# Telescopes 101

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## 1 Introduction

This is written as a short primer for those interesting in purchasing a first astronomical telescope. It is a complement to the section in telescopes in my astronomy mini-book (which is presently an extremely rough draft), which discusses telescopes from more pedantic perspective. That section is available at:
`http://www.stevenstanek.com/Science/Moon_Site/science.html#Telescopes`.

## 2 Overview of Telescopes

Telescopes serve two roles. They magnify distant objects to make them larger, and they allow us to see faint objects by gathering much more light than the human eye. As counterintuitive as it may sound, the latter application may well be the more important. Many celestial objects aren't particularly small, its just that they are faint. If you go outside at night with a decent pair of binoculars and stare at the night sky you will see many times as many stars as you can with your naked eye. This is because the lenses at the front of the binocular are much larger than the lenses in your eyes. They focus all of the light that strikes their surface onto your eyes, so your eyes receive much more light. Telescopes are usually even larger than binoculars, and the larger your astronomical telescope, the easier it is to see fainter objects.
All amateur telescopes consist of a system of mirrors, lenses or both which focus light into a small opening where an eyepiece can be inserted. The eyepiece determines the magnification and field of view of the telescope. Also, an eyepiece can be removed and replaced by a camera, in which case the telescope behaves as a camera lens instead.

## 3 Telescope Characteristics

### 3.1 Aperture

The first question most astronomers probably ask about a telescope is "how big is it?" What they mean by this is: "how much light does it gather?" They are referring to aperture, the diameter of the primary mirror or lens. Large apertures allow astronomers to see fainter objects and magnify distant objects more. When it comes to aperture *more is better*.

#### 3.1.1 Maximum Theoretical Magnification

The larger the telescope, the more you can magnify the image. The reason for this involves some rather complicated physics which I will not go into here. Mathematically, the maximum theoretical magnification of a telescope is somewhere around 2.4 times its aperture in millimeters: $MaximumMagnification = 2.4 \times Aperture\_In\_mm$. So, a 102 mm (4 inch) telescope has maximum theoretical magnification of around 240 times.
It should be noted that it is extremely difficult to achieve very high magnifications in most places on Earth, because the quality (or in astronomical terms "seeing") of the atmosphere distorts images at high powers. At most places on Earth, even under good conditions, magnifications greater than 600x or so are difficult to attain clearly. For terrestrial observation, which involves looking through large amounts of atmosphere, even 100x can be difficult to attain over distances.

#### 3.1.2 Measuring Brightness & Limiting Magnitude

Stars and other celestial objects such as galaxies and nebulas are measured on a relative brightness scale known as the magnitude scale. Like the magnitude scale used for earthquakes, the magnitude scale for brightness is logarithmic. A star of magnitude 2 is 2.5 times *brighter* than a star of magnitude 3. Stars with *higher* magnitude numbers are *fainter* than those with lower magnitude numbers. Magnitude numbers may also be negative for extremely bright objects such the moon, the Sun and some select planets and stars.
Larger telescopes gather more light so an observer can see fainter objects through a larger telescope than a smaller one. Limiting magnitude refers to the faintest possible object a good naked eye observer could see through the telescope under ideal seeing conditions. In practice, you will probably never be able to see anything close to ideal conditions. The formula

for limiting magnitude is approximately: $LimitingMagnitude = 2.5 + 5log(Aperture\_In\_mm)$. So, a 102 mm telescope has can be used to visually observe stars of up to about magnitude 12.

## 3.2 Focal Length, F/Ratio and Magnification

### 3.2.1 Focal Length

For the purposes of most amateurs, the focal length can be thought of as the magnification of the telescope tube itself. Longer focal length tubes produce higher magnifications than short focal length tubes.

### 3.2.2 F/Ratio

The focal length and aperture of a given telescope design often scale together. Mathematically, F/Ratio (or speed) of a telescope is the ratio of the focal length of a telescope to the aperture of a telescope: $F/Ratio = \frac{FocalLength}{Aperture}$.

### 3.2.3 Magnification

The magnification of a telescope is a ratio of the focal length of the telescope and the focal length of the eyepiece: $Magnification = \frac{FocalLengthofTelescope}{FocalLengthofEyepiece}$. Eyepiece focal lengths tend to have a reasonably small upper limit of somewhere between 30mm and 50mm depending on physical size of the eyepiece slot in the telescope. Because of these upper limits on eyepiece focal length, the focal length of the telescope tube tends to determine the minimum magnification of a telescope.

## 3.3 Telescope Types

There are three different types of telescopes: refractors, reflectors and Cassegrains.

### 3.3.1 Refractors

Refractors use a single large lens at the front of the telescope to focus light down to a hole for an eyepiece at the rear of the tube. Refractors are thought to produce the best overall views per unit aperture, but they have several problems. They are extremely expensive to produce, heavy and long. They experience chromatic aberration, false color which results from glass bending light of different frequencies different amounts. Is it also very difficult to produce large aperture refractors, so in practice there are no amateur refractors larger than 6" (150 mm).
*Note:* It is possible to partially or completely correct for chromatic aberration. Achromatic telescopes partly correct it and apochromatic telescopes claim to completely correct for it. These telescopes are built using many lens elements and various exotic glasses. Apochromatic telescopes are extremely expensive.

### 3.3.2 Newtonian Reflectors

Classical Newtonian Reflectors consist of a single large mirror near the back of the telescope tube with gathers light and reflects it to a flat secondary mirror which reflects the light through the side of the telescope to an eyepiece. Newtonian Reflectors tend to be the cheapest telescopes per unit aperture, but are bulky and experience coma, the blurring of images that are far from the center of the eyepiece. Newtonians also experience some image spikes due to the "spider", the structure which holds the secondary mirror in place.

### 3.3.3 Cassegrains

Cassegrain telescopes use a combination of mirrors to produce shorter and less bulky telescopes which are free of many of the disadvantages Newtonians. They tend to be relatively long focal length telescopes, with a large primary mirror near the rear and a small convex secondary mirror near the front. Light strikes the primary mirror, is focused onto the secondary mirror and bounces back to an eyepiece which is located in a hole in the primary mirror. Both the primary and secondary mirrors produce magnification, so the Cassegrain design allows for long focal length telescopes that are physically short and light. Additionally, the twin mirror design often corrects for the coma and other aberrations which plague Newtonian Reflectors and refractors. Unfortunately, the mirrors in these designs are often more difficult to fabricate than those Newtonian Reflectors, so they come at a price premium.
Most amateur Cassegrain telescopes are either Maksutov-Cassegrain or Schmidt-Cassegrain designs. These telescopes use a spherical primary mirror which is cheap to produce but does not focus light particularly well. In order to compensate for this spherical aberration, these telescopes use a corrector lens at the front of the telescope. This lens also holds the secondary mirror. Generally the images through these telescopes are among the highest quality of inexpensive amateur telescopes.
The Ritchey-Chrétien Cassegrain design is generally accepted as the best overall telescope design. Almost all professional telescopes use this design, but it requires extremely expensive hyperbolic mirrors. Some companies such as RC-Optical Systems and Takahashi make Ritchey-Chrétien Cassegrains, but they are extraordinarily expensive–they start at over $10,000.

*Note:* Meade Instruments makes a line of telescopes called RCX400 which claim to be Ritchey-Chrétien Cassegrains, but from the design perspective, they better described as a modified Schmidt-Cassegrain design.

## 3.4 Mount Types

Objects in the sky don't stay at a perfectly static position in the sky over the course of the night. The Earth's rotation causes them to move over the course of the night. Although this rotation may seem to be relatively minor–after all, it takes 24 hours for Earth to complete one rotation–when you are observing celestial objects at several hundred times magnification, stars will zip in and out of the eyepiece's field of view in just tens of seconds. Thus, being able to both point a telescope at objects and follow them, either manually or electronically, is a must.
Many telescopes are sold with a mount and tripod, but some astronomers prefer to purchase the mount and the telescope separately. Larger and heavier telescopes tend to require sturdier and better built mounts. For larger scopes, quality mounts may end up costing as much as the telescope's optical tube.

### 3.4.1 Altitude-Azimuth (Alt-Az) Mounts

Altitude-Azimuth or Alt-Az mounts are like regular photographic tripods. They move up and down and left to right. Smaller telescopes often are mounted on higher end photographic or video tripods. Larger alt-az mounts generally are motorized fork mounts which hold the telescope on a fork which itself is mounted on a turn table. In fork mounts, motors in the fork can rotate the telescope up and down and motors in the turn table can move it left and right. Alt-Az mounts are a must if you want to try to use your telescope for terrestrial observation, and they are generally easy to set up. They are difficult to use photographically and must be moved constantly on both axes to follow celestial objects.

### 3.4.2 Equatorial Mounts

Equatorial mounts are built so they move along a single axis to track a celestial target. They can be driven either by hand cranks or motors. The most common variety of equatorial mount is the German Equatorial which uses a counter-weighted mechanism to follow stars. Some alt-az fork mounts can be turned into equatorial mounts by inclining the entire telescope, turntable and fork mechanism on a wedge. Equatorial mounts are thought to be superior photographic mounts, but they generally are considered a pain to set up. If you want to do terrestrial observation, you should not purchase an equatorial mount.

### 3.4.3 Dobson Mounts

Both equatorial and traditional alt-az mounts are extremely expensive. An amateur astronomer by the name of John Dobson designed a very inexpensive alt-az mounting scheme that places a Newtonian Reflector on turntable and pivot near the bottom of the telescope. The user can pull or push the top telescope left or right or up or down to point it correctly. The Dobson is never motorized[1], but can support computerized object locators. Because they are not motorized, Dobsons are not used for photographic astronomy, but they can make excellent observational scopes and are very cheap. Along with many commercial models, there are many hobbyist web site that instruct you how to manufacture your own Dobson mount from materials you can find at your local hardware store. If you want to do terrestrial observation or astrophotography, you should not purchase an Dobson mount.

## 3.5 Motorized Goto and Computerized

Motorized Goto telescopes have a small electronic hand controller which allows you to enter the locations of celestial objects. The telescope's motors automatically slew the telescope to point it at the requested object and then follow the object as the Earth rotates. Because motorized goto telescopes require very precise gears, expensive motors and a variety of electronics (often including a GPS), they are quite expensive.
Motorized telescopes are quite expensive to build, but finding celestial objects manually is difficult. Fortunately, there is also a middle ground. Some telescopes have computerized object locators which tell you where to move the telescope to find requested objects, but do you have move it manually. These telescopes are generally much cheaper than motorized goto telescopes, but are manually powered, so they do not automatically track objects as the Earth rotates.
From my experience, locating objects manually, without the use of a computerized object locator or goto system, can be extremely time consuming. Many "old school" astronomers consider finding objects in the night sky to be part of the fun of astronomy. On the other hand, goto and computerized telescopes allow you to find objects in seconds that may have taken tens of minutes to locate manually. With a computerized telescope, you can probably see more objects on your first night than you could have manually in months.
*Note:* The terms goto and computerized are often interchanged in the telescope business. Some manufacturers seem to regard "goto" as meaning that a telescope has computer controlled motors to slew to a star, while others mention human powered

[1] I know of no commercial attempts to motorize the Dobson, but some hobbyists have manufactured their own motorized Dobsons

”manual goto” telescopes. Generally the phrase ”goto mount” or ”motorized goto” is used to indicate that a telescope is capable of actually slewing to a celestial target based on hand controller input. There is also an odd third type of mount which is motorized, and has a computerized object locator, but the computerized object locator cannot control the motors; the user must control the motors manually with a motor controller. (ex: A version of Orion’s SkyView Pro)

# 4 Eyepieces

The telescope itself is the tube that collects light, but the eyepiece is the lens that you look through. The eyepiece determines both the magnification and the size of the field of view you see. Almost all telescopes come with at least one eyepiece, but you will probably build a collection of them over time.
Eyepieces are standardized. There are two common barrel diameters, 1.25” and 2”. You can purchase eyepieces in these sizes from any manufacturer and use them in any telescope which accepts them. Virtually all telescopes can take the 1.25” eyepieces, and some can take the 2” as well (any telescope that can take a 2” can also take 1.25” through the use of simple adapter). I would advise you not to purchase any of the small minority of telescopes that cannot take the 1.25” because that will dramatically limit your eyepiece choices.
Although eyepieces, like telescopes, have lots quantifiable characteristics, qualitative evaluation of eyepieces seems to be much more important than quantitative metrics used for telescopes. Some eyepieces are known to give good views across a wide range of telescopes, while others have known problems. I suggest reading reviews before purchasing expensive eyepieces.

## 4.1 Focal Length

As written before: $Magnification = \frac{FocalLengthofTelescope}{FocalLengthofEyepiece}$. The focal length of a telescope’s optical tube is fixed, so you vary the magnification of the instrument by changing eyepieces. Short focal length eyepieces offer higher magnifications than longer focal length eyepieces. The focal length of the eyepiece is seldom much larger than the size of the eyepiece slot, so 2” eyepieces are used almost exclusively for very long focal length, low magnification, astronomy. Higher power viewing is done almost exclusively with 1.25” eyepieces.

### 4.1.1 Notes on Magnification

As previously mentioned, all telescopes have a maximum magnification which is a function of aperture. You can of course put in an eyepiece that produces a magnification higher than this maximum magnification, but you will get an extremely blurry image which reveals no additional features.
Also, you will find that higher powers (shorter focal lengths) produce fainter images of objects. This is because the telescope only gathers so much light. By magnifying that light, you are spreading it out over a greater area. When observing faint objects, it is sometimes preferable to use longer focal length eyepieces which produce brighter images.

## 4.2 Eye Relief

Eye relief is simply how far from the eyepiece you can place your eye before the image becomes difficult to view. Generally, the longer the eye relief, the better, especially for viewers with glasses.

## 4.3 Field of View

Field of View is the angular size of the viewable area and is measured in degrees. It is different from magnification, though the difference is sometimes hard to understand. Magnification is how many times objects are magnified. If a telescope/eyepiece combination magnifies a bird by 50x, it will appear 50 times larger in the eyepiece than it does to the naked eye. Field of view is *how much you can see*. A small field of view eyepiece might show just the bird, while a wider field of view eyepiece with the same focal length might show the bird and part of the tree it is sitting on. Although the bird appears to be the same size in both eyepieces, you can see more in the wider field eyepiece.
In general, wider field is always preferable. Some designers refer to the ”spacewalk” experience in wide field of view eyepieces. If the field of view of the eyepiece is greater than that of the human eye, you get the feeling that you are actually in space looking at celestial objects as opposed to looking at them through a telescope.

### 4.3.1 Apparent Field of View vs. Actual Field of View

*Note:* If you find this section too confusing, skip it.
There is a difference between ”apparent field of view” and ”actual field of view”. When you are looking at distant objects through a telescope, they are magnified, so they appear much larger. When we discuss the field of view of an eyepiece, we are referring to its ”apparent field of view”, that is, how wide the scene through the eyepiece appears. The ”actual field of view”, is non-magnified angular size of object we are looking at through the telescope.

Going back to the bird example. When we look at the bird through an eyepiece, it appears to be quite large, but even through a very wide field eyepiece, we cannot see very much of the scene compared to what we can see with our real eyes. The unmagnified angular size of everything we can see through the eyepiece is the actual field of view, while the magnified angular size is apparent field of view.
Mathematically: $ActualFieldofView = \frac{ApparentFieldofView}{Magnification} = ApparentFieldofView \times \frac{FocalLengthofEyepiece}{FocalLengthofTelescope}$. Apparent field of view is always much larger than the actual field of view.

# 5 Telescope Manufacturers

Most astronomers believe that telescopes that you find at department stores are generally junk with poor optics, and regardless of advertised aperture, they will not produce good images. These are generally sold under brands such as Bushnell, Tasco and Galileo, though there are doubtlessly many more.
The three big "legitimate" telescope brands in the United States are Meade, Celestron and Orion. Meade and Celestron manufacture many of their own telescopes, while Orion is a brand which sells other manufacturer's products (including Celestron) under the Orion name. However, Orion equipment is generally relatively inexpensive and reasonably high quality. All three of these brands have a comprehensive offering of telescopes, eyepieces and accessories.
There are some other well known telescope manufacturers, but their scopes are generally more expensive than Meade, Celestron and Orion. They include:

- Coronado: Coronado specializes in constructing telescopes and filters for observing the Sun. Solar astronomy is a potentially dangerous field, but Coronado claims to have a exemplary safety record.
- Discovery: Discovery specializes in building large, inexpensive Dobson telescopes.
- Questar: Questar makes some very expensive Maksutov-Cassegrain telescopes which feature very compact, "elegant" designs. Questar has a cult following and has been very popular among celebrities.
- RC Optical Systems: Perhaps the epitome of mass produced telescopes, RC Optical Systems builds extremely high quality Ritchey-Chrétien Cassegrains. RC Optical Systems scopes are used by advanced (and deep-pocketed) amateurs, professional astronomers and the military. An RC Optical Systems telescope will even be launched into space for use in satellite reconnaissance. As one would expect, RC Optical Systems telescopes are extremely expensive; they start at $14,000.
- Takahashi: Takahashi manufactures expensive telescopes such as large apochromatic refractors and various exotic Cassegrain designs.
- Televue: Al Nagler's Televue is generally considered the top manufacturer of refractors and eyepieces in the world. Televue eyepieces are legendary and the favorite of most serious astronomers. That said, you pay a premium for the best.

# 6 Putting it All Together

Here are some things to think about

- Do you want all the bells and whistles? Figuring out how to use a complex telescope can be very time consuming. If you want to start observing quickly, simpler is better. Setting up a goto telescope, especially on an equatorial mount can be quite confusing. Sometimes, a simple alt-az mount or Dobson is better. Also, large reflector and Cassegrain telescopes occasionally require a calibration procedure called collimation, which can be quite tricky.
- Does portability matter to you? Unless you are strong and burly, a 80 pound telescope may be very difficult to move long distances. Even though aperture is extremely important, a large telescope that you never use is useless. Get a telescope that's light enough to use.
- Inexpensive telescopes particularly introduce tradeoffs. More aperture allows for higher magnifications and allows you to see fainter objects, but it may come at the expense of a good tripod or mount with an object locator or goto system. As I learned the hard way, even if you do not want a fancy mount, you at least need a tripod which is good enough to keep the telescope stable. Likewise, buying a poorly built telescope from a dubious manufacturer is far worse than buying a smaller tube of the same price from a quality brand.
- Would you like to use the telescope for terrestrial observation as well as astronomical observation? If so, you should purchase an alt-az mount with a refractor or Cassegrain telescope. Newtonian reflectors and equatorial or Dobson mounts do not work very well for terrestrial observation.