Optics of the Hubble Space Telescope

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1 The Hubble Space Telescope

To illustrate the workings of a real optical instrument, let's examine some of the optical details of the Hubble Space Telescope (HST). Hubble is arguably the most successful and productive astronomical instrument of all time, so a study of some of its inner workings will be instructive.

1.1 Overview

Hubble is a large astronomical telescope that was placed in orbit around the Earth on April 25, 1990. It is about the size of a school bus, and has a mass of about 11,000 kg. Hubble is in a low-Earth orbit (so it can be serviced by the Space Shuttle), and orbits the Earth about once every 96 minutes. Each orbit is about 1 hour in sunlight (orbit day) and 1/2 hour in darkness (orbit night).

Hubble is designed to make observations of astronomical objects in visible light, near infrared, and near ultraviolet wavelengths—it can observe wavelengths in the range of 100–2500 nm. (Visible light lies within this range, from 400–700 nm.)

The reason Hubble is in orbit around the Earth, rather than on the ground, is to get above the Earth's atmosphere. Turbulence in the Earth's atmosphere causes blurring of the images, which is avoided when the telescope is above the atmosphere. Also, the atmosphere absorbs some wavelengths of light, a complication that is also avoided by being in orbit. Finally, some light is lost when it passes through the atmosphere. By being in orbit above the atmosphere, Hubble avoids this light loss and can see very faint objects.

1.2 Instruments

Unlike ground-based amateur telescopes, there is nobody looking at Hubble's images directly through an eyepiece. Instead, the images observed by Hubble are sent to a complement of scientific instruments (cameras and spectrometers), each of which can perform its own analysis and relay the resulting spectra and images to the ground by radio. The five instruments currently on board Hubble are:

- Wide Field Camera 3 (WFC3)
- Space Telescope Imaging Spectrograph (STIS)
- Cosmic Origins Spectrograph (COS)
- Advanced Camera for Surveys (ACS)
- Near Infrared Camera and Multi-Object Spectrometer (NICMOS)

2 Astronomical Photometry

Photometry—the science of the measurement of the brightness of light—is done a little differently by astronomers than by physicists. Astronomers use a system of *magnitudes* to describe the brightness of an object. The magnitude scale used by astronomers is a logarithmic scale, and measures dimness rather than brightness; that is, higher magnitudes describe dimmer objects. The magnitude scale was originally designed so that the brightest stars you can see with the naked eye have a magnitude of about 0, while the dimmest stars you can see with the naked eye are magnitude 5. Each magnitude is dimmer than the last by a factor of $\sqrt[5]{100} \approx 2.5119$, so that a magnitude 0 star is exactly 100 times brighter than a magnitude 5 star. The brightest star in the sky, Sirius, has a magnitude of -1.5. The full Moon has a magnitude of about -12, while the Sun has a magnitude of about -27.

Your eye can see stars as faint as magnitude 5 or 6 under good conditions, and with good binoculars you can see objects as faint as magnitude 10 or so. With a really good amateur telescope you might be able to see objects as faint as magnitude 15. But the Hubble Space Telescope can see objects fainter than magnitude 30 (which is $very$ faint).

3 HST Optics Overview

The Hubble Space Telescope's optics is all based on *mirrors* (no lenses). Lenses are generally not suitable for large astronomical telescopes for a number of reasons. First, a large lens requires a large solid piece of glass, which are subject to bubbles and other irregularities that degrade the image. Also, some light is always lost when passing through a lens, no matter how carefully the lens is made. Weight is another issue: large lenses are very heavy, but they can only be supported from around the edges, which can cause them to sag under gravity. Finally, lens designers are at the mercy of the optical properties of the glass (such as dispersion) over which they have little control, except for inserting additional corrective lenses. Nevertheless, some lens-based astronomical telescopes (called *refracting telescopes*) are still in use; the largest is the 40-inch diameter telescope at the Yerkes observatory in Wisconsin.

Mirrors, on the other hand, have numerous advantages. They have only one optical surface, so the back of the mirror can be hollowed out to make the mirror lighter. The mirror can be supported along the edges and along the back, so there are fewer problems with sagging. Also, mirrors don't suffer from some optical issues like chromatic aberration that plague lens designers, and don't have the light loss issues that lenses do. For these reasons, most modern large astronomical telescopes use mirrors; these are called *reflecting telescopes*.

The simplest design of a reflecting telescope is a *Newtonian* telescope, in which a single parabolic mirror (the *primary mirror*) forms an image, which is reflected out of the side of the telescope with a flat *secondary mirror* and into an eyepiece. A more compact design, used by many larger reflecting telescopes, is a *Cassegrain* telescope. In this design, light first strikes a curved primary mirror, reflects to a curved secondary mirror, and back through a hole in the primary mirror to the eyepiece. This design allows for a primary mirror with a long focal length to be placed in a relatively small space, since the optical path is "folded" on itself.

The Hubble Space Telescope is a reflecting telescope that is a variation of the Cassegrain design, called a *Ritchey-Chrétien Cassegrain* design. In this design, both the large primary mirror and the smaller secondary mirror are sections of hyperboloids of two sheets. The two hyperboloids work together to focus an image just behind the hole in the primary mirror.

Hubble's primary mirror has a diameter of $D = 2.4$ meters (94.5 inches), and has a focal length of $f = 57.6$ meters. Another parameter often used to characterize astronomical telescopes is the so-called f-number, which is defined to be the ratio of the focal length to the aperture diameter:

$$f\text{-number} = \frac{f}{D} \tag{1}$$

For Hubble, the primary mirror has an f-number of $f/24$.

4 Resolution

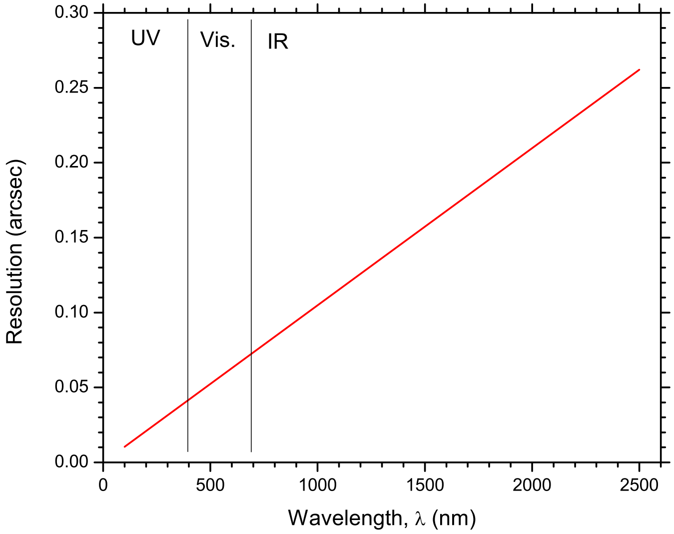
Because of single-slit diffraction, any astronomical object observed through a telescope with a finite aperture will create a diffraction pattern, and this diffraction effect limits the resolution of the image. In general, the larger the aperture of the telescope, the better the resolution (and also the fainter the objects it can see, since it can collect more light).

The *resolution* of an astronomical telescope (or other optical device) is defined to be the smallest angular separation of two point sources of light that will still allow them to be resolved as individual point sources, despite their overlapping diffraction patterns. The exact point at which two adjacent diffraction patterns are overlapping "too much" is a bit vague, but one commonly used definition is the *Rayleigh criterion*. Under the Rayleigh criterion, the smallest angular separation θ that two point sources can have and still be resolvable as two individual point sources is

$$\theta = 1.22\frac{\lambda}{D} \tag{2}$$

where θ is the angular resolution in radians, λ is the wavelength of the light, and D is the diameter of the aperture of the instrument. For the Hubble Space Telescope, $D = 2.4$ meters, and λ varies between 100 and 2500 nanometers. Using equation (2) for the Rayleigh criterion, we can plot the angular resolution of Hubble as a function of wavelength (Figure 1).

Figure 1. Hubble Space Telescope Optical Resolution



As you can see from the figure, Hubble's resolution in visible light is about 0.05 arcseconds (where 1 arcsecond = 1/60 arcminute = 1/3600 degree). To give some idea of what this means, if the Hubble Space Telescope were in Washington DC, it could distinguish two objects in New York City if they were separated by a distance of just 3 inches:

$$\begin{aligned} s &= r\theta \\ &= (331321\ \mathrm{m}) \left[(0.05\ \mathrm{arcsec}) \left(\frac{1\ \mathrm{deg}}{3600\ \mathrm{arcsec}}\right) \left(\frac{\pi\ \mathrm{rad}}{180\ \mathrm{deg}}\right)\right] \\ &= 0.080\,\mathrm{m} \\ &= 3\ \mathrm{inches} \end{aligned}$$

5 Spherical Aberration

Shortly after its launch in 1990, it was discovered that Hubble's primary mirror had a *spherical aberration*, in the sense that it had not been ground exactly to the required hyperbolic shape. It turned out that the outer edges had been made too flat by about 2 μm—about 1/50 the thichness of a human hair, but enough to severely degrade the images. Light striking the primary mirror near the edges focused at a different point than light striking the mirror near the center, resulting in a significant blurring of the images.

Some mathematical techniques were developed to partially compensate for this, but the real issue was that the optics needed to be fixed. This was done during the Hubble First Servicing Mission in 1993, when a set of corrective optics called COSTAR (for "Corrective Optics Space Telescope Axial Replacement") was installed. COSTAR consisted of a set of mirrors (one for each instrument) that were curved in such a way that they corrected for the spherical aberration in the primary mirror. The light path then became one where light would first strike the primary mirror, then reflect off of the secondary mirror, then down through the hole in the primary mirror where it would strike a COSTAR corrective mirror, then on to the instruments. Since the installation of COSTAR, the Hubble Space Telescope has operated right at the theoretical limit of resolution imposed by single-slit diffraction effects.

Since the First Servicing Mission, all new Hubble instruments that have been installed have included their own built-in corrective optics. By the time of Servicing Mission 3B in 2002, all the instruments had their own corrective optics built in, and COSTAR was no longer required. COSTAR was finally removed during Servicing Mission 4 in 2009, freeing up room for another scientific instrument to be installed during this mission, the Cosmic Origins Spectrograph.