Lecture 7:
“Real” Telescopes & Cameras

Stephen Eikenberry
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“Real” Telescopes

• Research observatories no longer build Newtonian or Parabolic telescopes for optical/IR astronomy
  • Aberrations from their single powered optical surface are too large
• More advanced telescopes available
• Typically, for us, these are “2-mirror” (meaning 2 powered mirrors) telescopes
• The secondary mirror is curved, as well as the primary
• Two powered surfaces means that we can use the combination to “correct” aberrations from a single-mirror approach
# Common 2-Mirror Scopes

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Primary</th>
<th>Secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cassegrain</td>
<td>Parabola</td>
<td>Hyperbola</td>
</tr>
<tr>
<td>Gregorian</td>
<td>Parabola</td>
<td>Prolate Ellipse</td>
</tr>
<tr>
<td>Ritchey-Chretien (Aplanatic Cass)</td>
<td>Hyperbola</td>
<td>Hyperbola</td>
</tr>
<tr>
<td>Aplanatic Gregorian</td>
<td>Ellipse</td>
<td>Prolate Ellipse</td>
</tr>
</tbody>
</table>
Cassegrain

- All well-designed 2-mirror scopes of this sort have good performance on/near-axis
- Cass field-of-view is typically limited by coma
- Field curvature also an issue

http://www.daviddarling.info/images/Cassegrain.gif
Gregorian

- Note that secondary is concave (reason chosen for Magellan ⇒ discuss)
- Gregorian has slightly longer tube (⇒ longer/bigger structure; bigger dome)
- Gregorian field-of-view is also typically limited by coma
- Field curvature also an issue; however, Gregorian curvature is OPPOSITE in sign compared to Cassegrain, and ~x2 smaller for typical cases

http://www.abdn.ac.uk/~u09lb5/px2013/Gregorian_telescope.jpg
Ritchey-Chretien

- Looks a lot like Cassegrain, to the eye
- Deviations used to correct coma
- Limit to useful FOV is astigmatism
- This sets in at field angles typically >2-3 times that of Cassegrain \(\Rightarrow\) x4-10 improvement in FOV
- Field curvature still an issue
- This has become the “standard” for large telescopes in the last 50 years or so …
  - Hubble
  - Keck
  - Gemini
  - VLT
  - GTC
  - etc
Schmidt Telescopes

- Newtonian telescopes are nice, because spherical mirrors are cheap and easy to build
- Spheres are also easy to align:
  - offset and tilt cancel each other out mathematically
  - NOT true for conics with $\delta \neq 0$ (!!!!)
- But … aberrations are big $\Rightarrow$ can’t we cancel them? YES
Schmidt Telescopes -- II

- Spherical primary mirror with aspheric refractive “corrector plate”
- Asphere designed to remove spherical aberration over WIDE field
- Hard to make the corrector plate for large telescopes (rarely, if ever done for D > 1m), but good for others
- FOV ~ degrees (!)
- ZEMAX
Schmidt - Cassegrain

- Cassegrain 2-mirror telescope w/ corrector plate
- Asphere designed to remove aberrations over WIDE field
- Hard to make the corrector plate for large telescopes, but good for small ones
- Standard for many serious-amateur telescopes (Meade, Celestron, etc.)
- FOV ~ degrees (!)
- Fancy word for the day: “catadioptric”
Big Telescopes: Field curvature

• Serious issue for R-C telescopes (look at Gemini again)
• Remember yesterday – singlet spherical lenses have field curvature too
• Can select a “field flattener” lens to correct this aberration in an R-C (or other 2-mirror) telescope
• For R-C, this is thin negative lens:
  • placed near focal plane
  • If at the focal plane, all aberrations from lens would be 0
  • But … need to put the detector SOMEWHERE 😊
Big Telescopes: Field curvature

- For R-C, this is thin negative lens:
  - placed near focal plane
  - If at the focal plane, all aberrations from lens would be 0
  - But … need to put the detector SOMEWHERE 😊
- Often called a “Petzval lens”

Atmospheric Dispersion

- Optical impacts (deviation and dispersion)
- Atmospheric Dispersion Corrector (ADC)

http://star-www.dur.ac.uk/~jra/gmos_optics.gif
Cameras: Wide-Field Corrector

- Reduce aberrations over large field (say 10-30-arcminutes)
- Chromatic challenge
Cameras: Wide-field Issues

- Problem with large 2-mirror telescopes:
  - Check the plate scale vs. pixel size (!)
  - Also, secondary mirror size and vignetting (look at Gemini)

- Solution: Prime focus imaging
- Typical primary mirror f/# is <3.5 (re-check plate scale)
- No vignetting issue (no secondary!) (well … sort of)
- But … now we have only one (hyperbolic?) optical surface
Cameras: Prime Focus

- Prime Focus Corrector
- Wynne solution


Focal length increase : 10%, here F4 beam
Lecture 8: “Real” Cameras

Stephen Eikenberry
Sampling, etc.

• Sampling for an image:
  • Nyquist sampling requires 2 pixels per resolution element \( (N_{\text{samp}} = 2) \)
  • Typical experience is that for high-accuracy photometry, often want 3-5 pixels per resolution element \( (N_{\text{samp}} = 3-5) \)

• Field-of-View:
  • Number of pixels needed \( \propto (\text{FOV/seeing})^2 \times N_{\text{samp}}^2 \)
  • Detector cost proportional to \( N_{\text{pix}} \)

• Detector noise:
  • Read noise and detector noise add in quadrature for independent pixels
  • So … noise \( \propto N_{\text{samp}} \)
Focal Reducers

- Also known as “beam accelerator”
- Variation on direct imaging
- If we KNOW we want a certain pixel scale, then we know the resulting EFL we need for the system
- Insert a lens of appropriate focal length to modify the EFL of the telescope to match this
What’s Wrong with Reduction?

- Perfectly fine for many applications
- Where do the filters go? Right in front of the detector
- Why? Cost often proportional to diameter\(^2\)\(^3\)
- What does that mean for filter defects or dust spots? They are projected onto the detector (‼️)
- This means that the system throughput can change dramatically from point to point
- Why is that bad? We can use a “flatfield” image to correct this
- But … flatfield accuracy seldom much better than \(~0.1\text{-}1\%\)
- So … if we introduce large spatial variations into the camera response function, we introduce photometric noise (even for differential photometry)
Dust Example

http://www.not.iac.es/instruments/notcam/guide/dust.jpg
Camera/Collimator Approach

- These systems use a “collimator” to create an image of the telescope exit pupil
- Light rays from a given field point are parallel (“collimated” after the collimator optics
- Another optical system (the “camera”) accepts light from the collimator and re-focuses the image plane onto a detector

http://etoile.berkeley.edu/~jrg/ins/node1.html
Camera/Collimator & Filters

- Pupil image is where the parallel rays from different field points cross
- A filter can now be placed at the pupil image
- Any dust spots on the filter reduce the total system throughput
- However, they are now projected onto the pupil, NOT the image plane
- Thus, this light loss is now IDENTICAL for all field points
- This eliminates the contribution to flatfield “noise”!!
Infrared Cameras

- Need for cold stop

\[ m = \frac{f_{\text{cam}}}{f_{\text{col}}} \]

http://etoile.berkeley.edu/~jrg/ins/node1.html
Interference Filters

• How they work (roughly)
• Angular dependence
• Field dependence versus wavelength spread
• Example

http://www.olympusmicro.com/primer/lightandcolor/filtersintro.html
Lecture 9:
Spectrograph Basics

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10 October 2017
Spectroscopy: What is it?

• **How Bright?** (our favorite question):
  • Versus position on the sky
  • Versus wavelength/energy of light
  • Typically “spectroscopy” means \( R = \frac{\lambda}{\Delta \lambda} > 10 \) or so …

• One approach: energy-sensitive detectors
  • Works for X-rays! CCDs get energy for every photon that hits them!
  • Also STJs for optical; but poor QE & R, plus limited arrays

• Another approach:
  • Spread (“disperse”) the light out across the detector, so that particular positions correspond to particular \( \lambda \)
  • “Standard” approach to optical/IR spectroscopy
Conjugate, conjugate, conjugate

- Conjugates table for collimator/camera

<table>
<thead>
<tr>
<th>Plane</th>
<th>X</th>
<th>( \theta )</th>
<th>Conjugate To</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope pupil</td>
<td>Position on pupil</td>
<td>Angle on Sky</td>
<td>-</td>
</tr>
<tr>
<td>Telescope focus</td>
<td>Angle on sky</td>
<td>Position on primary</td>
<td>-</td>
</tr>
<tr>
<td>Collimator focus (Pupil Image)</td>
<td>Position on pupil</td>
<td>Angle on sky</td>
<td>Telescope pupil</td>
</tr>
<tr>
<td>Camera focus (detector)</td>
<td>Angle on Sky</td>
<td>Position on pupil</td>
<td>Telescope focus</td>
</tr>
</tbody>
</table>

\[
m = \frac{f_{\text{cam}}}{f_{\text{col}}}
\]
Dispersion Conundrum

- Hard to find dispersers that map wavelength to position
- Easy to find dispersers that map wavelength to angle (prisms, gratings, etc.)
- Hard to find detectors that are angle-sensitive
- Easy to find detectors that are position-sensitive (CCDs, etc.)

- We want an easy life! ⇒ find a way to use angular dispersion to map into position at detector
- Solution: place an angular disperser at a place where angle eventually gets mapped into position on detector ⇒ at/near the image of the pupil in a collimator/camera design!
Slits and Spectroscopy

- Problem:
  - Detector position \([x_1, y_1]\) corresponds to sky position \([\alpha_1, \beta_1]\) at wavelength \(\lambda_1\)
  - Detector position \([x_1, y_1]\) ALSO corresponds to sky position \([\alpha_2, \beta_2]\) at wavelength \(\lambda_2\) !!
Slits and Spectroscopy

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Slits and Spectroscopy

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  - Detector position \([x_1,y_1]\) ALSO corresponds to sky position \([\alpha_2,\beta_2]\) at wavelength \(\lambda_2\) !!
Common Solution:

- Introduce a small-aperture field stop at the focal plane, and only allow light from one source through.
- This is called a spectrograph “slit.”
Angular dispersion

- Define $d\beta/d\lambda$ for generic disperser (draw on board)
- Derive linear dispersion on detector
  - Shift $x = \beta * f_{cam}$
  - $dx/d\lambda = d\beta/d\lambda * f_{cam} = A * f_{cam}$
Limiting resolution

• Derive relation for limiting resolution
  • \( R \equiv \frac{\lambda}{(\Delta \lambda)} \)
  • \( R = \frac{\lambda A D_{\text{pupil}}}{(\theta_{\text{slit}} D_{\text{tel}})} \)
  • Note that this is NOT a “magic formula”
Slit width: I

- Note impact of slit width on resolution:
  - Wide slit $\Rightarrow$ low resolution
  - Skinny slit $\Rightarrow$ high resolution

- How wide of a slit? **Critical** issue for spectrograph design
Slit width: II

- Higher width ⇒
  - Higher throughput (and thus higher S/N)
  - But lower resolution
  - And higher background/contamination (and thus lower S/N)

- Typical choice (NOT always the best/correct choice) = FWHM of input image (i.e. seeing)
Dispersers: Prisms

- Derive dispersion relation
  - $A = \alpha \frac{dn}{d\lambda}$
  - $A = \frac{t}{a} \frac{dn}{d\lambda}$
- Limiting resolution of prisms
Dispersers: Diffraction Gratings

- Grating equation: \( m\lambda = \sigma (\sin \alpha + \sin \beta) \)
- Angular dispersion: \( A = (\sin \alpha + \sin \beta) / (\lambda \cos \beta) = m/(\sigma \cos \beta) \)
- Note independence of relation between \( A, \lambda \) and \( m/\sigma \)

http://rst.gsfc.nasa.gov/Sect13/grating12.jpg
Dispersers: Diffraction Gratings

- Note order overlap/limits, need for order-sorters
- Littrow configuration ($\alpha=\beta=\delta$)
- Results:
  - $A = 2 \tan \delta / \lambda$
  - $R = m W \lambda / (\sigma \phi D)$
  - $R = m N \lambda / (\phi D)$
- Quasi-Littrow used (why?)
- Do some examples

http://www.shimadzu.com/products/opt/oh80jt0000001uz0-img/oh80jt00000020ol.gif
Blaze Function

• Define and show basic geometry

http://www.freepatentsonline.com/7187499-0-large.jpg
Blaze Function

- Impact
- How we can “tune” this
Free Spectral Range

- Blaze function and order number
- Define & give rule of thumb:
  - FSR = “high-efficiency” wavelength range of grating
  - FSR \( \approx \frac{\lambda}{m} \) (VERY crude approximation)
Dispersers: Echelles

- Operated at high order
- Why?
- Impact on resolution and wavelength coverage
- Small bandpass per order
- Cross-dispersion (examples of spectral format)