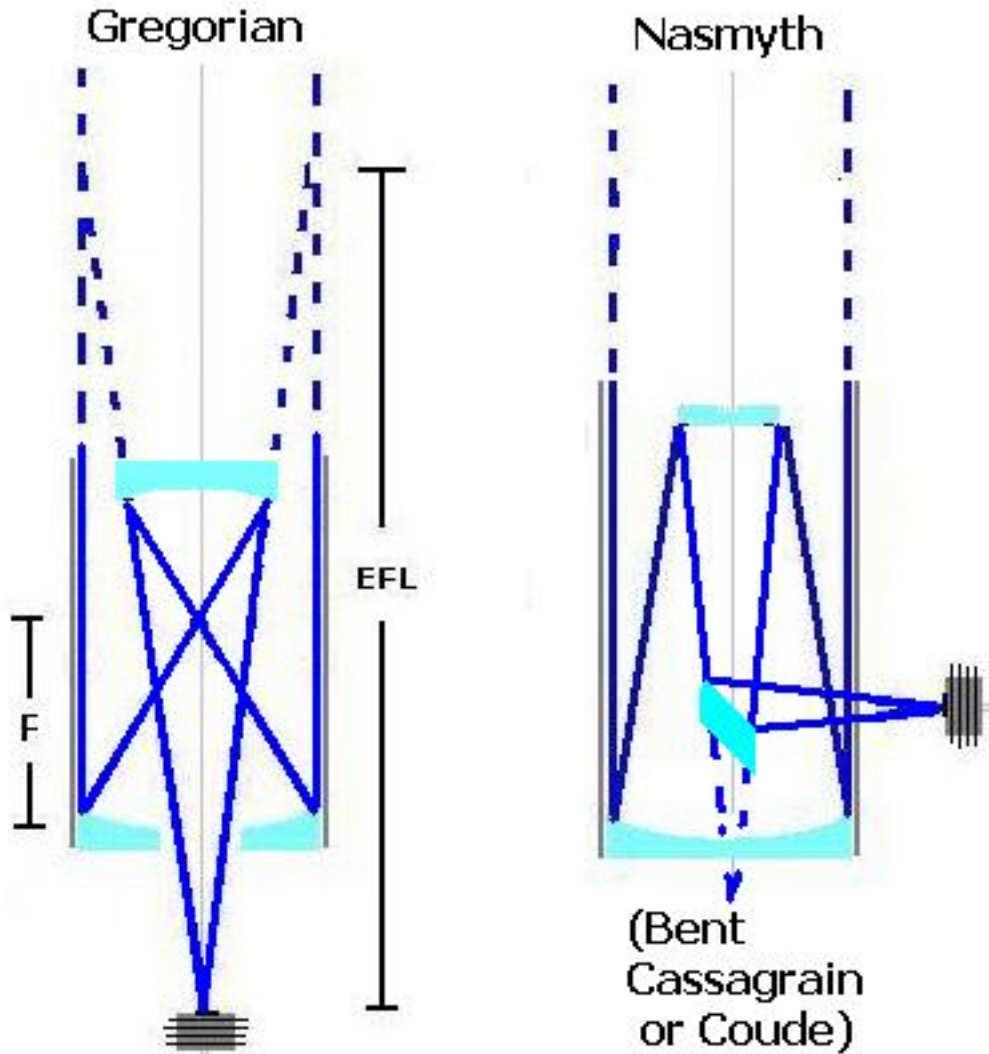
8.2m Subaru

1.4m Kepler





# Other Telescope Variations



**Gregorian** - For a Gregorian the secondary is placed after, rather than before the focus of the primary mirror.

**Nasmyth** - Incorporates features of both Cassegrain and Newtonian. A secondary sends the light back towards the Cassegrain focus, but a tertiary diagonal mirror redirects light to the side. A significant advantage is that instruments can be placed upon a "Nasmyth platform".

While the Gregorian optical system is seldom used (it requires a longer tube than the Cassegrain), the Nasmyth and Coude optical system are common, especially on large modern telescopes. Telescopes such as the Gran Telescopio Canarias (GTC) typically have several Nasmyth and bent (or folded) Cassegrain instrument stations.



# Other Telescope Variations

## Combined Lens-Mirror Telescopes (catadioptrics designs)

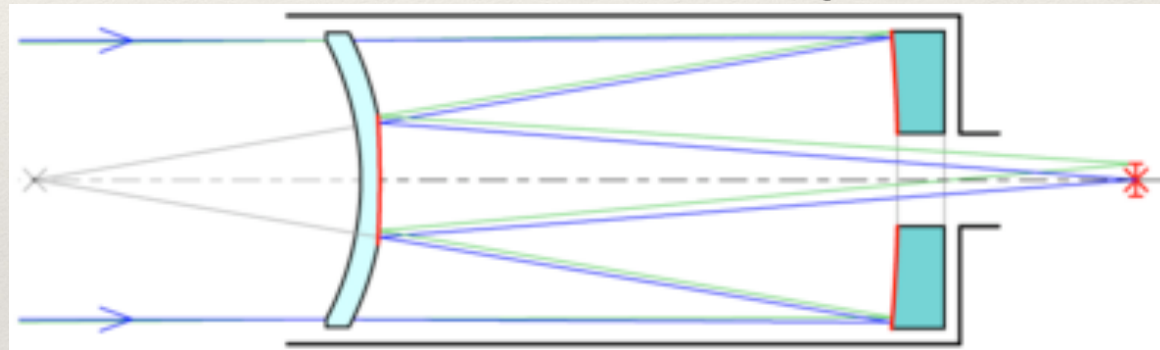
**Schmidt** and **Maksutov** optical systems use a spherical primary mirror (and hence no aberrations other than spherical) and correct the spherical aberration with a lens (a complex thin lens in the case of the Schmidt, a thick meniscus lens for the Maksutov). These optical systems can have very wide fields of view.

Both the Schmidt-Cassegrain and Maksutov-Cassegrain are closely related to the normal Cassegrain telescope. The two main differences are simply:

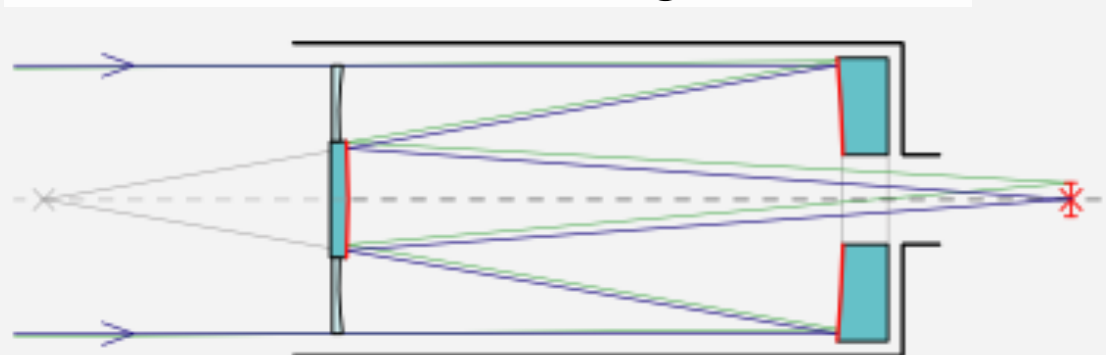
Spherical primary  
Corrector lens



## Maksutov-Cassegrain



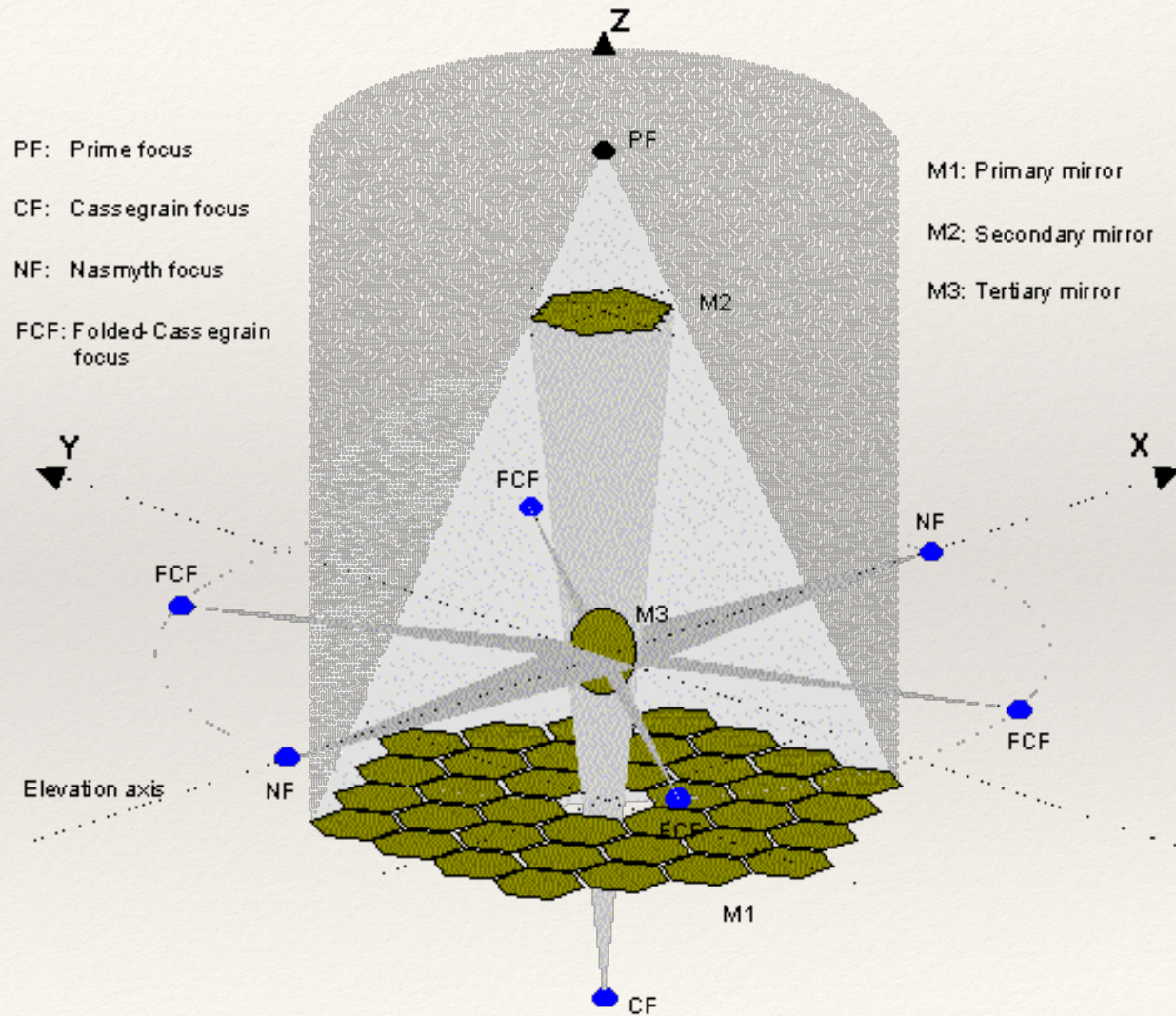
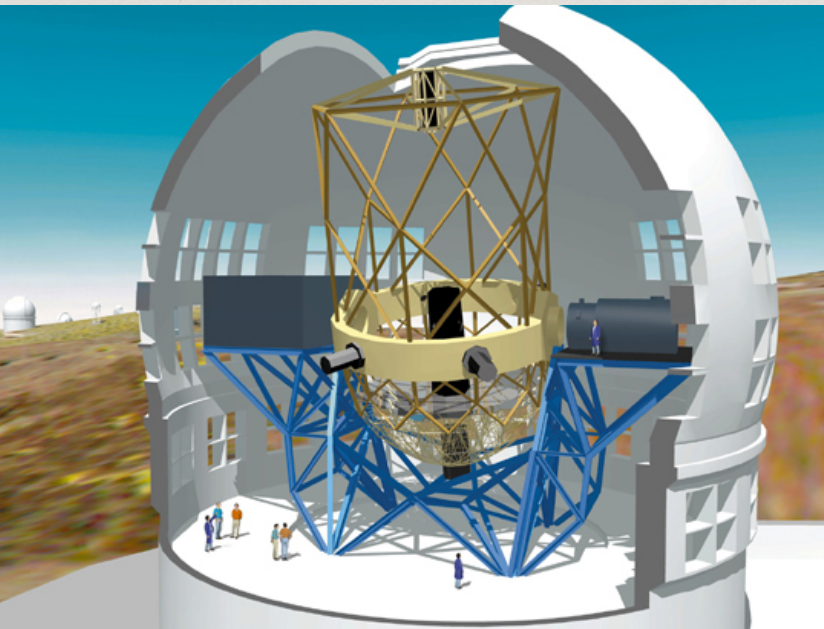
## Schmidt-Cassegrain





# The GTC

Cassegrain Focus  
Nasmyth Focus



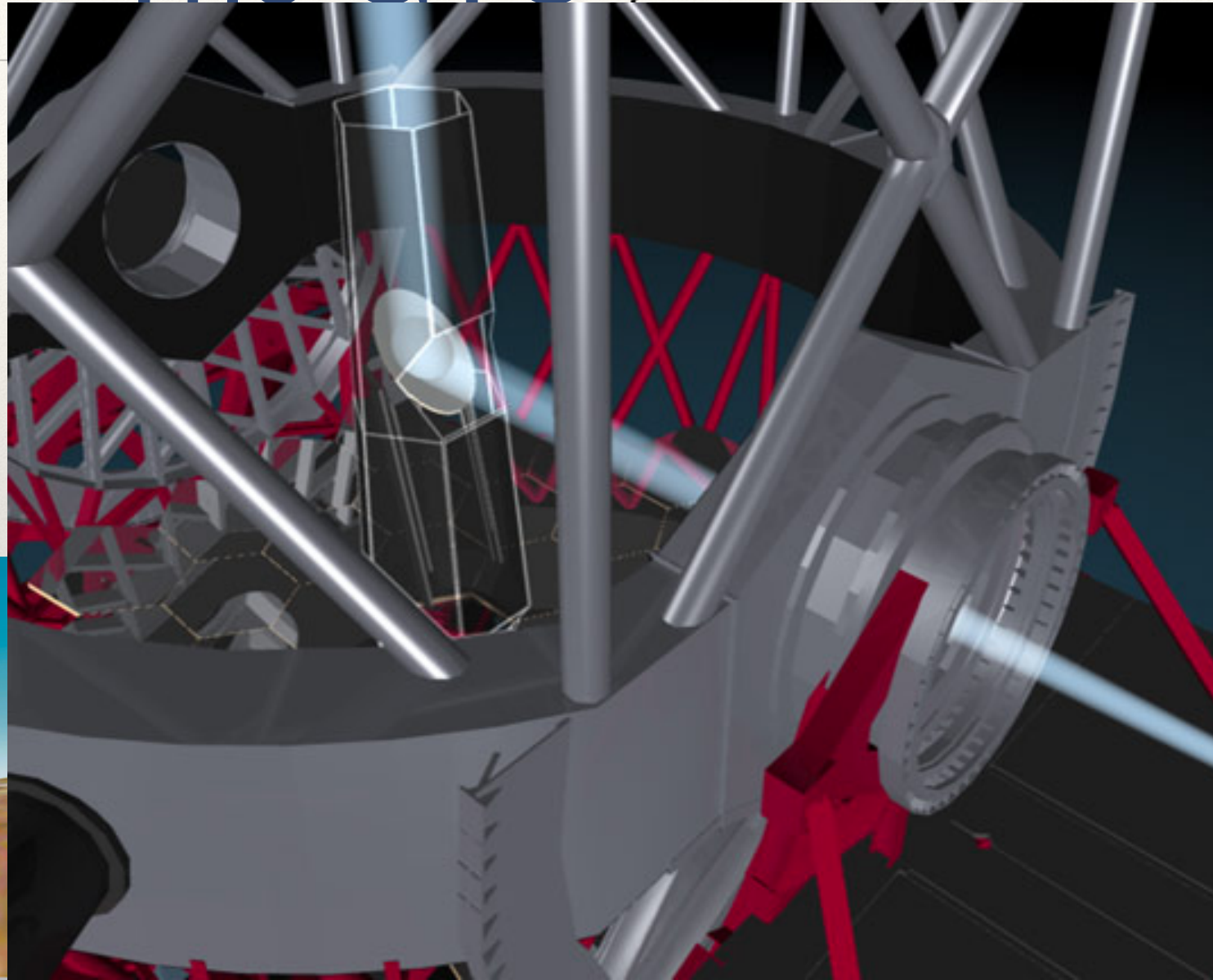
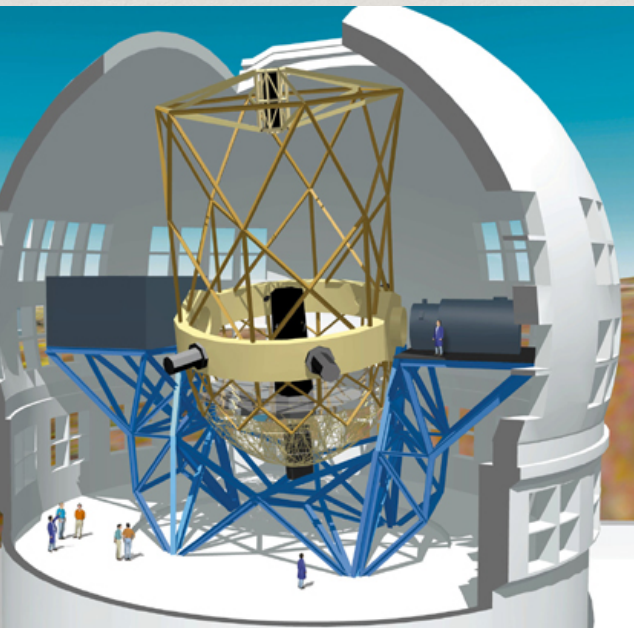
PF: Prime focus  
CF: Cassegrain focus  
NF: Nasmyth focus  
FCF: Folded-Cassegrain focus

M1: Primary mirror  
M2: Secondary mirror  
M3: Tertiary mirror



# The GTC

Cassegrain Focus  
Nasmyth Focus





# Telescope Mounts

The two basic types of telescope mounts are equatorial and Alt-Az.

## Alt-Az

Axes of rotation:

- horizontal axis
- perpendicular axis

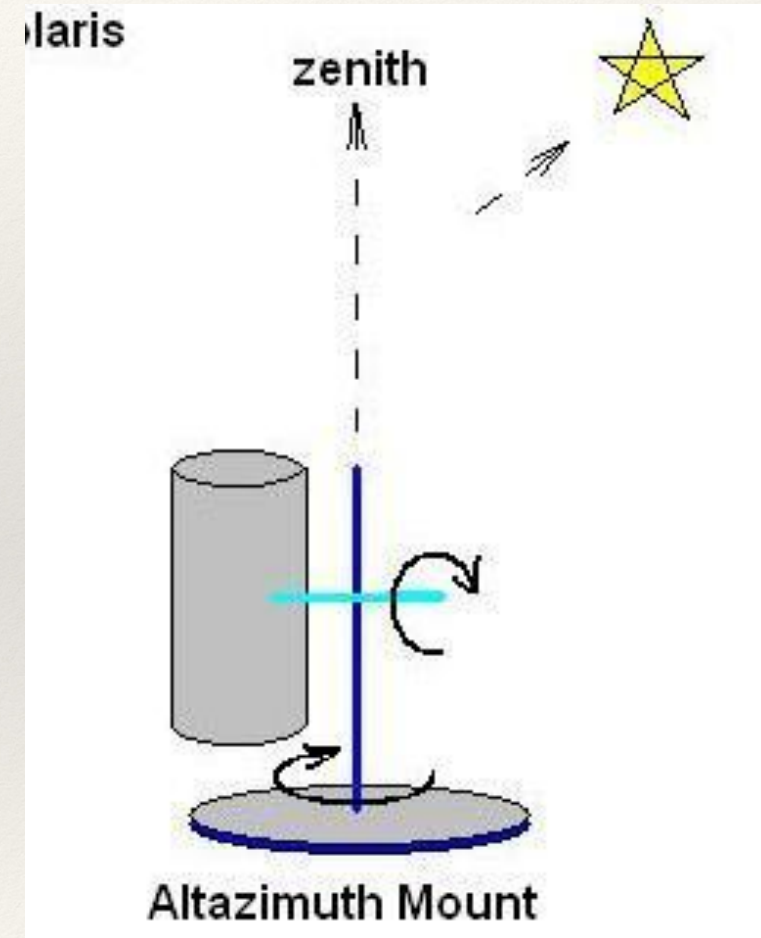
Advantages:

An axis aligned with zenith (zero gravity vector)

Disadvantages:

- Must move on 2 axes for tracking object
- “Dead zone” at zenith
- Field rotation

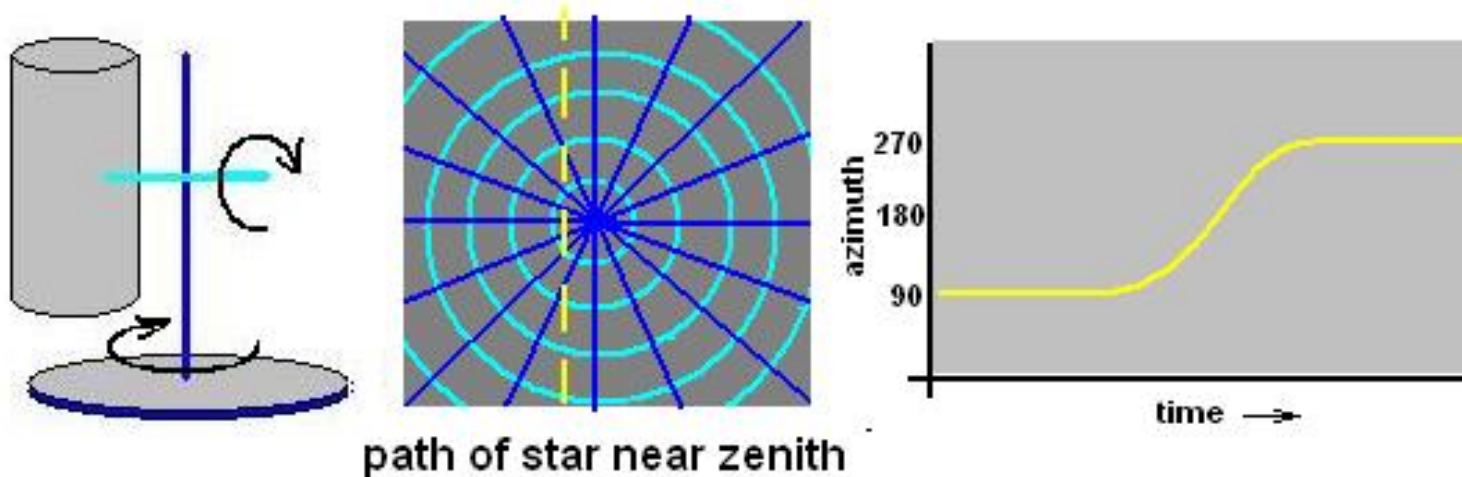
Examples: GTC, Keck





# Telescope Mounts

## Tracking and zenith issues with an Alt-Az mount



A modern telescope has motors on both axes to point the telescope and to track the rising and setting of objects (diurnal motion). Usually these motors are computer controlled and the position of each axis is read out to the computer by angle encoders. Tracking can be accomplished by motion around the polar axis alone with an equatorial mount but requires motion of both axes with an altazimuth mount. Tracking near the zenith requires a very rapid motion in azimuth, approaching infinity in the limit of a star passing exactly through the zenith. The result is a "dead zone" near the zenith for altazimuth mounts. Observations are stopped a few minutes before zenith passage and the telescope is pointed at the position on the other side of the zenith where the object will be required. (A similar problem with movement can occur for an equatorial mount near the pole but it affects only pointing and not tracking.)



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# Telescope Mounts

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## Field Rotation



With an equatorial mount, the field seen in an eyepiece or camera is fixed in orientation (e.g. perhaps west to the right, north up, etc.). This is not the case with an alt-azimuth mount. Consider the case of tracking a star that passes near the zenith: as the zenith is passed the telescope must rotate nearly  $180^\circ$  in azimuth which means that a camera mounted rigidly to the telescope tube would rotate relative to the objects being imaged. Thus instruments on an altazimuth mounted telescope must be mounted on a bearing which must be rotated at the correct rate to compensate for field rotation.



# Telescope Mounts

The two basic types of telescope mounts are equatorial and Alt-Az.

## Equatorial

Axes of rotation:

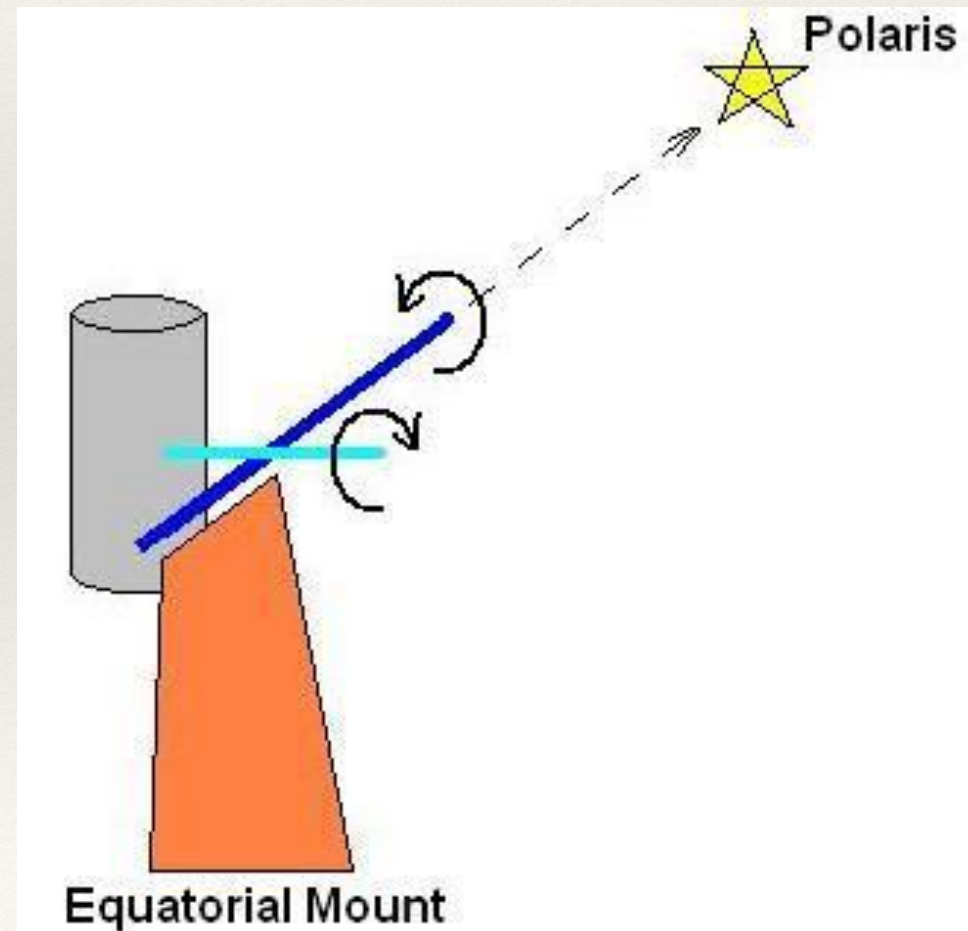
- polar axis aligned with Earth's axis (pointing at Polaris)
- perpendicular axis

Advantages:

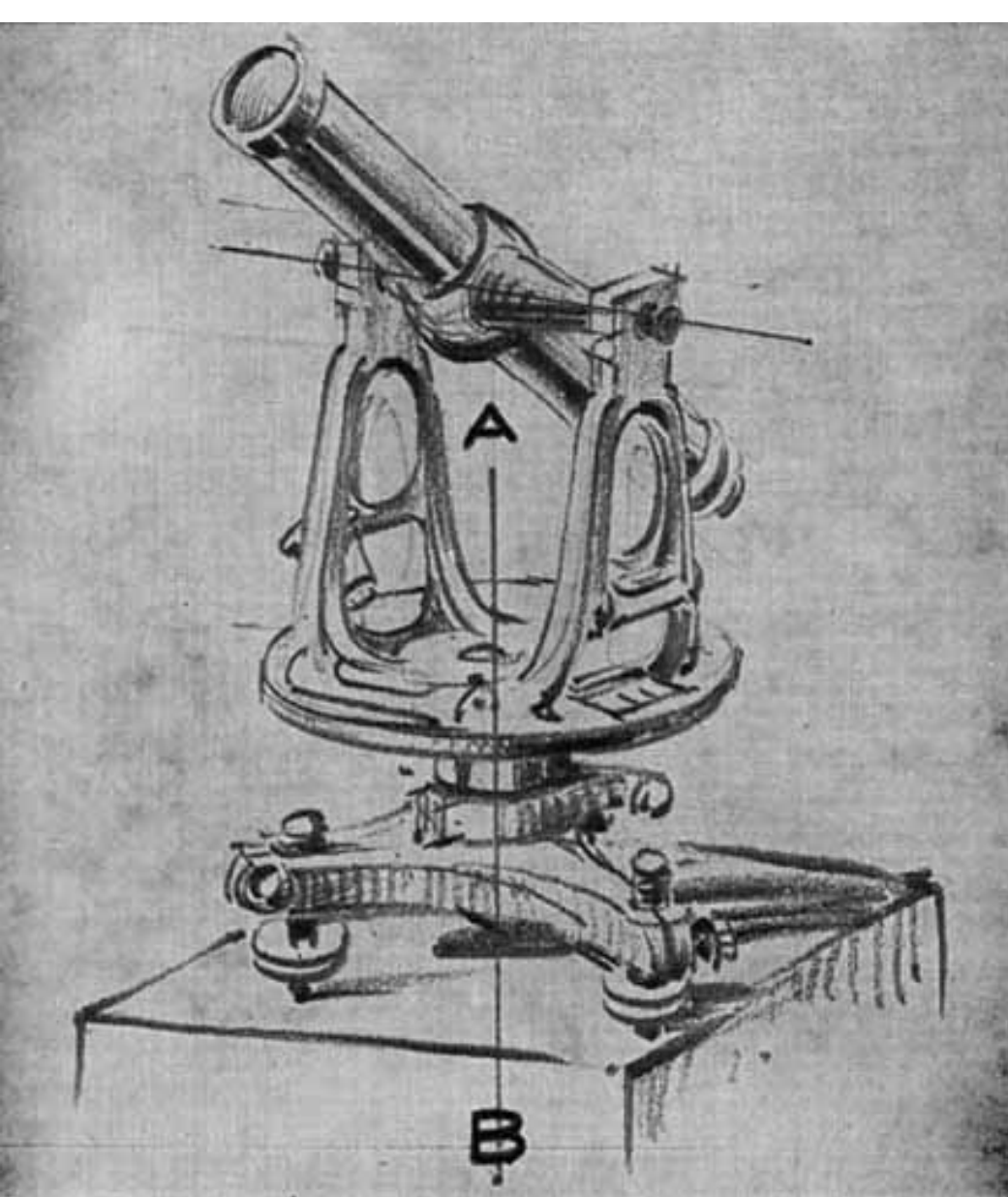
Ease of tracking -- only rotate along one axis

Disadvantages:

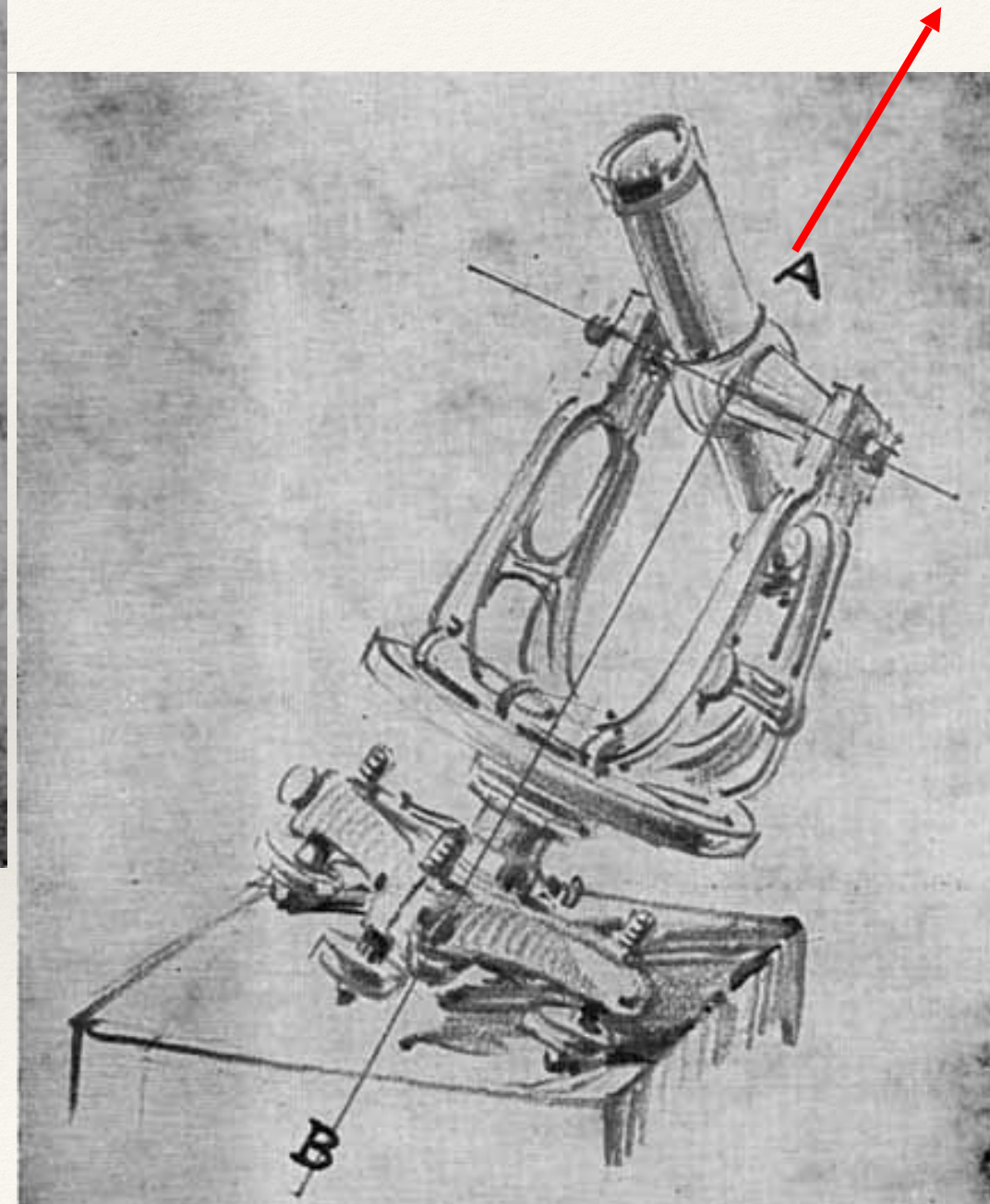
Asymmetry to gravity





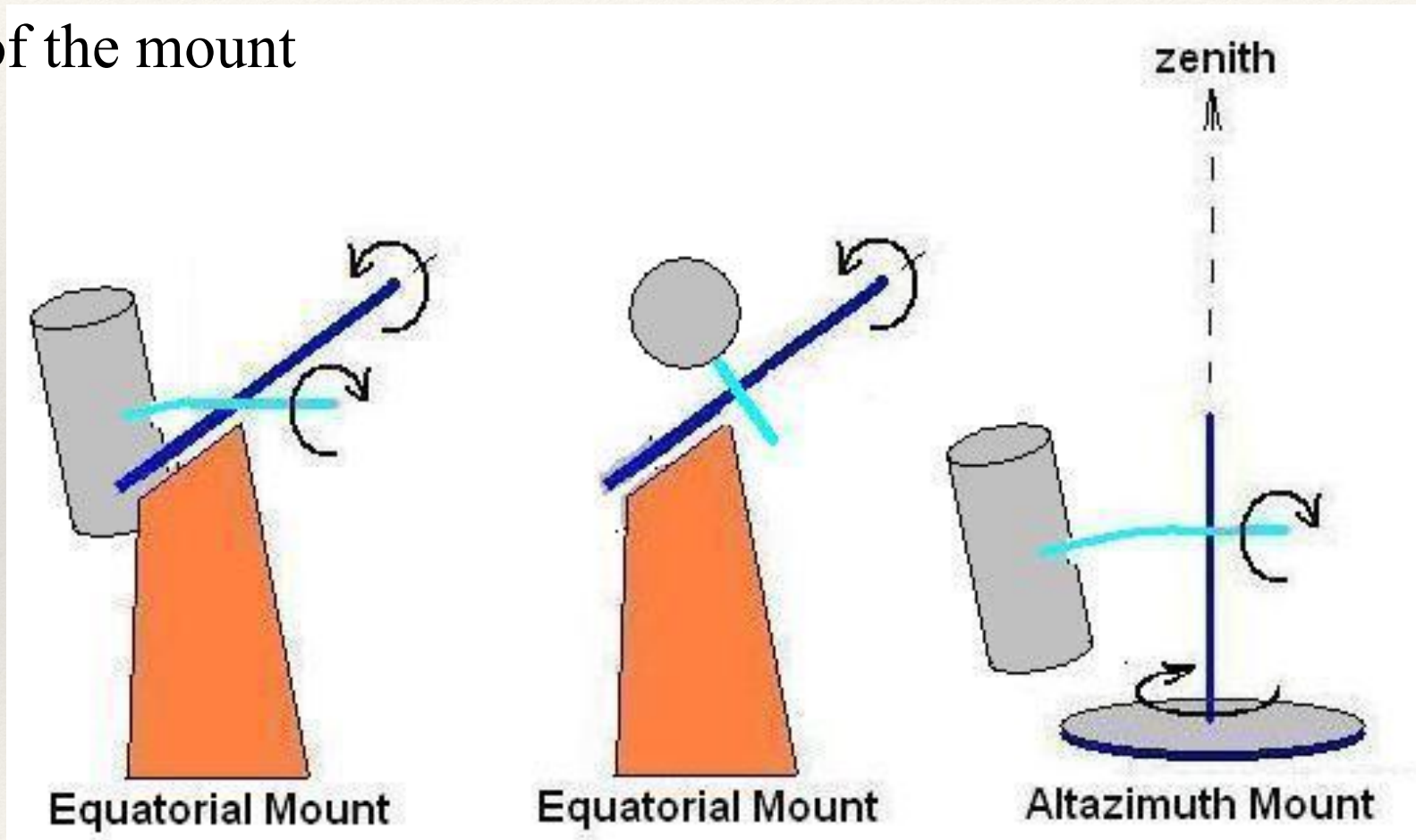


To Polaris



# Telescope Mounts

## Flexure of the mount



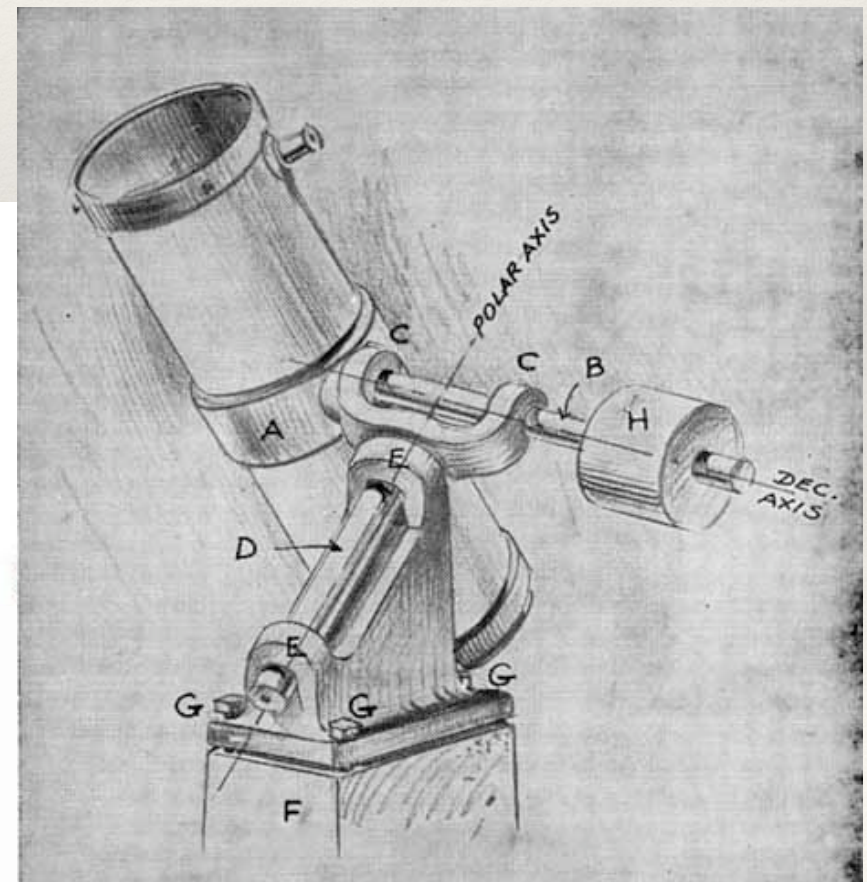
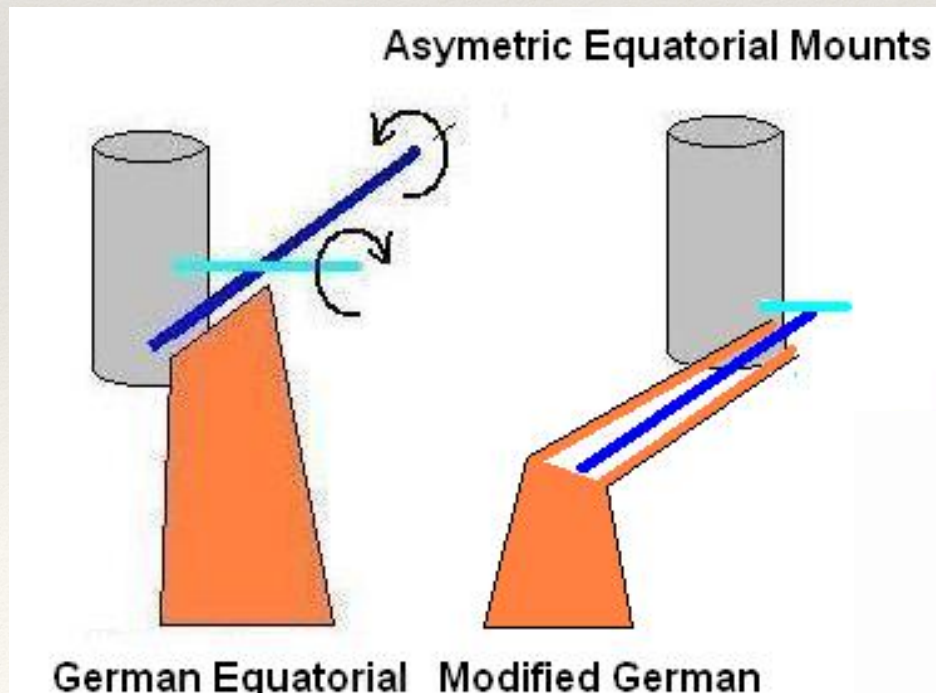
The bending of the declination axis of a German Equatorial mount will change depending on the part of the sky being observed, causing tracking and pointing errors (a similar problem occurs with the forks of a Fork Mount). While the altitude axis of an altazimuth mount may bend, the bending is constant and can be compensated by realignment of the tube or optics.



# Telescope Mounts

There are various means of building an equatorial mount.

- German Mount: Most frequently used for refracting telescopes. Must be "reversed" to observe on both sides of the meridian.
- Modified German Mount: By extending the polar axis (and providing support at the far end) the tube can clear the pier without the need to reverse.

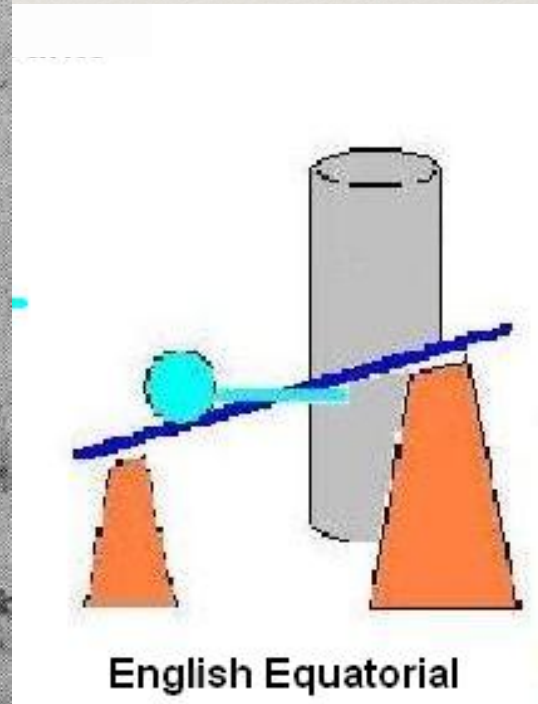
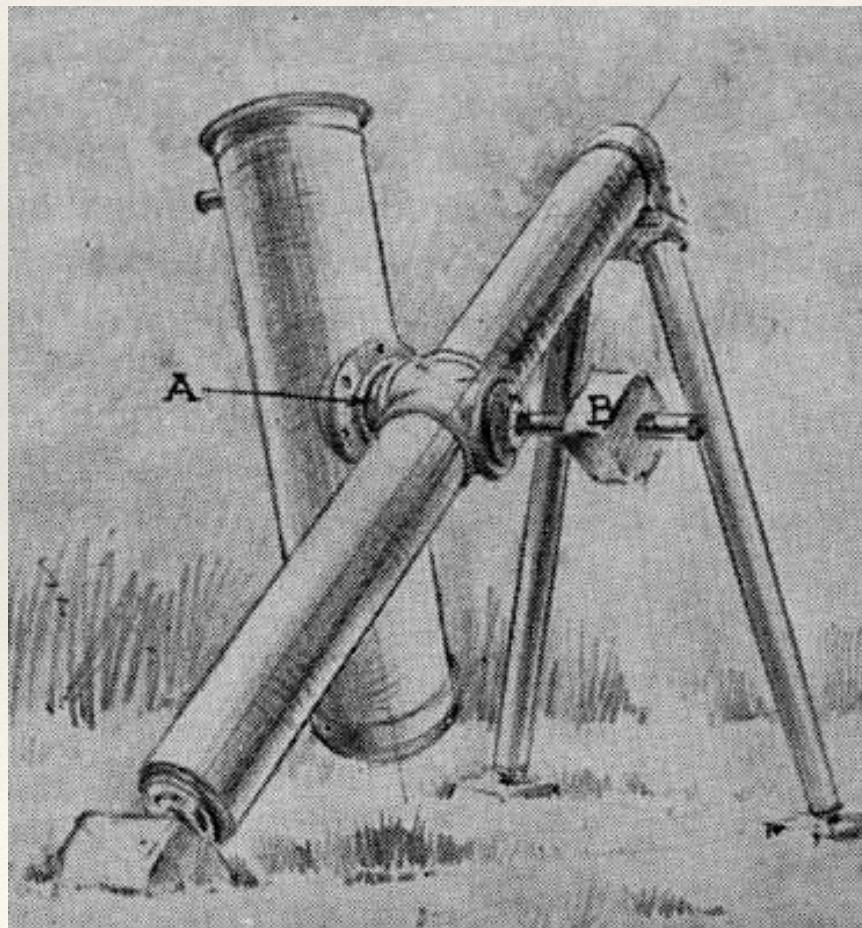




# Telescope Mounts

There are various means of building an equatorial mount.

- English Mount: Must be "reversed" to observe on both sides of the meridian. Full support for both ends of the polar axis may restrict use near the pole.

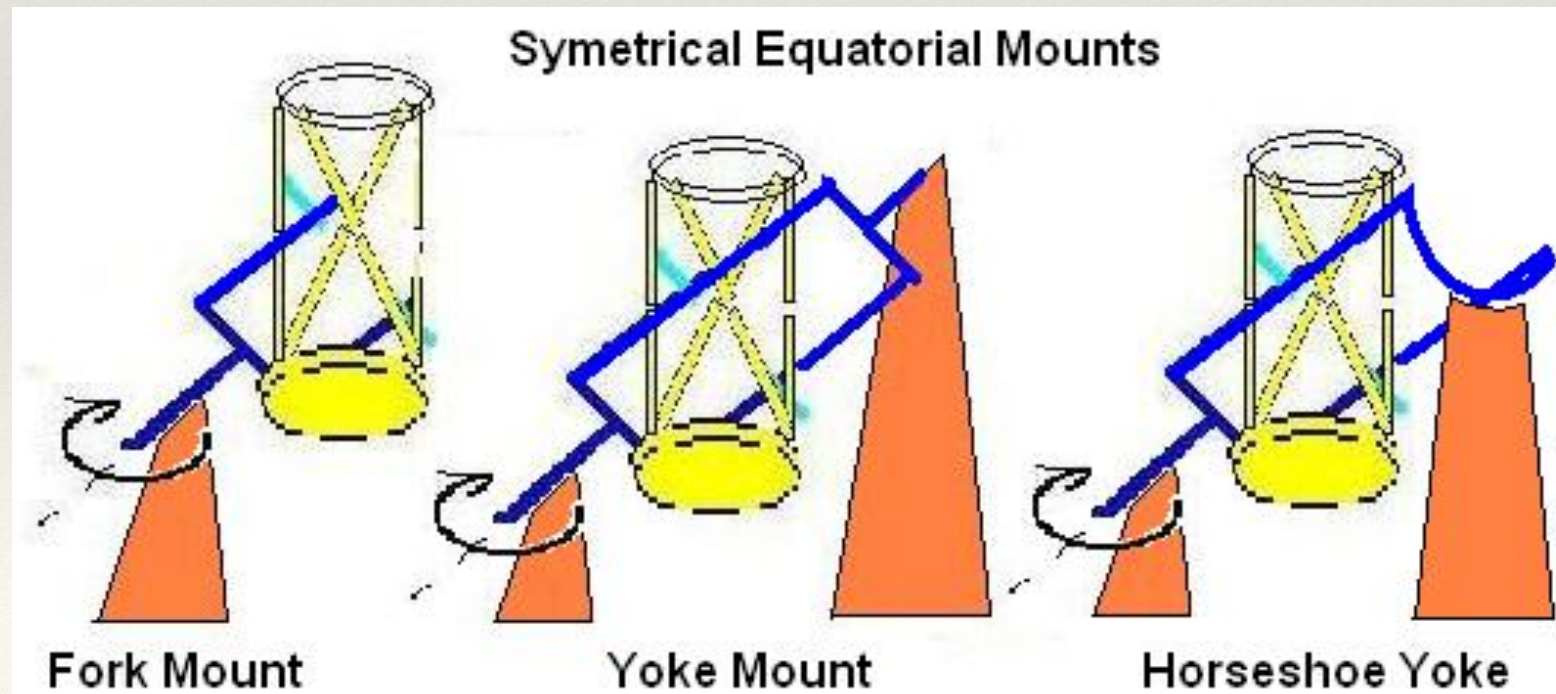




# Telescope Mounts

The other general class of equatorial mounts are symmetric mounts.

- Fork Mount: most frequently used for reflecting telescopes. To reach pole, tube must clear fork.
- Yoke Mount: Added support for polar axis. Cannot reach pole.
- Horseshoe Yoke Mount: Allows reaching pole while providing support at both ends of polar axis.



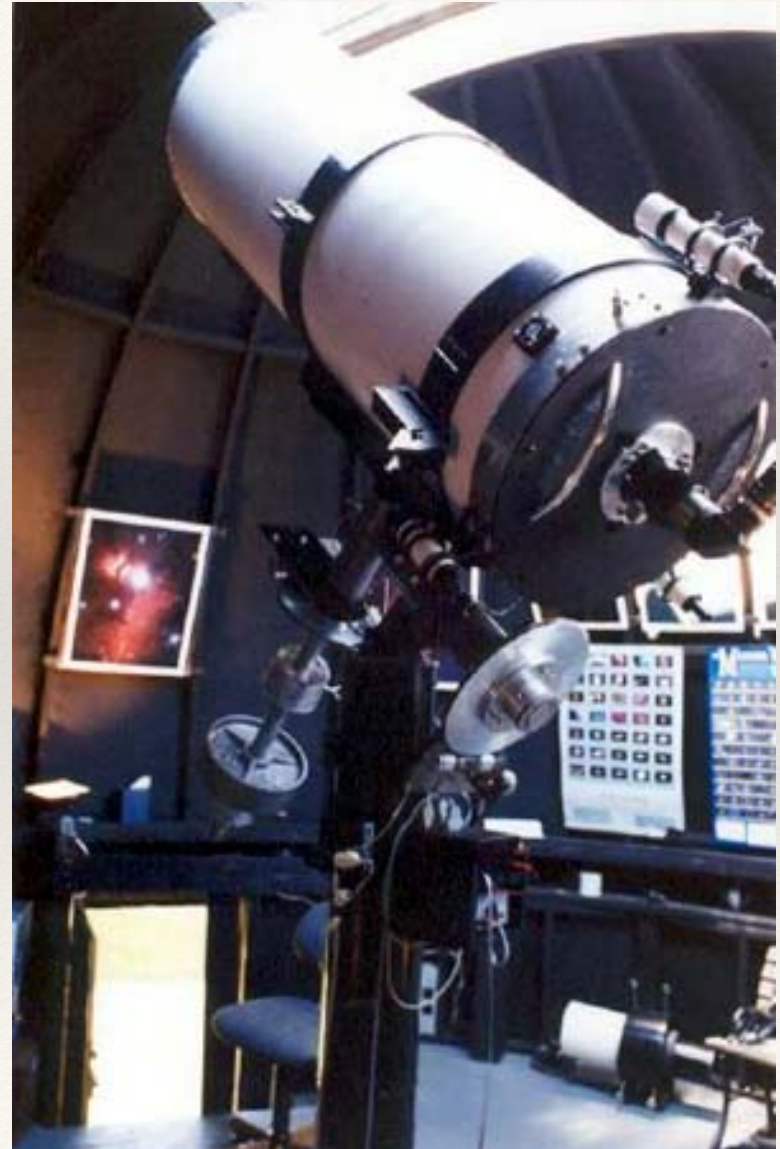


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# Telescope Mounts

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German Equatorial Mount



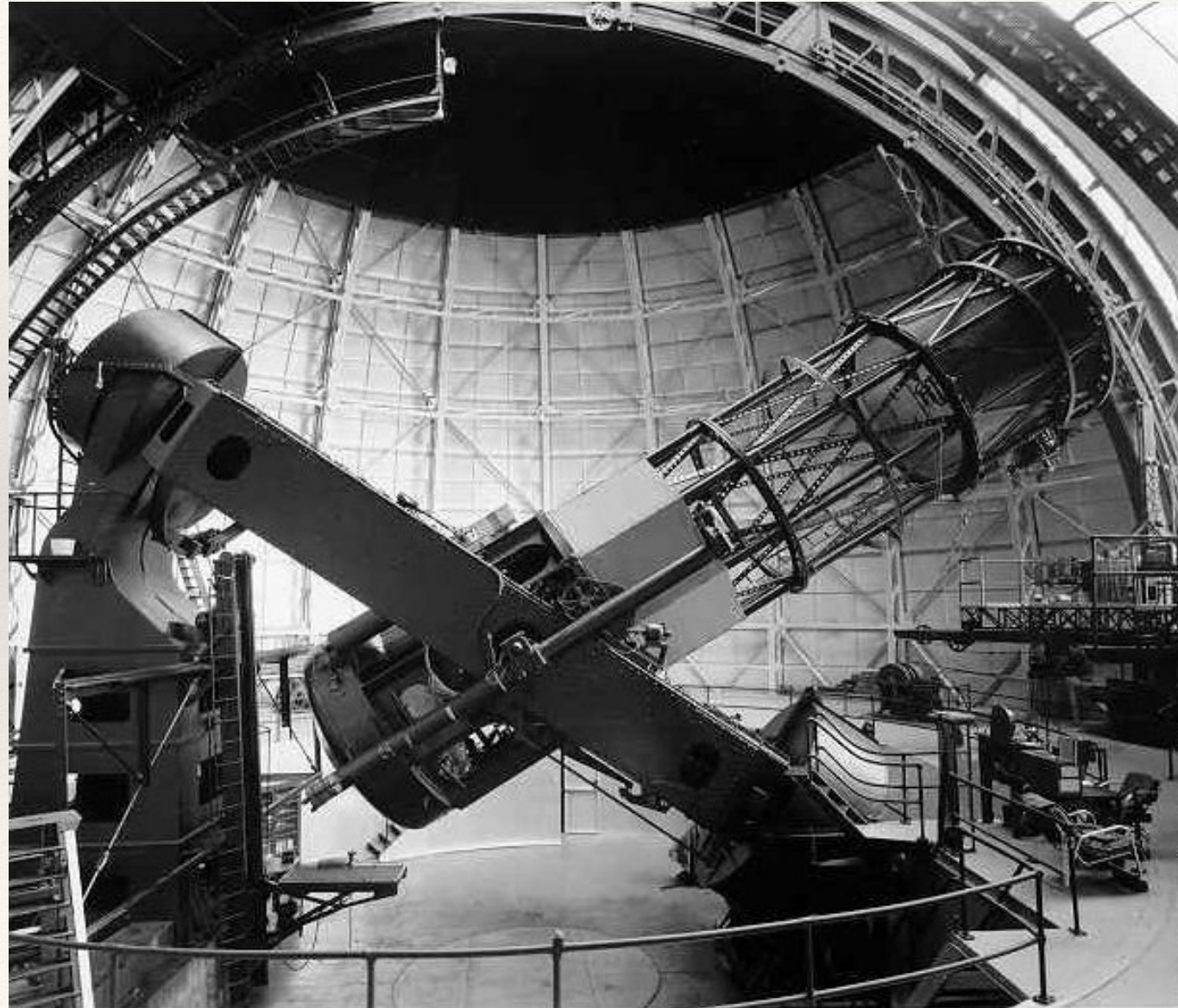


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# Telescope Mounts

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Mt Wilson 2.5m  
Yoke Mount





Palomar 200''  
Horseshoe Yoke





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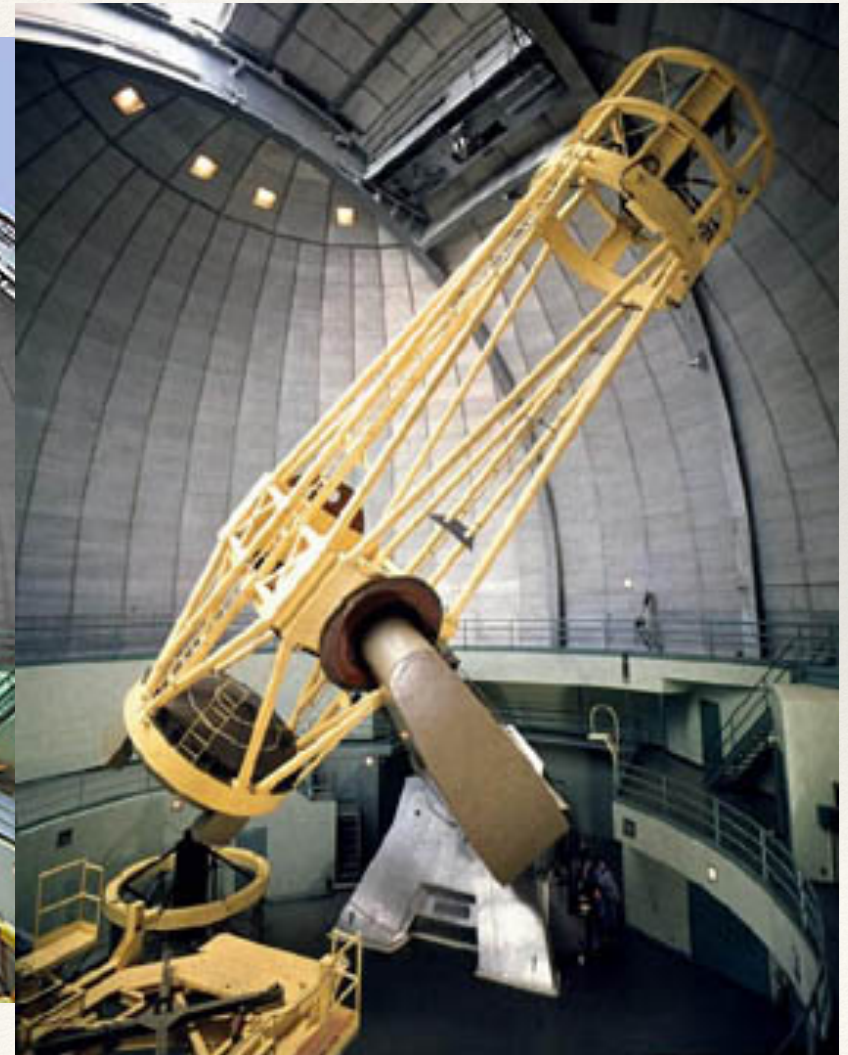
# Telescope Mounts

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Lick Observatory 120''  
Fork Mount



Laure Hatch



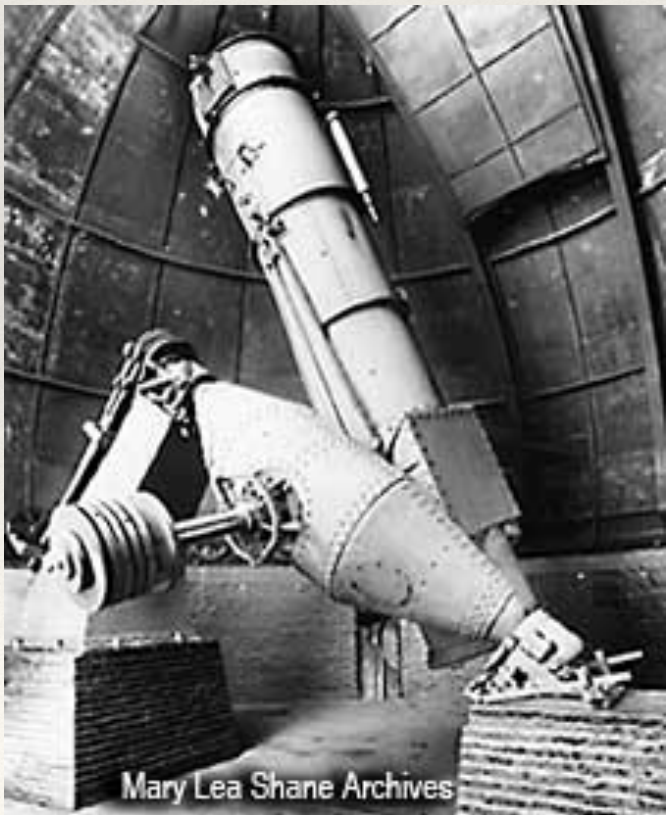


11-14" Telescopes  
Fork Mount

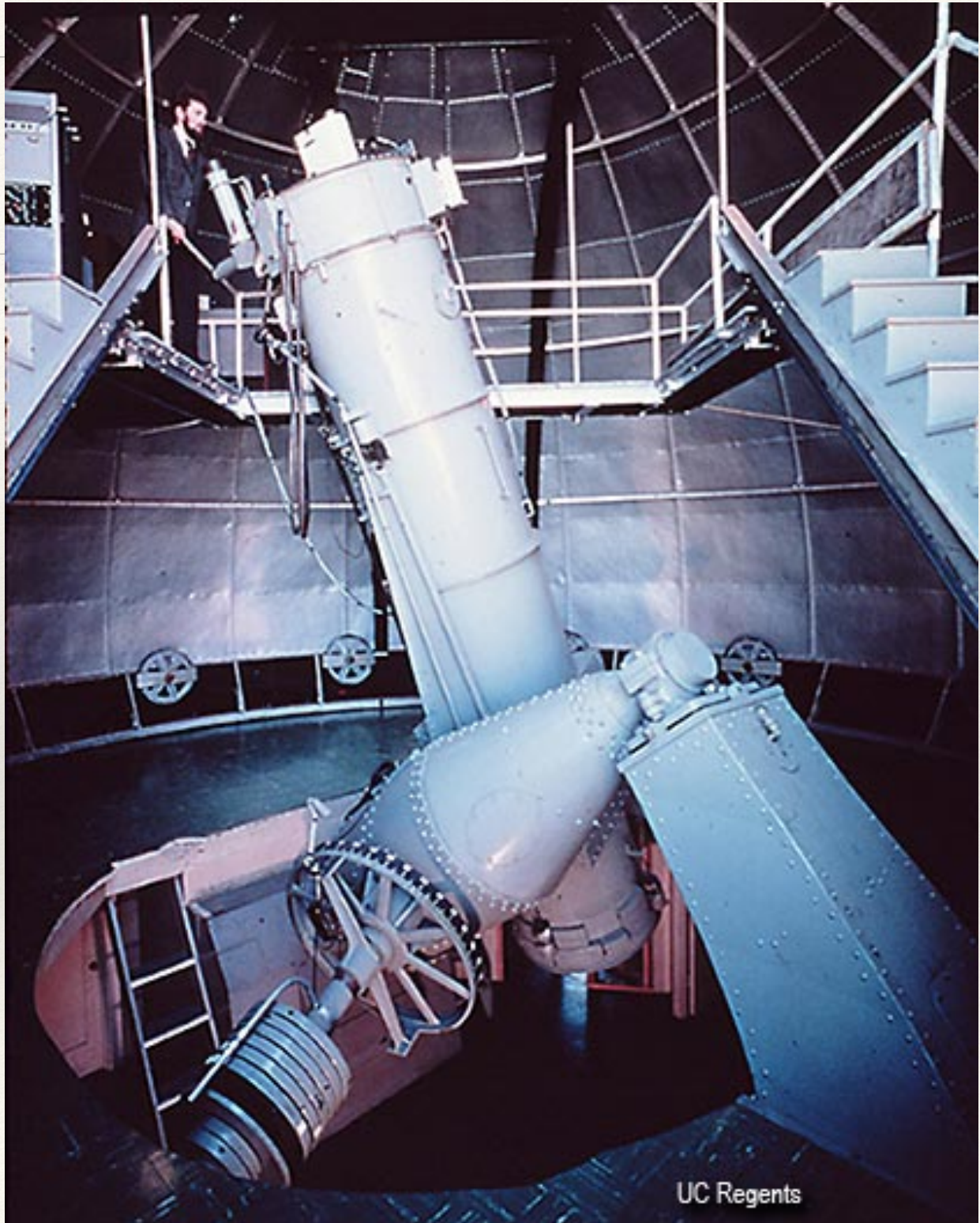




Lick Observatory 0.91m Crossley  
English Equatorial



Mary Lea Shane Archives



UC Regents





Istituto e Museo di Storia della Scienza





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# Segmented Mirror Telescopes

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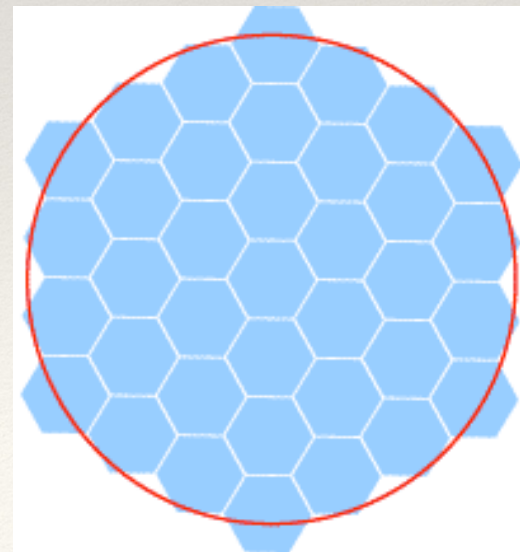
Some of the largest telescopes in the world (Keck, HET, GTC) and on the drawing boards (GSMT, TMT) have segmented primary mirrors. The two key motivations for such designs are practicality and cost.

As a mirror gets larger:

- ❖ Transporting it to the telescope gets complicated (remember that these have to be taken up winding roads to the tops of mountains)
- ❖ Polishing and aluminizing the mirrors gets harder
- ❖ Manufacturing the mirrors gets challenging and expensive

In practice, at present monolithic mirrors are practical up to about 8m diameter; for larger telescopes segmented mirror systems rapidly become more economical.

*There is, of course, a price to be paid in terms of increased complexity...*





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# Segmented Mirror Telescopes

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Complications:

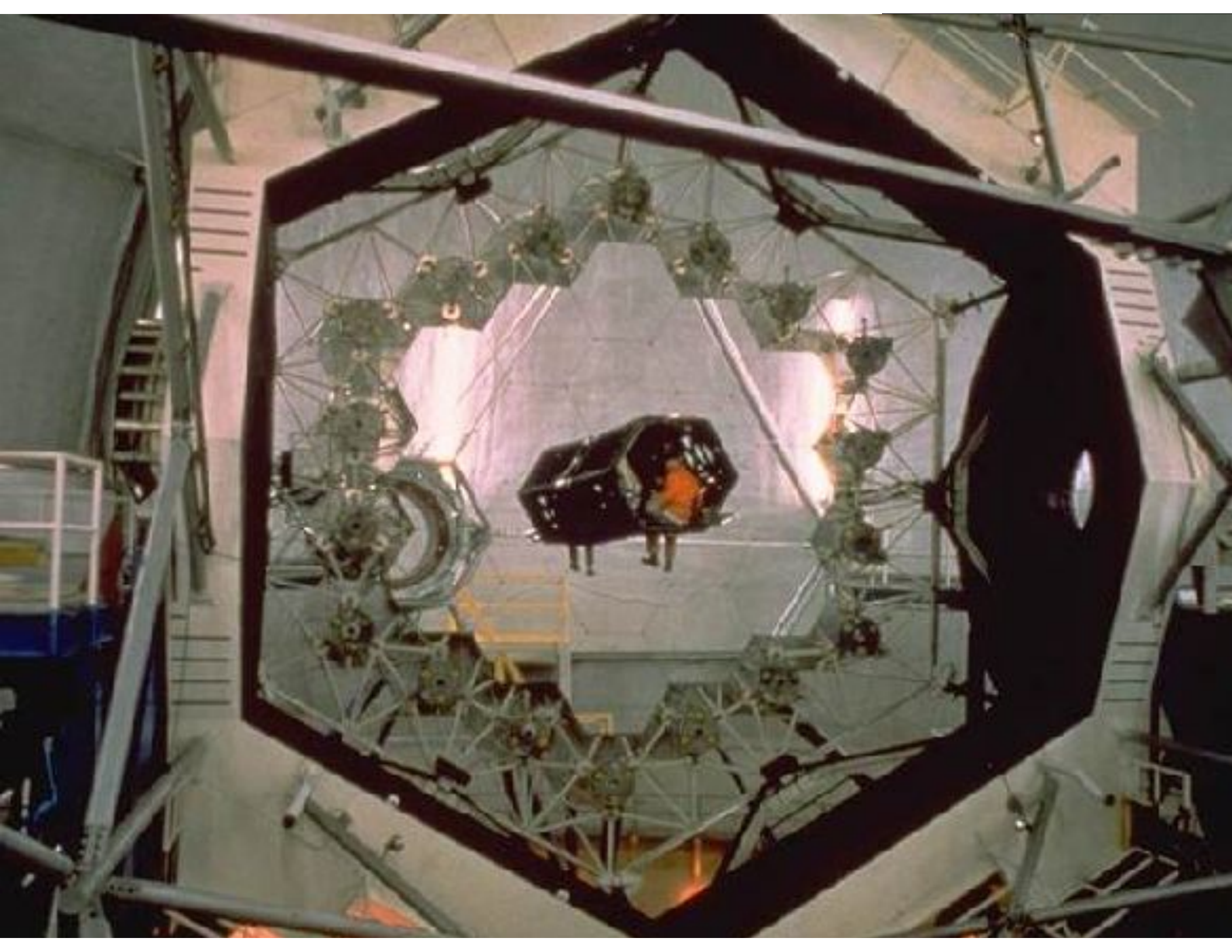
## *Making the Mirrors*

One key complication is that each mirror segment must be ground to have the right curvature for its location in the mirror mosaic. What this means is that the mirrors at different distances from the center have different curvatures. This curvature generally corresponds to an off-axis hyperboloid, which is complicated to manufacture.

## *Mirror Alignment*

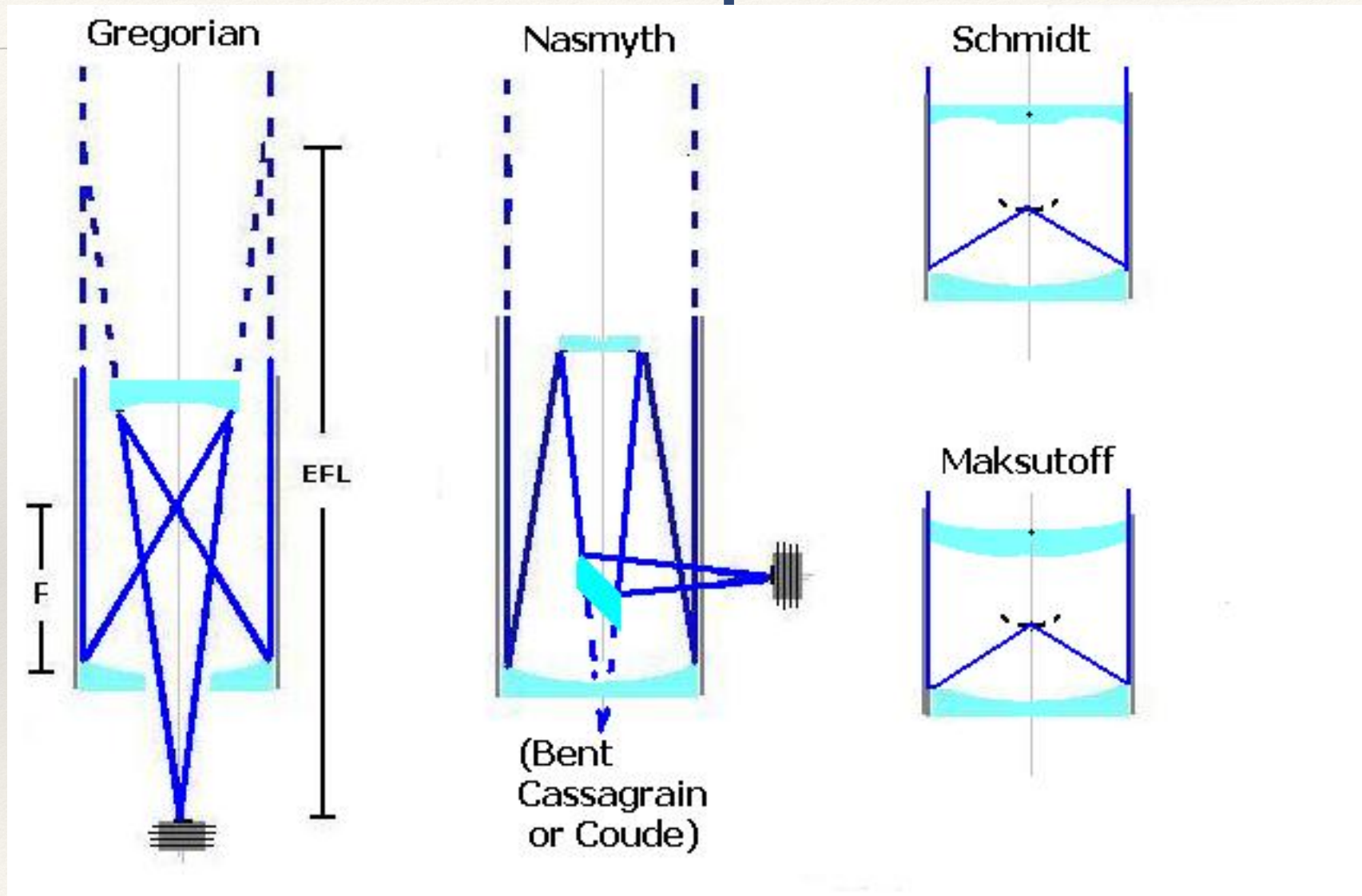
A second complication is that you have to keep all the mirrors correctly aligned so that they point to a common focus. This requires having active control systems with pistons (or equivalent) to slightly nudge the corners of every mirror and get them aligned, and a software+hardware system to do this alignment automatically.







# Other Telescope Variations

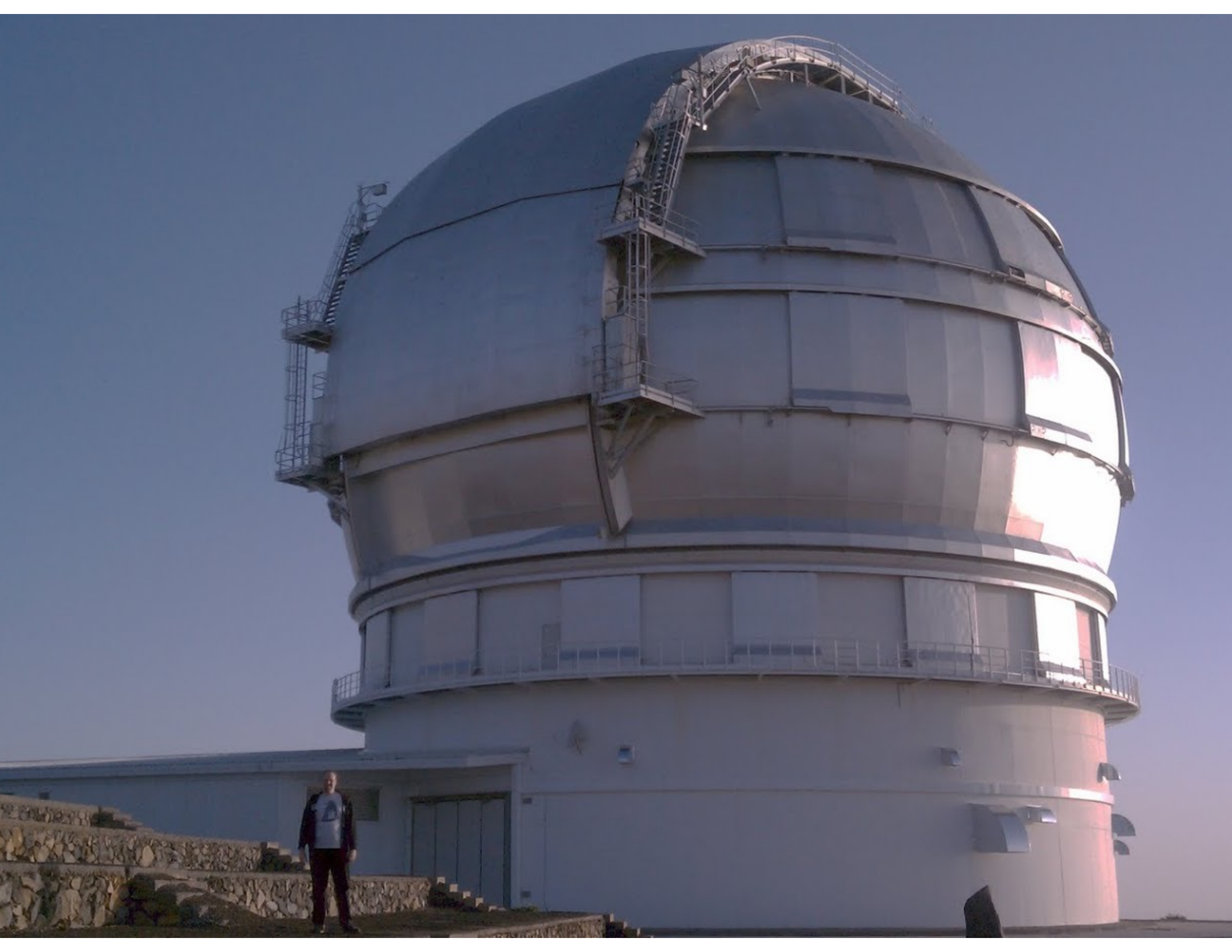


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And now for a trip down memory lane....





























ASTA

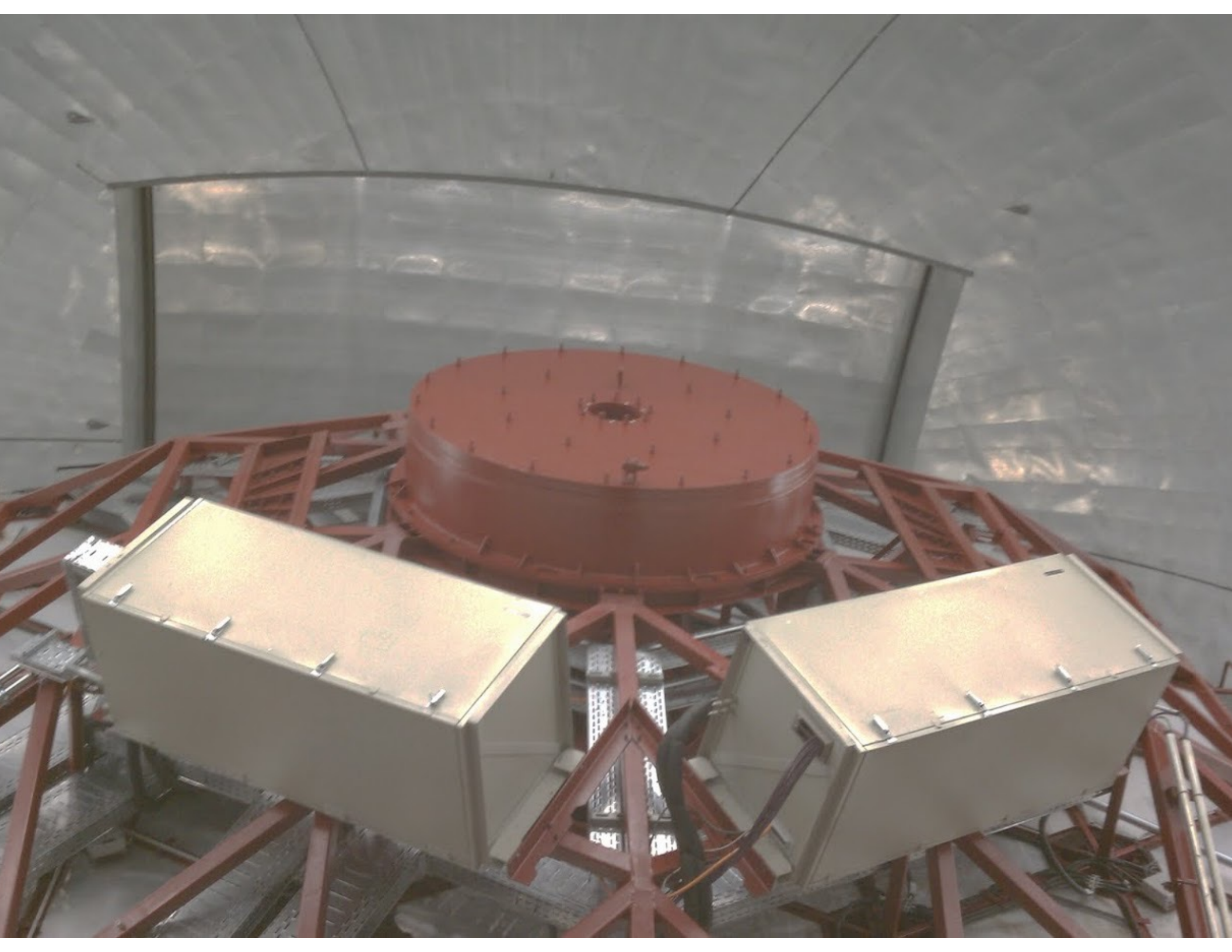


























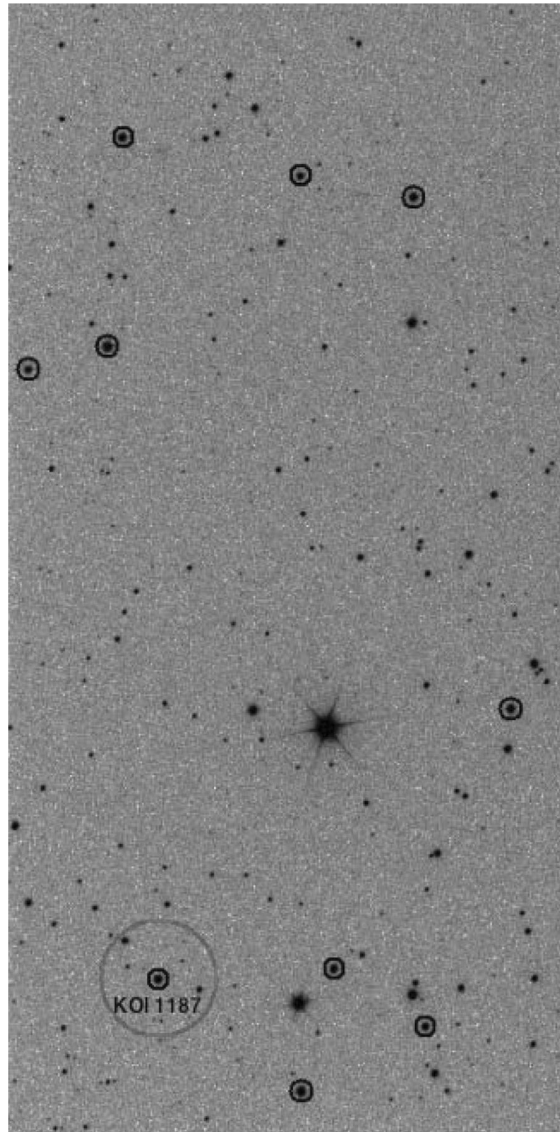






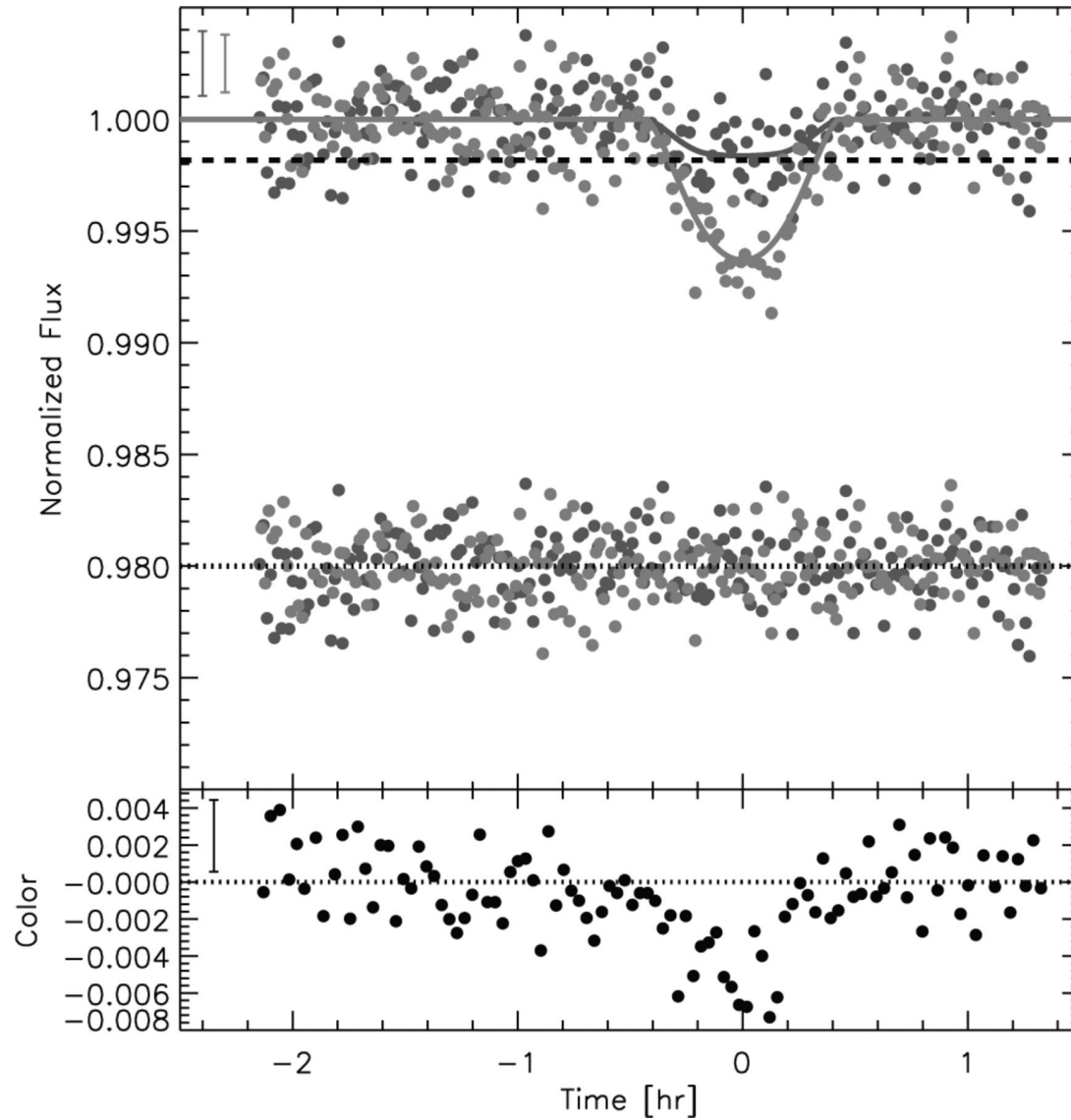


**Image of the field of view around KOI 1187 as acquired using the GTC/OSIRIS and the 666/36 nm order sorter filter.**



**Knicole D. Colón et al. MNRAS 2012;426:342-353**

Same as Fig. 6, but for the transit of KOI 1187.01 as observed on 2011 June 12.



Knicole D. Colón et al. MNRAS 2012;426:342-353