



Telescope Optics 101 with demos!

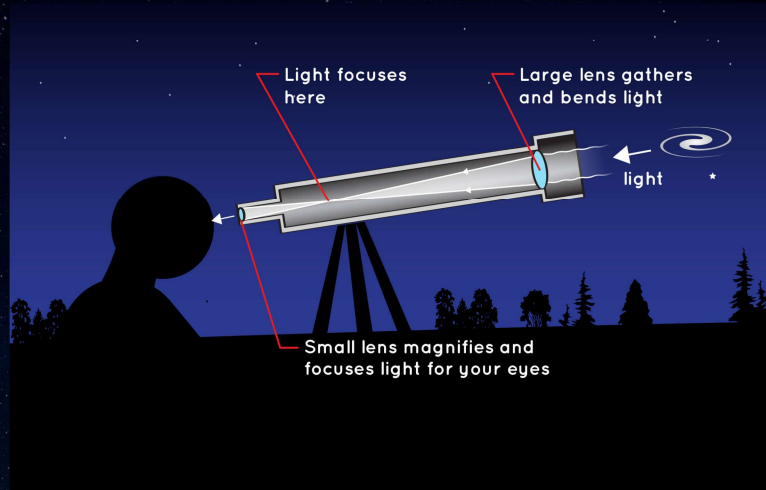
Tom Heisey
Solar System Ambassador
Sept. 17, 2026



Sections

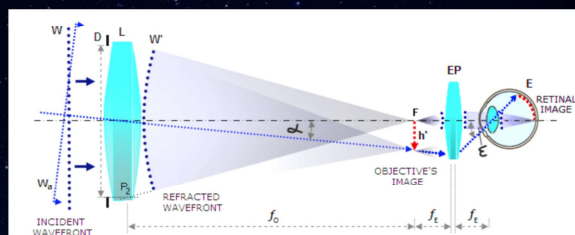
• A bit of math

- Aberrations
- Eyepiece designs
- Telescope designs
- What is an Airy disk?
- Demonstration with optical experiment kits



A Telescope's Purpose

1. **Gather Light** (make it brighter)
2. **Increase detail** (make it sharper)
3. **Magnify** (make it larger)



www.telescope-optics.net

- **Objective size** increases light gathering.
- **Optical quality** increases detail.
- **Focal length** controls magnification range.

<https://www.telescope-optics.net/system.htm>

My talk will walk through the basics of eyepiece and telescope optics and how the design affects what you see. It pays to keep a few facts in mind when discussing telescope optics:

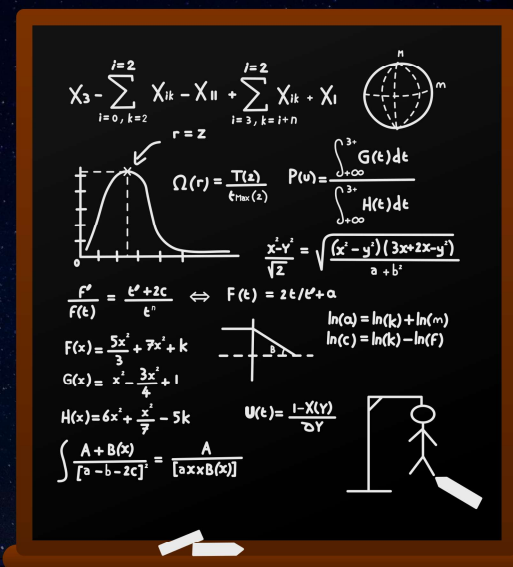
- * The most important purpose of a telescope is to gather light, so larger apertures see more distant objects.
- * Quality lenses and mirrors increase detail in ideal conditions. No scope will see much detail during turbulent atmospheric conditions!
- * The focal length of a telescope controls the range of magnification of the scope.

Line diagrams are essential to understand how the lenses, mirrors, and aberrations work. If you want to learn more about optical line diagrams, see the companion document "Ray Tracing for Astronomy".

Telescope Math

- To examine telescope optics, you'll need to do some fairly simple math.

- Focal Ratio
- Field of View
- Magnification
- Min/Max Magnification
- Resolving Power
- Stellar Magnitude Limit



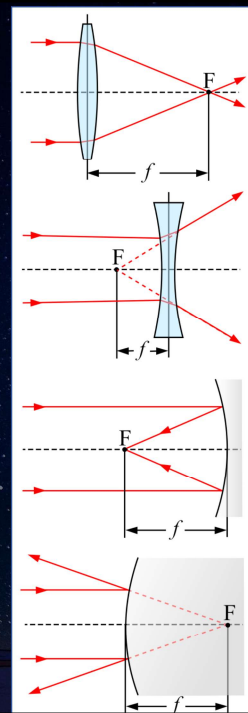
To know how an eyepiece or telescope should perform, you need a little bit of simple math based on the optical components.

<https://telescopeschool.com/astrophysics-formulas-explained-with-sample-equations/>
<https://clipground.com/math-chalkboard-clipart.html>

Definitions

- **Objective** - first & largest lens/mirror
- **Focal point** is the location where the parallel rays converge.
- **Focal length** is the distance from the objective and the focal point.
 - Measure from the CENTER LINE of the lens or the CENTER SPOT of the mirror.
 - **Positive FL** focal point is **behind the lens** or **before the mirror**.
 - **Negative FL** focal point is **before the lens** or **behind the mirror**.

F = Focal point
f = focal length



By Henrik

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Both lenses and mirrors have concave (inward) or convex (outward) curves. (For the purpose of these calculations and the line diagrams ignore flat mirrors such as secondary mirrors in Newtonian telescopes)

* Mirrors are simple, they have one optical surface that is usually concave. The other side is there to support the reflective surface, so no matter if it's thick, thin, smooth, or waffled, it doesn't affect the light reflection.

* Lenses have two surfaces that can be flat, convex, or concave in many configurations. We are looking at a **simple lens** (yes, that's a real term) where the same curve is mirrored across the lens' center plane.

* We'll talk about assymetric lenses, lens sets, and mirror sets later.

Focal Ratio

- Focal Ratio

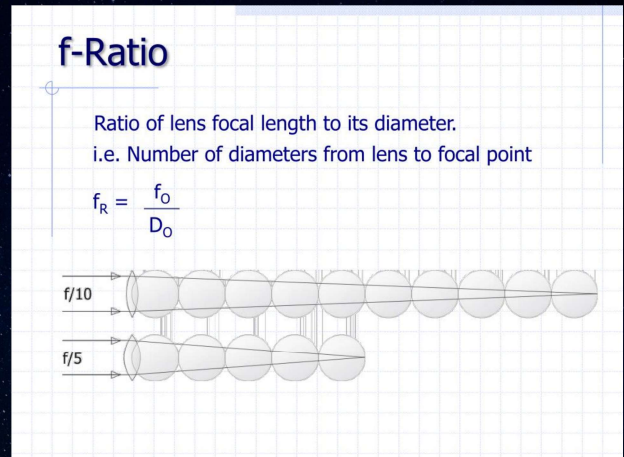
- Lens focal length over
- Aperture Diameter

- Focal Ratio Generalities

(within the same diameter):

- f/2-f/4 - Wide field, low magnification
- f/5-f/7 - General purpose
- f/8-f/15 - narrow field, high mag.

- Objective diameter = the free diameter of the light at the objective



www.slideserve.com

<https://www.slideserve.com/royal/telescope-equations>

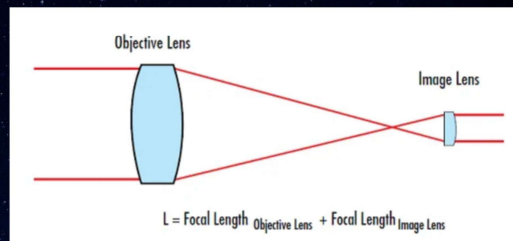
No matter the size of the scope, the focal ratio gives you an idea of the general performance of that scope compared against other scopes of the same diameter. The focal length is baked into the design of the optics.

NOTE: The objective diameter is the maximum width of the light path. The light path usually matches the lens/mirror size, but some cheaper telescopes use light baffles inside the tube to hide defects that the mirror/lens edge, so the objective diameter could be restricted.

An old-school trick to increasing magnification is to restrict the incoming light with a hole in the objective cap, reducing the objective size, which effectively increases the focal ratio. Unfortunately, you lose light gathering and detail you have with the full objective.

Telescope Magnification

- The focal length controls the magnification range of your eyepieces
- Compare two 100mm scopes



f/#	Eyepiece	Math	Mag.
f/5	20 mm	500/20	25x
f/10	20 mm	1000/20	50x
f/5	10mm	500/10	50x
f/10	10mm	1000/10	100x

Focal ratio = $FL_{tel} / \text{Aperture}$

Magnification = FL_{tel} / FL_{ep}

FL_{tel} = telescope focal length

Physics dictates that larger scopes have longer focal lengths (f/ratios are multiples of objective size), so in general, they have higher magnification than smaller ones. That's why small refractors and binoculars give wide views while 8" and larger are needed for narrow, high magnification views. There is very little you can do to change this basic fact of physics. (more on that in a bit)

Field of View & Magnification

- **Field of View (FOV)** is the amount of sky seen in the scope.
- **Apparent Field of View (AFOV)** FOV of an eyepiece.
- **True Field of View (TFOV)** the actual space between stars.
- The amount of magnification changes with eyepiece fl.

$$TFOV = \frac{AFOV}{MAG \text{ or Magnification}}$$

$$MAG = \frac{\text{Focal length of telescope}}{\text{Focal length of the eyepiece}}$$

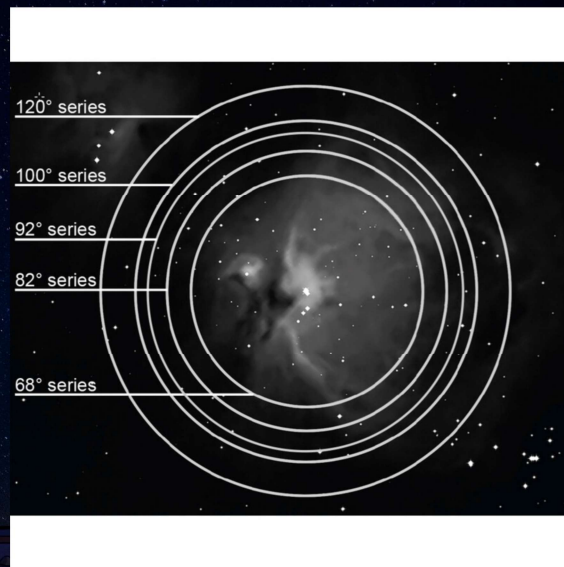
Telescope FL	Eyepiece FL	Eyepiece AFOV	Magnification	FOV
1000	10	50°	100x	.5°
1000	10	82°	100x	.82°
1000	25	50°	40x	1.25°
1000	25	82°	40x	2.05°

<https://telescopeschool.com/astronomy-formulas-explained-with-sample-equations/>

AFOV is usually advertised with the eyepiece sales page. Common Plossls have 50° AFOV while wide-field, specialized eyepieces go up to 100° AFOV.

What does a wide FOV do for you?

- You see more of the object
- Wide FOV EPs are difficult to design around distortions:
 - “kidney bean” black spots
 - Barrel distortion (convex)
 - Pincushion (concave)
- You may have to “swim around” the image to see it all.



Wide field eyepieces are a huge help on longer focal lengths with narrow fields of view, but a small refractor with a wide field eyepiece is wonderful to wander through the Milky Way.

Power Per Inch (PPI)

- PPI is a rough guide to magnification
- Excellent seeing - up to 50 PPI
- Average seeing - up to 30 PPI

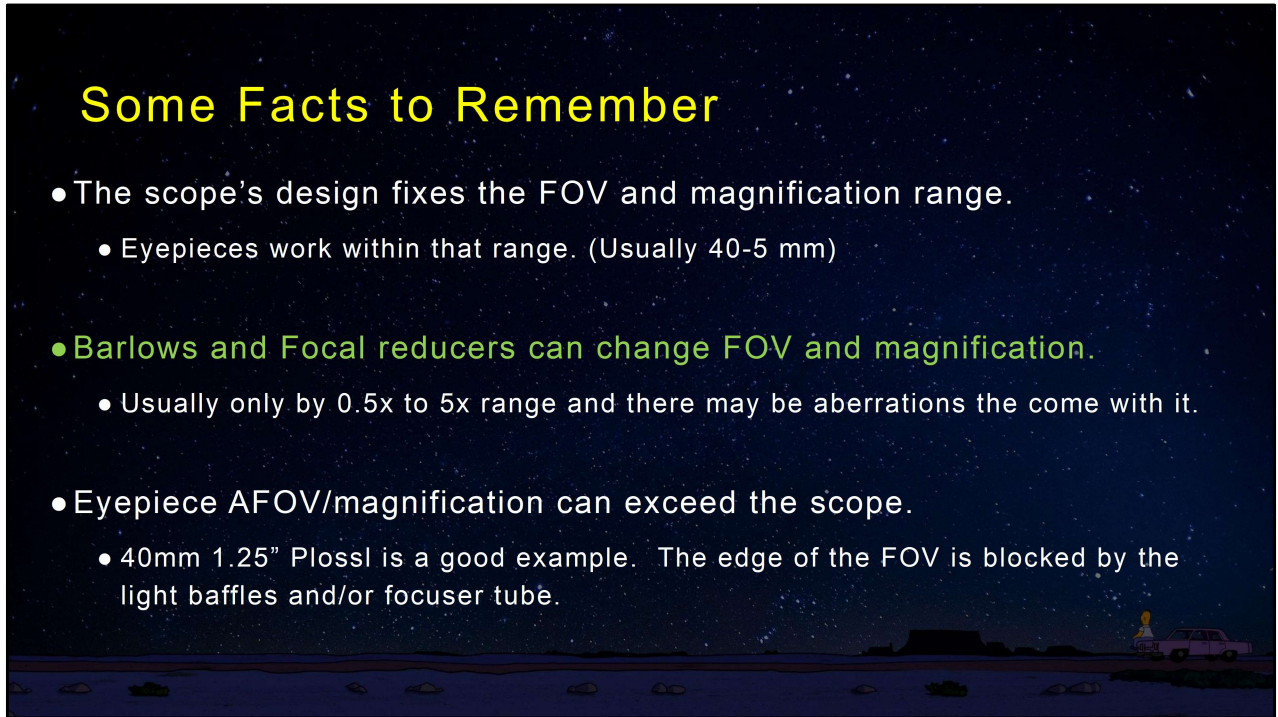
$$\text{MAGNIFICATION} / \text{APERTURE (IN.)} = \text{PPI}$$

Magnification	Aperture	PPI
200x	3"	66
200x	4"	50
200x	6"	33
200x	8"	25
300x	3"	100
300x	4"	75
300x	6"	50
300x	8"	37

Power Per Inch is an oft-ignored rule of thumb for how much magnification the atmosphere allows. This is a general rule and a truly exceptional night of good or bad seeing blows this rule out of the water. I've had one night in 25 years where I got to 800x on the Moon with my 8" SCT. The view was astounding, but filled with floaters from my eyes. LOL! I've also done some wild double star-splitting with small refractors over the decades, but those astounding nights are far less common than bad seeing.

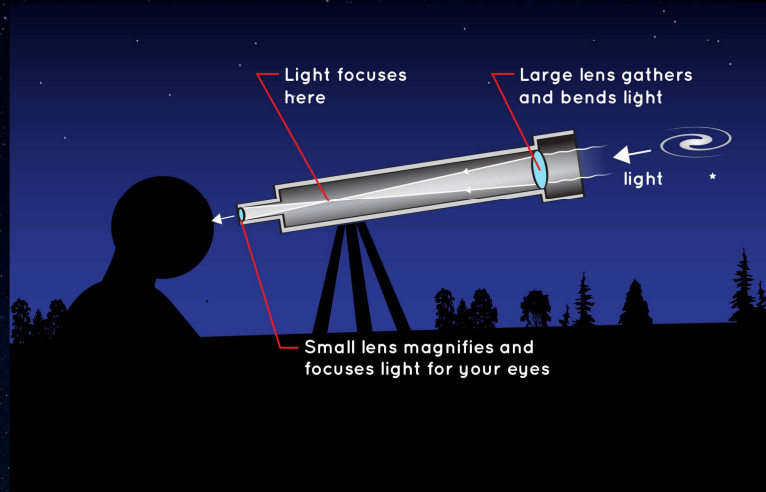
Some Facts to Remember

- The scope's design fixes the FOV and magnification range.
 - Eyepieces work within that range. (Usually 40-5 mm)
- Barlows and Focal reducers can change FOV and magnification.
 - Usually only by 0.5x to 5x range and there may be aberrations the come with it.
- Eyepiece AFOV/magnification can exceed the scope.
 - 40mm 1.25" Plossl is a good example. The edge of the FOV is blocked by the light baffles and/or focuser tube.



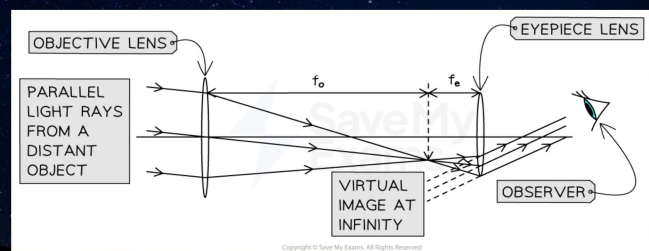
Sections

- A bit of math
- **Aberrations**
- Eyepiece designs
- Telescope designs
- What is an Airy disk?
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How Does The Image Form?

- Ray trace diagrams are simplified to show a single light source
 - A single point on the center line is common.
 - Light rays are **parallel from that source**.
 - Off center stars have angled, but parallel light as in this diagram:
- **Focus occurs where the focal points of objective and eyepiece meet.**
 - **Co-planar (flat)**
 - **Exact focus**



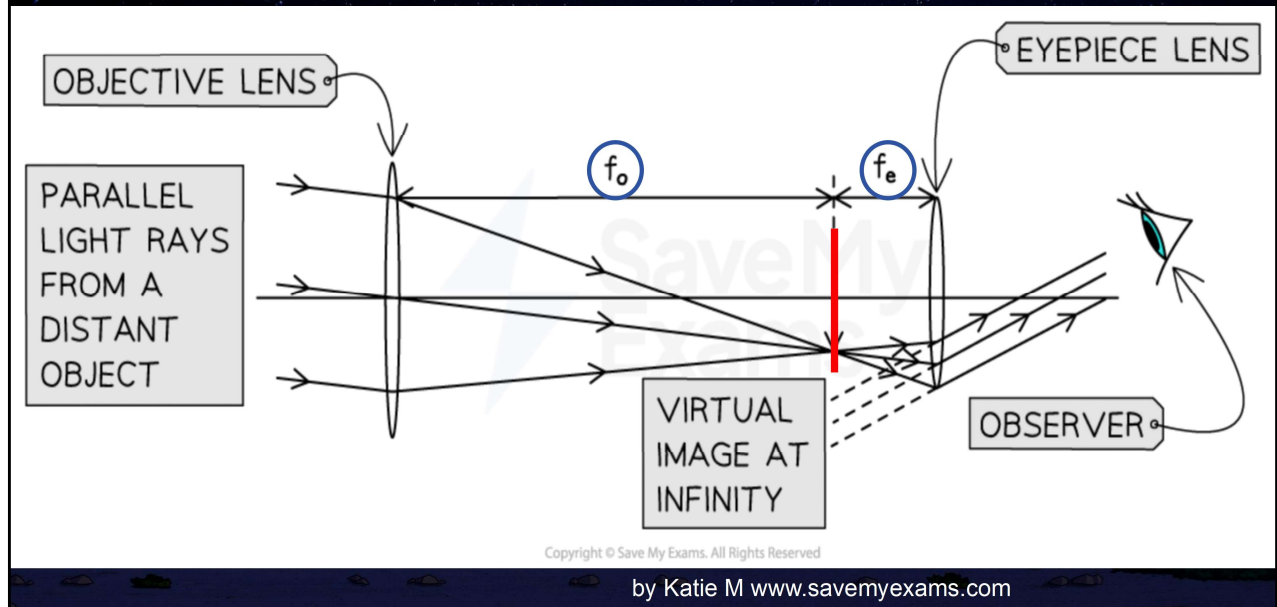
by Katie M www.savemyexams.com

<https://www.savemyexams.com/a-level/physics/aqa/17/revision-notes/9-astrophysics/9-1-telescopes/9-1-2-refracting-telescopes/>

To understand aberrations, we must first understand a bit about how and where the image forms in a telescope, which was something I didn't understand well. However, it finally registered that:

- * The line diagrams are greatly simplified to show the light from one star within the field of view.
- * The single focus point shown is just one dot on a larger focal plane perpendicular to the objective's center line.
- * The star at the exact center focuses at the centerline.
- * Off-center stars spread out from the center to the edge of the focal plane (the edge of the FOV)
- * Stars outside the FOV focus still focus on the focal plane, but hit one of the light baffles rather than lighting up the side of tube.

Focal Points meet at focus!



<https://www.savemyexams.com/a-level/physics/aqa/17/revision-notes/9-astrophysics/9-1-telescopes/9-1-2-refracting-telescopes/>

f_o is the focal length of the objective

f_e is the focal length of the eyepiece

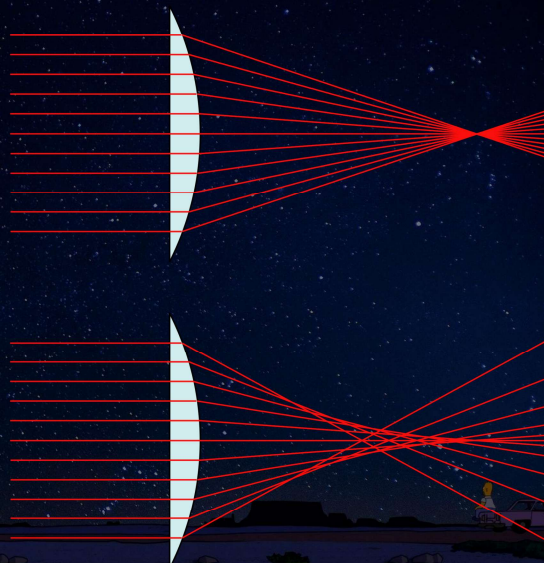
The red line represents the focal plane - the size is a guess.

Based on this diagram, the observer is looking at the fringe of the eye lens, so that puts an outer limit on the size of the focal plane.

The key point is that **for sharp focus, the focal planes of the objective and eyepiece must meet exactly**. Each star's focal point on the telescope's focal plane must hit the eyepiece's focal plane. If the planes are not parallel, then some stars will always be out of focus.

Abserrations

- Abserration is an optical defect
- Mirrors and lenses suffer from different sets of abserrations
- Each telescope is designed to eliminate some and manage other abserrations



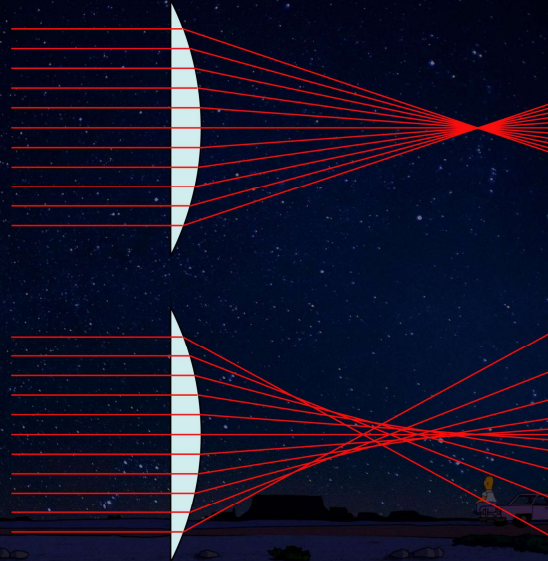
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https://en.Wikipedia.org/wiki/Spherical_abserration

All scopes and eyepieces will have abserrations to some extent. Most good scopes will eliminate most of the obvious abserrations, but if you look carefully under the right/wrong circumstances, you'll see at least a small sign of it.

Spherical Aberration

- Affects lenses and mirrors
- Spherical surfaces are easy to manufacture
- Off-center light does not fall on the focal plane, blurring the image

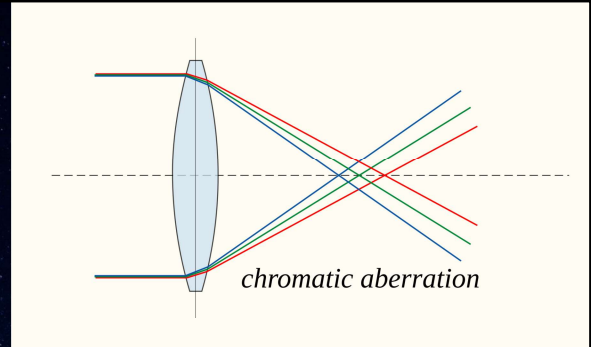


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https://en.Wikipedia.org/wiki/Spherical_aberration

In spherical aberration, the light from a single star fails to focus at one point as shown in the diagram. This is not a mistake in manufacture, but the nature of light reflecting on a sphere. To combat this aberration, objectives are figured to a parabola, which is more expensive to figure. Modern production machines can produce mirror surfaces to within a fraction of the wavelength of light, so this is a rare problem in quality telescopes.

Chromatic aberration

- Affects lenses only
- The the lens bends light waves at varying amounts blue least, red most. (yellow blue fringe)
- Lens design can reduce, but not completely eliminate \$\$\$
 - Low dispersion glass
 - Multiple lenses with different refractive indexes.



By DrBob

By Stan Zurek



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https://en.Wikipedia.org/wiki/Chromatic_aberration

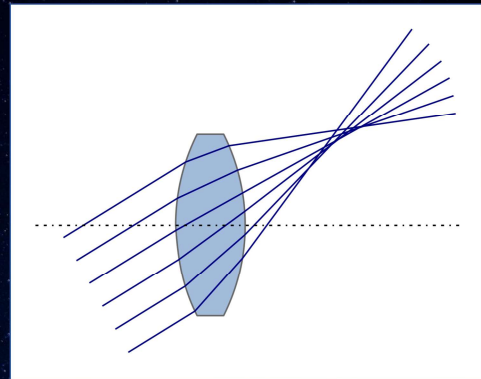
Chromatic aberration is found in lenses and just as with sunset, blue bends most and red the least. While it's pretty at sunset, the view in a telescope with CA results in a halo around bright objects and blurred details.

The cure is to use expensive glass with a different refractive index so the move closer to the central focal point. Another fix is to use long focal lengths, which bend the light less than longer focal lengths and therefore have less aberration. That's why the early refractors had incredibly long focal lengths. However, if you push a refractor to very high magnification on a very bright object like Sirius, you'll probably see at least a small halo, even on the most expensive refractors.

Since mirrors reflect the light rather than refracting the light, they do not suffer from chromatic aberration.

Coma

- Affects mirrors (common) and lenses (less common)
- Off-axis point sources distorted into comet-like shapes at the edges
 - Caused by a change in curvature between center and edge
- Can be corrected with a coma corrector

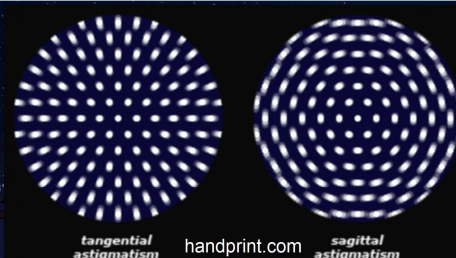
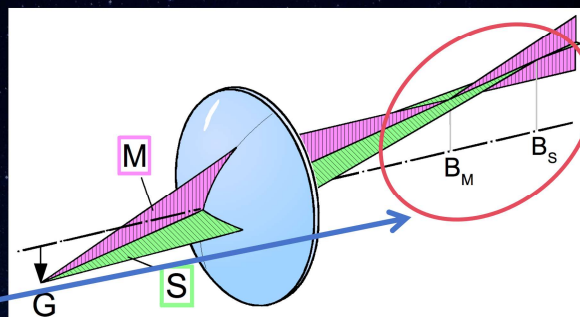


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[https://en.Wikipedia.org/wiki/Coma_\(optics\)](https://en.Wikipedia.org/wiki/Coma_(optics))

Coma is present at the fringe of the FOV, turning stars into ovals or in the worst case comets, which is how it got its name. Coma is primarily an aberration of mirrors, though it can affect lenses. Coma is common in portrait camera lenses, which are often made for soft out-of-focus backgrounds, which makes it hard to find a good lens for astrophotography. Newtonian telescopes with parabolic mirrors suffer from Coma and need coma correctors to eliminate most of the problem. The correctors must be made for specific focal lengths and objective sizes, so a corrector for one model won't work on another.

Astigmatism

- Affects lenses and mirrors
 - Poor alignment of optical surfaces
 - Optical flaws in optical surfaces
 - Critical for astrophotography, but may affect visual use.
- Areas of FOV have separate focal points, often at 90°
 - Causes oblong stars that won't come to a point
- Fixes - check alignment of optical surfaces



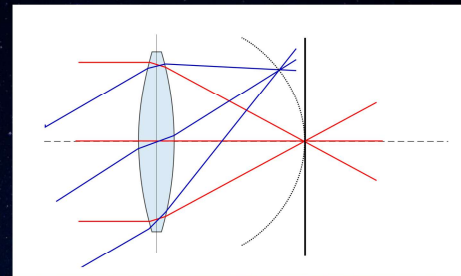
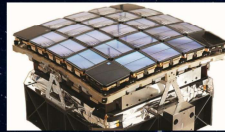
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[https://en.Wikipedia.org/wiki/Astigmatism_\(optical_systems\)](https://en.Wikipedia.org/wiki/Astigmatism_(optical_systems))

I've had astigmatism since my teens, but I never had a good explanation of exactly how it made it hard to read. For me, it's hard to distinguish E, F, f, H, A and other letters with horizontal lines, but O, Q, and G were obvious. The generic explanation of a misshaped eyeball really didn't explain the problem. After seeing this diagram, it's easy to understand why letters with strong verticals and horizontals are hard to read - The vertical lines focus at a different plane than the horizontal ones!

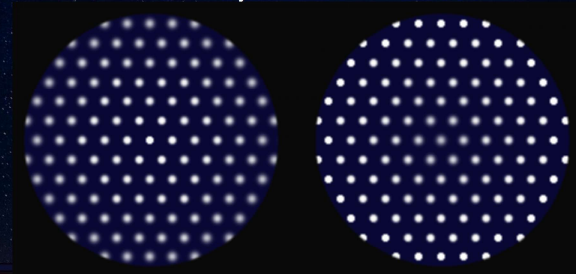
In most scopes, astigmatism is always possible, present when the optical surfaces are misaligned or have optical flaws. Since you can't have perfect alignment or perfect surfaces, astigmatism is always present, but in good scopes, the impact is minor or negligible. Because a camera can easily see much dimmer stars than the naked eye, astigmatism impacts astrophotography more than visual astronomy.

Field Curvature

- Affects both lenses and mirrors,
 - mainly found with imaging.
 - Visual astronomy less noticed
- Image center and edges focus at different points
- Corrected by
 - curved imaging surface (NASA)
 - Field flattener



By BenFrantzDale



handprint.com

curvature of field

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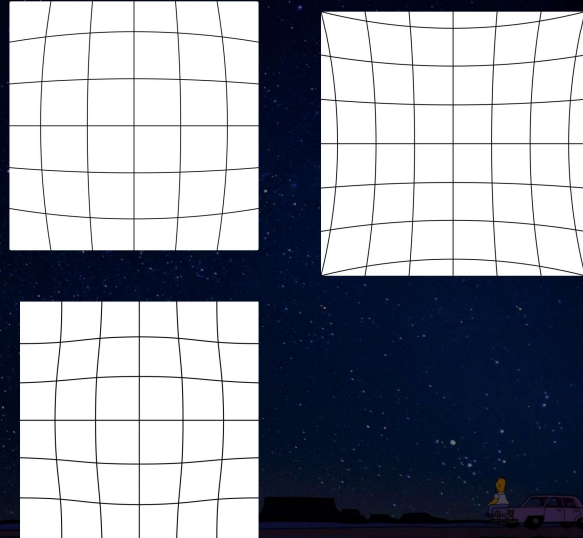
<https://www.handprint.com/ASTRO/ae4.html>

[en.Wikipedia.org/wiki/Petzval field curvature](https://en.Wikipedia.org/wiki/Petzval_field_curvature)

Field curvature affects both lenses and mirrors. The clue is that the edges are out of focus when the center is in focus and you'll see the stars come into focus in rings around the center as you move the focuser. The fix NASA uses for space telescopes is to curve the sensors so everything is properly in focus. Here on Earth, you can purchase a field flattener made for your telescope. Each scope model will have a unique curvature, so a flattener made for one scope won't work on another model.

Barrel, Pincushion, Mustache, Oh My!

- Affects both mirrors and (more often) lenses
- Distortions of optical surfaces that change the shape of the object being viewed
- Difficult to correct

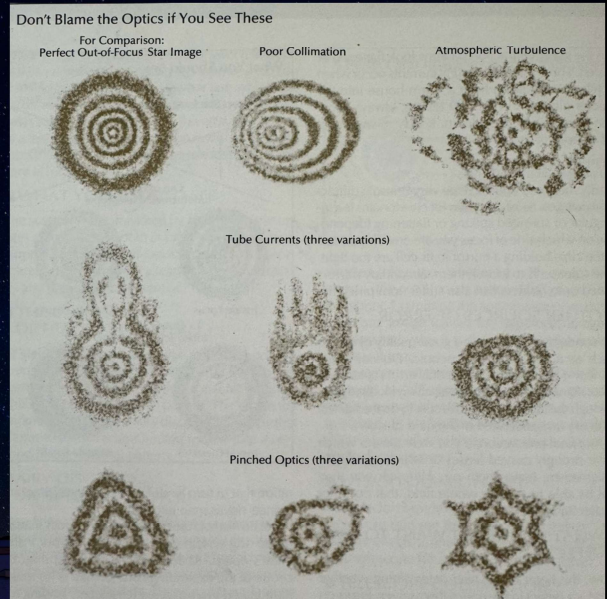


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[https://en.Wikipedia.org/wiki/Distortion_\(optics\)](https://en.Wikipedia.org/wiki/Distortion_(optics))

Common distortions are barrel (outward bend), pincushion (inward bend), and mustash (compound bend). When you correct for chromatic aberration with multiple lenses, it's easy to induce distortions, so lenses are susceptible to them. Mirrors with defects in the suface can also suffer from these distortions, but it's less common given the single surface that can be figured within a fraction of a wavelength of light.

Some more that are easy to fix

- Poor collimation leads to coma
- Poor seeing makes a mess
- Tube currents mean a hot mirror
- Pinched optics mean the lens/mirror mounts are too tight
 - Often triangular (3 hold-downs)



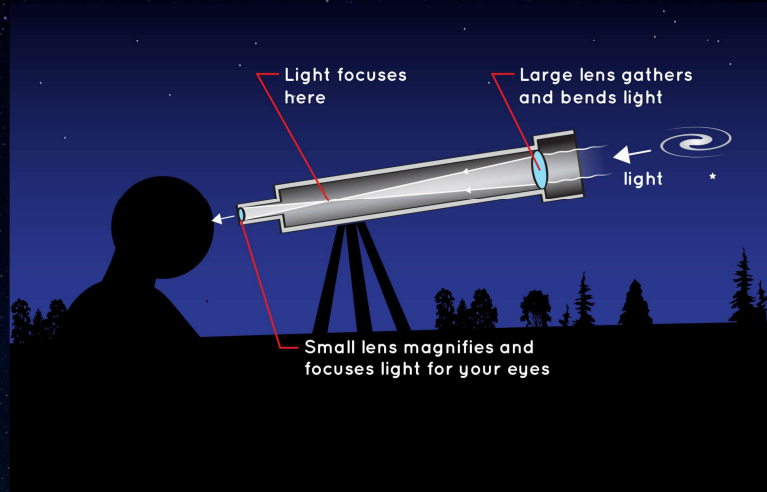
<https://www.cloudynights.com/forums/topic/898621-pinched-optics-what-does-it-look-like/>

Other distortions you may see at the eyepiece include:

- * Poor collimation - Refractors are usually immune to collimation issues. Thanks to relatively heavy mirrors, reflectors need at least occasional collimation. Out of collimation images look like coma, but it's across the view.
- * Atmospheric turbulence (seeing) - will make the stars bounce and smear randomly, sometimes with flashing colors. The key is the random movement all across the FOV.
- * Tube Currents - TC mainly affects open-air reflectors while the mirror is cooling down to the nighttime air temperature. Closed tube reflectors and refractors are less affected, though large SCTs sometimes come with cooling fans.
- * Pinched optics - PO is a symptom of the mirror hold-down or lens cell too tight and warping the optics. The result will be an odd shape, often triangular, short coma, or star, depending on the number of hold-downs that are too tight.

Sections

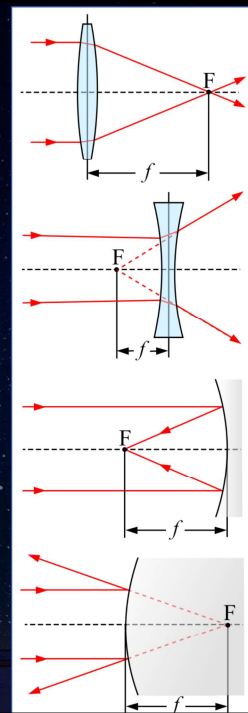
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Lens & Mirror Types

- **Objective** - first & largest lens/mirror
- **Lens** - Clear object with two optical surfaces that are **convex, concave, or flat**
- **Mirror** - Reflective surface that is usually concave, but may be convex or flat. The back of the mirror is only there for support.
- **Focal Point** is the plane where the image forms.
 - **Positive FL** focal point is **behind the lens** or **before the mirror**.
 - **Negative FL** focal point is **before the lens** or **behind the mirror**.

F = Focal point
f = focal length



By Henrik

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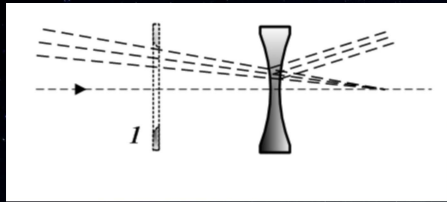
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* Measure from the CENTER LINE of the lens or the CENTER SPOT of the mirror.

* We'll talk about assymetric lenses, lens sets, and mirror sets later.

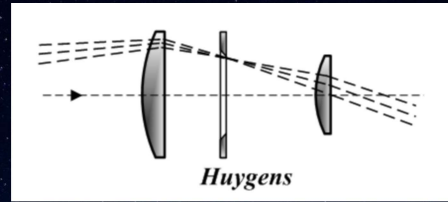
Early Eyepiece Designs



By Tamasflex

Galilean Lens 1609

- Erect image in refractors
- Very narrow FOV



By Tamasflex

Huygens Eyepiece 1660s

- Focal plane between lenses
- First compound eyepiece
- Low chromatic aberration
- works well with long focal lengths

<https://en.Wikipedia.org/wiki/Eyepiece>

Galilean Lens

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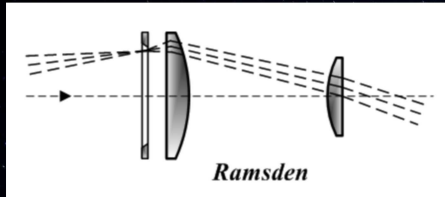
Huygens lens

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<https://commons.wikimedia.org/w/index.php?curid=9839275>

The early lenses had severe limitations and are not used today. Galilean telescopes had a very narrow FOV. Christian Huygens in the late 1660s improved by changing Galileo's single double concave lens to two plano-convex lenses (plano = flat, convex curved). This lens was easier to make than the double curved surfaces of Galileo's lens. The maker could curve the one side, then simply grind the flat side to make it parallel. It's much more difficult to grind two perfectly parallel, perfectly curved surfaces. However, Huygens design put the focal plane (gray bar) within the eyepiece. It was only good for long focal lengths, but was a good start.

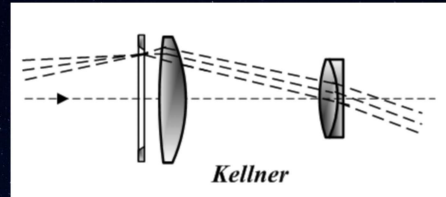
Early Eyepiece Designs



By Tamasflex

Ramsden Lens 1782

- Focal plane outside the eyepiece
- Can read micrometer cross-hairs
- Improved on Huygens



By Tamasflex

Kellner Eyepiece 1849

- Less chromatic aberration
- AFOV ~ 40-50°
- Fairly good image low-med mag.
- Needs anti-reflection coatings

<https://en.Wikipedia.org/wiki/Eyepiece>

Ramsden lens

By Tamasflex - Own work, CC BY-SA 3.0,

<https://commons.wikimedia.org/w/index.php?curid=9839350>

Kellner Lens

By Tamasflex - Own work, CC BY-SA 3.0,

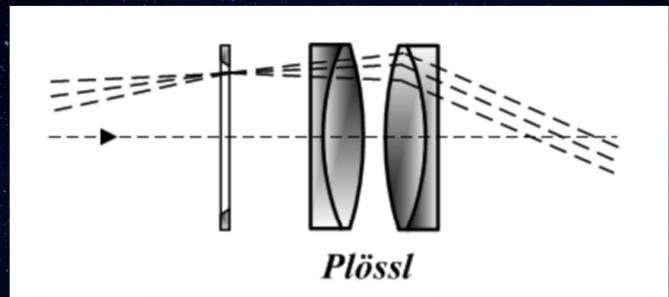
<https://commons.wikimedia.org/w/index.php?curid=9839286>

Ramsden improved on Huygens design that placed the focal plane (the gray bar) outside the eyepiece. It's made of two plano-convex lenses, less than one eye-lens focal length apart. With the focal plane outside the lens, astronomer could read micrometers to gauge the distance between stars or the size of planets.

Kellner's eyepiece is a step up from the early ones, with a wider FOV and less chromatic aberration. It does suffer from internal reflections, so it needs coatings to limit the reflections. You can buy Kellner eyepieces today, though a basic Plossl eyepiece will beat a well-made Kellner in field of view and quality of view. Kellner eyepieces are often bundled with cheap "department store" telescopes, labeled with K and the focal length, like K25.

Plossl or Symmetrical Eyepiece

- Today's standard made in 1860!
- AFOV ~50° wider than older designs
- Eye relief is not generous, especially below 10mm
- Somewhat expensive to produce quality versions with all lens curvatures matching



By Tamasflex

<https://en.Wikipedia.org/wiki/Eyepiece>

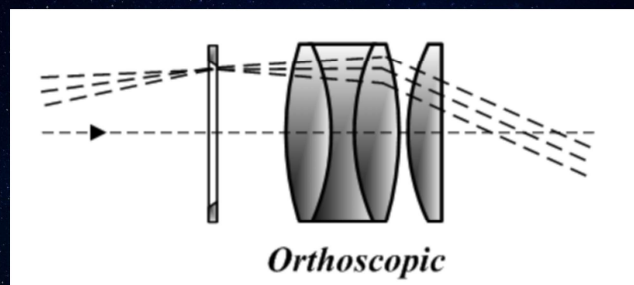
By Tamasflex - Own work, CC BY-SA 3.0,

<https://commons.wikimedia.org/w/index.php?curid=9839340>

The Plossl is today's standard eyepiece and high quality Plossls provide excellent views. However, eyeglass users will find higher magnification eyepieces hard to use because the eye relief is only 70-80% of the focal length. Compared to previous designs, the Plossl is more expensive to produce because the pairs of cemented lenses must be symmetric, so six curved surfaces must be identical and parallel. However, modern lens machines provide consistent and fairly inexpensive lenses.

Orthoscopic or Abbe Eyepiece

- Designed in 1880
- Nearly perfect image quality
- AFOV 40°-50°
- I like these for some viewing (Orion's Orthoscopic eyepieces)



By Tamasflex

<https://en.Wikipedia.org/wiki/Eyepiece>

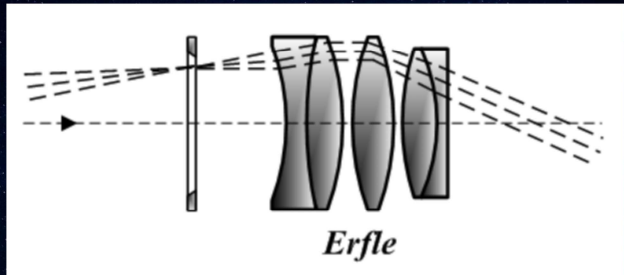
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The Orthoscopic eyepiece were somewhat popular in the early 2000s because the eyepiece delivers incredible image quality, though with narrower FOV than in a Plossl. Orion Telescopes sold orthoscopic eyepiece sets and I have enjoyed views through several medium focal lengths on the Moon and planets.

Erfler Eyepiece

- Designed during WWI for military use
- AFOV $\sim 60^\circ$ with large eye lenses
- Unusable at high powers, excellent 30-40mm+
- Sometimes found in inexpensive 2" eyepieces



By Tamasflex

<https://en.Wikipedia.org/wiki/Eyepiece>

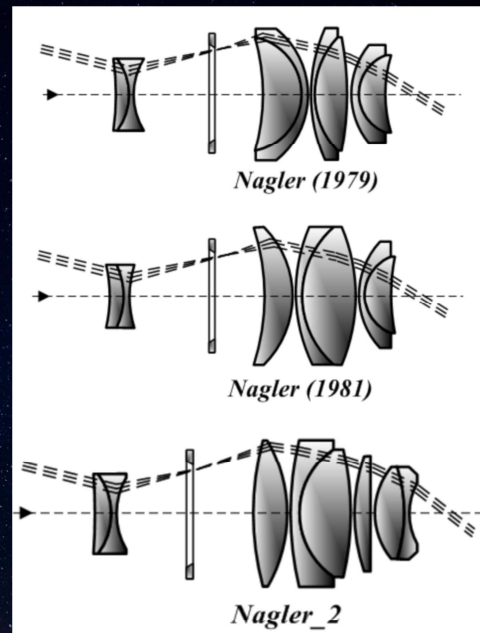
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The Erfler eyepiece is two achromatic doublets with a simple lens in between. Developed in WWII for military optics. It has the advantage of a wide 60 degree FOV, but is unusable at higher magnifications. If the lenses are coated, 20mm and up are usable. I've got a few inexpensive 2" Erflers that work pretty well with my short and medium focal length refractors.

Nagler's Mastery

- 1979-2025 (Type 7)
- Known for wide AFOV and high optical quality
- Wide range of focal lengths, in both 1.25" and 2" formats
- Highly valued



By Tamasflex

<https://en.Wikipedia.org/wiki/Eyepiece>

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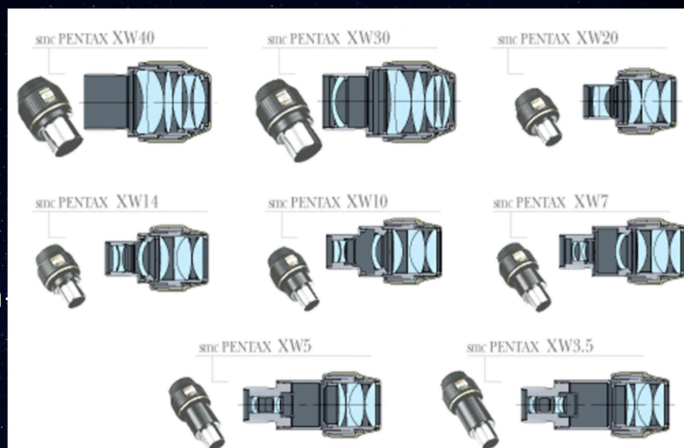
<https://commons.wikimedia.org/w/index.php?curid=9884114>

Al Nagler has proven his expertise in designing around the limitations that have limited others. His eyepiece and telescope designs started in 1979 and exploded onto the market in the following decades. Many still consider his eyepieces the peak of eyepiece development. One of the secrets to success is using the plano-convex and concave doublet on the telescope side, which is essentially a Barlow lens that gives more throw to let the wide field lenses do their work. Other lens makers have However, this much glass has the downside of being much heavier than the average eyepiece and the cost is quite high, but you get super wide 70-110 degree FOV and/or large eye relief.

I have enjoyed many views through the Nagler "holy hand grenades" of others. LOL! Seriously, his eyepieces really are superb

Today there are many more types

- Pentax WX are some of my favorites
- Explore Scientific
- Takahashi and a few other high-end manufacturers
- Masuyama (small batch)

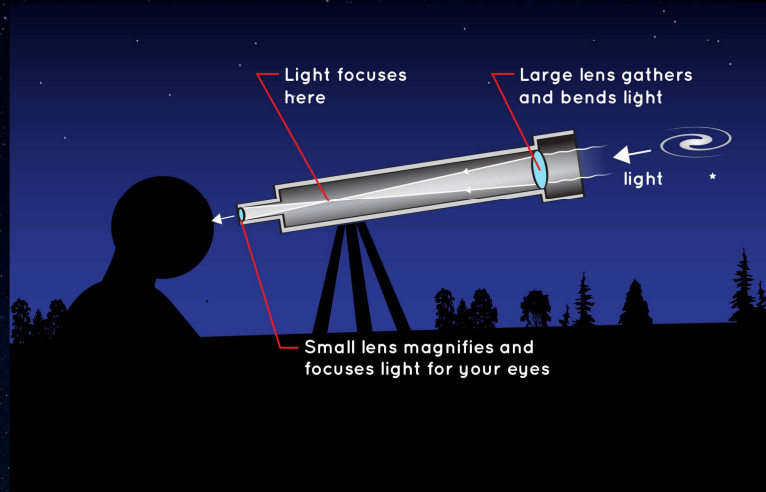


Pentax

Pentax, Explore Scientific, and Takahashi eyepieces are fairly common at star parties with expensive scopes. Masuyama eyepieces are pretty rare because they are small batch manufactured. All four provide competing designs to Nagler's eyepieces and bring a variety of capabilities. This gives us a wonderful and often confusion amount of choices. My eyepiece collection varies from Naglers and Pentax to simple Plossls and even a Kellner or two that I use for solar projection. It's good to have this many choices!

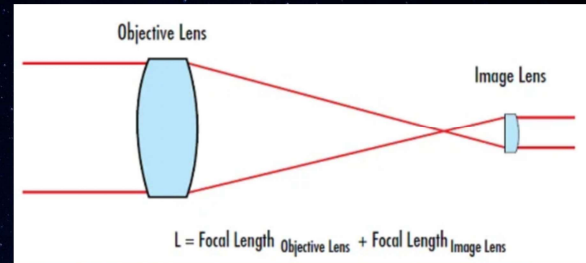
Sections

- A bit of math
- Aberrations
- Eyepiece designs
- **Telescope designs**
- What is an Airy disk?
- Demonstration with optical experiment kits

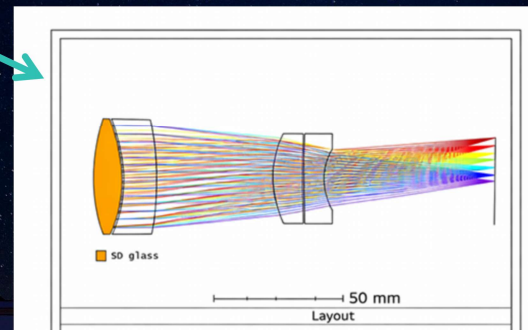


Refractor Telescopes

- Simplified refractor shown
 - Achromats 1-2 lenses
 - Apochromats 2-4 lenses
 - Petzval 2 sets of two
- Pros
 - Low/no maintenance & rugged
 - “Punchy” high contrast views
 - Short refractors very portable
- Cons
 - expensive per inch³ and smaller
 - Chromatic aberration
 - Pinched lenses & astigmatism in cheaper models



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agenaastro.com / Askar Telescopes

<https://www.edmundoptics.com/knowledge-center/application-notes/optics/telescope-optics-for-hobbyists/>

<https://agenaastro.com/askar-telescope-50p-50mm-f-3-8-quadruplet-Petzval-apo-refractor.html>

Achromats - Inexpensive glass with visible chromatic aberration

Apochromats - Expensive glass with well-controlled chromatic aberration

Some advantages inherent to refractive telescopes are:

- The enclosed housing protects the system from environmental/temperature changes.
- Refractive elements tend to have higher resolving power per inch of aperture.
- There are no optical path obscurations inherent in their design.
- The well-supported glass rarely needs to be aligned.
- Longer focal ratios tend to allow cheaper glass without much chromatic aberration.

There are some disadvantages inherent to refractive telescopes:

- Most expensive per aperture inch.
- Achromats tend to be long focal ratios (Short tube series are the exception)
- Chromatic aberration must be corrected.

Newtonian Reflectors

- Newtonian design

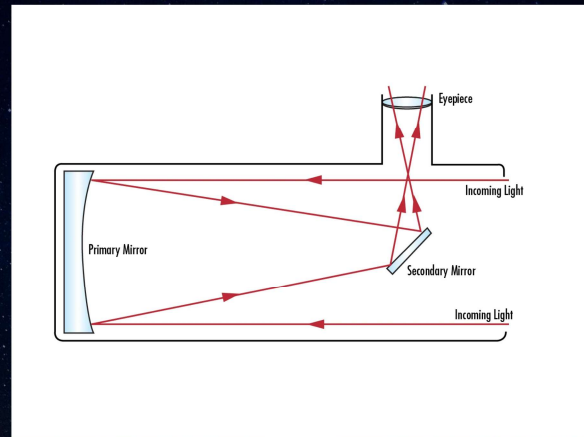
- Primary parabolic mirror
- Secondary flat (elliptical) mirror

- Pros

- Least costly per inch³ and larger
- Slightly less contrast (secondary)
- Very portable for its size
- No chromatic aberration
- Short focal lengths common

- Cons

- Collimation needed
- Coma, spherical, diffraction spikes aberrations



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Some advantages inherent to reflective telescopes are:

- Larger mirrors gather light at lower cost than refractors or compound scopes.
- The only visible chromatic aberration comes from the eyepiece.
- Amateur scope builders of the mid-1900s ground their own mirrors, which continues to this day.

There are some disadvantages inherent to reflective telescopes:

- They usually have lower imaging performance capabilities.
- Collimation needs to be considered/reset every time these are used.
- If using an open design concept, they are more vulnerable to environmental/temperature changes.

Schmidt–Cassegrain telescope

- SCT Design

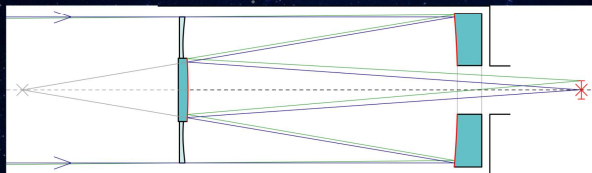
- Primary spherical mirror
- Secondary spherical mirror
- Corrector plate (front)
- Opt. field flattener (rear)

- Pros

- Very compact
- Relatively low cost (spherical)
- Excellent for high mag. views

- Cons

- Heavy
- Narrow FOV
- Lower contrast (secondary)



By Griffenjbs

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<https://commons.wikimedia.org/w/index.php?curid=6136538>

https://en.Wikipedia.org/wiki/Schmidt%E2%80%93Cassegrain_telescope

Originally developed for WWII optics for recon aircraft, the design eventually found its way into amateur and professional observatories. The spherical mirrors are cheaper to manufacture than the parabolic primary of the Newtonian telescope, but requires a corrector plate to correct the spherical aberration.

The compact design usually carries f/10 optics, so it is well-suited for high magnification views, but f/3.3, f/6.3, and f/7 focal reducers are common. Celestron SCTs with removeable secondary mirrors can use a Hyperstar adapter that places the camera in front of the corrector plate gives you f/1.9-f/2.1 depending on the model.

SCTs commonly come as fork-mounted computerized telescopes, but can also come as an “optical tube only” to be mounted on a telescope mount. In either cast, SCTs are known for high magnification views for visual or astrophotography.

Maksutov-Cassegrain telescope

- Mak-Cass Design

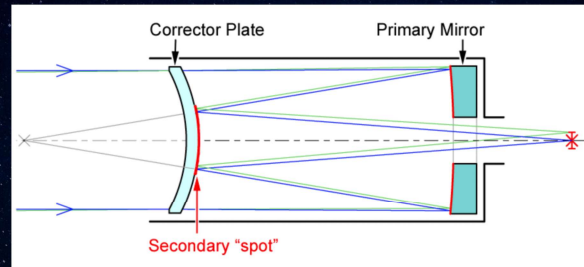
- Negative meniscus lens
- Spherical primary mirror
- Spherical secondary mirror

- Pros

- Very compact
- Relatively low cost (spherical)
- Excellent for high mag. views

- Cons

- Heavier than an SCT
- Narrow FOV
- Lower contrast (secondary)



By Halfblue at the English Wikipedia, CC BY-SA 3.0,
<https://commons.wikimedia.org/w/index.php?curid=30465727>

Mak-Cass uses the spherical aberration of the negative meniscus lens to correct the spherical aberration of the main mirror. The thick meniscus is much heavier than the thin SCT corrector plate. The secondary is a small mirrored spot at the center of the meniscus lens and adds its own aberration that counters the spherical aberration of the system.

Mak-Cass scopes share many of the characteristics of SCTs. Mak-Cass scopes are often at f/15 to avoid spherical aberration, so they give superb high-magnification views. Given the weight, Mak-Cass scopes are usually 8" or smaller.

Ritchey–Chrétien telescopes

- RC Design

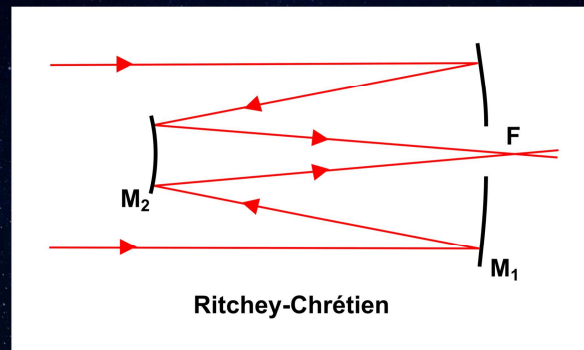
- Hyperbolic primary mirror
- Large hyperbolic secondary

- Pros

- Designed to eliminate coma
- Wider FOV than SCT
- Compact like SCT
- Great for imaging (HST & ESO VLT)

- Cons

- More expensive than SCT (hyperbolic)



By HHahn

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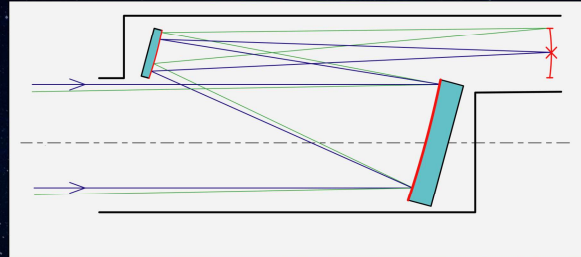
<https://commons.wikimedia.org/w/index.php?curid=9900451>

https://en.Wikipedia.org/wiki/Ritchey%E2%80%93Chr%C3%A9tien_telescope

RC scopes are mainly astrographs with large (up to 33%) secondary mirrors and medium-long focal lengths. The hyperbolic mirrors are difficult to figure, so RCs can be expensive, but produce fantastic images. Visually, the large secondary reduces contrast, so the views lack the punch of a refractor.

Off Axis Design - Schiefspiegler

- Designed to avoid the secondary obstruction
 - Variety of concave-convex mirrors
 - Some cut a primary mirror from a larger parabolic mirror
- Pros
 - No secondary obstruction
- Cons
 - Coma & astigmatism at short FL
 - Often $f/15$ or longer
 - Home made only



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https://en.Wikipedia.org/wiki/Reflecting_telescope

The Schiefspiegler has fascinated me for a long time. I started reading about them back in the dark ages of the 70s in either Popular Mechanics or Popular Science. Since this was the prime age for grinding your own mirrors, experimenting with designs that avoided a secondary obstruction was common. These home-brewed scopes are often shaped like a lumpy z-shaped box instead of a round tube. The mirror design varies wildly with concave primary and secondary or a concave primary with a convex secondary. The mirror's figure varies greatly, depending on the skill of the maker. They are usually $f/15$ or longer to correct for the distortions of reflecting off of a tilted mirror.

The most expensive way to make a tilted mirror for one of these scopes is to grind and polish a mirror large enough to house 4 Schiefspiegler scopes so you can then offset the aberration. However, that is hard to do because cutting the mirror after fine polishing is like to damage the mirror, but cutting it out early in the process means you need to find a way to correctly polish one small section of a larger mirror correctly.

Prime Focus Telescopes

- Design

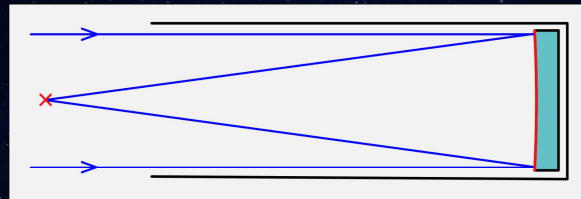
- Parabolic primary mirror
- Camera at secondary

- Pros

- Less glass = more light
- Excellent for imaging (most professional observatories)

- Cons

- No visual use
- All the faults of a parabolic mirror



By Oleg Alexandrov

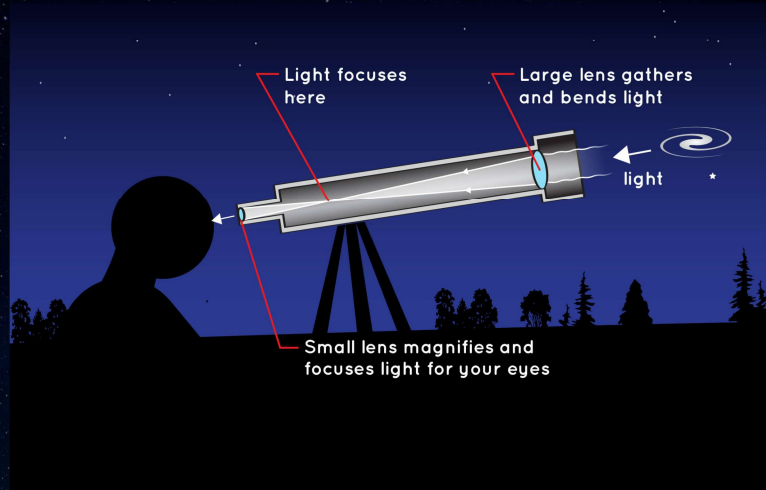
By Oleg Alexandrov (talk) - Own work based on Image:Nasmyth-Telescope.svg by Jailbird which was in turn based on Image:Cassegrain-Teleskop.svg by ArtMechanic, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=6966135>

https://en.Wikipedia.org/wiki/Reflecting_telescope

Prime focus telescopes are astrographs in observatories where the camera sits at the secondary. This has the downside of not being usable for visual use and you'll need to keep the camera's cables routed to minimize their contribution to diffraction spikes.

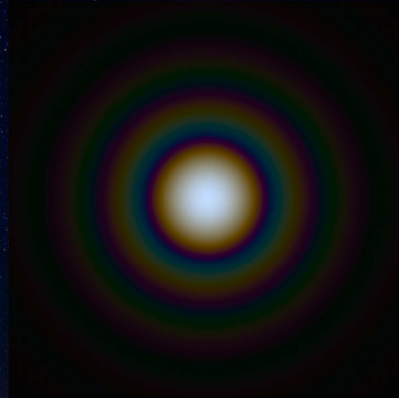
Sections

- A bit of math
- Aberrations
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- Telescope designs
- **What is an Airy disk?**
- Demonstration with optical experiment kits



Collin's question - Airy Disks

- Sir George Biddell Airy, Astronomer
Royal 1835-1881
 - 1st theoretical paper 1835
- John Herschel article in 1828:
 - ..the star is then seen (in favourable circumstances of tranquil atmosphere, uniform temperature, etc.) as a perfectly round, well-defined planetary disc, surrounded by two, three, or more alternately dark and bright rings, which, if examined attentively, are seen to be slightly coloured at their borders. They succeed each other nearly at equal intervals round the central disc....



By SiriusB

By SiriusB - Own work, CC0,

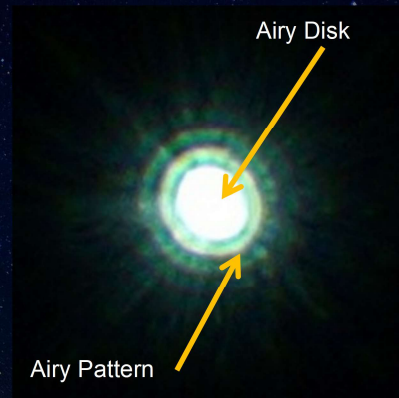
<https://commons.wikimedia.org/w/index.php?curid=68302545>

The image is a computer generated simulation of a perfect Airy Disk with the colors enhanced.

An Airy disk forms when you achieve nearly perfect focus at high magnification. (The disks form a lower magnification, but are very hard to see.) Sir George Biddell Airy and John Herschel wrote about the disk in the early 1800s as telescopes and eyepieces improved.

The disk is an image of the objective mouth (or light baffle). The rings are formed by diffraction, the same thing that forms spikes on bright stars in a Newtonian scopes. The image here is an idealized computer-generated diagram of an Airy disk and rings. Real life won't be this smooth or colorful, but just like the sunset, red bends less than blue, resulting in this rainbow.

- It forms as uniform light diffracts through **circular aperture**.
 - The Airy disk is only the center.
 - The Airy pattern are the diffraction rings.
- **The smallest point a lens or mirror can focus is the Airy Disk.**
 - Imperfections increase the disk.
 - If a lens is perfect, then it is said to be **diffraction limited**.



Romuello - Own work

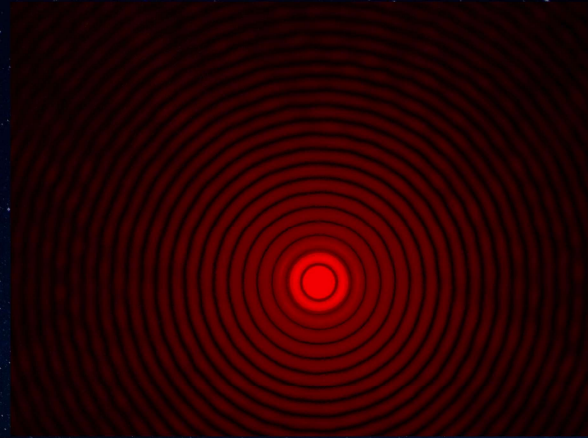
By Romuello - Own work, CC BY-SA 4.0,
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The Airy Disk was initially discovered and discussed as telescopes improved and magnification increased. Most disks are larger than the math would compute thanks to dust, imperfections in the optics, and instability in the atmosphere.

If a lens, mirror, or telescope are listed as diffraction limited, the optics are considered perfect and diffraction (plus atmospheric) will be the major force affecting the focused image of an Airy disk. This takes a huge amount of work, high quality materials, special glass (for lenses), and constant quality assurance, so that usually translates to “lotsa dough”.

An Ideal Airy Disk

- Laboratory setting
- Red Laser beam
- 90-micrometer pinhole
- Produces 27 orders of diffraction!



By Bautsch

By Bautsch - Own work, CC0,

<https://commons.wikimedia.org/w/index.php?curid=55156518>

This is an actual photo of an ideal Airy disk formed in a laboratory out of a laser coming through a tiny aperture. In the real world, you're lucky if you can see 3-4 rings! (remember the last slide?)

An imperfect Airy Disk I produced

- Celestron Onyx ED80 (i think)
- White flashlight with brass pinhole
- 3" convex mirror across the house
- Defects include
 - Dust in the telescope
 - Air currents from the heater
 - Dust on the camera sensor
 - Cheap convex mirror

Tom Heisey

I realized that I had the answer to Collin's question when I experimented focusing masks back in 2002. I was starting astrophotography and was tired of missing focus.

The first part of the setup was to ensure focus was sharp, which is getting an Airy Disk as sharp as possible. The setup includes:

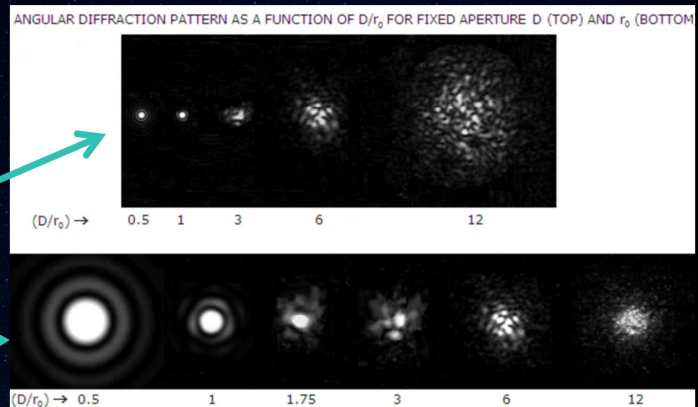
- AAA battery mini-maglite flashlight shining through a brass disk with a tiny aperture on the scope
- A cheap 3" convex mirror across the living room and dining room on the far wall of the bedroom
- My 80mm refractor or LX-90 pointed at the convex mirror.

This was rather dim, but it worked well enough to get the Airy pattern rings from across my house.

If you look at the darker parts you'll see a bunch of dark, somewhat colored splotches - This is atmospheric seeing caused by heat from the vents and cool air from the windows along that path inside the house!

Seeing Impacts Airy Disks

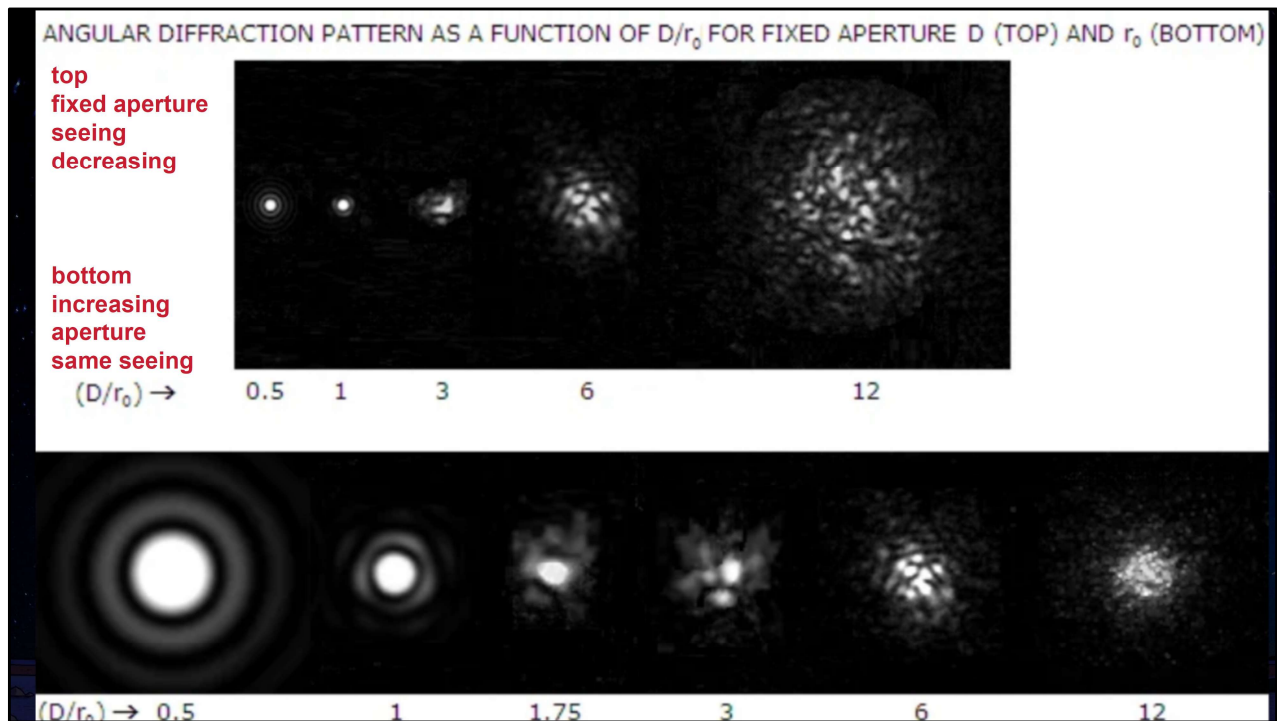
- Seeing is an effect of atmospheric turbulence
 - Lower turbulence, higher seeing
- As seeing gets worse, the Airy Disk blurs and breaks up
 - Dimmer stars disappear
 - **Larger scopes are impacted more severely**
 - Higher magnification
 - Larger light path



<https://www.edmundoptics.com/knowledge-center/application-notes/optics/telescope-optics-for-hobbyists/>

Just as with any image, poor seeing (turbulent atmosphere) degrades the image. And just as with observing any object, large telescopes are affected more severely than small scopes. I've heard there are two reasons. First, the scopes have higher base magnification (even with wide eyepieces) so any seeing error is magnified more than smaller scopes. A larger scope has a larger light path through the atmosphere, so a large scope intercepts more turbulence cells, especially below 45 degrees above the horizon.

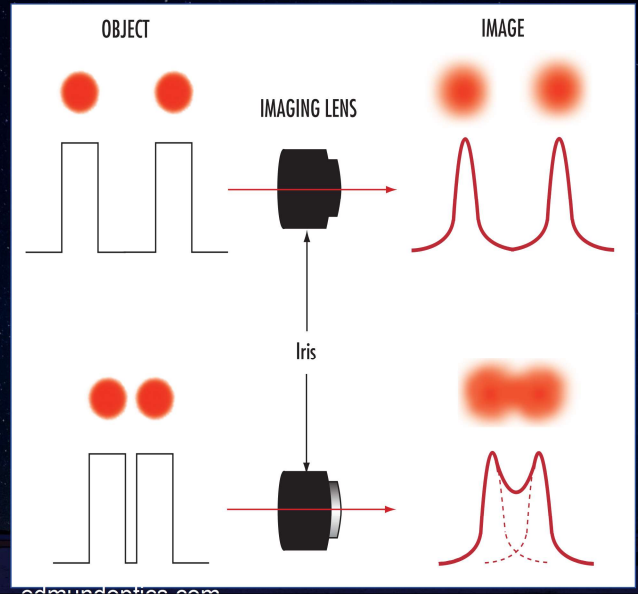
Imagine a big bundle of drinking straws standing vertically that represents the turbulence of the atmosphere - A scope of six straws will see through many more cells than a scope of one. Also, you'll see far more cells with either scope at 25 or 45 degrees than at 75 or 85 degrees.



<https://www.edmundoptics.com/knowledge-center/application-notes/optics/telescope-optics-for-hobbyists/>

Splitting Stars - Airy Disks and Resolution

- Close stars' Airy disks merge until they are impossible to split
 - Bright equal stars easiest
 - Unequal stars difficult
 - Dim stars difficult
 - Larger scopes easier
 - Poor seeing blurs stars
- There will always be a limit for each telescope

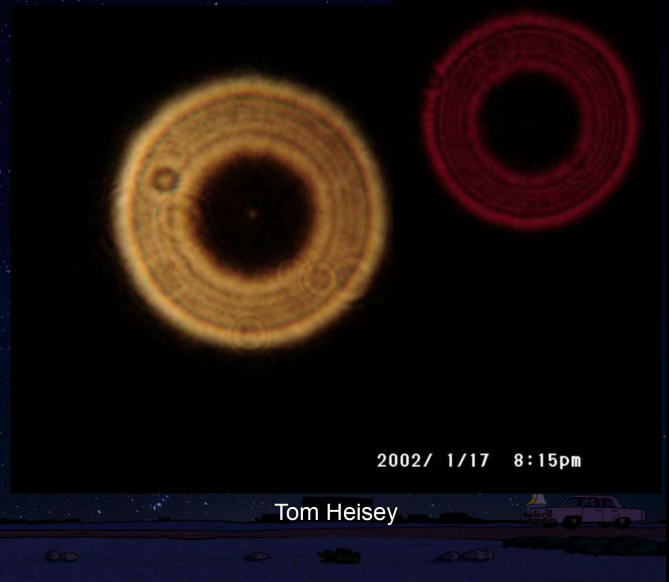


<https://www.edmundoptics.com/knowledge-center/application-notes/optics/telescope-optics-for-hobbyists/>

We often use double stars to gauge seeing and optical quality of telescopes. Airy disks come in to play when attempting to split close doubles. At some point, the stars will merge into an oblong blur. Larger telescopes, excellent seeing, and brighter stars increase your chances of splitting stars - up to a point. Large scopes eventually run into an upper limit on magnification, thanks again to diffraction.

How Does The Aperture Change the Disk?

- Many of us use a diffraction pattern to collimate an SCT. This is a form of an Airy disk.
- Diffraction rings of an LX-90
 - Complete with dust spots!
 - Good collimation, too!
- Higher magnification gave much better resolution and detail



These images are through my LX-90 in my informal “test range” with the original white light and with a laser, which was much brighter. The spots, rings, and fringe “strings” on the inner and outer edges are dust artifacts within the LX-90, diagonal, and camera.

The donut ring is a slightly out-of-focus image of the point source that we use to collimate an SCT. The secondary mirror has screws to adjust the image. You tweak the screws until the central obstruction is centered. This is pretty well collimated, though the white image is slightly off from where I’d like it.

How Does The Aperture Shape Change the Disk?

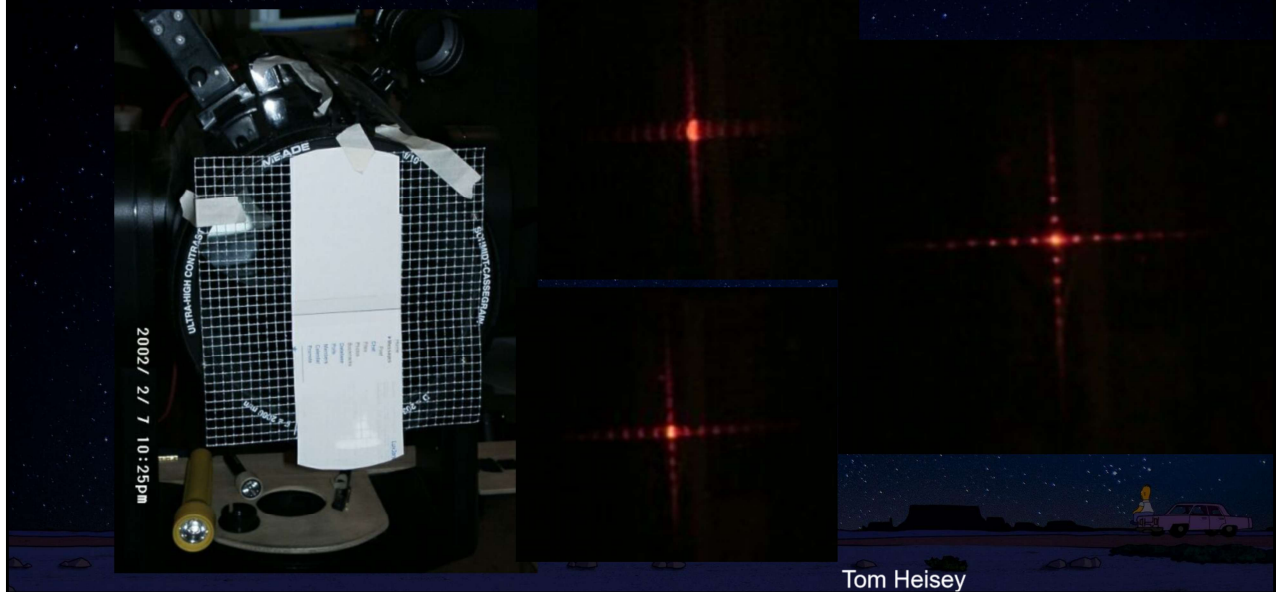


These were experiments in 2002 and have been left orphaned on my poorly maintained web site at <http://www.tomheisey.com/masks/> I experimented with many shapes to generate a focus mask.

Back in 2002, I was trying astrophotography, but was frustrated by an inability of ensuring I had good focus with the camera. In this transition from film to digital, you couldn't open the back of the camera and use a knife edge focuser, but there wasn't much info on how to focus a digital camera. There were a few informal posts on Cloudy Nights and other discussion boards about various experiments, but they often lacked details, so I decided to run my own experiments, cutting various shapes out of file folders and various materials. I'll show a few of the better ones here, but these days, the Bahtinov and Hartmann masks outperform my masks.

In the image above, you can see how an Airy disk is modified by square aperture, with bars across the out-of-focus image instead of rings you saw in the last slide. The Airy disk takes up the shape of the aperture and the corners cause spikes. If you look at the bottom-left near-focus image, you can see the two squares nearly merged, forming a rectangle while the top-right image in focus is a square with spikes off the corners.

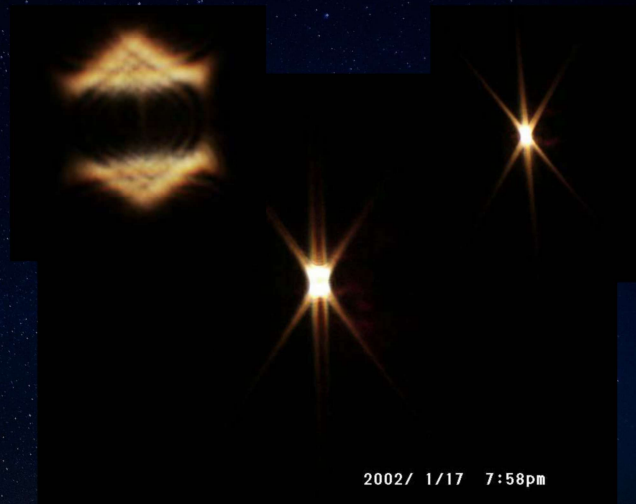
How Does The Aperture Change the Disk?



This was an adaptation of a mask I read about on Cloudy Nights. They used only the hardware cloth, but I found the focus point was a bit hard to determine. Adding the bar in the middle helped, since out of focus images would grow in one axis, helping refine the focal point compare the two images at left with the in-focus image.

While this actually worked great, I decided not to use it to avoid damaging the scope or my hands with the hardware cloth, but it gave the brightest image given the large unblocked aperture. I tried window screen material, but I think the threads weren't straight enough to make a good image.

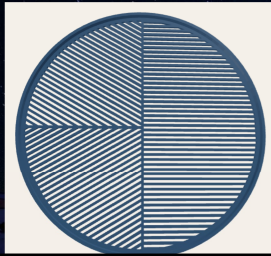
The Mask I used



At the end of this experiment, I settled on this mask. The large diamonds let in lots of light and it was a bit like a Bhatinov mask in that you could see the parallel bars merge at focus. The Bahtinov mask (next slide) improves on this by adding more bars to reinforce the spikes, which means you see more on dimmer stars so you can use it on the target. However, this one helped my learn astrophotography with my low-end equipment.

Bhatinov Mask - Diffraction Spikes

- Bhatinov focusing masks use the diffraction of light to show when the stars are in focus
- Modifies the Airy pattern by introducing sharp-angled bars



Tom Heisey

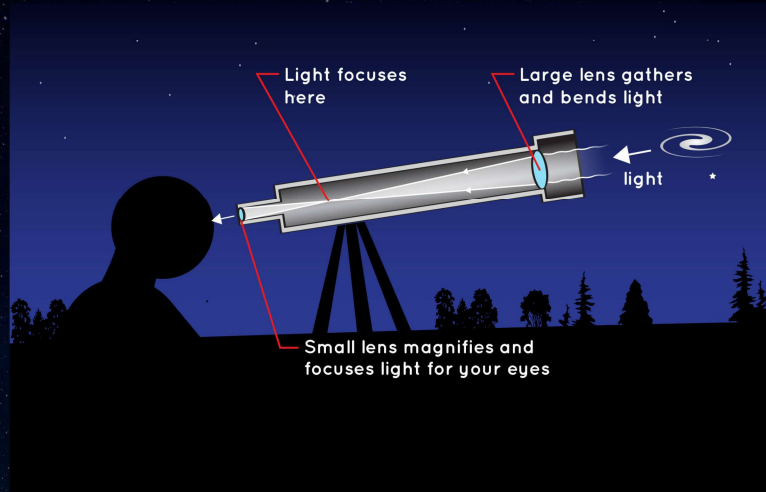
<https://stargazingbuddy.com/calculators/bahtinov-mask-generator>

The Bhatinov mask is a true miracle for astrophotography because using the generator above (or one of the many out there) will let you design a mask suited for the focal length and objective of your scope that you can 3D print or cut by hand. The miracle of the Bhatinov is that the spikes move to show precisely when it's centered. Compare the precise focus at left with the just-out-of focus on the right. This is very clear in the image or eyepiece.

Sections

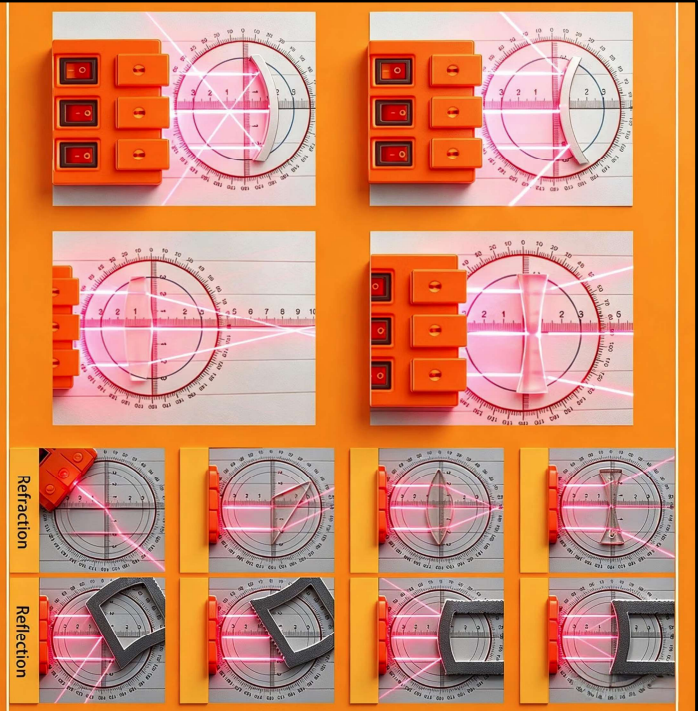
- A bit of math
- Aberrations
- Eyepiece designs
- Telescope designs
- What is an Airy disk?

- **Demonstration with optical experiment kits**



Time to Demo!

- Laser module
- Lens types
- Grid to measure lenses
- Mirror use
- Eyepiece
- Multiple modules for off-axis focus



<https://www.amazon.com/dp/B0CD2KKFQ8>

<https://www.aliexpress.us/item/3256806374368974.html>

These inexpensive kits are fantastic for learning about optics. Amazon charges \$19, but you can get them for \$9 from AliExpress. I'm building a set of these for potential outreach to schools, but these are also fantastic for amateur astronomers or photographers to understand how their systems work. It's inexpensive fun for all ages!

Time to experiment!

- What is the focal length of the SIX curved lenses?
- They are 6cm in diameter. What is their focal ratio?
- What happens to the focal length when you add a concave lens?
- Model a simple Galilian refractor

Here are some questions to answer using the sets. If you can answer these, you can answer those questions for your gear, too!