Observational Astronomy Lab
UPES Dehradun

Nitesh Kumar

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Contents

Chapter 1

Telescopes

Telescopes have been the primary window through which humanity has explored the universe. From the earliest simple devices to today's sophisticated, computer-controlled instruments, telescopes have continually evolved—both in their optical designs and in the breadth of the electromagnetic spectrum they can observe.

1.1 The Tale of Telescopes

Once upon a time, in the early decades of the 17th century, in a modest workshop in the Netherlands, a curious spectacle maker named Hans Lippershey began experimenting with glass lenses. In his small, bustling workshop—where the sound of glass being shaped mingled with the excitement of newfound ideas—Lippershey crafted a simple optical tube. His invention, a device that made distant objects appear closer, quickly set the world abuzz with possibilities.

The news of this remarkable contraption reached the far corners of Europe and soon found its way to the inquisitive mind of Galileo Galilei in Italy. In a humble study lit by flickering candlelight, Galileo built his own improved version of the telescope. As he peered through his freshly crafted instrument, the universe unfolded before him: the rugged mountains and deep craters of the Moon, the puzzling phases of Venus, and a myriad of stars hidden from the naked eye. Galileo's discoveries sparked both wonder and controversy, forever challenging the established view of the cosmos.

Not long after Galileo's revelations, a brilliant English mathematician and scientist, Sir Isaac Newton, sought to overcome the limitations of refracting telescopes. In the quiet solitude of his study, Newton devised an entirely new approach by replacing lenses with a curved mirror—a reflecting telescope. This ingenious design eliminated the troubling chromatic aberrations and allowed for much larger instruments, laying the foundation for the next great leap in astronomical observation.

As time marched on, the spirit of exploration continued to guide visionary astronomers. William Herschel, driven by insatiable curiosity and armed with his own handcrafted mirrors, built ever-larger telescopes that revealed vast star clusters and nebulae, expanding humanity's understanding of the universe. Each breakthrough, from the handcrafted lenses of the early pioneers to the advent of segmented mirrors and active optics, was a stepping stone in a grand journey—a journey that transformed a modest optical tube into a powerful window to the cosmos.

Today, as modern observatories peer deep into space with instruments like the James Webb Space Telescope and the upcoming Extremely Large Telescopes, we continue the legacy of those early innovators. The story of the telescope is not merely a chronicle of technological advancements, but a testament to the human spirit—a narrative of curiosity, perseverance, and the relentless pursuit of knowledge that has allowed us to unlock the secrets of the universe.

1.2 Types of Telescopes: Designs, Wavelengths, and Applications

Telescopes come in many varieties, each tailored to meet the unique challenges of gathering and analyzing light from the universe. Over the centuries, astronomers and engineers have developed a rich taxonomy of telescopes, broadly classified by their optical design, wavelength coverage, and specialized applications. In this section, we explore these types and highlight a range of real-world examples.

1.2.1 Based on Optical Design

Refracting Telescopes. The earliest telescopes were refractors, which use convex lenses to bend light and bring distant objects into focus. Early devices, such as those built by Hans Lippershey and refined by Galileo Galilei, used simple lenses to reveal the craters of the Moon and the phases of Venus. Modern refracting telescopes, though less common for research due to inherent limitations such as chromatic aberration, are still prized for their sharp, high-contrast images. Notable examples include the Yerkes Observatory refractor—the largest ever built with a 40-inch lens—and smaller high-quality instruments used by amateur astronomers.

Reflecting Telescopes. To overcome the limitations of lenses, reflecting telescopes use curved mirrors as the primary light-gathering element. Isaac Newton's design in 1668 set the stage for a revolution in telescope technology. Reflectors are the workhorses of modern astronomy; they are not subject to chromatic aberration and can be built much larger. Classic examples include the 200-inch Hale Telescope at Palomar Observatory and the modern segmented mirror telescopes such as the twin 10-meter Keck Telescopes in Hawaii, which use an array of hexagonal segments to form one large, precise reflecting surface.

Catadioptric Telescopes. These hybrid instruments combine lenses and mirrors to correct for various optical aberrations while maintaining a compact size. Schmidt-Cassegrain and Maksutov-Cassegrain telescopes are popular among both amateur astronomers and educational institutions. Their design provides a long effective focal length in a relatively small package; models such as those from Celestron and Meade are widely used for both deep-sky imaging and planetary observation.

Interferometers and Aperture Synthesis. In recent decades, astronomers have developed methods to combine light from multiple telescopes to simulate a much larger aperture. Optical and infrared interferometry, as practiced by facilities such as the Very Large Telescope Interferometer (VLTI) and the CHARA Array, enables resolutions far beyond what a single telescope can achieve. These techniques have been crucial for studying stellar surfaces, active galactic nuclei, and fine structures in distant galaxies.

1.2.2 Based on Wavelength Coverage

Optical Telescopes. Designed to collect visible light, these telescopes have been the cornerstone of astronomical observation since Galileo's time. Ground-based observatories such as the European Southern Observatory's Very Large Telescope (VLT) and space telescopes like the Hubble Space Telescope have provided breathtaking images of star clusters, nebulae, and galaxies.

Infrared Telescopes. Infrared telescopes are built to detect heat radiation, allowing astronomers to peer through dust clouds and study objects that are too cool or too distant to be seen in visible light. The James Webb Space Telescope (JWST), with its large, segmented mirror and elaborate sunshield, is designed to explore the early universe by capturing faint infrared signals. Other examples include the Spitzer Space Telescope and ground-based facilities like the United Kingdom Infrared Telescope (UKIRT).

Radio Telescopes. Rather than collecting light in the optical range, radio telescopes capture long-wavelength radio waves. These instruments often consist of large parabolic dishes or arrays of smaller antennas. The now-decommissioned Arecibo Observatory, the Green Bank Telescope, and the Very Large Array (VLA) are renowned for mapping cosmic phenomena such as pulsars, interstellar gas clouds, and the cosmic microwave background.

Ultraviolet, X-ray, and Gamma-ray Telescopes. Telescopes designed to observe high-energy wavelengths must typically be placed in space to avoid atmospheric absorption. Ultraviolet telescopes like GALEX, X-ray observatories such as the Chandra X-ray Observatory, and gamma-ray telescopes like Fermi have expanded our understanding of energetic processes—from the behavior of supernova remnants and black holes to the study of cosmic rays and the most violent events in the universe.

1.2.3 Specialized Telescopes and Hybrid Systems

Many modern observatories combine multiple techniques and wavelength capabilities to provide a more comprehensive picture of the cosmos. For example, some ground-based observatories are outfitted with adaptive optics systems that dynamically correct for atmospheric distortions, while others integrate interferometric techniques to boost resolution. Furthermore, telescopes like the Sloan Digital Sky Survey (SDSS) have combined wide-field imaging with spectroscopic capabilities to map vast regions of the sky in unprecedented detail.

1.2.4 Examples from Modern Astronomy

To illustrate the diversity of telescope designs:

- The **Keck Observatory** in Hawaii features two 10-meter reflecting telescopes with segmented mirrors and advanced active optics systems.
- The **Hubble Space Telescope**, a pioneering optical instrument operating from space, has provided deep-field images that revolutionized our view of distant galaxies.

- The **James Webb Space Telescope** represents the next generation of space-based observatories, using a 6.5-meter segmented mirror to capture infrared light from the earliest epochs of the universe.
- The **Very Large Array** (VLA) in New Mexico is a prime example of a radio telescope array, where multiple antennas work together to simulate a giant dish.
- The **Chandra X-ray Observatory** has enabled detailed studies of high-energy phenomena by capturing X-rays from supernova remnants, galaxy clusters, and black holes.

Each of these telescopes, whether based on refractive, reflective, or hybrid optical designs, and whether observing in optical, infrared, radio, or high-energy wavelengths, plays a crucial role in advancing our understanding of the universe. Their varied designs underscore the innovative spirit that has driven astronomical research through the ages.

1.3 Technical Details of Optical Telescopes

Understanding the performance of an optical telescope involves several key technical parameters that determine how effectively it gathers light and resolves fine details in astronomical objects. In this section, we discuss the core concepts—such as diameter, light gathering power, focal length, focal ratio, field of view, magnification, and plate scale—and provide sample exercises to reinforce these ideas.

1.3.1 Diameter and Light Gathering Power

The primary mirror or lens diameter, D, is one of the most critical parameters of a telescope. It directly affects the light gathering power (LGP), which is proportional to the area of the aperture:

$$\text{LGP} \propto \pi \left(\frac{D}{2}\right)^2.$$

This means that a telescope with a larger diameter can collect more light and thus detect fainter objects. For example, a telescope with a 1-meter diameter has an area about 200 times greater than the human eye's pupil (approximately 7 mm in diameter).

1.3.2 Focal Length and Focal Ratio

The **focal length**, F, is the distance from the primary mirror or lens to the point where the light converges (the focal point). The **focal ratio** (or f-number) is defined as:

$$f/\# = \frac{F}{D}.$$

A lower $f/\#$ means a "faster" telescope, which is particularly advantageous for imaging faint extended objects because it results in a brighter image on the detector.

Magnification in a telescope is typically achieved by combining the telescope with an eyepiece. The magnification, M, is given by:

$$M = \frac{F}{f_e},$$

where f_e is the focal length of the eyepiece.

1.3.3 Field of View and Plate Scale

The **field of view** (FOV) is the angular area of the sky that is imaged by the telescope. It depends on both the focal length of the telescope and the size of the detector or eyepiece field stop.

The **plate scale** provides a way to convert distances in the focal plane (e.g., millimeters) to angular measurements on the sky (e.g., arcseconds). The plate scale, P, in arcseconds per millimeter is given by:

$$P \approx \frac{206265}{F} \quad \text{(with } F \text{ in mm).}$$

This relation helps determine the size of celestial objects on the detector and is crucial for planning observations.

1.3.4 Additional Considerations

Other important technical details include:

- **Diffraction Limit:** Defined by the Rayleigh criterion, the diffraction-limited angular resolution is approximately:

  $$\theta \approx 1.22\frac{\lambda}{D},$$

  where λ is the wavelength of light. This sets the fundamental limit on the resolution of the telescope.

- **Magnification and Eyepiece Design:** In visual observations, the choice of eyepiece affects both the magnification and the eye relief, which is the distance between the eyepiece and the observer's eye for comfortable viewing.

- **Optical Aberrations:** Issues such as spherical aberration, coma, and chromatic aberration are minimized in well-designed telescopes through careful shaping of optical elements and the use of corrective optics.

1.3.5 Sample Exercises and Problems

Problem 1: Light Gathering Power Comparison
An optical telescope has a primary mirror with a diameter of 1 m. Compare its light gathering power with that of the human eye, which has an average pupil diameter of 7 mm.
Solution:

$$\text{Area of telescope} = \pi\left(\frac{1\,\text{m}}{2}\right)^2 \approx 0.785\,\text{m}^2,$$

$$\text{Area of human pupil} = \pi\left(\frac{7\times10^{-3}\,\text{m}}{2}\right)^2 \approx 3.85\times10^{-5}\,\text{m}^2.$$

The ratio of light gathering power is:

$$\frac{0.785}{3.85\times10^{-5}} \approx 20390.$$

Thus, the telescope gathers roughly 20,000 times more light than the human eye.

Problem 2: Plate Scale Calculation
A telescope has a focal length of 10 m. Calculate the plate scale in arcseconds per millimeter.
Solution:
First, convert the focal length to millimeters: $10\,\text{m} = 10000\,\text{mm}$. Then,

$$P \approx \frac{206265}{10000} \approx 20.63\,\text{arcsec/mm}.$$

Problem 3: Magnification Determination
A telescope with a focal length of 2000 mm is used with an eyepiece of focal length 25 mm. What is the magnification?
Solution:

$$M = \frac{2000\,\text{mm}}{25\,\text{mm}} = 80.$$

Thus, the eyepiece produces an 80x magnified image.

Problem 4: Diffraction Limit
Estimate the diffraction-limited angular resolution for a 1 m telescope observing light at a wavelength of 550 nm.
Solution:
Using the Rayleigh criterion,

$$\theta \approx 1.22\frac{\lambda}{D} = 1.22\frac{550 \times 10^{-9}\,\text{m}}{1\,\text{m}} \approx 6.71 \times 10^{-7}\,\text{radians}.$$

Converting to arcseconds (1 radian $\approx$ 206265 arcseconds),

$$\theta \approx 6.71 \times 10^{-7} \times 206265 \approx 0.138\,\text{arcseconds}.$$

These exercises illustrate the practical application of the technical concepts that define the performance of optical telescopes. Understanding these parameters is crucial for both designing new instruments and planning astronomical observations.

1.4 Modern Technologies and Innovations

Modern telescopes benefit from a convergence of innovations in materials science, computer control, and optical engineering. One major breakthrough is the use of segmented mirrors. Instead of one massive, monolithic mirror (which is limited by size and weight), many large observatories now use arrays of smaller, precisely shaped mirror segments that work together as a single surface. This technology is critical for facilities like the Keck Telescopes and the upcoming Extremely Large Telescope.

Active optics systems are employed to adjust the mirror segments in real time. By using computer-controlled actuators and sensors, these systems compensate for deformations caused by gravity, temperature variations, and other environmental factors. Additionally, adaptive optics techniques are used to correct for the blurring effects of Earth's atmosphere, allowing ground-based telescopes to achieve near-diffraction-limited performance.

Interferometry is another powerful method that combines light from multiple telescopes to simulate a much larger aperture. This technique has enabled astronomers to achieve sub-milliarcsecond resolution, crucial for detailed imaging of stellar surfaces and distant galaxies.

1.5 Modern Observatories and Future Prospects

Modern observatories span both ground-based and space-based platforms. Space telescopes, such as the Hubble Space Telescope and the James Webb Space Telescope, operate above the Earth's atmosphere, providing unobstructed views across various wavelengths. On the ground, facilities like the Keck Observatory and the Very Large Telescope leverage advanced adaptive optics and segmented mirror designs to push the limits of resolution and sensitivity.

Looking ahead, the next generation of extremely large telescopes, including the Thirty Meter Telescope and the Giant Magellan Telescope, promise to revolutionize our understanding of the cosmos. With apertures far larger than current instruments, these observatories will not only capture fainter and more distant objects but also provide detailed spectroscopy and imaging across the electromagnetic spectrum.

1.6 Mounts and GOTO Telescopes

Telescopes do not work in isolation—they require a stable and versatile mount to track celestial objects as the Earth rotates. Two common types of mounts are used in modern astronomy:

1.6.1 Types of Mounts

Equatorial Mounts: Equatorial mounts are designed so that one of their axes (the polar axis) is aligned with the Earth's rotational axis. This alignment means that, once the mount is properly polar-aligned, the telescope needs only to rotate about a single axis to track an object across the sky. Such mounts are especially favored for long-exposure astrophotography and are common on many high-quality amateur instruments.
Alt-Azimuth Mounts: Alt-azimuth mounts move in two perpendicular directions: altitude (up and down) and azimuth (side to side). These mounts are mechanically simpler and are often found on large research telescopes as well as many commercial instruments. However, they require more complex computerized tracking (and sometimes field de-rotators) to compensate for the rotation of the sky.

1.6.2 GOTO Telescopes

The advent of computerized mounts has given rise to the "GOTO" telescope—a system that, once aligned, can automatically slew to any target in the sky with the push of a button. The GOTO functionality relies on precise motors, encoders, and integrated software that, after an initial star-alignment procedure, can accurately point the telescope to coordinates provided by the user. This automation not only simplifies the observing process for amateurs but also enables rapid and efficient surveys and data collection for more advanced research.

1.7 Setting Up an 8-inch Celestron Telescope with an Equatorial Mount in Dehradun

Setting up your 8-inch Celestron telescope on an equatorial mount in Dehradun involves several key steps to ensure that your instrument is stable, properly aligned, and ready for clear, detailed observations. The following step-by-step guide outlines the process:

1.7.1 Site Preparation

1. **Choose a Suitable Location:** Select a dark, level spot away from local sources of light and vibration. In Dehradun, try to find a location with a clear view of the northern horizon for polar alignment.

2. **Clear the Area:** Ensure that the area is free of debris and obstacles, and set up a sturdy observing platform or tripod.

1.7.2 Mount Assembly and Polar Alignment

1. **Assemble the Equatorial Mount:** Follow the manufacturer's instructions to attach the mount's legs or tripod securely. Use a bubble level to verify that the base is flat.

2. **Set the Latitude:** Adjust the mount's latitude scale to match Dehradun's latitude (approximately 30.3° N). This step helps position the polar axis at the correct altitude above the horizon.

3. **Polar Alignment:** The mount must be aligned with the North Celestial Pole. In the Northern Hemisphere, this typically involves sighting Polaris. Use a polar scope (if provided) or align manually by:

   - Loosening the mount's slow-motion controls.
   - Adjusting the mount so that the polar axis points due north and rises to an altitude equal to your local latitude.
   - Fine-tuning the alignment by observing a known star near the pole and checking for drift.

1.7.3 Optical Tube and Balance

1. **Attach the Optical Tube:** Secure the telescope's optical tube to the mount's dovetail plate. Ensure all connectors are tightened firmly.

2. **Balance the Telescope:** Adjust the counterweights on the mount so that the telescope is balanced in both the right ascension (RA) and declination axes. A well-balanced setup minimizes strain on the motors and improves tracking accuracy.

1.7.4 Electronics and GOTO Alignment

1. **Power Up and Initialize:** Connect the mount's power supply (batteries or external power) and turn on the telescope's computer control system.

2. **Perform the Star-Alignment Procedure:** Using the telescope's hand controller, select a series of bright stars for alignment. The system will guide you through the process—slewing to the chosen stars, centering them in the eyepiece or camera, and then updating its internal database.

3. **Test the GOTO Functionality:** Once aligned, test the system by entering the coordinates or name of a well-known object. The telescope should automatically slew to the target and display it in the field of view.

1.7.5 Final Checks and Observing

1. **Verify Focus and Image Quality:** Adjust the focus using the telescope's focuser to obtain a sharp image. Make any necessary adjustments to the balance or alignment if you notice drift during tracking.

2. **Begin Observations:** With your telescope properly set up, you are now ready to observe the night sky. Enjoy stargazing and consider recording your observations for later study.

These detailed steps will help ensure that your 8-inch Celestron telescope with an equatorial mount is set up correctly, providing you with a reliable platform to explore the wonders of the cosmos from Dehradun.

1.8 Attaching a ZWO ASI585MC Planetary Camera and Calculating Field of View

In modern amateur and semi-professional astronomy, planetary cameras such as the ZWO ASI585MC have become popular for their ability to capture high-speed, high-resolution images of bright celestial objects. This section explains how to attach the camera to your telescope and details the calculations required to determine the field of view (FOV) when using an 8-inch, f/10 Celestron telescope.

1.8.1 Attaching the ZWO ASI585MC Camera

The ZWO ASI585MC is typically mounted at the telescope's focuser or on a dedicated imaging port. To attach the camera:

1. **Remove the Eyepiece:** Detach any eyepiece from the focuser to provide a direct optical path.

2. **Install a T-Adapter:** Connect a T-Adapter to the focuser's output. This adapter converts the focuser's standard barrel to a T-thread connection.

3. **Connect the Camera:** Screw the ZWO ASI585MC onto the T-Adapter. Make sure the connection is secure to avoid any light leaks or misalignments.

4. **Focus and Balance:** After mounting, adjust the telescope's focuser to achieve a sharp focus on a bright star. It is also important to check that the system is well balanced, especially if the telescope is on an equatorial mount.

1.8.2 Calculating the Field of View

For an 8-inch Celestron telescope with an f/10 focal ratio, the focal length F is given by:

$$F = f/\# \times D,$$

where D is the diameter of the telescope's primary mirror. An 8-inch telescope has a diameter of approximately 203.2 mm, so:

$$F = 10 \times 203.2\,\text{mm} \approx 2032\,\text{mm}.$$

The ZWO ASI585MC camera has a sensor with an effective resolution of 1920 × 1200 pixels and a pixel size of about 2.9 μm. This gives the sensor dimensions:

$$\text{Sensor Width} = 1920 \times 0.0029\,\text{mm} \approx 5.57\,\text{mm},$$

$$\text{Sensor Height} = 1200 \times 0.0029\,\text{mm} \approx 3.48\,\text{mm}.$$

The plate scale P (in arcseconds per millimeter) is calculated as:

$$P \approx \frac{206265}{F},$$

where F is in millimeters. For $F = 2032\,\text{mm}$:

$$P \approx \frac{206265}{2032} \approx 101.5\,\text{arcsec/mm}.$$

Now, the FOV in each dimension is found by multiplying the sensor size by the plate scale:

$$\text{FOV}_{\text{width}} = 5.57\,\text{mm} \times 101.5\,\text{arcsec/mm} \approx 565\,\text{arcseconds},$$

$$\text{FOV}_{\text{height}} = 3.48\,\text{mm} \times 101.5\,\text{arcsec/mm} \approx 353\,\text{arcseconds}.$$

Converting these values into arcminutes (since 1 arcminute = 60 arcseconds):

$$\text{FOV}_{\text{width}} \approx \frac{565}{60} \approx 9.42\,\text{arcminutes},$$

$$\text{FOV}_{\text{height}} \approx \frac{353}{60} \approx 5.88\,\text{arcminutes}.$$

Thus, with the ZWO ASI585MC attached to an 8-inch f/10 Celestron telescope, the field of view is approximately $9.4' \times 5.9'$.

1.8.3 Sample Exercise

Exercise: An 8-inch telescope operating at f/10 is equipped with a camera that has a sensor with dimensions of 6.0 mm by 4.0 mm. Calculate the field of view in arcminutes for both the width and height. (Assume the same focal length of 2032 mm.)

Solution:

- **Plate Scale:**

$$P = \frac{206265}{2032} \approx 101.5\,\text{arcsec/mm}.$$

- **FOV (Width):**

$$\text{FOV}_{\text{width}} = 6.0\,\text{mm} \times 101.5\,\text{arcsec/mm} \approx 609\,\text{arcseconds} \approx \frac{609}{60} \approx 10.15\,\text{arcminutes}.$$

- **FOV (Height):**

$$\text{FOV}_{\text{height}} = 4.0\,\text{mm} \times 101.5\,\text{arcsec/mm} \approx 406\,\text{arcseconds} \approx \frac{406}{60} \approx 6.77\,\text{arcminutes}.$$

This exercise demonstrates how sensor dimensions and telescope focal length combine to define the area of sky captured in each image.

By carefully attaching the camera and understanding these technical details, astronomers can optimize their observations and ensure that their setup is both robust and capable of capturing the desired celestial details.

Chapter 2

CCD Characterization: Readout Noise and Gain

Charge-Coupled Devices (CCDs) have revolutionized astronomical imaging thanks to their high sensitivity, low noise, and excellent linearity. In this chapter, we explore the fundamentals of CCDs, their operational principles, and the key performance parameters—readout noise and gain—using a combination of descriptive paragraphs and bullet-point summaries.

2.1 Overview of CCDs

CCDs are the primary sensors in modern astronomy. They work on the principle of the photoelectric effect, where incoming photons are converted into electrical charges. These charges are then transferred, pixel by pixel, to an output node where they are converted to digital values. This capability allows astronomers to record faint signals from distant celestial objects with remarkable precision.

2.1.1 Basic Principles of CCD Operation

When light strikes the silicon substrate of a CCD, it generates electron-hole pairs. The electrons are captured in potential wells within each pixel and are later transferred through the device in a process known as *clocking*. The accumulated charge is then read out and digitized, forming the basis of the recorded image.

Key steps in the CCD readout process include:

1. **Photon Detection:** Photons hit the pixel array, generating electron charges.

2. **Charge Transfer:** Clocking signals shift the charge from pixel to pixel toward the output node.

3. **Amplification:** The charge is converted into a voltage at the output amplifier.

4. **Digitization:** An Analog-to-Digital Converter (ADC) transforms the voltage into digital numbers for storage and processing.

2.1.2 Structure of a CCD Sensor

A typical CCD sensor is composed of several key components:

- **Pixel Array:** A grid of light-sensitive elements that collects electrons.
- **Gate Electrodes:** Control the transfer of charge between pixels.
- **Output Node:** Converts the charge into a voltage signal.
- **Analog-to-Digital Converter (ADC):** Digitizes the voltage signal into digital numbers (ADU).

2.1.3 Types of CCDs

Different CCD architectures are optimized for specific observational needs:

- **Full-Frame CCDs:** Offer the highest sensitivity but require a mechanical shutter.
- **Frame-Transfer CCDs:** Feature a separate storage region that allows rapid image readout without a shutter.
- **Interline CCDs:** Incorporate alternating light-sensitive and masked columns for fast frame capture.
- **Electron Multiplying CCDs (EMCCDs):** Provide enhanced sensitivity, particularly useful in very low-light conditions.

2.1.4 Performance Characteristics

Several key parameters determine how well a CCD performs:

- **Quantum Efficiency (QE):** The percentage of incident photons converted into electrons.
- **Dark Current:** Thermal electrons that accumulate over time in each pixel, adding unwanted noise.
- **Readout Noise:** The uncertainty introduced during the charge readout process; a critical factor for low-light observations.
- **Dynamic Range:** The range between the smallest and largest signals the CCD can accurately record.
- **Charge Transfer Efficiency (CTE):** The effectiveness with which charge is transferred from one pixel to the next.

2.1.5 Advantages of CCDs in Astronomy

CCDs have become the standard in astronomical imaging because they offer:

- **High Sensitivity:** Excellent detection across a wide spectral range.
- **Low Noise:** Superior signal-to-noise performance compared to photographic plates.
- **Linearity:** A linear response that allows for precise photometric measurements.
- **Long Integration Capability:** Ability to integrate exposures over long durations to capture faint sources.

2.2 Readout Noise

Readout noise arises from the electronic processes involved in transferring the charge from the CCD to the digital storage system. It is typically expressed in electrons (e^-) and is a key component in determining the overall signal-to-noise ratio (SNR) of an observation.

- Sources of readout noise include:
  - Amplifier noise during the conversion of charge to voltage.
  - Quantization noise from the ADC.
  - Other electronic disturbances inherent in the readout circuitry.
- A practical method to estimate readout noise is by taking multiple bias frames (zero-exposure images) and computing the standard deviation of the difference between two such frames:

$$RN = \frac{\sigma_{\text{bias1}-\text{bias2}}}{\sqrt{2}},$$

  where $\sigma_{\text{bias1}-\text{bias2}}$ is the standard deviation of the difference image.

2.3 Gain

Gain (G) is the conversion factor that relates the number of electrons collected in a pixel to the digital number (DN) output by the ADC. It is measured in electrons per digital number (e$^-$/DN) and is essential for translating CCD counts into physical quantities.

- Gain allows for the conversion of pixel values (ADU) into the actual number of electrons.
- It is typically calculated using flat-field images by comparing the mean signal S to the variance V in those images:

$$G = \frac{S}{V}.$$

2.4 Measurement of Readout Noise and Gain

Characterizing a CCD involves analyzing calibration images:

1. **Bias Frames:** Capture multiple zero-exposure images to compute the standard deviation of pixel differences, yielding the readout noise.

2. **Flat-Field Frames:** Acquire flat-field images at known exposure times, subtract the bias, and compute both the mean signal and variance.

3. **Variance vs. Signal Plot:** Plot the variance against the mean signal to derive the gain from the slope (which should approximate $1/G$).

2.4.1 Graphical Representations

Graphical analysis can aid in understanding these measurements:

- **Histogram of Bias Differences:** Illustrates the distribution of pixel differences and helps estimate readout noise.

- **Variance vs. Mean Signal Plot:** A linear trend in this plot confirms proper gain estimation.

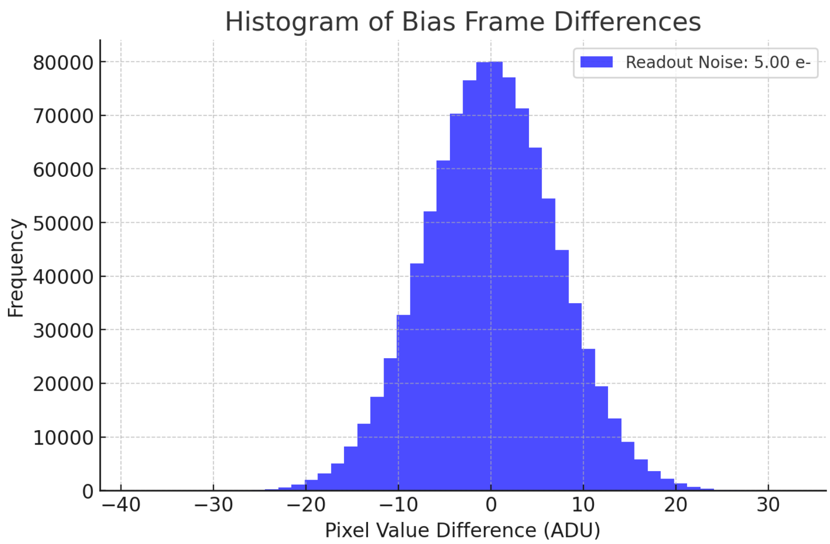

Figure 2.1: Histogram of pixel value differences in bias frames, used for estimating readout noise.

2.5 Python Code Example for CCD Characterization

The following Python script demonstrates how to estimate readout noise and gain using calibration images:

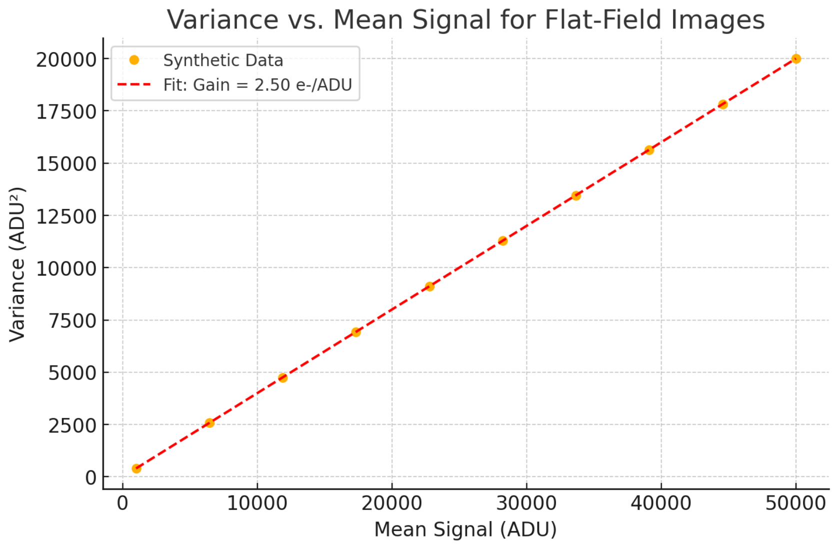

Figure 2.2: Variance vs. mean signal plot for flat fields. The slope is inversely proportional to the gain.

```python
from astropy.io import fits
import numpy as np
import glob

# Function to create a master frame from multiple files
def create_master_frame(file_list):
    images = [fits.getdata(f) for f in file_list]
    return np.median(images, axis=0)

# Gather bias and flat files
bias_files = glob.glob('bias_*.fits')
flat_files = glob.glob('flat_*.fits')

# Create master bias
master_bias = create_master_frame(bias_files)

# Calculate readout noise using the first two bias frames
bias1 = fits.getdata(bias_files[0])
bias2 = fits.getdata(bias_files[1])
readout_noise = np.std(bias1 - bias2) / np.sqrt(2)
print(f'Readout Noise: {readout_noise:.2f} e-')

# Process flat frames by subtracting bias
flat1 = fits.getdata(flat_files[0]) - master_bias
flat2 = fits.getdata(flat_files[1]) - master_bias

# Compute mean signal and variance to estimate gain
signal = np.mean(flat1)
variance = np.var(flat1 - flat2) / 2
gain = signal / variance
print(f'Gain: {gain:.2f} e-/DN')
```

Listing 2.1: Python code to compute readout noise and gain

2.6 Conclusion

CCD characterization through precise measurements of readout noise and gain is critical for the accurate analysis of astronomical images. By combining bias and flat-field calibration with computational analysis and graphical verification, astronomers can confidently convert raw data into scientifically meaningful measurements. This understanding enables the optimization of exposure settings and enhances the overall quality of observational data.

Chapter 3

A Beginner's Handbook to Astronomical Image Processing

This chapter serves as a comprehensive guide for first-time users who wish to understand and process astronomical images. It covers the fundamentals of CCD (Charge-Coupled Device) sensors, explains the different kinds of calibration frames, and walks you through the steps to preprocess your images. We also discuss key CCD parameters—readout noise and gain—and provide practical examples using Python.

3.1 Introduction

Astronomical images captured with CCD cameras contain not only the light from celestial objects but also various forms of unwanted signals and noise. Before these images can be used for scientific analysis (such as measuring the brightness or color of stars), they must be carefully preprocessed to remove these artifacts. Preprocessing involves:

- Removing electronic noise inherent in the CCD (bias).
- Correcting for thermal noise (dark current).
- Normalizing for variations in pixel sensitivity and optical imperfections (flat-fielding).

3.2 Understanding Different Types of Frames

Before we dive into the preprocessing steps, it is essential to understand the various types of frames used in calibration. Each type of frame plays a specific role in correcting the raw image data.

3.2.1 Bias Frames

Definition: Bias frames are images taken with a zero exposure time. They capture the electronic offset (or bias) inherent in the CCD readout process. **Purpose:**

- To record the base electronic noise level present in every image.
- To serve as a reference for subtracting this offset from all other images.

3.2.2 Dark Frames

Definition: Dark frames are images captured with the shutter closed and with the same exposure time as the science images. **Purpose:**

- To measure the thermal noise (dark current) that accumulates in the CCD over time.
- To remove this unwanted signal from the science images.

3.2.3 Flat-Field Frames

Definition: Flat frames are images taken of a uniformly illuminated source (e.g., a dome flat or twilight sky). **Purpose:**

- To correct for pixel-to-pixel variations in sensitivity.
- To account for optical effects such as vignetting and dust on the optical elements.

3.2.4 Science Frames

Definition: Science frames are the actual astronomical images capturing celestial objects. **Purpose:**

- To record the light from stars, galaxies, nebulae, and other astronomical targets.
- These images need to be calibrated using bias, dark, and flat frames before scientific analysis.

3.3 Preprocessing Workflow

The goal of preprocessing is to remove the unwanted signals from raw images. The typical workflow involves:

1. **Bias Subtraction:** Remove the electronic bias from the raw image:

$$I_{\text{bias-corrected}} = I_{\text{raw}} - I_{\text{bias}}$$

2. **Dark Frame Correction:** Subtract the dark current, using dark frames taken with the same exposure time:

$$I_{\text{dark-corrected}} = I_{\text{bias-corrected}} - I_{\text{dark}}$$

3. **Flat-Field Correction:** Correct for variations in sensitivity by dividing by a normalized master flat:

$$I_{\text{flat-corrected}} = \frac{I_{\text{flat}} - I_{\text{bias}} - I_{\text{dark}}}{\text{median}(I_{\text{flat}} - I_{\text{bias}} - I_{\text{dark}})}$$

   Then, apply the flat-field to the science image:

$$I_{\text{final}} = \frac{I_{\text{dark-corrected}}}{I_{\text{flat-corrected}}}$$

3.4 CCD Characterization: Readout Noise and Gain

Accurate calibration not only depends on preprocessing but also on understanding the CCD's behavior. Two important performance parameters are readout noise and gain.

3.4.1 Readout Noise

Overview:

- Readout noise is the uncertainty introduced during the electronic readout of the CCD.
- It is usually measured in electrons (e^-) and can significantly affect observations of faint objects.

Measurement: A common method to estimate readout noise is by taking multiple bias frames and calculating the standard deviation of the difference between them:

$$RN = \frac{\sigma_{\text{bias1}-\text{bias2}}}{\sqrt{2}}$$

where $\sigma_{\text{bias1}-\text{bias2}}$ is the standard deviation of the pixel differences.

3.4.2 Gain

Overview:

- Gain (G) is the conversion factor between the number of electrons collected in a pixel and the digital number (ADU) output.
- It is expressed in electrons per digital number (e$^-$/DN) and is critical for quantitative measurements.

Calculation: Gain is calculated by comparing the mean signal (S) in flat-field images to the variance (V) of that signal:

$$G = \frac{S}{V}$$

3.5 Practical Example: Python Implementation

Below is an integrated Python script that demonstrates the creation of master calibration frames (bias, dark, and flat) and processes science images. This script also includes calculations for readout noise and gain.

3.5.1 Preprocessing Code Example

```python
from astropy.io import fits
import numpy as np
import glob

# Function to create a master frame by median combining images
def create_master_frame(file_list):
```



```python
    images = [fits.getdata(f) for f in file_list]
    return np.median(images, axis=0)

# File lists for calibration frames and science images
bias_files = glob.glob('bias_*.fits')
dark_files = glob.glob('dark_*.fits')
flat_files = glob.glob('flat_*.fits')
science_files = glob.glob('science_*.fits')

# Create master calibration frames
master_bias = create_master_frame(bias_files)
master_dark = create_master_frame(dark_files)

# Correct flat frames for bias and dark current
flat_corrected = [(fits.getdata(f) - master_bias - master_dark) for f in
    flat_files]
master_flat = np.median(flat_corrected, axis=0)
master_flat /= np.median(master_flat)  # Normalize the master flat

# Process science images
for science_file in science_files:
    science = fits.getdata(science_file)
    corrected = (science - master_bias - master_dark) / master_flat
    fits.writeto(f'corrected_{science_file}', corrected, overwrite=True)
```

Listing 3.1: Python script for full image preprocessing

3.5.2 CCD Characterization Code Example

```python
# Calculate readout noise using two bias frames
bias1 = fits.getdata(bias_files[0])
bias2 = fits.getdata(bias_files[1])
readout_noise = np.std(bias1 - bias2) / np.sqrt(2)
print(f'Readout Noise: {readout_noise:.2f} e-')

# Process flat frames by subtracting bias
flat1 = fits.getdata(flat_files[0]) - master_bias
flat2 = fits.getdata(flat_files[1]) - master_bias

# Compute mean signal and variance to estimate gain
signal = np.mean(flat1)
variance = np.var(flat1 - flat2) / 2
gain = signal / variance
print(f'Gain: {gain:.2f} e-/DN')
```

Listing 3.2: Python code to compute CCD readout noise and gain

3.6 Visualization and Final Checks

After processing, use SAOImage DS9 to visualize your corrected science images:

```
ds9 corrected_science_*.fits &
```

This step allows you to verify that the calibration has effectively removed noise and artifacts from the raw images.

Chapter 4

Astronomical Coordinate Systems

Understanding the position of celestial objects requires a framework of coordinate systems. These systems allow astronomers to pinpoint locations in the sky with precision. The primary astronomical coordinate systems include:

4.1 Terrestrial Coordinate System

The Terrestrial Coordinate System is used to specify locations on Earth's surface. It employs two main coordinates:

- **Latitude:** Measures the angular distance north or south of the Equator, ranging from 0° at the Equator to 90° at the poles.
- **Longitude:** Measures the angular distance east or west of the Prime Meridian, ranging from 0° at the Prime Meridian to 180° eastward and westward.

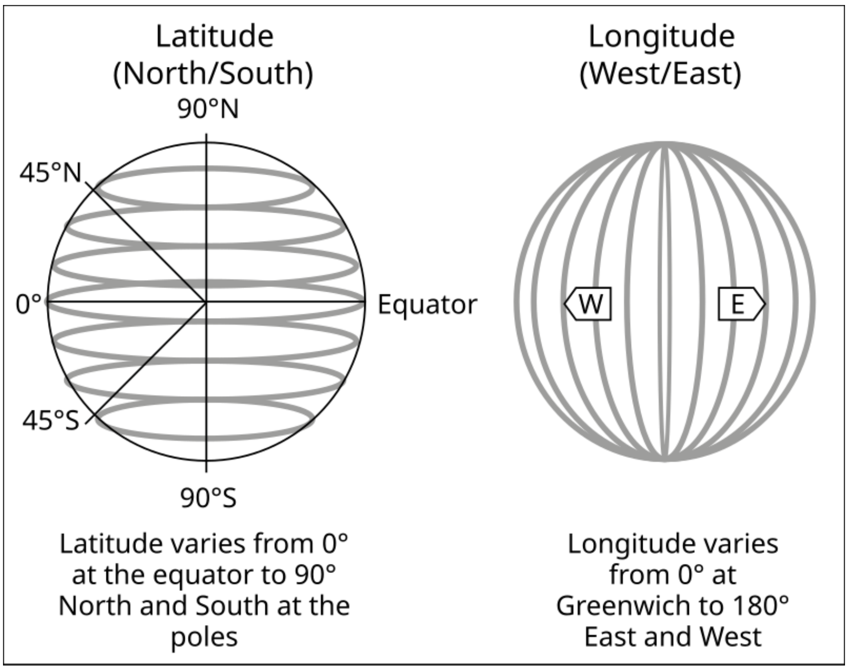

Figure 4.1: Terrestrial Coordinate System. Image source: Source

4.2 Horizon Coordinate System

The Horizon Coordinate System is based on the observer's local horizon. It uses two main coordinates:

- **Altitude (Alt):** The angle between the object and the observer's horizon.
- **Azimuth (Az):** The angle measured clockwise from the North point along the horizon to the point directly below the object.

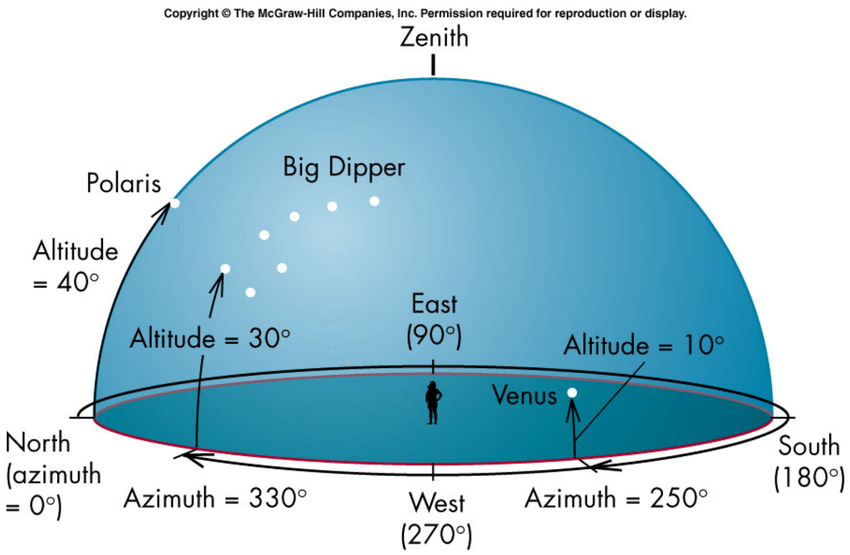

Figure 4.2: Horizon Coordinate System. Image source: https://homepage.physics.uiowa.edu/~spangler/2961_04/GA_04_files/slide0004.htm

4.3 Equatorial Coordinate System

The Equatorial Coordinate System is aligned with Earth's rotation axis and is widely used in astronomy. Its main coordinates are:

- **Right Ascension (RA):** Analogous to longitude, it measures the object's position eastward along the celestial equator.
- **Declination (Dec):** Analogous to latitude, it measures the object's position north or south of the celestial equator.

4.4 Ecliptic Coordinate System

The Ecliptic Coordinate System is based on the plane of Earth's orbit around the Sun. Its coordinates are:

- **Ecliptic Longitude (λ):** Measures the angular distance along the ecliptic from the vernal equinox.
- **Ecliptic Latitude (β):** Measures the angular distance north or south of the ecliptic plane.

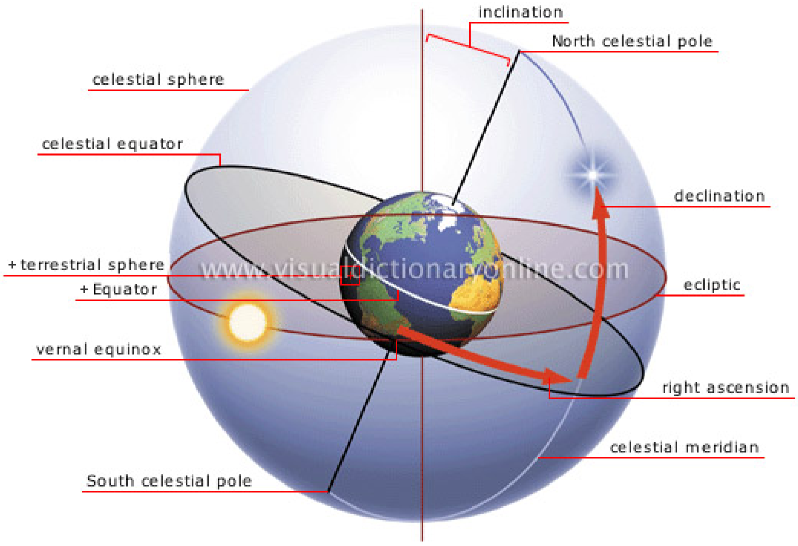

Figure 4.3: Equatorial Coordinate System. Image source: https://visualdictionaryonline.com/astronomy/astronomical-observation/celestial-coordinate-system.php

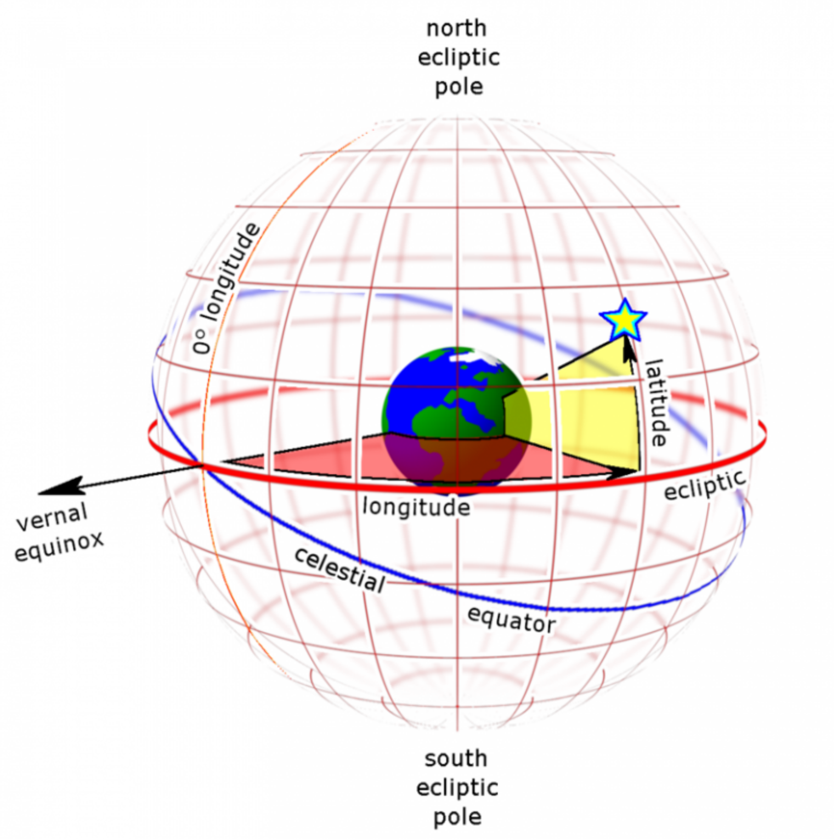

Figure 4.4: Ecliptic Coordinate System. Image source: https://www.secretsofuniverse.in/celestial-coordinate-system/

4.5 Galactic Coordinate System

The Galactic Coordinate System is centered on the Milky Way galaxy. Its coordinates are:

- **Galactic Longitude (l):** Measures the angular distance along the galactic plane from the galactic center.
- **Galactic Latitude (b):** Measures the angular distance above or below the galactic plane.

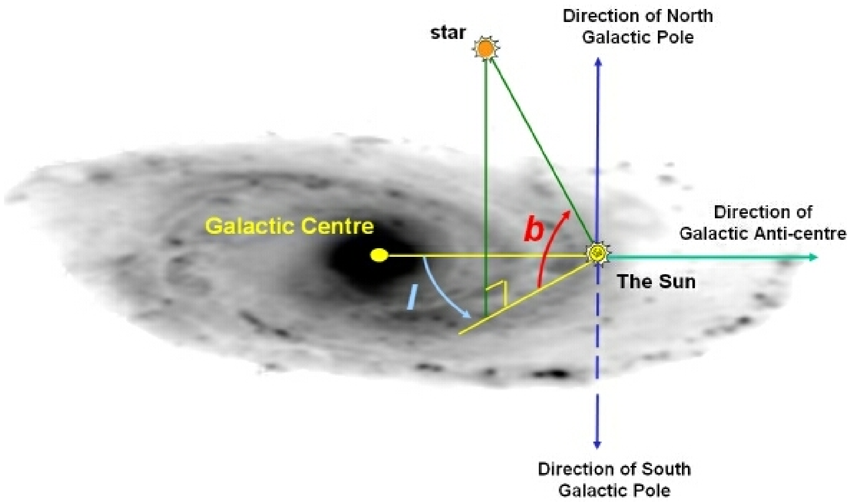

Figure 4.5: Galactic Coordinate System. Image source: https://lovethenightsky.com/celestial-coordinate-system-guide/

4.6 Transformations Between Coordinate Systems

Transforming coordinates from one system to another involves spherical trigonometry. For example, converting from equatorial to ecliptic coordinates requires accounting for the obliquity of the ecliptic ($\epsilon \approx 23.44°$):

$$\begin{aligned}
\sin(\beta) &= \sin(\delta)\cos(\epsilon) - \cos(\delta)\sin(\epsilon)\sin(\alpha),\\
\cos(\beta)\cos(\lambda) &= \cos(\delta)\cos(\alpha),\\
\cos(\beta)\sin(\lambda) &= \sin(\delta)\sin(\epsilon) + \cos(\delta)\cos(\epsilon)\sin(\alpha),
\end{aligned}$$

where (α, δ) are the right ascension and declination in the equatorial system, and (λ, β) are the ecliptic longitude and latitude.

Chapter 5

Deriving Airmass Corrected Magnitudes for a Cluster of Stars Using Aperture Photometry

In this chapter, we describe a step-by-step method for deriving airmass-corrected magnitudes for a cluster of stars, such as those near the Orion Belt, using aperture photometry. We cover the entire process—from planning observations to applying corrections for atmospheric extinction—to ensure that the final magnitudes accurately reflect the intrinsic brightnesses of the stars.

5.1 Planning Observations

Successful photometry begins with careful observation planning. Consider the following factors to maximize data quality:

5.1.1 Date and Time

- **Target Visibility:** Choose nights when the target cluster (e.g., near the Orion Belt) is high in the sky, minimizing atmospheric interference.
- **Airmass Considerations:** Observations should ideally be conducted when the airmass is low (typically less than 1.5) to reduce the effects of atmospheric extinction.
- **Time of Night:** Aim for times when the target is near culmination (i.e., its highest point) to further reduce airmass.

5.1.2 Moon Phase and Sky Conditions

- **Moon Illumination:** Schedule observations during a new moon or when the moon is below the horizon. The presence of moonlight increases sky brightness and can adversely affect photometric accuracy.
- **Transparency and Seeing:** Check local weather forecasts for clear, stable conditions with good atmospheric seeing. Cloud cover, humidity, and turbulence all affect the quality of your measurements.

5.1.3 Observation Setup

- **Calibration Frames:** Plan to acquire a set of bias, dark, and flat-field frames during the same night to calibrate the science images.
- **Exposure Times:** Choose exposure times that provide sufficient signal-to-noise ratios for the stars in your cluster while avoiding saturation.
- **Standard Stars:** If possible, include observations of standard stars with known magnitudes to aid in calibrating your instrumental magnitudes.

5.2 Aperture Photometry Basics

Aperture photometry involves measuring the total light (flux) received from a star by summing pixel values within a defined circular aperture.

5.2.1 Steps in Aperture Photometry

1. **Selecting an Aperture:** Choose an aperture radius that encompasses most of the star's light while minimizing background noise.
2. **Background Estimation:** Define an annulus around the star to measure and subtract the background sky brightness.
3. **Flux Calculation:** Sum the pixel values inside the aperture and subtract the estimated background contribution.

5.2.2 Instrumental Magnitudes

The instrumental magnitude, m_{inst}, is computed from the measured flux F using the relation:

$$m_{\text{inst}} = -2.5 \log(F) + C,$$

where C is an arbitrary constant that depends on the instrument.

5.3 Airmass and Atmospheric Extinction

Atmospheric extinction dims starlight as it passes through the Earth's atmosphere. The amount of dimming depends on the airmass X, which is a measure of the path length through the atmosphere relative to the zenith.

5.3.1 Calculating Airmass

A simple approximation for airmass when the zenith angle z is small is:

$$X \approx \sec(z).$$

For larger zenith angles, more refined formulas should be used.

5.3.2 Extinction Correction

The observed (instrumental) magnitude is affected by atmospheric extinction:

$$m_{\text{obs}} = m_{\text{true}} + kX,$$

where:

- m_{obs} is the observed magnitude,
- m_{true} is the intrinsic magnitude,
- k is the extinction coefficient (in mag/airmass),
- X is the airmass.

Rearranging the equation provides the airmass-corrected (true) magnitude:

$$m_{\text{true}} = m_{\text{obs}} - kX.$$

5.4 Deriving Magnitudes for a Cluster of Stars Near Orion Belt

5.4.1 Data Acquisition

- **Science Images:** Capture a series of images of the star cluster near the Orion Belt. Ensure that you record the time of each observation to compute the corresponding airmass.
- **Calibration Frames:** Obtain bias, dark, and flat-field frames as described in the preprocessing chapter.
- **Standard Star Observations:** If possible, observe standard stars with known magnitudes to calibrate your photometry.

5.4.2 Aperture Photometry Workflow

1. **Preprocess the Images:** Apply bias subtraction, dark frame correction, and flat-fielding to all science images.
2. **Select an Aperture and Annulus:** For each star, choose an aperture radius (in pixels) that captures the star's light, and an annulus for background estimation.
3. **Compute Flux and Instrumental Magnitudes:** Sum the counts within the aperture, subtract the background, and calculate the instrumental magnitude.
4. **Determine Airmass:** For each image, calculate the airmass X using the known time and the star's coordinates.
5. **Apply Extinction Correction:** Using the measured extinction coefficient k (determined from standard stars or literature), correct each instrumental magnitude:

$$m_{\text{true}} = m_{\text{inst}} - kX.$$

6. **Calibrate with Standard Stars:** Adjust your magnitudes to the standard photometric system if observations of standard stars were performed.

5.4.3 Example Calculation

Suppose a star in the Orion Belt cluster has an instrumental magnitude $m_{\text{inst}} = 12.3$ and was observed at an airmass $X = 1.4$. If the extinction coefficient is $k = 0.2$ mag/airmass, then:

$$m_{\text{true}} = 12.3 - (0.2 \times 1.4) = 12.3 - 0.28 = 12.02.$$

This corrected magnitude represents the star's brightness as if it were observed at the zenith (airmass $X = 1$).

5.5 Planning an Observation Session in Dehradun

When planning your observing session, especially for a target near the Orion Belt, consider the following:

5.5.1 Site and Timing

- **Location:** Dehradun, India (Latitude $\approx 30.3°$ N).
- **Date and Time:** Choose a date when Orion is visible at high altitude. In winter months (December–February), Orion is well-placed in the evening sky.
- **Airmass:** Aim for observations near culmination (when the target is highest in the sky) to achieve a low airmass.

5.5.2 Lunar Conditions

- **Moon Phase:** Schedule observations during a new moon or when the moon is below the horizon to minimize sky brightness.

5.5.3 Observation Setup

- **Equipment Check:** Ensure your telescope (with a CCD camera) is well-aligned and that all calibration frames (bias, dark, flat) are acquired during the same night.
- **Exposure Planning:** Choose exposure times that maximize signal-to-noise without saturating the CCD.
- **Standard Stars:** Include one or more standard stars in your field or observe them separately for calibration.

By carefully planning your observations and applying systematic preprocessing steps, you can derive accurate airmass-corrected magnitudes for clusters of stars. This chapter has provided a beginner-friendly guide covering everything from the acquisition of calibration frames to the detailed process of aperture photometry and extinction correction. With these techniques, even first-time users can confidently transform raw astronomical images into scientifically valuable data.

Chapter 6

Measuring Solar Rotation with Sunspot Tracking

6.1 Introduction

The Sun is not a solid body; its surface rotates differentially—faster at the equator than near the poles. One of the simplest methods to study solar rotation is by tracking sunspots over several days. In this experiment, we will measure the apparent motion of sunspots across the solar disk and derive the solar rotation period. This handbook is designed for first-time users with a typical amateur setup, including a telescope, solar filter, and imaging system.

6.2 Objectives

The goals of this experiment are:

- To safely observe and image the Sun using appropriate solar filters.
- To record the positions of sunspots over several nights.
- To calculate the angular displacement of sunspots as a function of time.
- To derive an estimate of the Sun's rotation period.

6.3 Equipment and Software Required

Observational Equipment

- A telescope with a solar-grade aperture (e.g., an 8-inch or larger telescope) equipped with a certified solar filter.
- A stable equatorial mount with GOTO capability.
- A CCD or CMOS camera (e.g., a ZWO ASI series) for solar imaging.
- A computer with image acquisition software.

Software and Tools

- Python with `astropy`, `numpy`, and `matplotlib` for data analysis.
- SAOImage DS9 for image visualization.
- Image processing software (e.g., DeepSkyStacker or similar) for calibration if needed.

6.4 Safety Considerations

Observing the Sun poses significant risks if proper precautions are not taken. Always adhere to the following safety measures:

- **Always use a certified solar filter:** Attach the solar filter securely at the front end of the telescope. Never remove or bypass the filter during observations.
- **Never look directly at the Sun through the telescope:** Direct viewing can cause irreversible eye damage.
- **Inspect the filter regularly:** Ensure there are no scratches or damage that might allow harmful sunlight to reach your optics.

6.5 Planning the Observation Session

Successful solar observations require careful planning:

6.5.1 Date, Time, and Sky Conditions

- **Target Visibility:** Schedule observations when the Sun is high in the sky to minimize atmospheric airmass effects.
- **Time of Day:** Late morning to early afternoon often provides stable atmospheric conditions.
- **Weather Conditions:** Ensure the sky is clear with minimal cloud cover and low atmospheric turbulence.

6.5.2 Lunar Conditions

- **Moon Illumination:** Although the Sun is much brighter, avoid nights when moonlight might affect the calibration frames if you plan to observe during twilight.

6.5.3 Observation Setup

- **Calibration Frames:** Prepare to acquire calibration images (bias, dark, and flat fields) for your imaging system.
- **Standard Stars:** While not essential for solar imaging, note the Sun's position accurately using time and location data for later analysis.
- **GOTO Alignment:** Use the mount's GOTO functionality for precise tracking, ensuring that the solar filter remains securely in place.

6.6 Experimental Setup and Procedure

6.6.1 Equipment Assembly

1. **Mount and Telescope:** Assemble your telescope on the equatorial mount. Ensure the mount is polar-aligned for accurate tracking.
2. **Solar Filter Installation:** Attach the solar filter securely to the telescope's front end. Double-check for proper fit and integrity.
3. **Camera Attachment:** Mount your CCD/CMOS camera at the telescope's focal plane. Use any necessary adapters to ensure a secure connection.

6.6.2 Observation Procedure

1. **Initial Setup:**
   - Power up the telescope and camera system.
   - Use the GOTO function to point the telescope at the Sun.
   - Acquire a test image to verify that the solar filter is correctly installed and that the Sun's disk is properly imaged.
2. **Image Acquisition:**
   - Over the course of several days, capture a series of images of the solar disk. It is best to record the exact time of each image.
   - Focus on capturing clear images of sunspots and other surface features.
3. **Calibration:**
   - Capture calibration frames (bias, dark, and flats) during the same session.
   - Preprocess the images to correct for instrumental effects before measuring sunspot positions.

6.7 Data Analysis and Deriving Solar Rotation

6.7.1 Aperture Photometry of Sunspots

Use aperture photometry software to measure the positions of selected sunspots:

- Define a circular aperture around each sunspot.
- Use an annulus to estimate and subtract the background sky brightness.
- Record the pixel coordinates and flux values for each sunspot in every image.

6.7.2 Airmass Correction (Optional)

Since the Sun is bright and typically observed at low airmass, airmass correction might be minor. However, if your observations span a wide range of altitudes, calculate the airmass $X \approx \sec(z)$ (with z being the zenith angle) and correct the measured fluxes accordingly.

6.7.3 Deriving the Solar Rotation Period

1. For each sunspot, note its position (e.g., its angular distance from a fixed reference point on the solar disk) at different times.

2. Calculate the angular displacement $\Delta\theta$ over the elapsed time Δt for each sunspot.

3. The solar rotation rate ω can be approximated by:

$$\omega \approx \frac{\Delta\theta}{\Delta t}.$$

4. Average the rotation rates for multiple sunspots to derive a robust estimate of the Sun's rotation period.

6.7.4 Example Calculation

Suppose a sunspot moves 15° across the solar disk over 7 days. The daily rotation rate is:

$$\omega = \frac{15^\circ}{7 \text{ days}} \approx 2.14^\circ/\text{day}.$$

Since the full rotation (360°) corresponds to:

$$T \approx \frac{360^\circ}{2.14^\circ/\text{day}} \approx 168 \text{ days},$$

this example is for a sunspot at higher latitude (where the rotation is slower than at the equator). (Note: Typical equatorial rotation period is about 25 days.)

This experiment guides you through the process of safely observing the Sun, capturing images of sunspots, and deriving the solar rotation period using aperture photometry. By carefully planning your observations, ensuring proper calibration with bias, dark, and flat frames, and systematically measuring sunspot positions, you can obtain scientifically valuable measurements of the Sun's rotation. This experiment not only deepens your understanding of solar physics but also provides hands-on experience with the techniques of astronomical imaging and data analysis.

Chapter 7

Measuring Solar Limb Darkening

7.1 Overview

Solar limb darkening refers to the gradual decrease in brightness from the center of the solar disk to its edge. This experiment uses your current solar observation setup (telescope with solar filter, CCD camera, equatorial mount, etc.) to capture high-resolution images of the Sun and derive the limb darkening profile. The resulting curve helps us understand the temperature gradient in the solar atmosphere.

7.2 Objectives

By the end of this experiment you will:

- Safely capture calibrated images of the solar disk.
- Measure the radial intensity profile of the Sun.
- Derive the limb darkening curve and estimate the limb darkening coefficients.

7.3 Planning and Setup

7.3.1 Observation Planning

Consider the following before you begin:

- **Date and Time:** Choose a clear day when the Sun is high in the sky (minimal airmass) to reduce atmospheric interference.
- **Weather Conditions:** Ensure stable weather and minimal atmospheric turbulence.
- **Equipment Check:** Verify that the solar filter is properly secured and the CCD camera is connected to the telescope.

7.3.2 Equipment List

- Telescope (e.g., 8-inch or larger) with a certified solar filter.
- Equatorial mount with GOTO functionality.
- CCD camera (e.g., ZWO ASI series).
- Computer with image acquisition software and Python installed (with `astropy`, `numpy`, and `matplotlib`).
- SAOImage DS9 for image visualization.

7.4 Procedure

7.4.1 Data Acquisition

1. **Assembly and Alignment:**
   - Set up the telescope on the equatorial mount and perform polar alignment.
   - Attach the solar filter at the front end.
   - Connect the CCD camera to the telescope's focuser.
2. **Capturing Images:**
   - Use the GOTO function to center the Sun.
   - Acquire several images of the full solar disk at appropriate exposure times (ensure no saturation).
   - Record the time of each image.
3. **Calibration Frames:**
   - Capture bias, dark, and flat frames during the same session.
   - Preprocess these frames to create master calibration files.

7.4.2 Data Reduction and Analysis

1. **Image Preprocessing:**
   - Subtract the master bias and dark frames from each solar image.
   - Divide by the normalized master flat to correct for pixel sensitivity variations.
2. **Extracting the Radial Profile:**
   - Load the calibrated solar image into an image processing tool (such as DS9 or a Python-based script).
   - Define the center of the solar disk and extract the pixel intensities along a radial line (or compute an azimuthal average).
3. **Fitting the Limb Darkening Curve:**

- Plot the normalized intensity as a function of radial distance from the center.
- Fit the data using a limb darkening model (e.g., the linear law:

$$I(\mu) = I(1)[1 - u(1 - \mu)]$$

  where $\mu = \cos\theta$ and u is the limb darkening coefficient).

7.5 Expected Results and Analysis

Once the data is processed:

- You should obtain a smooth curve showing high intensity at the center and a gradual decrease toward the limb.
- The fitted model will yield the limb darkening coefficient, providing insights into the temperature gradient of the solar photosphere.

7.6 Conclusion

This experiment allows you to derive the solar limb darkening profile by processing calibrated images of the Sun. Through careful planning, data acquisition, and analysis, you can extract meaningful physical parameters about the Sun's atmospheric structure using your existing solar observation setup.

Chapter 8

Photometric Monitoring of a Variable Star

8.1 Overview

In this experiment, you will monitor the brightness variations of a variable star over time using aperture photometry. By observing a known variable star (e.g., Algol or another short-period variable) with your telescope and CCD camera setup, you can create a light curve and determine the star's variability period.

8.2 Objectives

The goals of this experiment include:

- Setting up the telescope for long-term imaging of a variable star.
- Acquiring a series of calibrated images over multiple nights.
- Performing aperture photometry to extract the star's flux.
- Correcting for atmospheric extinction and deriving the light curve.

8.3 Planning the Observations

8.3.1 Observation Planning

Careful planning is essential for variable star photometry:

- **Target Selection:** Choose a well-known variable star with a short variability period (e.g., Algol, which has a period of about 2.87 days).
- **Timing:** Schedule observations over several consecutive nights to fully capture the variability cycle.
- **Airmass:** Aim for observations when the target is high in the sky (low airmass) to minimize atmospheric effects.

8.3.2 Lunar and Weather Conditions

- **Moon Phase:** Ideally observe during a new moon or when the moon is below the horizon to ensure a dark sky.
- **Weather:** Monitor local weather forecasts to ensure clear and stable conditions.

8.3.3 Equipment Setup

- Use your telescope with the CCD camera mounted on an equatorial mount with GOTO capability.
- Ensure all calibration frames (bias, dark, flat) are taken on the same night as your science observations.
- Include one or more standard stars in your field (or observe them separately) for photometric calibration.

8.4 Observation Procedure

8.4.1 Data Acquisition

1. **Set Up the Telescope:**
   - Assemble and polar-align your telescope in your observing location.
   - Ensure the telescope is properly balanced.
2. **Capture Images:**
   - Use the GOTO function to center the variable star.
   - Acquire a series of images over the course of the night, recording the precise time for each frame.
3. **Acquire Calibration Frames:**
   - Take bias, dark, and flat frames during the same observing session.

8.4.2 Data Reduction and Analysis

1. **Preprocessing:**
   - Apply bias subtraction, dark frame correction, and flat-fielding to all images.
2. **Aperture Photometry:**
   - Use photometry software to select a circular aperture around the variable star.
   - Define an annulus to measure the background sky brightness.
   - Calculate the net flux by subtracting the background from the total flux within the aperture.
3. **Airmass Correction:**

- Determine the airmass for each observation using the target's altitude.
- Apply an extinction correction to the measured magnitudes.

4. **Constructing the Light Curve:**
   - Plot the corrected magnitudes against time to generate the light curve.
   - Identify the period of variability by analyzing the light curve.

8.4.3 Example Calculation

For instance, if a variable star exhibits an instrumental magnitude of 11.8 at an airmass $X = 1.3$ and the extinction coefficient k is 0.15 mag/airmass, the airmass-corrected magnitude is:

$$m_{\text{true}} = 11.8 - (0.15 \times 1.3) = 11.8 - 0.195 = 11.605.$$

Plot such values from multiple images to trace the light curve and determine the variability period.

8.5 Conclusion

This experiment guides you through photometric monitoring of a variable star using aperture photometry. By carefully planning the observation session, capturing calibration frames, and applying systematic preprocessing and photometric techniques, you can derive a light curve and measure the period of the variable star. This experiment not only enhances your understanding of stellar variability but also provides hands-on experience with the fundamental techniques of astronomical imaging and data analysis.