ASTR 535 : Observational Techniques

Observing concepts and tools

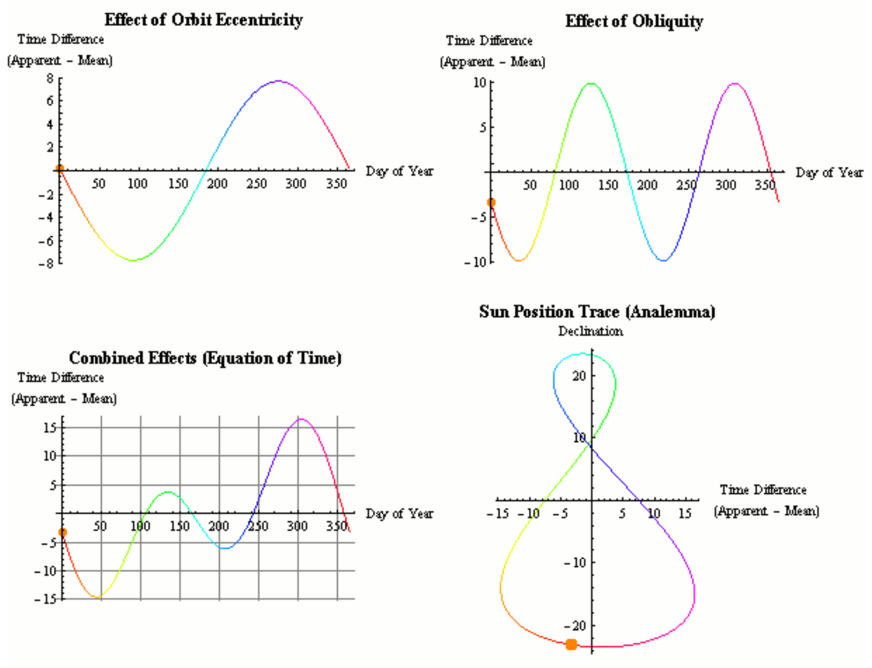
Time

Learning objectives

- Understand the different systems of time: solar time, atomic time, sidereal time
- Understand calendars used in astronomy: Gregorian and Julian date

Time: solar time

- Solar time : based on the position of the Sun
  - Split into 24-hour intervals
  - Local apparent solar time: position of the Sun
  - But Sun doesn’t move at uniform speed across the sky throughout the year because of tilt of earth’s axis and eccentricity of orbit
  - Mean solar time tracks a fictitious ”mean Sun” that moves at uniform rate
    - ”equation of time” describes difference between mean and apparent solar time
  - Local solar time depends on location on earth
    - Local mean solar time = 0 when anti-Sun crosses meridian (N-S line)
  - Solar time at Greenwich is called Universal Time
  - Local solar time = UT + longitude
  - “legal time” uses time zones
  - Problem: Earth’s rotation is not perfectly uniform, esp., slowing with time



Time: atomic time and UTC

- Atomic time: based on atomic transitions
  - TAI : International Atomic Time
- Coordinated Universal Time (UTC)
  - Mean solar time occasionally adjusted to match atomic time, with the addition of “leap seconds”

Time : sidereal time

- Sidereal time : also measured by Earth's rotation, but now relative to the stars
  - Since stars also move in space, sidereal time formally is measured by the position of the vernal equinox (location of mean Sun as it crossed the celestial equator)
  - Sidereal time also split into 24 hours
  - Sidereal day is slightly shorter (about 4 minutes, 23h 56m 4s) than solar day, because of Earth's revolution around the Sun
  - Over a year those extra minutes amount to one full rotation
  - At 4 minutes per day, sidereal time drifts with respect to solar time by about 2 hours per month
  - Stars cross the meridian (line between N and S) at the same sidereal time every day, so the solar time they cross the meridian every day drifts
- Local sidereal time = 0 when vernal equinox crosses the meridian
  - On ~March 21, LST=0 at noon: LST at midnight (standard time) = 12hr
  - On ~June 21, LST at midnight (standard time) = 18 hr
  - On ~Sep 21, LST at midnight (standard time) = 0 hr
  - On ~Dec 21, LST at midnight (standard time) = 6 hr

Calendars and Julian date

- Gregorian calendar:
  - Splits years into months and days
  - Since one year is not an even multiple of days (~365.25), periodically adds leap days, with complicated formula to account for the value of the fractional part of the length of the year in days
- Julian date : just counts days
  - Julian date (JD): number of days since UT noon, Monday, Jan 1, 4713 BC (note, starts at UT noon!) : 1/1/2021 → JD 2459216
  - Modified Julian date (MJD) = JD – 2400000.5 (starts at UT midnight)
- When giving precise times of astronomical events, may need to account for changing position of Earth with respect to object, and corresponding change in light travel time
  - Heliocentric Julian Date : Julian date for light arriving at the Sun (not Earth)
  - Difference from JD depends on location of object, can differ by up up ~8 minutes

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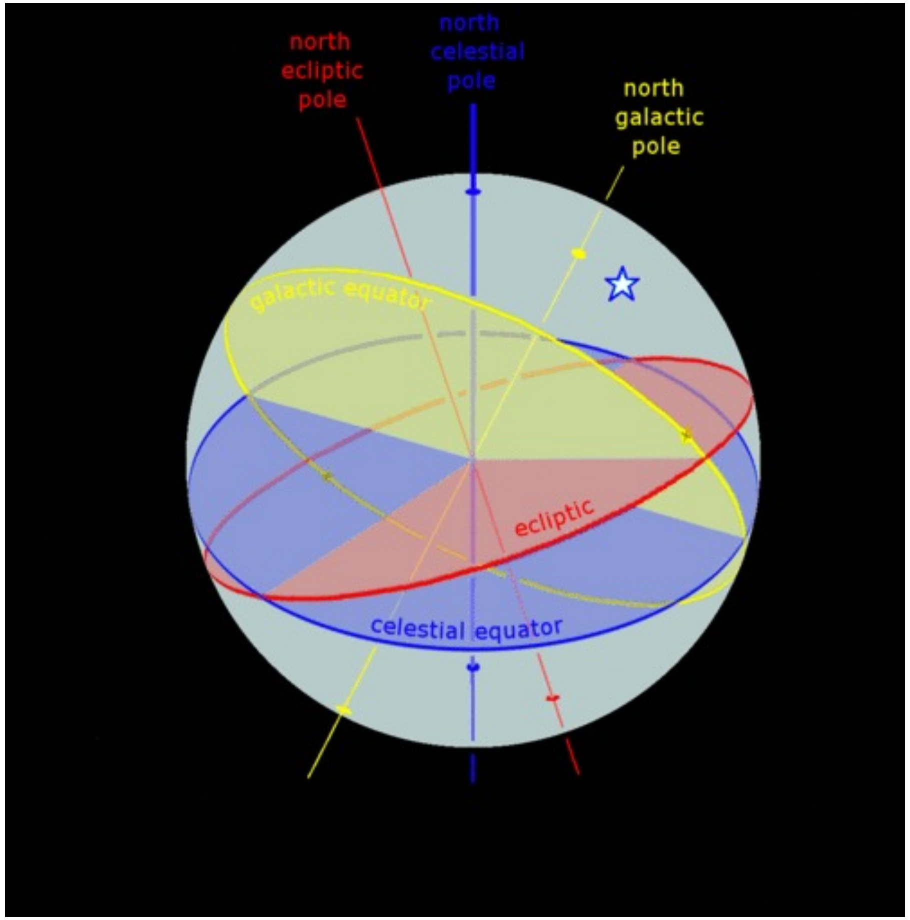
Coordinate systems

Learning objectives

- Understand the different celestial coordinate systems: equatorial, ecliptic, galactic
- Understand the different local coordinate systems: alt-az, HA/Dec
- Understand the effect of precession, and the meaning of the equinox of coordinates
- Understand the effects of motions of astronomical objects: parallax and proper motions and the meaning of the epoch of coordinates

Celestial coordinate systems

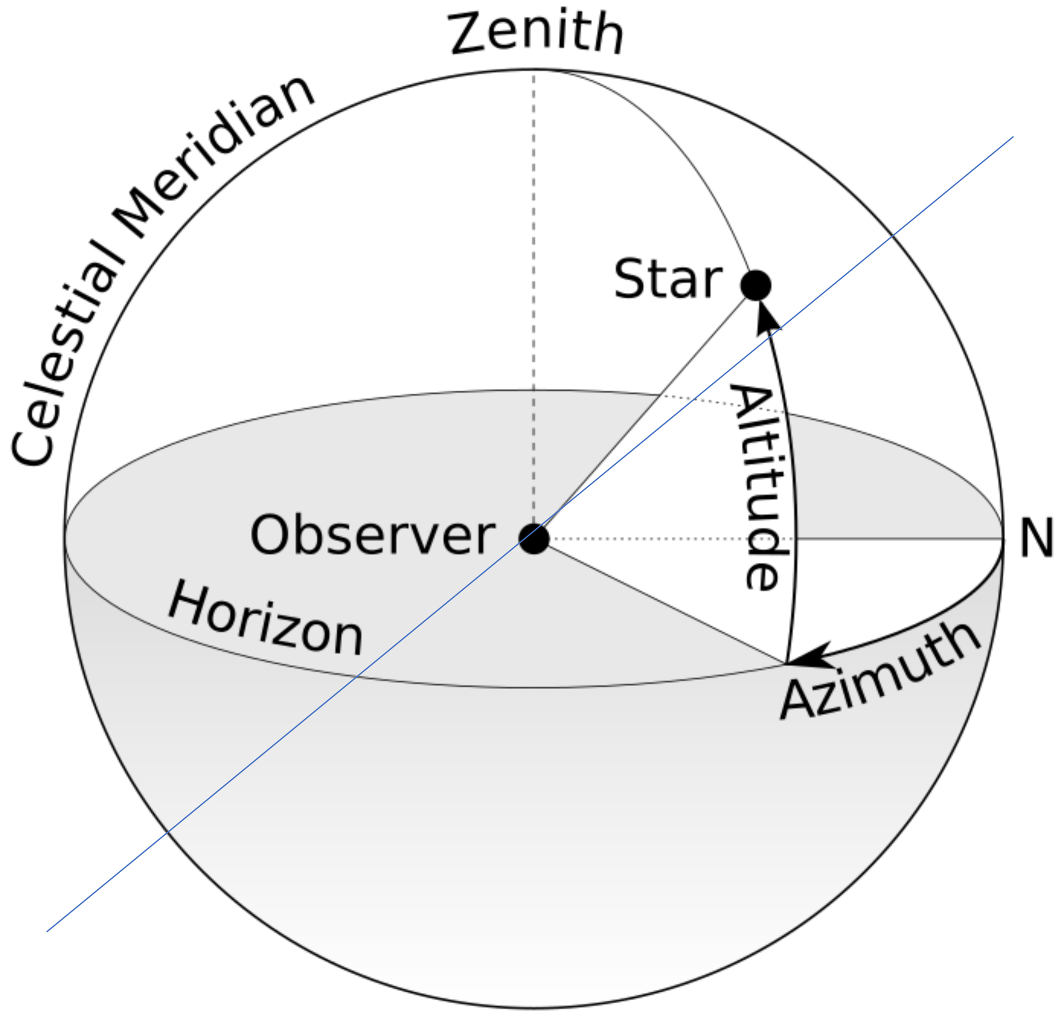
- Equatorial (RA/Dec) : aligned with Earth's rotation axis
  - Declination (== latitude) : 0 at celestial equator, 90 degrees at pole
  - Right ascension: 0 at location of vernal equinox
  - Conventionally, RA measured in units of hours (for good reason), but now sometimes measured in degrees (24h = 360 degrees, 1 hr = 15 degrees)
  - Note when you look at the sky, if N is up, E is to the left!
- Ecliptic (λ,β): aligned with plane of Earth's revolution, Sun at 0 ecliptic latitude
- Galactic (l,b) : aligned with plane of the Milky Way (galactic latitude = 0), with galactic center at 0 galactic longitude
- Can transform from one coordinate system to another using spherical trigonometry



Local coordinate systems

- Horizon (alt/az) : relative to surface tangent
- Equatorial: HA/Dec : relative to Earth's rotation axis, but fixed in time: hour angle/HA replaces right ascension
  - HA = 0 is the meridian
  - HA usually measured in hms, for obvious reasons when one watches stars move across the sky!
- Altitude related to declination on the meridian
  - Declination that passes through zenith is given by the latitude

Pole-to-zenith = 90-latitude



Precession

- Issue with celestial coordinates: Earth's rotation axis changes direction in time: precession and nutation
- Coordinates change through time
- Normally, this is "invisible" to the user because we use coordinates at some specified "equinox", usually J2000.0
  - Telescope pointing software has to know how to translate these coordinates to actual directions in the sky at any given time, including precession, etc.

Parallax

- Stars also change their position because of changing position of Earth as it orbits the Sun: parallax
- Generally, << 1 arcsec

Proper motion

- Other issue: astronomical objects also physically move through space!
- This is called *proper motion*
  - Angular motion is larger for objects with larger space velocities and also for closer objects
- For objects with measurable proper motion, need to also specify the *epoch* of the coordinates, i.e. the position (in some specified equinox, e.g. J2000) of the object.
  - Combined with proper motion, can get the position at any given date of observation
- With large automated precision surveys, these things can matter!
- GAIA provides proper motions for billions of stars!

Other effects

- There are other effects that need to be considered to go from a celestial position to a local position at a given time (i.e., pointing a telescope!)
  - Aberration of starlight : arises from Earth’s motion
  - Atmospheric refraction

Astronomical positions

- Various catalogs of astronomical objects
  - SIMBAD : astronomical object database
  - VizieR : catalogs
  - NED : extragalactic objects
  - JPL Horizons : solar system objects (orbital motion very important)

  - GAIA (!)

Describing orientations in the sky

- Orientations of objects in the sky, e.g., the major axis of a galaxy or the orientation of a slit in a spectrograph, are described by the *position angle,* which is the angle of the object axis from a N-S line, measured counterclockwise (i.e.,going from N through E)
- The position angle at any location in the sky of the line from zenith to horizon is called the *parallactic angle*

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Observability of astronomical objects

Learning objectives

- Understand the basic principles of optimizing observations of objects
- Be aware of and familiar with some tools for observation planning

Observability of objects

- To observe an astronomical object:
  - Want it to be above the horizon!
  - Prefer to observe through as little atmosphere as possible, since increasing atmospheric column increases light losses: stronger effect at shorter wavelengths
- Airmass quantifies thickness of atmosphere at a given direction in the sky
  - Overhead is minimum column: defined as 1 airmass
    - Note this is a "local" quantity, i.e. airmass at zenith is always 1, even from observatories at different elevations!
  - As one moves from zenith, airmass ~ 1/cos(Z), where Z is the zenith distance = 90 - altitude

Observability of objects

- As objects move across the sky, airmass is minimized when it crosses the meridian, i.e. at HA=0
- Relation between HA, RA, and LST:

  HA = LST – RA

- So, object at a given RA crosses the meridian when LST = RA

When can you best observe objects

- Airmass changes with hour angle depending on declination
- At the celestial equator, an HA of +/- 3 hours is an airmass of about 2 from mid-latitude observatories
- **Generally**, observers try to observe below an airmass of two
  - Sometimes, you can't, e.g. solar system observers of inner planets or comets!
- So, from the northern hemisphere, observing window is ~6 hours on the celestial equator, longer at higher declinations, shorter at lower declination

Observation planning

- Given list of objects to observe, want to maximize efficiency and data quality
- Try to observe all objects as they are crossing meridian, so start by sorting by right ascension and knowing the local sidereal time on the night you are observing
  - Don’t forget scientific priority!
  - Objects at higher declination are more forgiving of being observed off of the meridian than those at lower declination
  - Caveat: alt-az telescopes have a challenge tracking objects near the zenith, so there is often a “dead zone”, e.g. +/- 10 degrees from zenith, so for objects with declination near the latitude of the observatory, may need to *avoid* the meridian!
- Also may want to consider efficiency in terms of slew times: prefer to move shorter distances in the sky
  - Working by right ascension usually satisfies this
  - But beware of alt-az telescopes if you have objects with declinations both less than and greater than the latitude, as these can require long azimuth slews!

Observability tools

- skycalc/skycalendar : simple text based programs
- JSkyCalc :graphical Java program
- Python
  - astropy.coordinates : tools for working with coordinates and transforming between different systems
  - Astroplan : astropy affiliated package for observation planning
- WCSTools : various tools for transformations between coordinate systems, tools for working with coordinates in image files

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Observing concepts and tools

Telescope use and planning

Learning objectives

- Understand some of the key things to prepare for before going observing

Overall consideration

- At larger research telescopes, telescope time is valuable
  - Thousands of dollars per night
  - Often, oversubscription factors of several
- Make full, efficient use of the resource
  - Prepare in advance
  - Have plan for productive use of all of the time

Telescope and pointing

- Learn how telescope is commanded
- Object catalogs
  - Can save time and minimize chances of error, especially late at night
- Observation scripts
  - Critical for some types of observing, e.g., in the infrared
- Pointing accuracy and finding charts
  - How accurately does telescope point
  - How easy will it be to identify your objects?
  - Prepare finding charts in advance; understand orientation of images
  - Tools: SIMBAD, SkyView
- Tracking performance and guiding
  - Sharper images maximize S/N, don’t want them to be degraded by telescope tracking
  - When guiding is needed, understand how it is done
  - In some cases, identifying guide stars in advance may be useful, e.g., to adjust pointing

Focus /data inspection

- You need to inspect data as it comes in, to ensure you are getting what you expect, and that there are no issues
  - Can impact observing efficiency: two people help
- Tools for inspecting/analyzing images
  - Are data as expected?
  - Saturation issues?
  - Image quality
- Focusing a telescope/instrument
  - Can be achieved by moving instrument, but more common, by moving secondary mirror
  - Focus run goes through several positions, chooses best (or fits a curve to find the minimum)
  - Focus provides you a measurement of the seeing, which may affect your plans
  - Focus can change throughout the night, so continue to monitor image quality

Observation planning and logs

- Observation planning

  HA = LST – RA

  Consider slew times

  Consider scientific priorities

  Tools: skycalc, astropy-affiliated astroplan

- Observing logs
  - Although you may think you won’t forget details, you probably will
  - Take notes on everything, especially anything odd/unusual
  - Note conditions of the sky, including transparency and seeing
  - While a log spreadsheet giving details of each exposure is nice, often, much of this information is in the image files: it’s the less standard stuff that it’s REALLY important to log!
  - Set up observing log in advance, e.g. Google Doc

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Observing concepts and tools

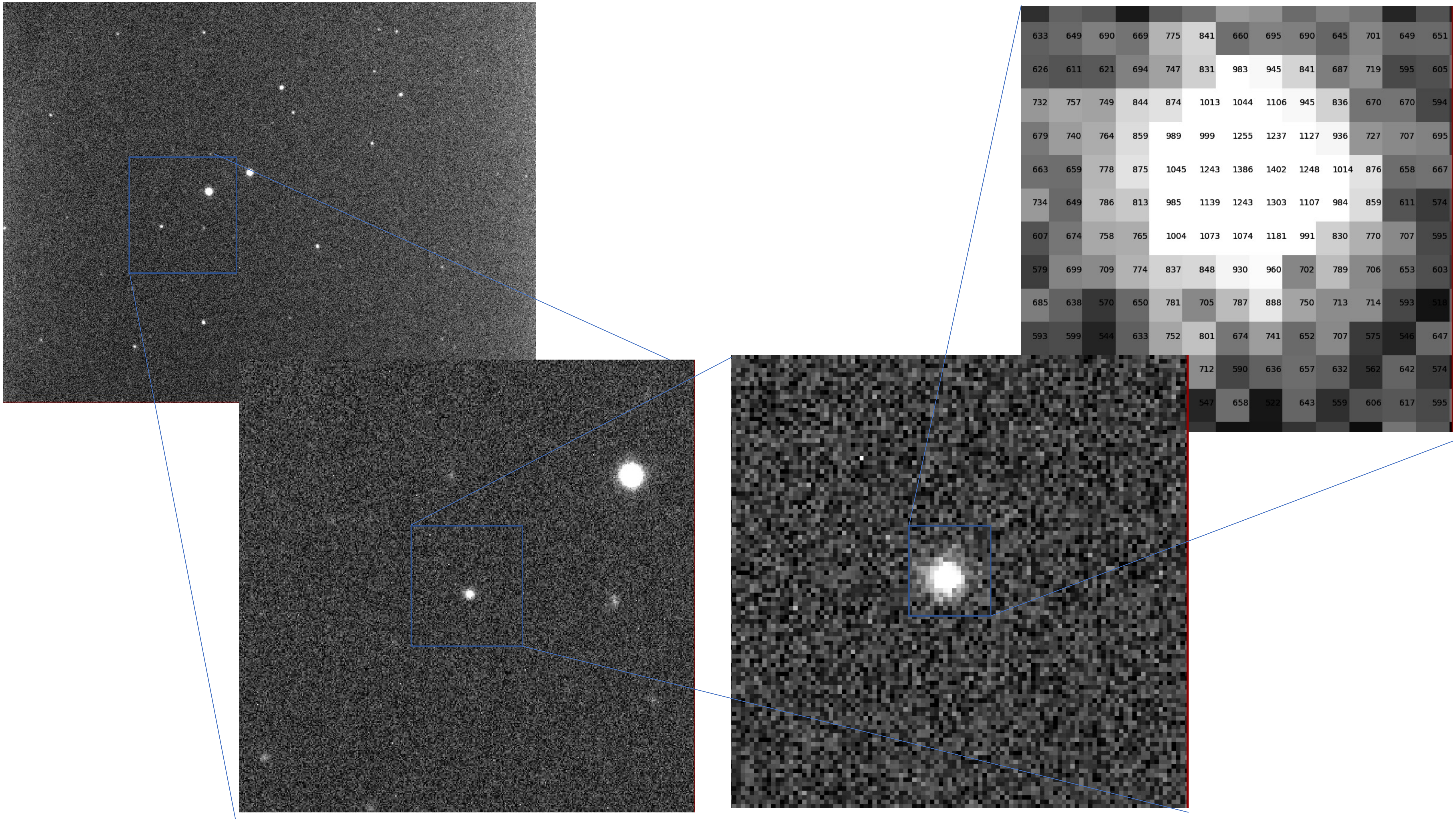
Digital imaging and image display

Learning objectives

- Understand what digital imaging is, and some of the challenges involved with looking at digital images
- Learn about intensity scaling
- Learn about some standard image display software

Digital imaging

- Quantitative detection of light
- Linear detector: number of photons recorded is proportional to number of incident photons
- Output of a detector is an array of numbers, often referred to as counts or DN (data numbers)
- Individual picture elements: pixels
- Potential issues in data visualization / inspection
  - Larger number of pixels than available on display
  - Larger dynamic range (intensities) than available on display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626 611 621 694 747 831 983 945 841 687 719 595 605
732 757 749 844 874 1013 1044 1106 945 836 670 670 594
679 740 764 859 989 999 1255 1237 1127 936 727 707 695
663 659 778 875 1045 1243 1386 1402 1248 1014 876 658 667
734 649 786 813 985 1139 1243 1303 1107 984 859 611 574
607 674 758 765 1004 1073 1074 1181 991 830 770 707 595
579 699 709 774 837 848 930 960 702 789 706 653 603
685 638 570 650 781 705 787 888 750 713 714 593 518
593 599 544 633 752 801 674 741 652 707 575 546 647
712 590 636 657 632 562 642 574
547 658 522 643 559 606 617 595

Digital imaging: spatial resolution

- Computer display, e.g., laptop 2560x1600, external monitor 1920x1200
- Digital cameras
  - High quality 2048x2048 detectors are widespread
  - TMO camera: 9600x6422 unbinned, 4800x3211 binned 2x2
- Not possible to see every pixel at the same time!
- Options:
  - Zoom
  - Every Nth pixel
  - Average NxN pixels
  - Beware of Moire patterns
- Be aware!

Demo

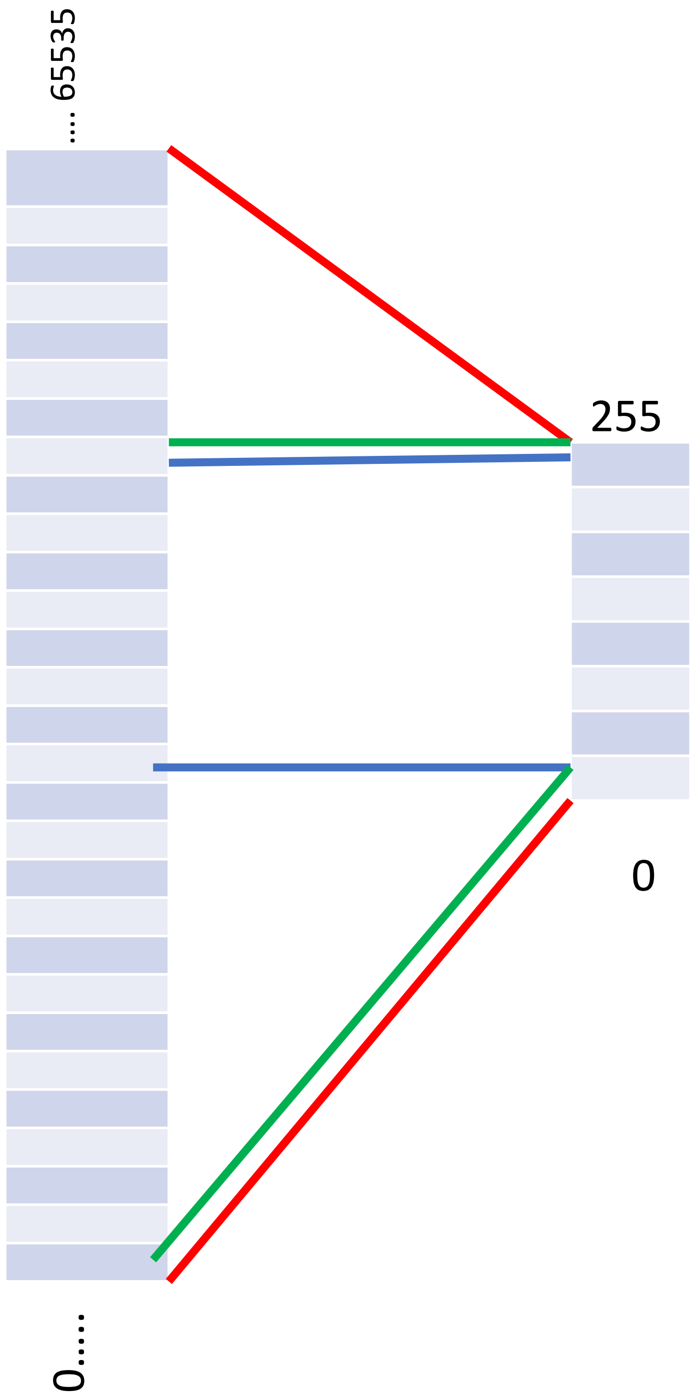
Digital imaging: image display

- Dynamic range : ratio of brightest to faintest objects
- Typical astronomical signal chains provide 16-bit data, i.e. DN from 0 to 65535
  - ARC/KOSMOS will have an 18-bit signal chain
- Typical graphics card and image display provide 8-bits of intensities, i.e. from 0 to 255, for each of 3 colors (eye may not be able to distinguish any more)

→ Not possible to see all intensity information at the same time

Brightness and contrast

- Given limits of display:
  - Show small range at full intensity resolution, but nothing outside of range (high contrast) (blue lines)
  - Show large range, but at reduced intensity resolution (low contrast) (red lines)
  - Some combination (green lines)
- If displaying at lower contrast, also choose which part of range to show (brightness)
- Brightness (level) and contrast (range)
  - Contrast: separation between lines
  - Brightness: location of lines
  - Alternatively, low and high levels



Display parameters

- Many software display routines will choose a default intensity scaling, or give you a choice of some algorithms:
  - Min-max (100%)
  - Various other percentiles (99% → 50%)
  - Histogram equalization
  - Nonlinear display scalings
- In many cases, the full dynamic range is not populated
  - Reasonable scaling: few sigma below sky to more sigma above
- Changing scaling requires recalculation and display

Demo

Color maps and pseudo color

- Given a scaling to 8-bits, can also associate a color with each one of the intensity levels
  - Black-and white (greys)
  - Inverted
  - Pseudo color: assign various colors to different intensity levels
- Quick brightness/contrast adjustment can be done by adjusting the color map, but at some loss of information

Demo

“True” color images

- True color images are made by combining images taken at multiple (usually 3) wavelength ranges
  - Standard color images: red, green, blue
  - Can encode other bandpasses into a “true” color:
    - UV, visual, IR
    - Broadband + narrowband

Other display functions

- Blinking images
- Annotating images
- Interactive display: marking objects
- Calculating quantities based on interactively marked objects

Some display tools

- SAOimage ds9 : https://sites.google.com/cfa.harvard.edu/saoimageds9
- ximtool : https://github.com/iraf-community/x11iraf
- gaia : http://star-www.dur.ac.uk/~pdraper/gaia/gaia.html
- Python image display
  - Basic display with matplotlib imshow
  - More advanced possibilities

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Digital imaging: file formats

Learning objectives

- Understand some basic concepts of how data are stored in files
- Understand how FITS files are structured

Storing image data

- Image data is just a grid of numbers
- In simplest format, one could just provide those numbers
  - For more compact files, store in binary representation
- Need some minimal basic information in addition to a string of bits
  - How many bits for each pixel
  - How many pixels per row
- For astronomical images, there is a lot of other potentially interesting ancillary information
  - telescope, coordinates, time, exposure time, etc.
  - what is on the axes
  - Instrument information

Flexible Image Transport System (FITS)

- Basic FITS image files: contain two pieces: header and image
- Header
  - Set of rows of 80 characters each
    - ”card” name (limited to 8 characters)
    - “card” value
    - “card” comment
  - Must come in multiples of 36 card (2880 bytes); pad with blanks
- Image
  - Binary sequence of data

FITS tables

- FITS has been generalized to also allow the storage of “tables”
- ASCII and binary tables
- Table column names not limited to 8 characters
- Mixed data types supported
- Some “data” files may be saved as FITS tables rather than FITS images
  - E.g., spectroscopic data

FITS multi-extension files

- Some data may not be limited to a single “image” or a single “table”
- Can have multiple “extensions” in a single FITS file
  - E.g., data, uncertainty, and mask
- Each extension is an “HDU” (header-data unit)

Tools for working with FITS files

- astropy.io.fits provides a comprehensive set of tools
- For tabular data astropy.table provides good tools
- Quick demo

Other file formats

- ascii (text) files : note astropy.io.ascii
- HDF format

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Observing concepts and tools

Digital imaging: gain and readout noise

Learning objectives

- Understand the concept of gain and why it is critical for characterizing the noise in your data
- Understand how you can measure the gain and readout noise

Gain

- Digital detector signal chains usually introduce an electronic “gain”: a multiplicative constant that modifies the signal coming from the detector before the signal is digitized
- Because of this, the data numbers do not directly give the number of detected photons (each of which generates an electron)
- Instead

$$N(\text{electrons}) = GC$$

where C is the number of counts (DN) and G is the “gain” in “units” of electrons/DN (all dimensionless), even though an electronics person would call this the ”inverse gain”

- **Knowing the gain is critically important, because the Poisson statistics is on the number of detected photons, not the DN value**

Gain and Poisson noise

N(electrons) = GC

So the noise in electrons is:

$$\sigma \text{ (electrons)} = \sqrt{N_{electrons}} = \sqrt{GC}$$

Usually, however, people don't convert images to units of electrons (although some do!)

In units of counts:

$$C = \frac{N_{electrons}}{G}$$

So

$$\sigma \text{ (counts)} = \frac{\sigma_{electrons}}{G} = \sqrt{\frac{C}{G}}$$

Determining the gain

- Gain usually must be determined from the noise properties
- Simple prescription:
  - Take two images with high (and similar) light levels
  - Measure the mean intensity in a region of ~constant intensity from an average of the two images: this measures the signal
  - Calculate the difference between the two images
  - Measure the standard deviation in the difference image in a region of ~constant intensity: this measures the noise, but since it comes from two images, it is a factor of $\sqrt{2}$ larger than the noise from a single image
  - Calculate the gain

$$\sigma \text{ (counts in difference image)} = \sqrt{\frac{2C}{G}}$$

$$G = \frac{2C}{\sigma^2}$$

- This **assumes** that Poisson statistics is applicable, i.e. that there are no unknown sources of noise (or problems!)
- Note that difference in two images is preferred to a region of a single image because the latter might include some variance from difference in pixel-to-pixel response or illumination

Gain: more comprehensive test

σ (counts in difference image) = $\sqrt{\frac{2C}{G}}$

$$G = \frac{2C}{\sigma^2}$$

- For a more comprehensive test, do this at multiple light levels and plot σ^2 vs C: this should be a straight line with slope given by 2/G

Readout noise

- At low light levels, readout noise contributes:

$$\sigma \text{ (counts)} = \sqrt{\frac{C}{G} + \frac{{\sigma_{rn}}^2}{G^2}} = \sqrt{\frac{S+B}{G} + \frac{{\sigma_{rn}}^2}{G^2}}$$

- To measure readout noise:
  - Take difference of two images with no light (bias frames), i.e. C=0, to determine ${\sigma_{rn}}^2$, once G is known

$$\sigma \text{ (counts in difference image)} = \sqrt{\frac{2{\sigma_{rn}}^2}{G^2}}$$

  - Difference image in case there is some “fixed pattern noise” in bias frames
  - Can also get from intercept of comprehensive gain test, but this can be susceptible to small uncertainties in measurements

$$\sigma \text{ (counts in difference image)} = \sqrt{\frac{2C}{G} + \frac{2{\sigma_{rn}}^2}{G^2}}$$

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Digital imaging: basic data reduction

Learning objectives

- Understand the most basic data reduction steps of bias level subtraction and flat fielding

Basic data reduction

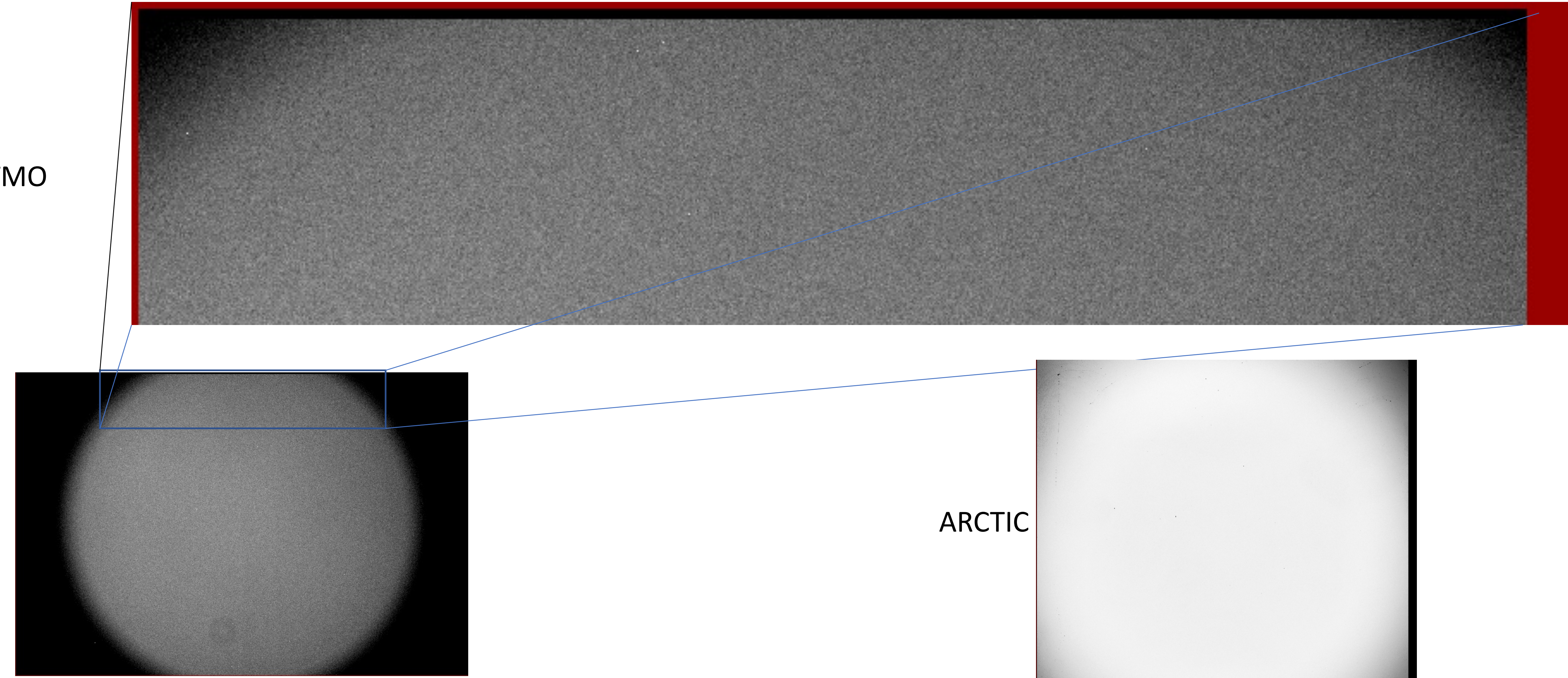
- While data reduction may need to include correction for multiple effects, the most basic data reduction of digital images is simple and consists of two steps:
  - Bias level (overscan) subtraction
  - Flat fielding
- Other things that we will address later:
  - Bias pattern subtraction
  - Dark current subtraction
  - Linearity correction
  - Shutter shading correction
  - Fringing subtraction
  - Spectroscopic data reduction (wavelength and flux calibration)

Bias level (overscan) subtraction

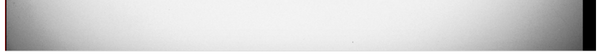
- Before digitizing the signal from a detector, the signal electronics will add some level so that, in the presence of noise, there will be no ”negative” signal
- This bias level does NOT contribute Poisson noise, so must be subtracted before the correct Poisson uncertainties can be determined
- This level, usually called the bias level, may not be perfectly stable in time, so, when possible, should be determined from each image independently
- This is usually achieved by adding a “overscan” region to each image, which adds ”virtual” pixels to an image, i.e. data values that are read through the signal chain but without any real pixel input
  - In CCDs, this generally adds columns to the “real” image
  - At TMO (CMOS detector), extra rows are added

Overscan

TMO



ARCTIC



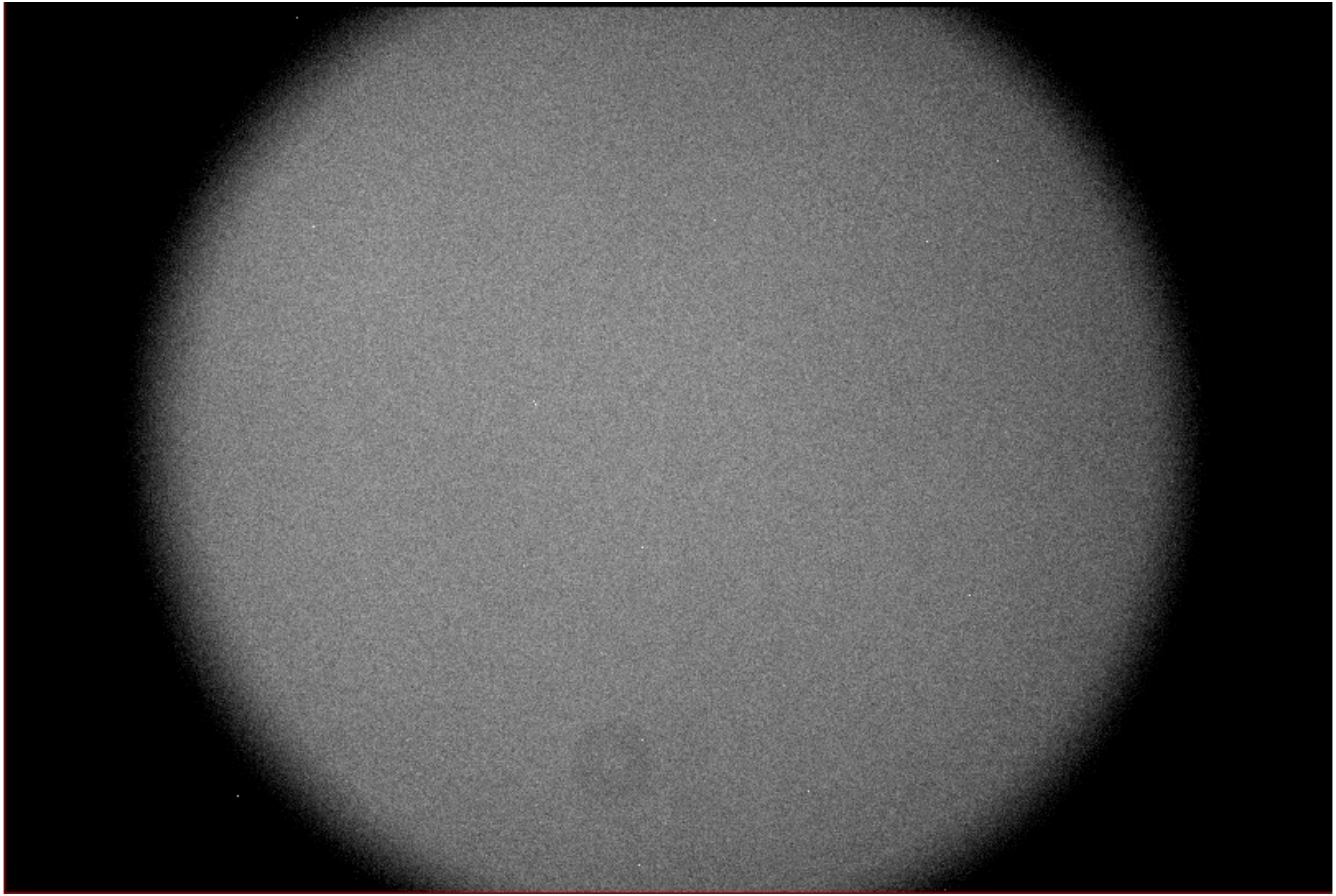
Bias level (overscan) subtraction

- In simplest form, one determines the mean value in the overscan, and subtracts this from the rest of the image
- In more complex cases, the bias level may drift over the course of the readout, so it may be necessary to do a row-by-row subtraction of bias level (or some smoothed version of it)

Flat fielding

- Flat fielding corrects for non-uniform throughput across the field-of-view, i.e. at different locations within an image
    - Variations in throughput can arise from optics (vignetting, non-uniformity of filter, dust, etc.) and/or from variations in sensitivity of the detector in different locations
    - Flat fielding is critical for comparing intensity at one location to intensity at another
        - If one compares intensity in one image to another at the same location, then the need for flat fielding is minimized

TMO flat field



Flat fielding

- Flat fields are created by observing an object that produces spatially uniform illumination, so that observed variations can be attributed to variations in throughput
- Typical sources:
  - “white spot” on side of dome
  - Illuminated mirror covers
  - Twilight sky
- No source is **perfectly** uniform, so deviations from uniformity will be propagated systematically into your images, at whatever level the non-uniformity is
- Any **noise** in your flat field will be propagated systematically into your images, so you generally want to achieve very high S/N in the flat fields
  - Usually combine multiple images, each one at high S/N