Optical Imaging

Part 1: Telescope Optics and Related Topics

Part 2: Astronomical Digital Images

http://www.stecf.org/~rhook/NEON

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Some Caveats & Warnings!

- I have selected a few topics, many things are omitted (eg, adaptive optics)!
- I have tried to not mention material covered in other talks (detectors, photometry, spectroscopy…)
- I am a bit biased by my own background, mostly Hubble imaging. I am not an optical designer.
- I have avoided getting deep into technicalities so apologise if some material seems rather trivial.

Part one: Telescope Optics - a very brief introduction

From the sky and through the atmosphere and telescope, but stopping just before the detector!

- Telescope designs, past, present and future
- Optical characteristics
- The point-spread function
- The atmosphere

The Earliest Telescopes

Galileo, ~1609

First scientific astronomical use of the telescope

Non-achromatic refractor:

>10 gain in light collecting power;

>10 gain in resolution;

compared to the human eye.

Immediately showed phases of Venus, moons of Jupiter, stars in Milky Way, craters on the moon…

A true revolution!

The Rise of the Reflector

Reflecting telescope invented by Newton in late 17th century. Parabolic primary.

William Herschel, in the late 18th century realised that aperture was the key to studying the universe outside the solar system.

Up to late 19th century mirrors were made of speculum metal - hard to polish and tarnished quickly.

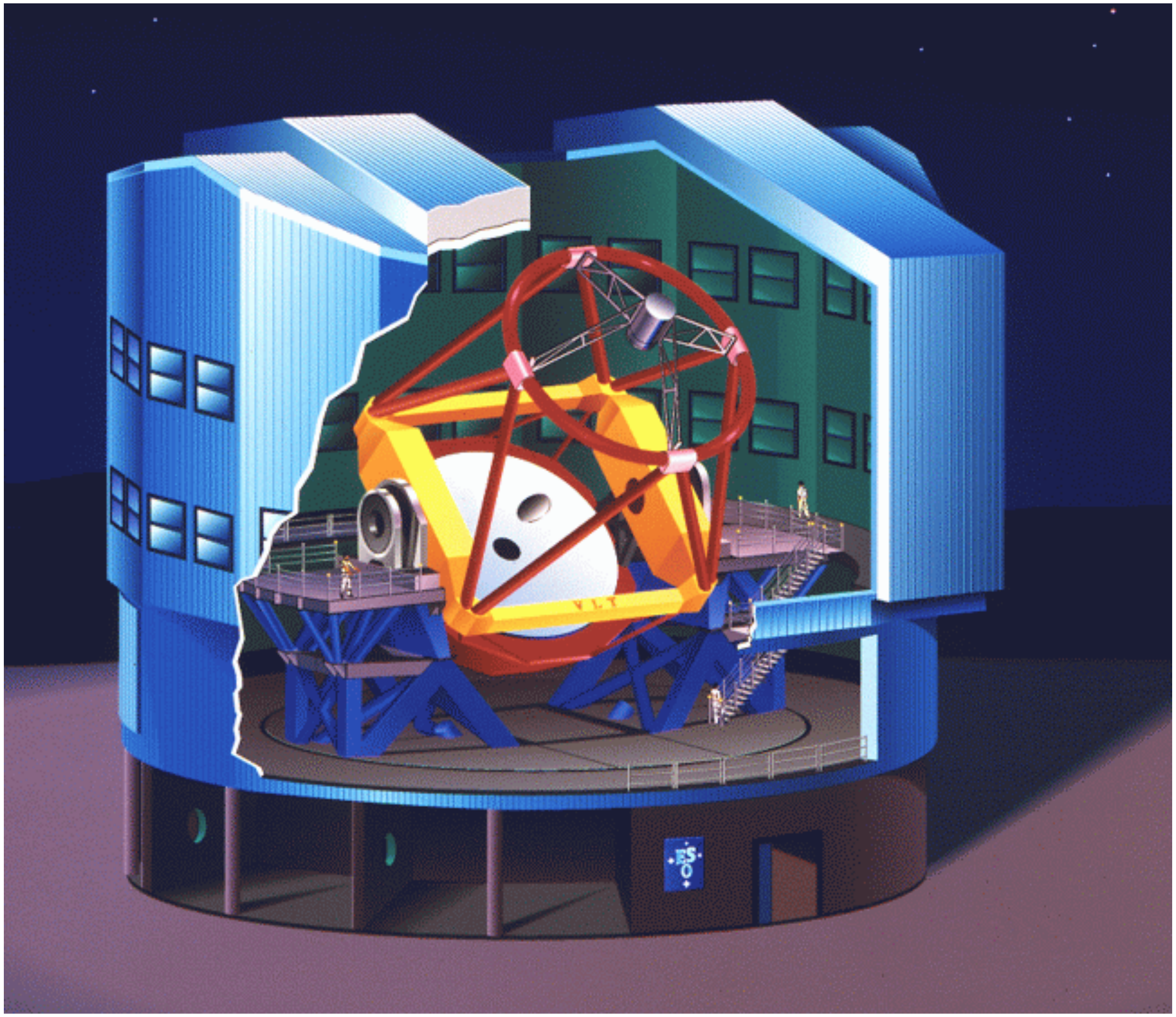
Use of coated glass mirrors led to further convenience, durability and larger apertures.

Culminated in 5m Palomar telescope (1948).

The Late-20th Century

- Telescope apertures didn't significantly exceed 5m between 1950 and 1990 but the transition from photography to digital detectors led to huge improvements.
- New technology was needed for larger telescopes:
  - Lighter mirrors with active control
  - More compact optics/tubes/domes
  - Altazimuth mountings
  - Better sites and understanding of "seeing"

The Era of 8-10m (1990-2010…)



Example: ESO VLT

4 x 8.2m telescopes

Short focal ratios

Thin and actively controlled primary

Compact alt-az mounting

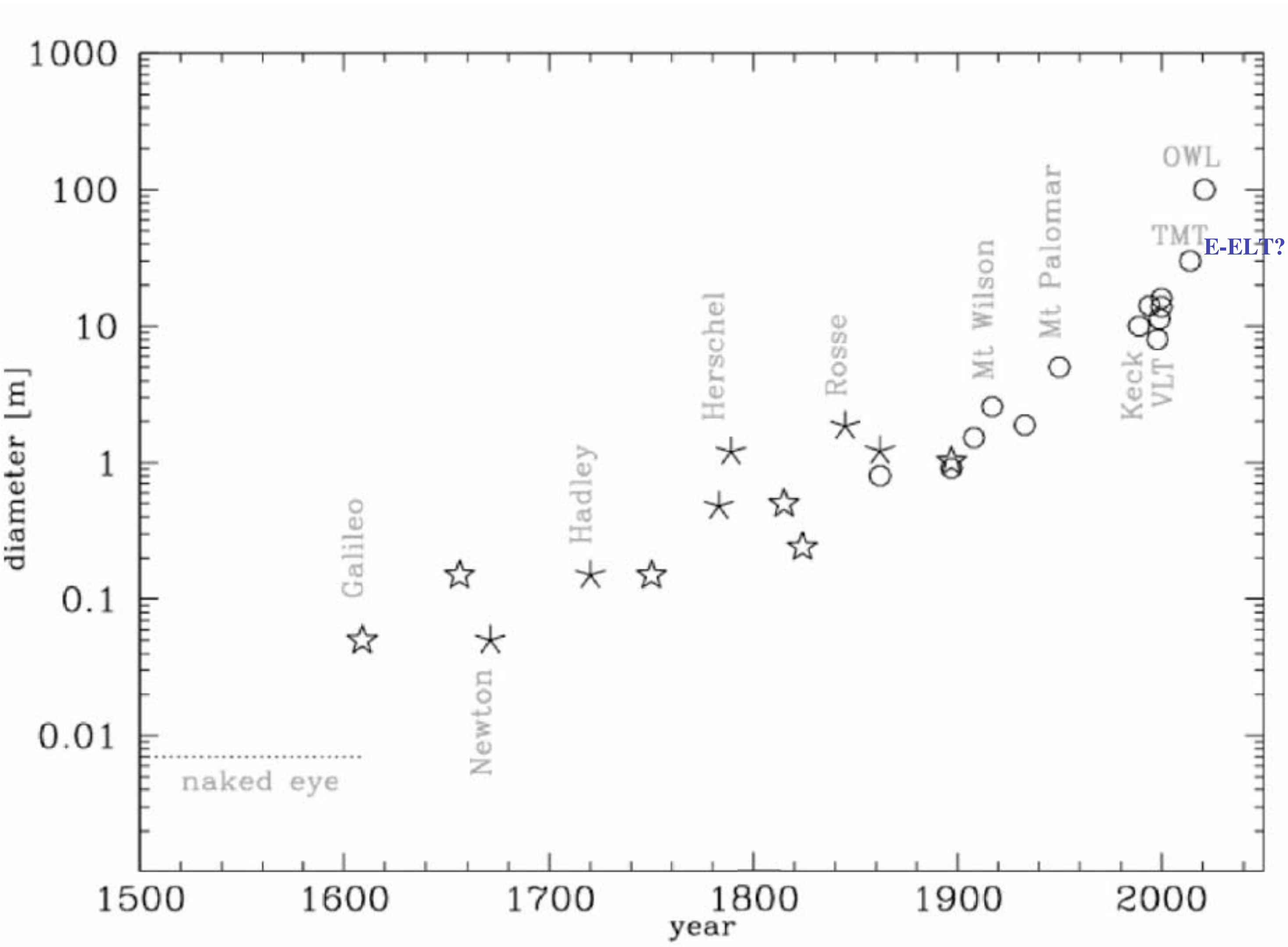
Nasmyth focal stations

Compact dome (smaller than Hale 5m dome)

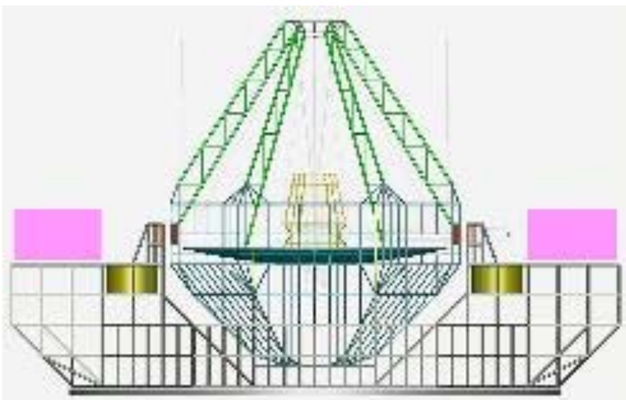
Control by digital electronics

Other technologies: segmented mirrors (Keck), lightweight honeycombe (LBT), interferometry, AO etc.

The Evolution of Aperture

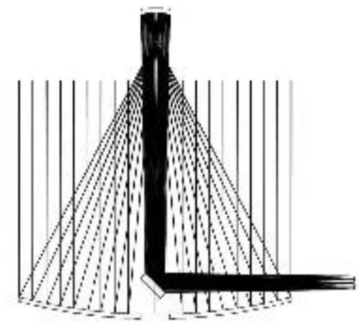


Future Telescopes I - much larger general purpose groundbased telescope: the European ELT

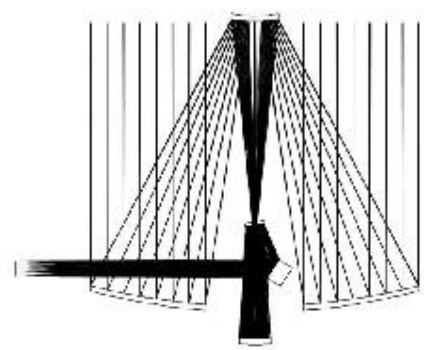


Possible mechanical structure

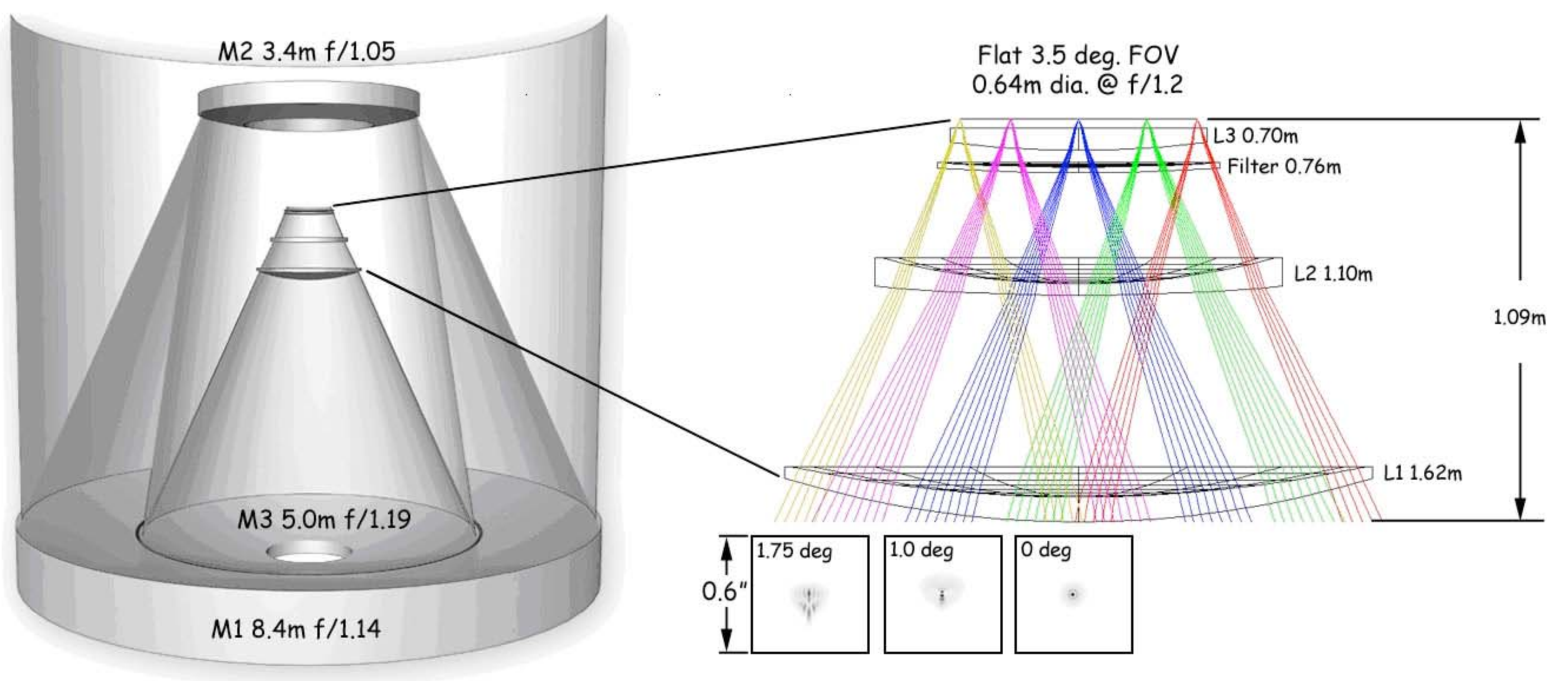
Proposed three-mirror
Gregorian optical design.
D=42m, primary, aspheric f/1.



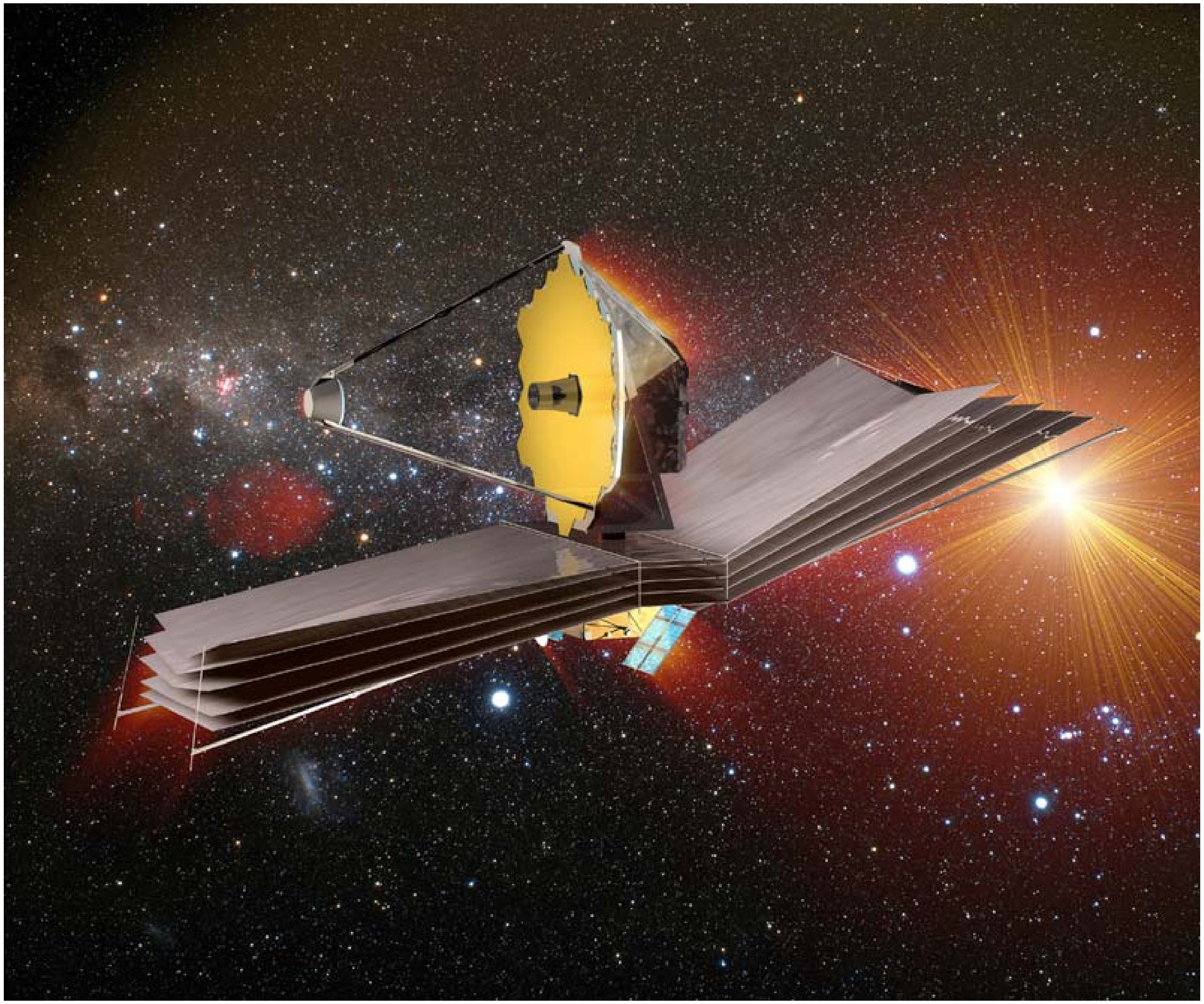
Proposed five-mirror
Cassegrain optical design.
D=42m, primary aspheric f/1.



Future telescopes II: large, widefield groundbased survey telescopes - the LSST



Future telescopes III: in Space: JWST



~6m effective aperture

Segmented primary mirror

Optimised for near-IR

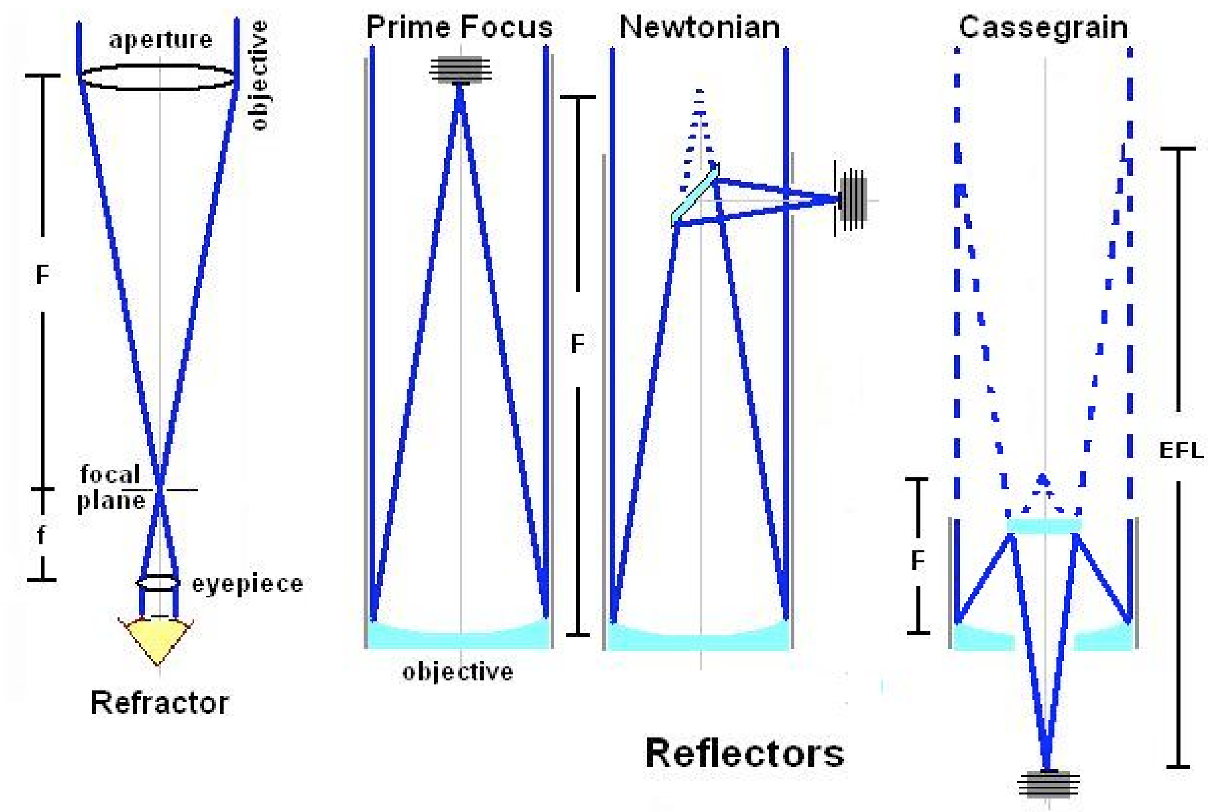
Passively cooled

At L2 Lagrangian point

Not serviceable

Launch in about 2013

Basic Telescope Optical Designs



Most modern large telescopes are variants of the Cassegrain design.

Basic Properties of Telescopes Optics

Aperture = D, Focal Length=f, Focal ratio=F=f/D
For telescopes of the same design the following holds.

- Light collecting power - proportional to D^2
- Theoretical angular resolution - proportional to 1/D (1.22 λ/D)
- Image scale (“/mm) - proportional to 1/f (206/f, “/mm, if f in m)
- Total flux of an object at focal plane - also proportional to D^2
- Surface intensity of an extended source at focal plane - proportional to $1/F^2$
- Angular Field of view - normally bigger for smaller F, wide fields need special designs
- Tube length proportional to $f_{primary}$
- Dome volume (and cost?) proportional to $f^3_{primary}$
- Cost rises as a high power (~3) of D

Telescope Aberrations

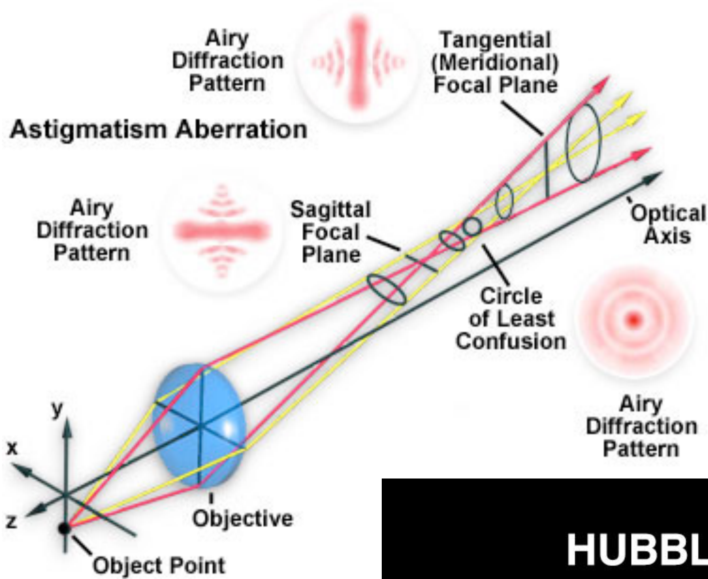
Aberrations are deviations from a perfect optical system. They can be due to manufacturing errors, alignment problems, or be intrinsic to the optical design.

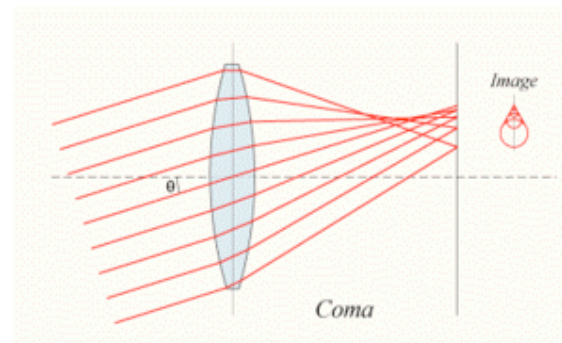
- There are five basic monochromatic (3rd order) aberrations:
  - Spherical aberration
  - Astigmatism
  - Coma
  - Field curvature
  - Distortion

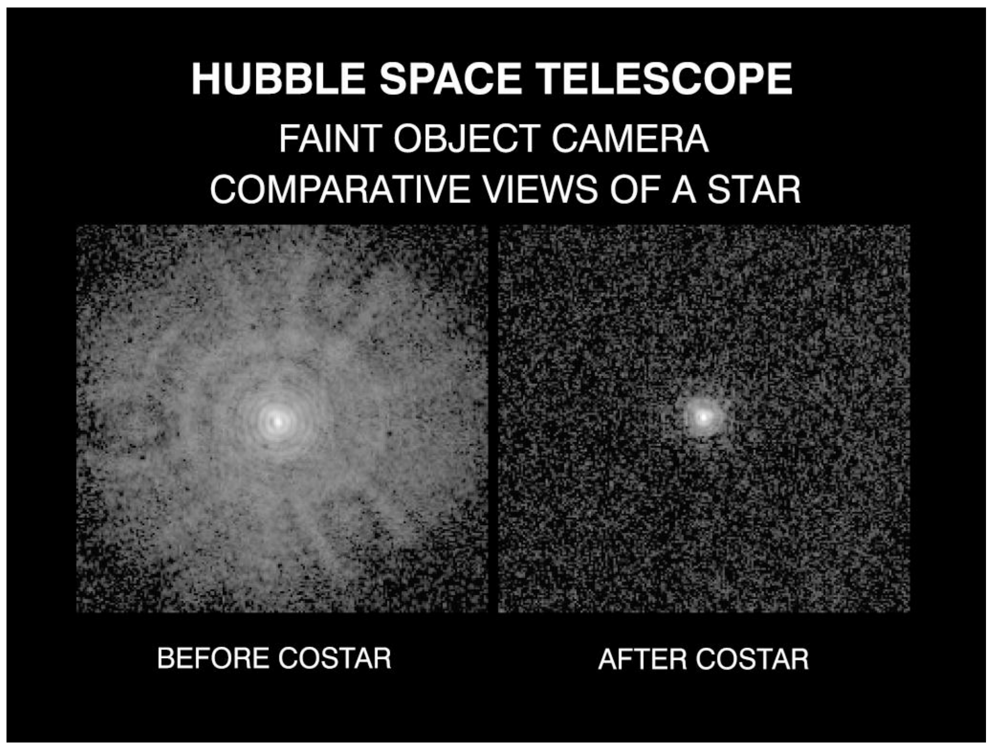
  The last two only affect the position, not the quality of the image of an object.

- Systems with refractive elements also suffer from various forms of chromatic aberration

Optical Aberrations







Spherical aberration

Zernike Polynomials

Aberrations may be represented as wavefront errors expressed as polynomial expansions in terms of angular position (θ) and radial distance (ρ) on the exit pupil.
The first few are:

$z1 = 1;$	Piston or Bias
$z2 = \rho\,\mathrm{Cos}[\theta];$	Tilt x
$z3 = \rho\,\mathrm{Sin}[\theta];$	Tilt y
$z4 = -1 + 2\rho^2;$	Power
$z5 = \rho^2\,\mathrm{Cos}[2\theta];$	Astig x
$z6 = \rho^2\,\mathrm{Sin}[2\theta];$	Astig y
$z7 = \rho\,(-2 + 3\rho^2)\,\mathrm{Cos}[\theta];$	Coma x
$z8 = \rho\,(-2 + 3\rho^2)\,\mathrm{Sin}[\theta];$	Coma y
$z9 = 1 - 6\rho^2 + 6\rho^4;$	Primary Spherical

Why the Ritchey-Chretien?

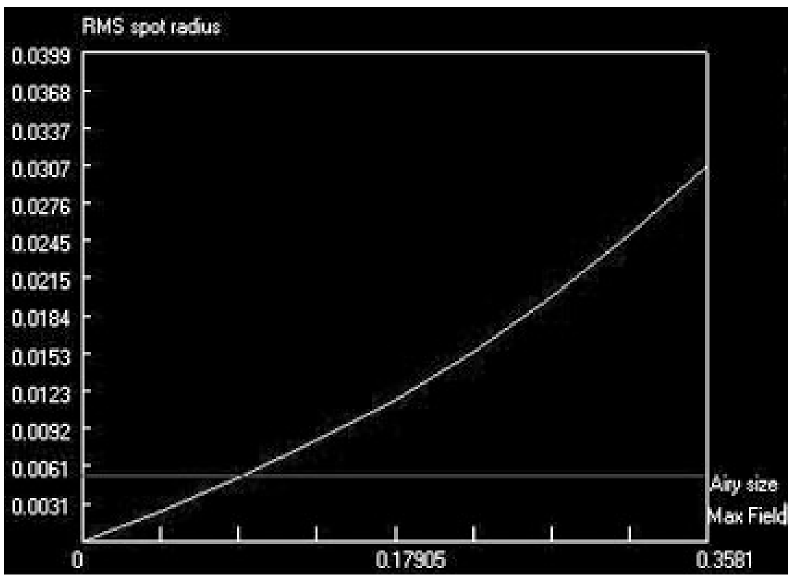
There are many options for two-mirror telescopes:

- •Classical Cassegrain - parabolic primary, hyperboloidal secondary (coma)
- •Dall-Kirkham - elliptical primary, spherical secondary (easy to make, more coma)
- •Ritchey-Chretien - hyperbolic primary, hyperbolic secondary (free of coma)
- •All suffer from mild astigmatism and field curvature

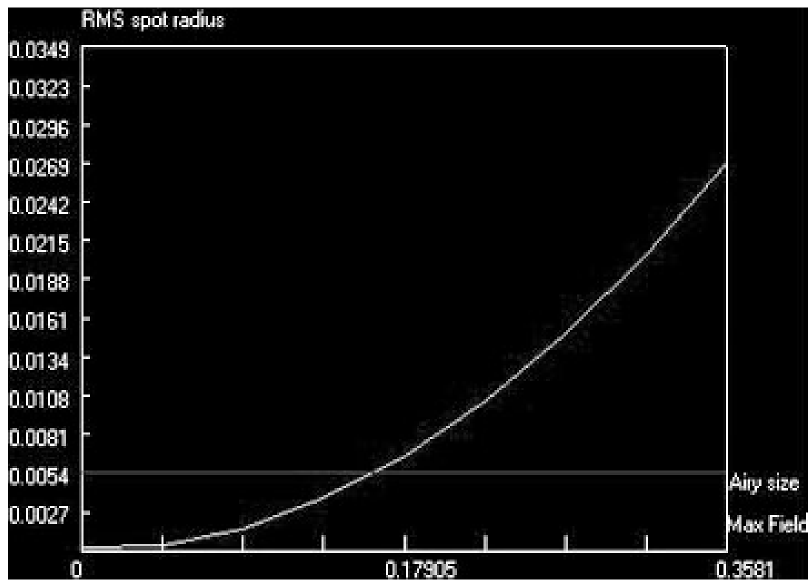
The RC gives the best off-axis performance of a two mirror system and is used for almost all modern large telescopes:

Keck, ESO-VLT, Hubble etc.

Classical Cassegrain



Ritchey-Chretien



Groundbased Point-Spread Functions (PSF)

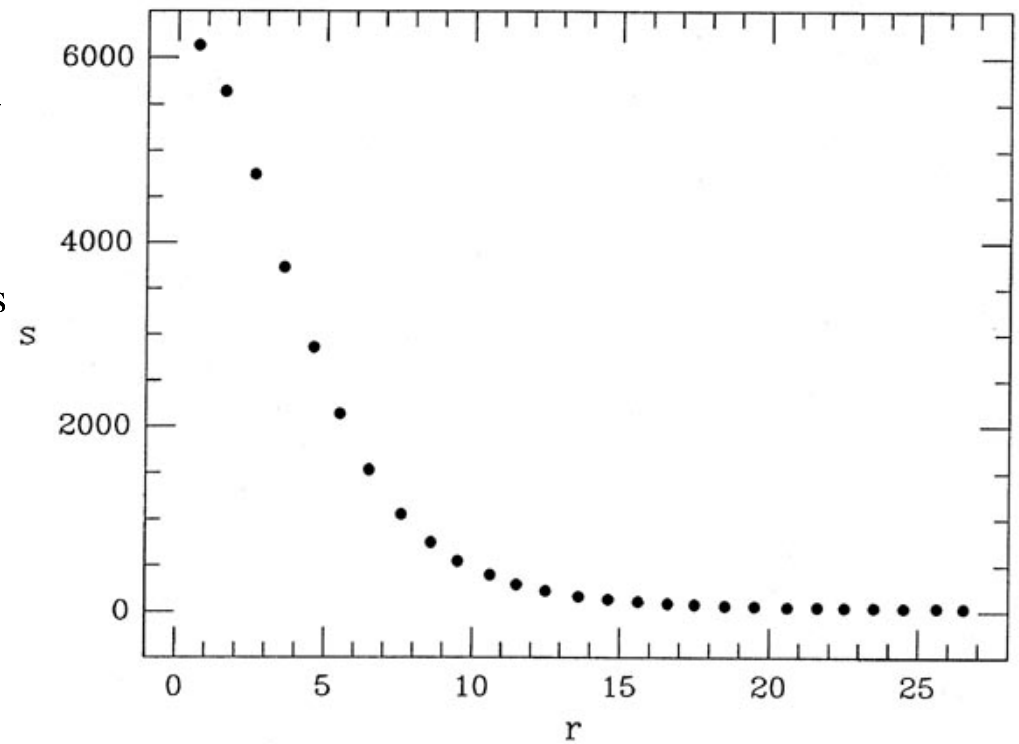
For all large groundbased telescope imaging with long exposures the PSF is a function of the atmosphere rather than the telescope optics,

The image sharpness is normally given as the “seeing”, the FWHM of the PSF in arcsecs. 0.3” is very good, 2” is bad. Seeing gets better at longer wavelengths.

The radial profile is well modelled by the Moffat function:

$$s(r) = C / (1+r^2/R^2)^{\beta} + B$$

Where there are two free parameters (apart from intensity, background and position) - R, the width of the PSF and β, the Moffat parameter. Software is available to fit PSFs of this form.

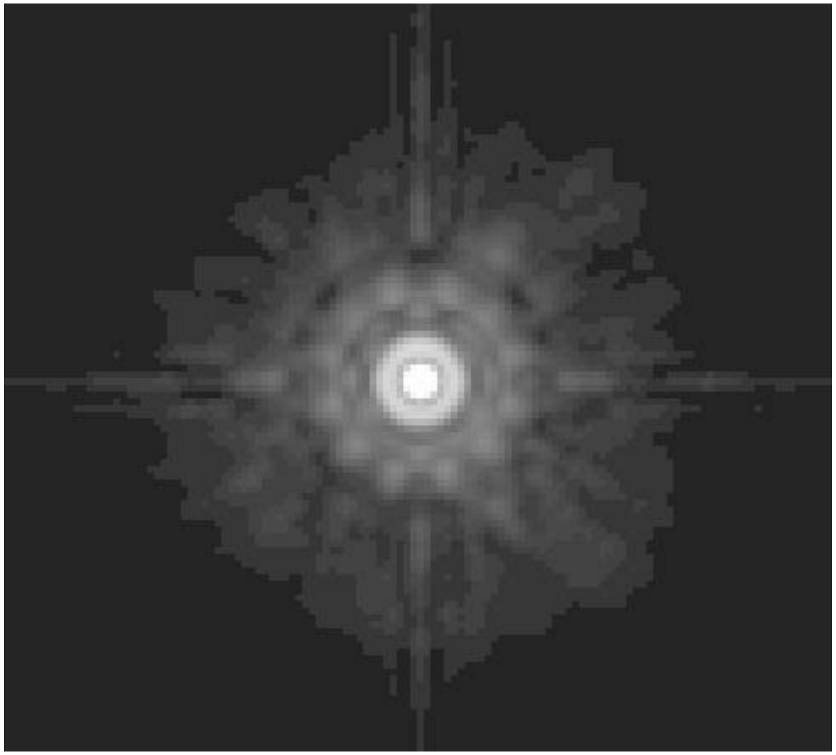


The radial profile of a typical groundbased star image.

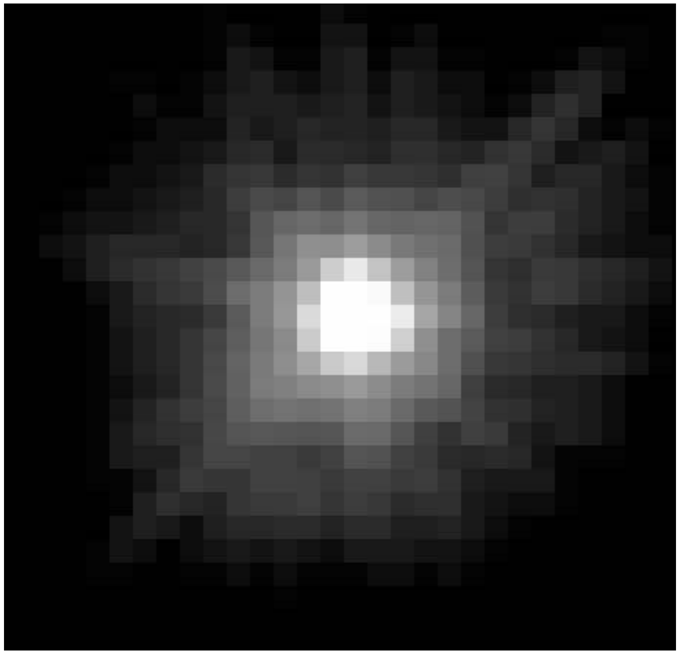
PSFs in Space

Mostly determined by diffraction and optical aberrations. Scale with wavelength.

PSFs for Hubble may be simulated using the Tiny Tim software (included in Scisoft). It uses a model of the telescope and Fourier optics theory to generate high fidelity PSF images for all of Hubble's cameras. There is also a version for Spitzer. See: www.stsci.edu/software/tinytim (V6.3)



ACS, F814W - well sampled (0.025" pixels)



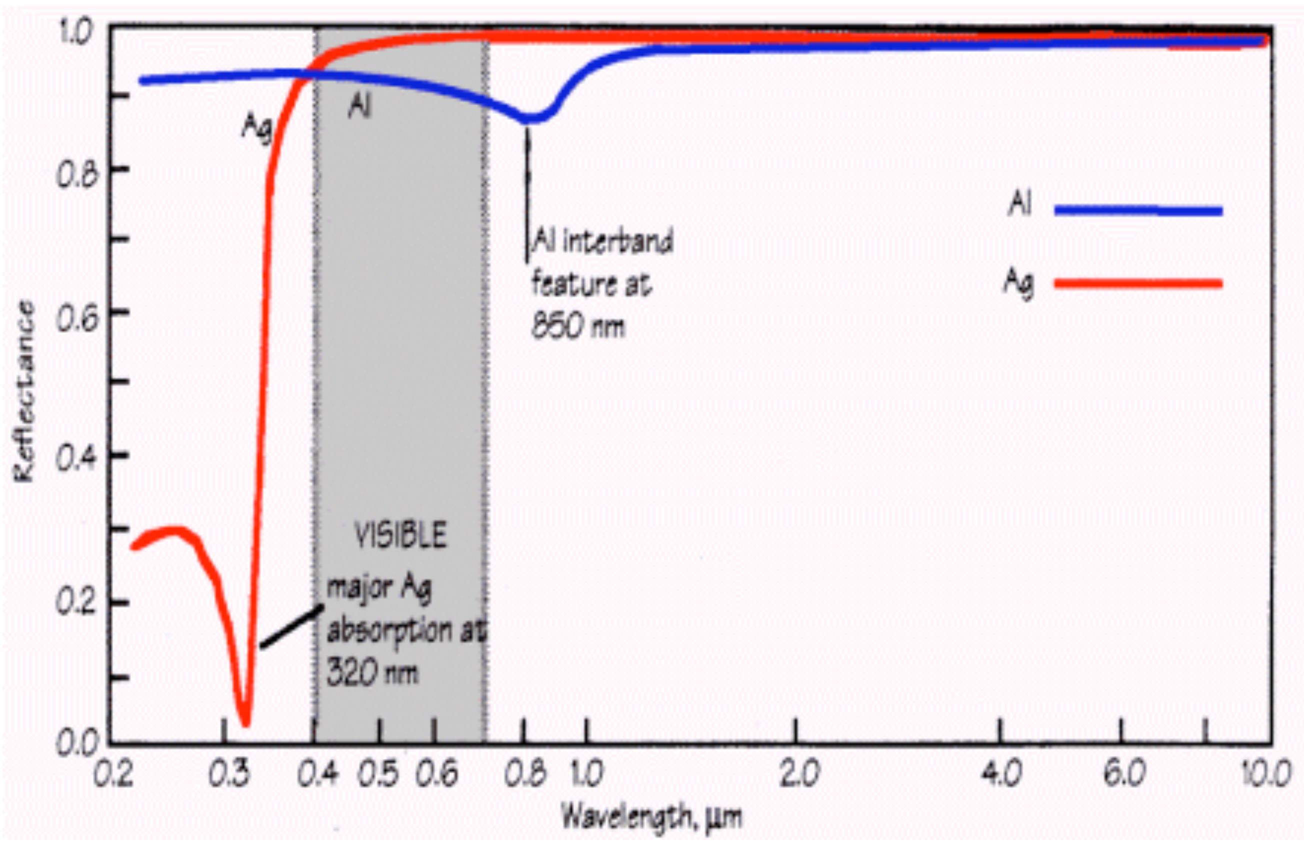
WFPC2, F300W - highly undersampled (0.1" pixels)

Simple Measures of Optical Image Quality

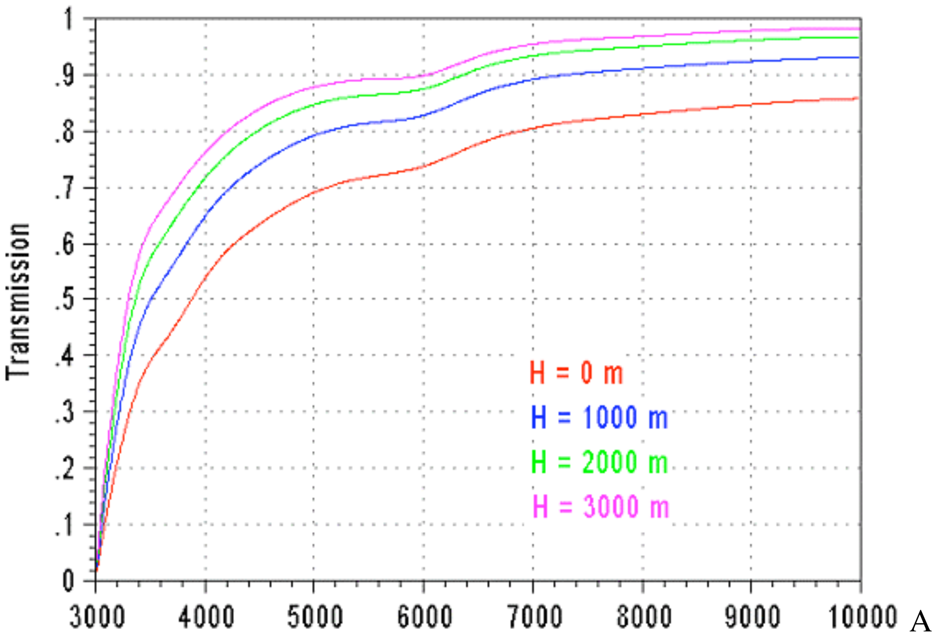
- FWHM of point-spread function (PSF) - measured by simple profile fitting (eg, imexam in IRAF)
- Strehl ratio (ratio of PSF peak to theoretical perfect value).
- Encircled energy - fraction of total flux in PSF which falls within a given radius.

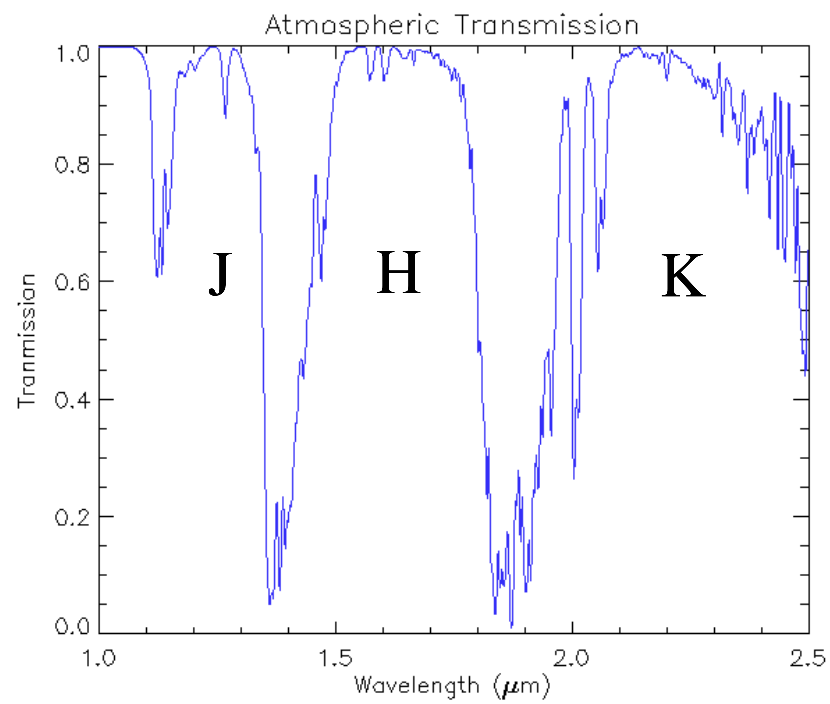
All of these need to be used with care - for example the spherically aberrated Hubble images had excellent FWHM of the PSF core but very low Strehl and poor encircled energy. Scattering may dilute contrast but not be obvious.

Mirror coatings

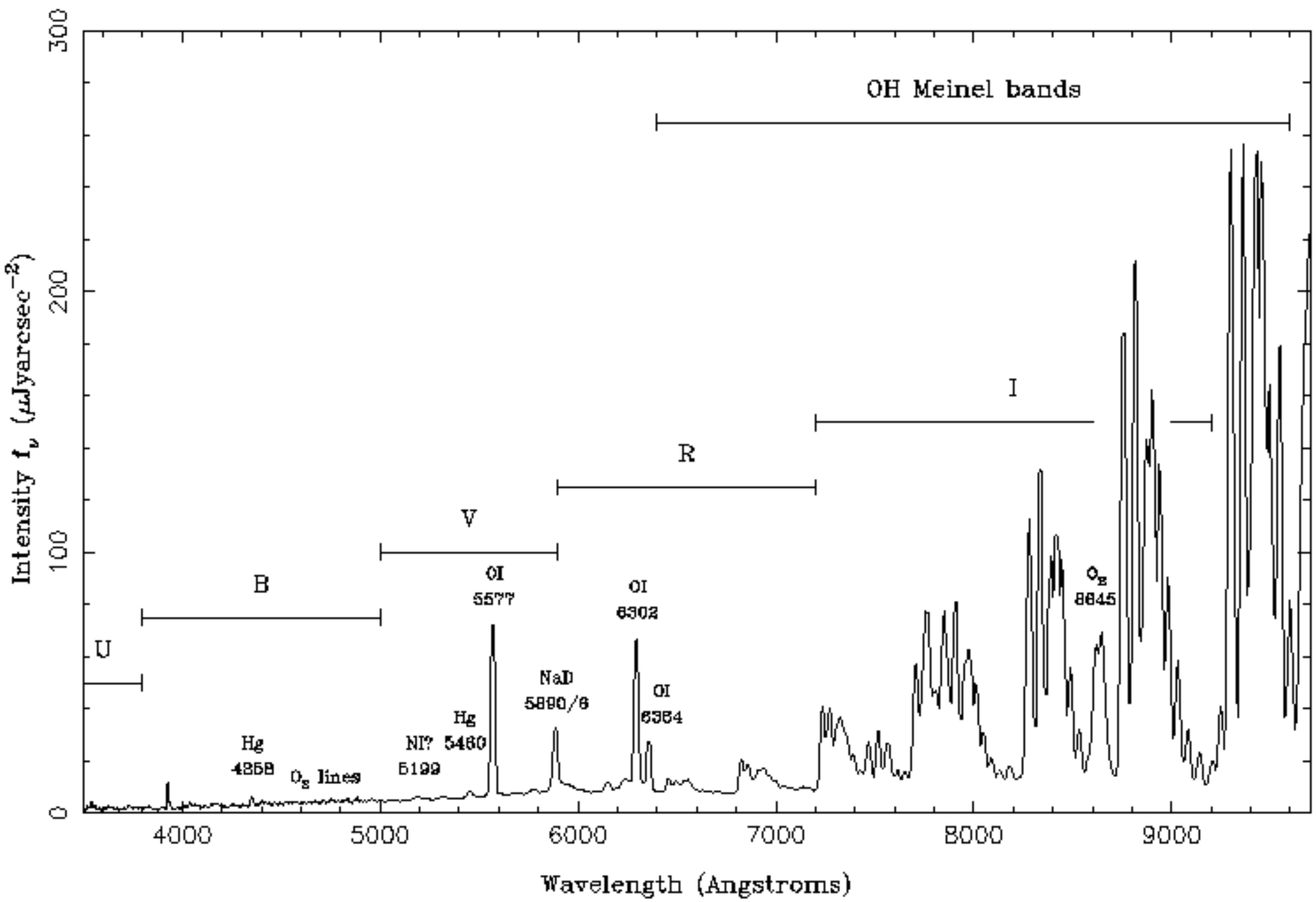


The Atmosphere - transmission





The Atmosphere - emission
(at a good dark observatory site, La Palma)



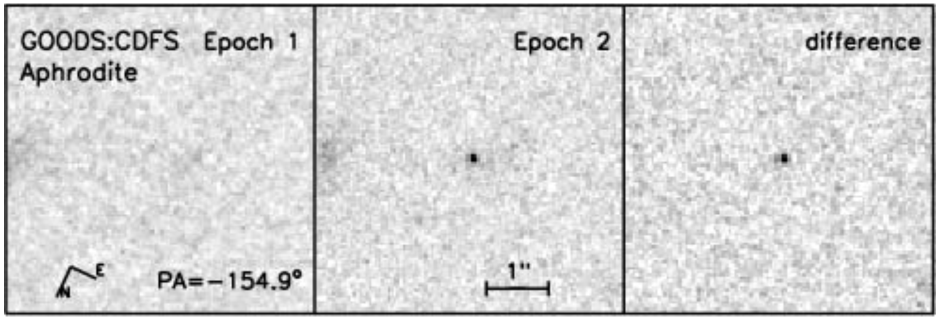
To be continued after coffee…

Part Two: Astronomical Digital Images

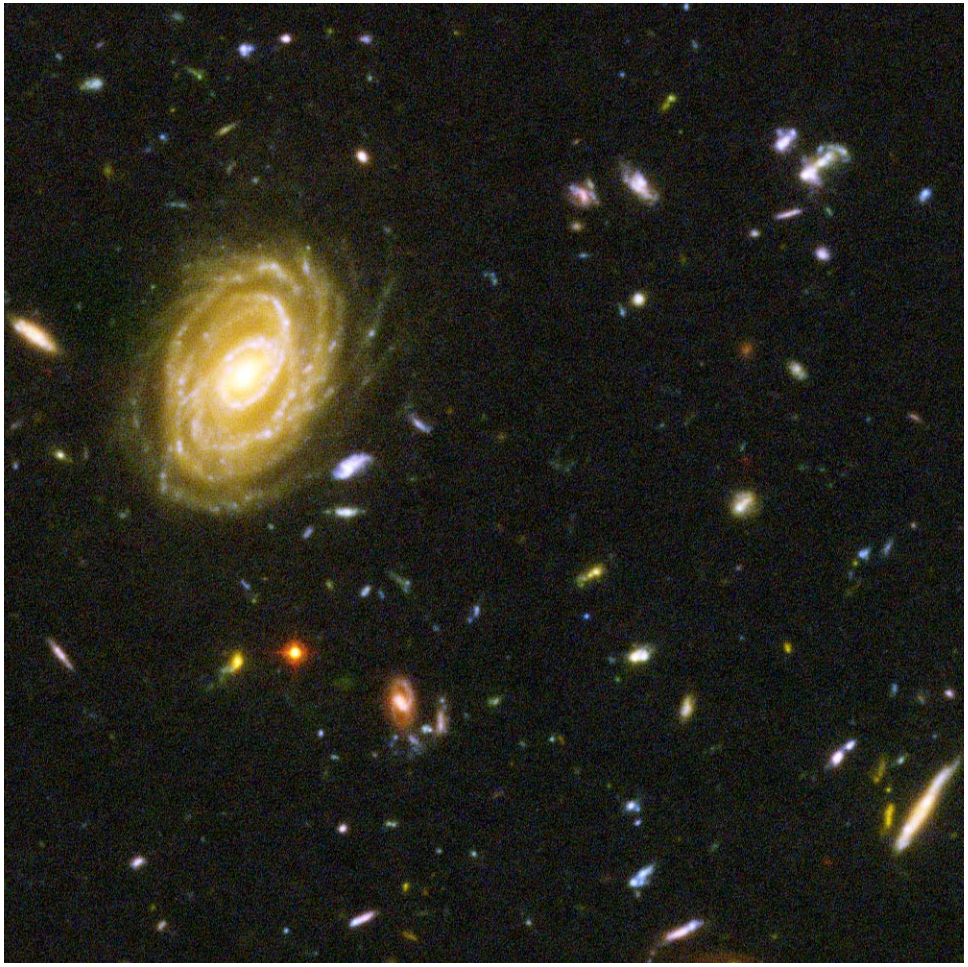
- The imaging process, with detector included
- The pixel response function
- Artifacts, defects and noise characteristics
- Basic image reduction
- Image combination, dithering and drizzling
- FITS format and metadata

- Colour
- Software - the Scisoft collection

Two Examples:
The power of imaging



A supernova at z>1 detected in the Great Observatories Origins Deep Survey (GOODS). z-band imaging with Hubble ACS/WFC at multiple epochs. Public data: www.stsci.edu/science/udf



A small section of the Hubble Ultra Deep Field (HUDF). The deepest optical image of the sky ever taken (i=31). 800 orbits with HST/ACS/WFC in BViz filters. Final scale 30mas/pix, format of entire image 10500x10500 pixels, FWHM of stars in combined image 80mas. Public data: www.stecf.org/UDF

Image Formation in One Equation

$$I = S \otimes O \otimes P + N$$

Where: S is the intensity distribution on the sky
O is the optical point-spread function (PSF, including atmosphere)
P is the pixel response function (PRF) of the detector
N is noise
$\otimes$ is the convolution operator

I is the result of sampling the continuous distribution resulting from the convolutions at the centre of a pixel and digitising the result into DN.

The Pixel-Response Function (P)

- The sensitivity varies across a pixel
- Once produced, electrons in a CCD may diffuse into neighbouring pixels (charge diffusion)
- The pixel cannot be regarded as a simple, square box which fills with electrons
- The example shown is for a star imaged by HST/NICMOS as part of the Hubble Deep Field South campaign. The centre of the NICMOS pixels are about 20% more sensitive than the edges
- CCDs also have variations, typically smaller than the NICMOS example
- This is worse in the undersampled case

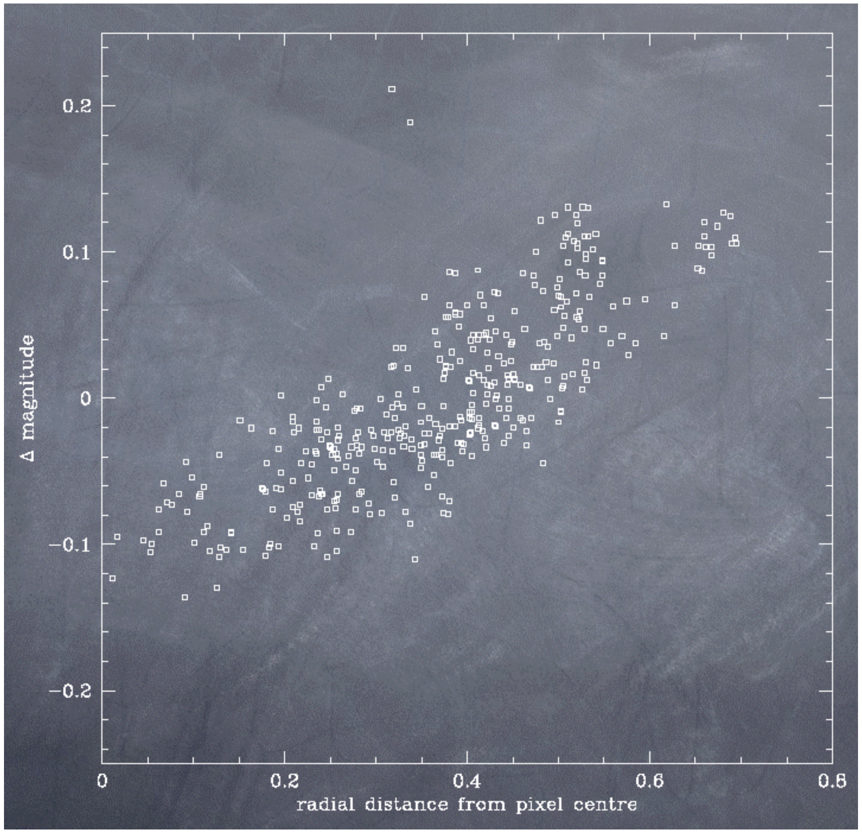
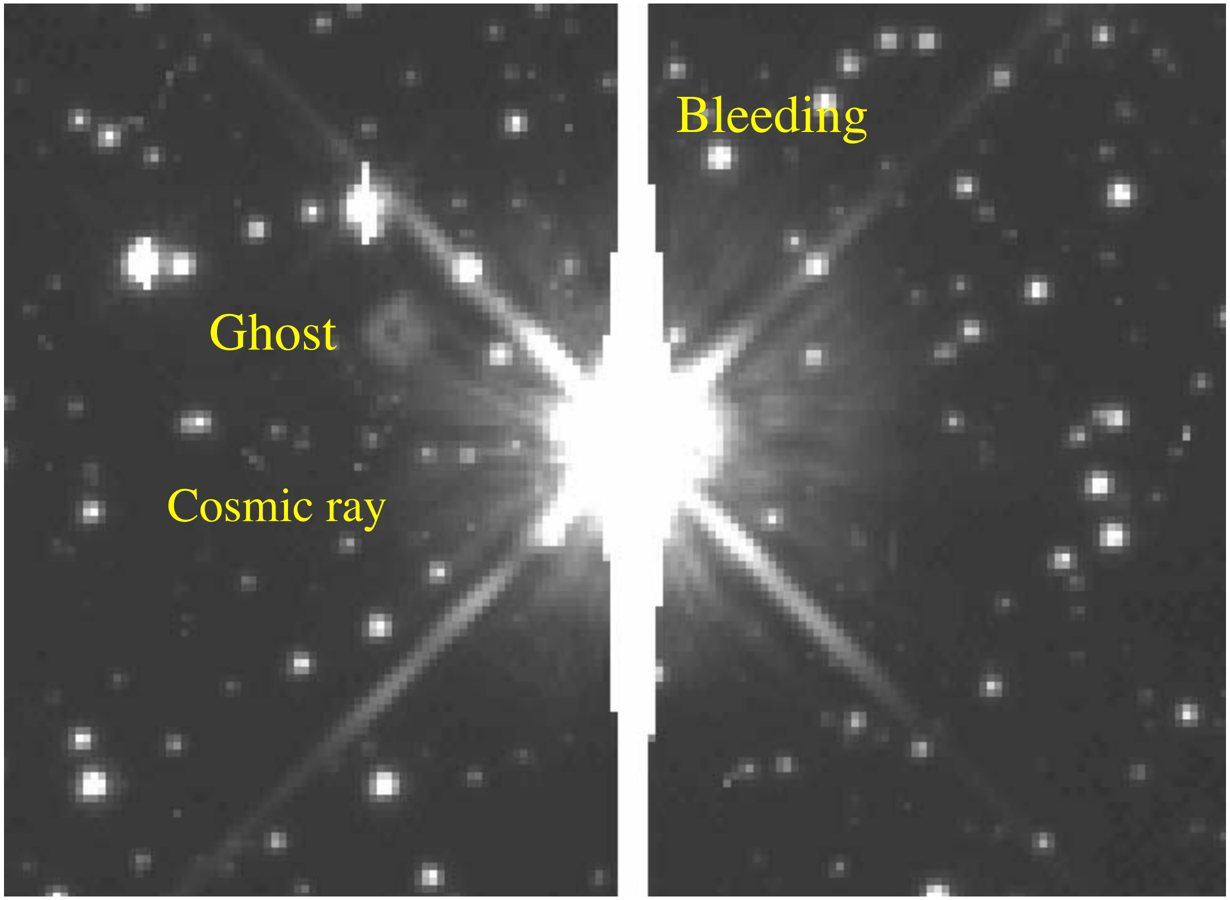


Image Defects and Artifacts

- Cosmic-ray hits - unpredictable, numerous, bright, worse from space
- Bad pixels - predictable (but change with time), fixed to given pixels, may be “hot”, may affect whole columns
- Saturation (digital and full-well) and resulting bleeding from bright objects
- Ghost images - reflections from optical elements
- Cross-talk - electronic ghosts
- Charge transfer efficiency artifacts
- Glints, grot and many other nasty things

Some real image defects (HST/WFPC2):

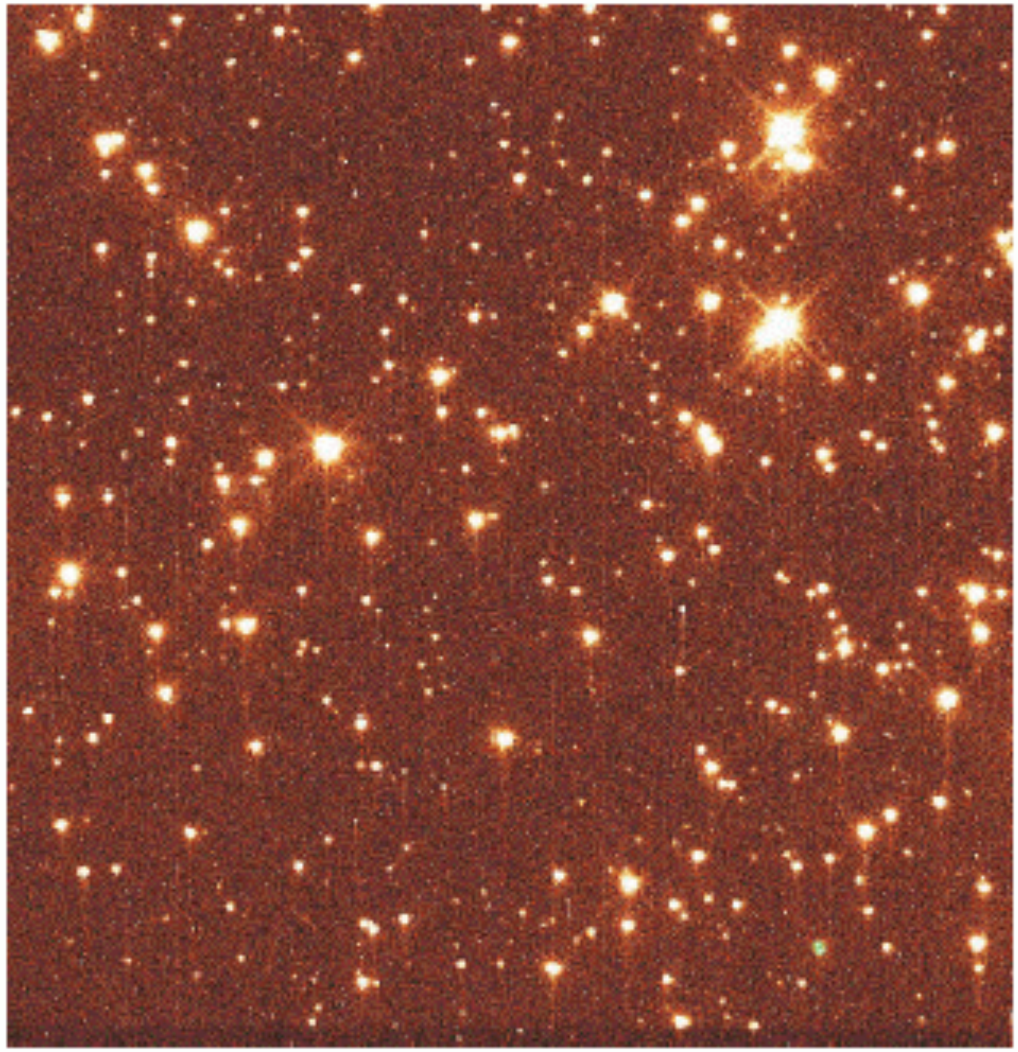


Charge Transfer (In)efficiency

CCDs are read out by clocking charge along registers. These transfers are impeded by radiation damage to the chips.

This effect gets worse with time and is worse in space,

This image is from the STIS CCD on Hubble. Note the vertical tails on stars.



Noise

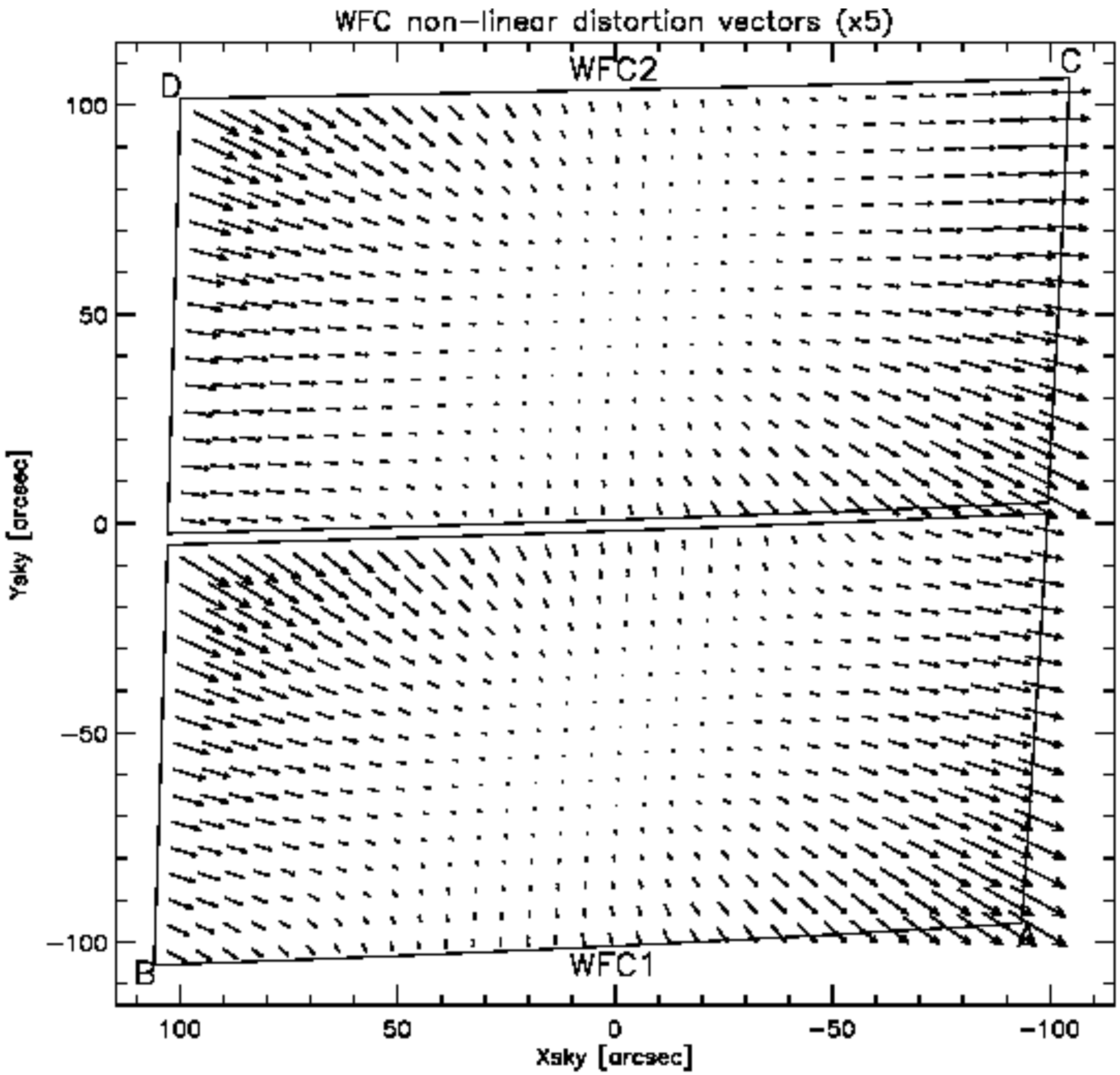
- For CCD images there are two main sources of noise:
  - Poisson "shot" noise from photon statistics, applies to objects, the sky and dark noise, increases as the square root of exposure time
  - Gaussian noise from the CCD readout, independent of exposure time
- For long exposures of faint objects through broad filters the sky is normally the dominant noise source
- For short exposures or through narrow-band filters readout noise can become important but is small for modern CCDs

Geometric Distortion

Cameras normally have some distortion, typically a few pixels towards the edges,

It is important to understand and characterise it to allow it to be removed if necessary, particular when combining multiple images.

Distortion may be a function of time, filter and colour.



HST/ACS/WFC - a severe case of distortion - more than 200 pixels at the corners. Large skew.

Basic Frame Calibration

- Raw CCD images are normally processed by a standard pipeline to remove the instrumental signature. The main three steps are:
  - Subtraction of bias (zero-point offset)
  - Subtraction of dark (proportional to exposure)
  - Division by flat-field (correction for sensitivity variation)
- Once good calibration files are available basic processing can be automated and reliable
- After this processing images are not combined and still contain cosmic rays and other defects
- Standard archive products for some telescopes (eg, Hubble) have had On-The-Fly Recalibration (OTFR) performed with the best reference files

Sampling and Frame Size

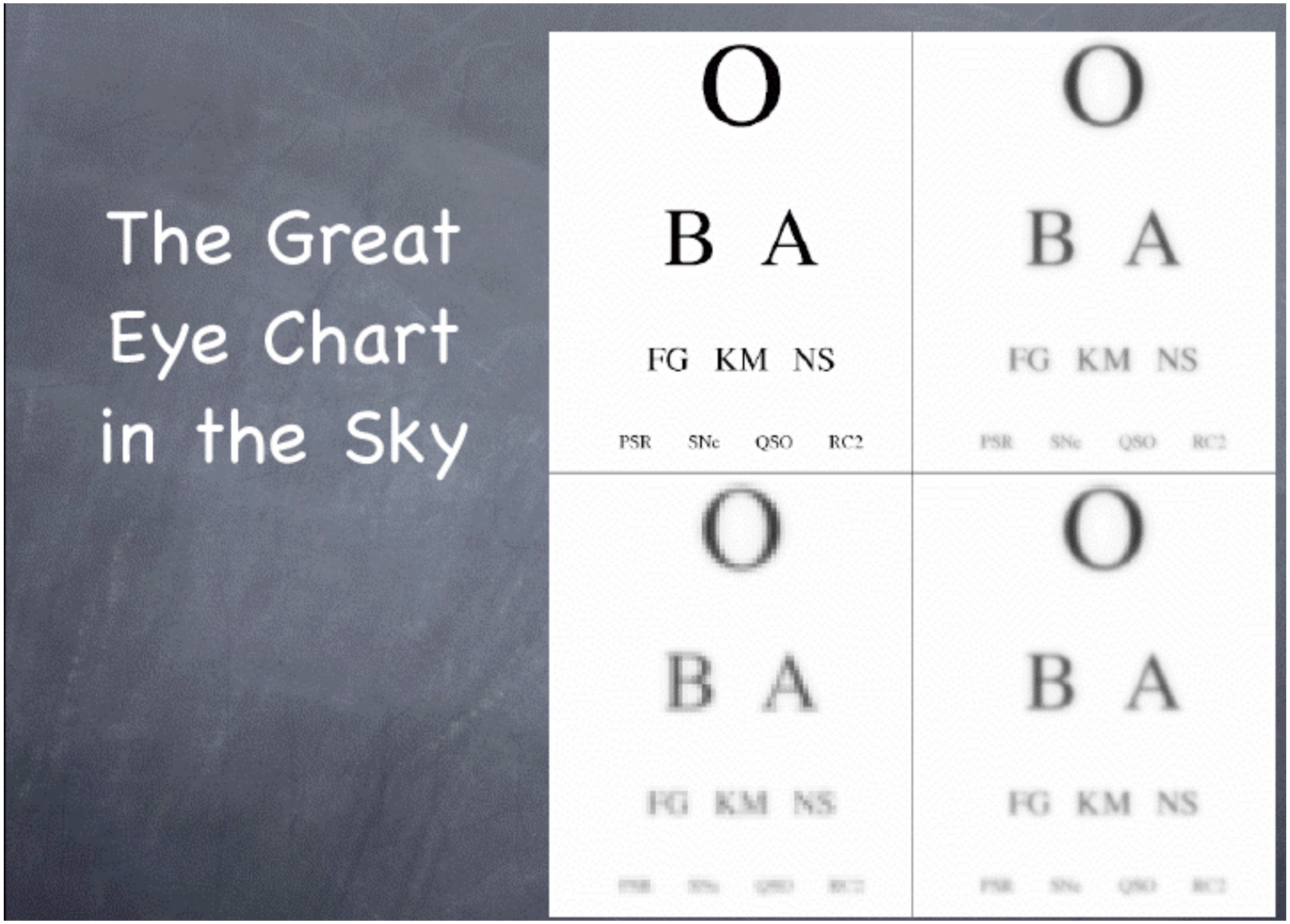
- Ideally pixels should be small enough to well sample the PSF (ie, PRF negligible). Pixel < PSF_FWHM/2.
- But, small pixels have disadvantages:
  - Smaller fields of view (detectors are finite and expensive)
  - More detector noise per unit sky area (eg, PC/WF comparison)
- Instrument designers have to balance these factors and often opt for pixel scales which undersample the PSF.
  - Eg, HST/WFPC2/WF - PSF about 50mas at V, PRF 100mas.
  - HST/ACS/WFC - PSF about 30mas at U, PRF 50mas.
- In the undersampled regime the PRF > PSF
- From the ground sampling depends on the seeing, instrument designers need to anticipate the likely quality of the site.

Image Combination

- Multiple images are normally taken of the same target:
  - To avoid too many cosmic-rays
  - To allow longer exposures
  - To allow dithering (small shifts between exposures)
  - To allow mosaicing (large shifts to cover bigger areas)
- If the multiple images are well aligned then they may be combined easily using tools such as imcombine in IRAF which can also flag and ignore certain image defects such as cosmic-rays
- Combining multiple dithered images, particularly if they are undersampled is less easy…

Undersampling and reconstruction

Truth After optics



After pixel After linear reconstruction

Dithering

- Introducing small shifts between images has several advantages:
  - If sub-pixel shifts are included the sampling can be improved
  - Defects can be detected and flagged
  - Flat field errors may be reduced
- Most Hubble images are now dithered for these reasons
- How do we combine dithered, undersampled, geometrically distorted images which have defects?
- For HST this problem arose for the Hubble Deep Field back in 1995
- It is a very general problem, affecting many observations

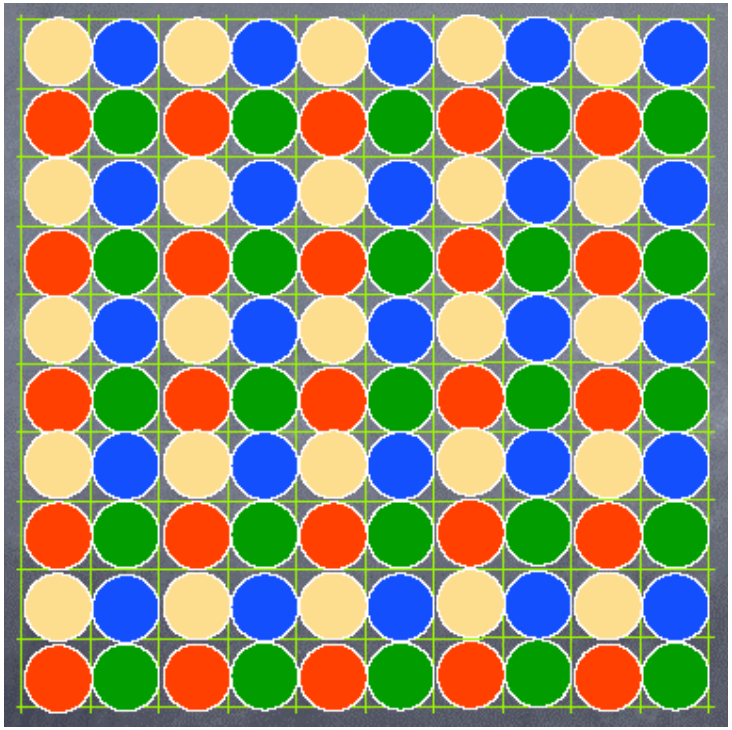
Simple ways of combining dithered data

- Shift-and-add - introduces extra blurring and can't handle distortion, easy, fast. Useful when there are many images and little distortion. Fast.
- Interlacing - putting input image pixel values onto a finer output grid and using precise fractional offsets.
- In all cases you need a way to measure the shifts (and possibly rotations)
- Need something more general…

Interlacing, nice but hard to do…

Four input images with exactly half-pixel dithers in X and Y are combined onto an output grid with pixels half the size by “interlacing” the input pixels.

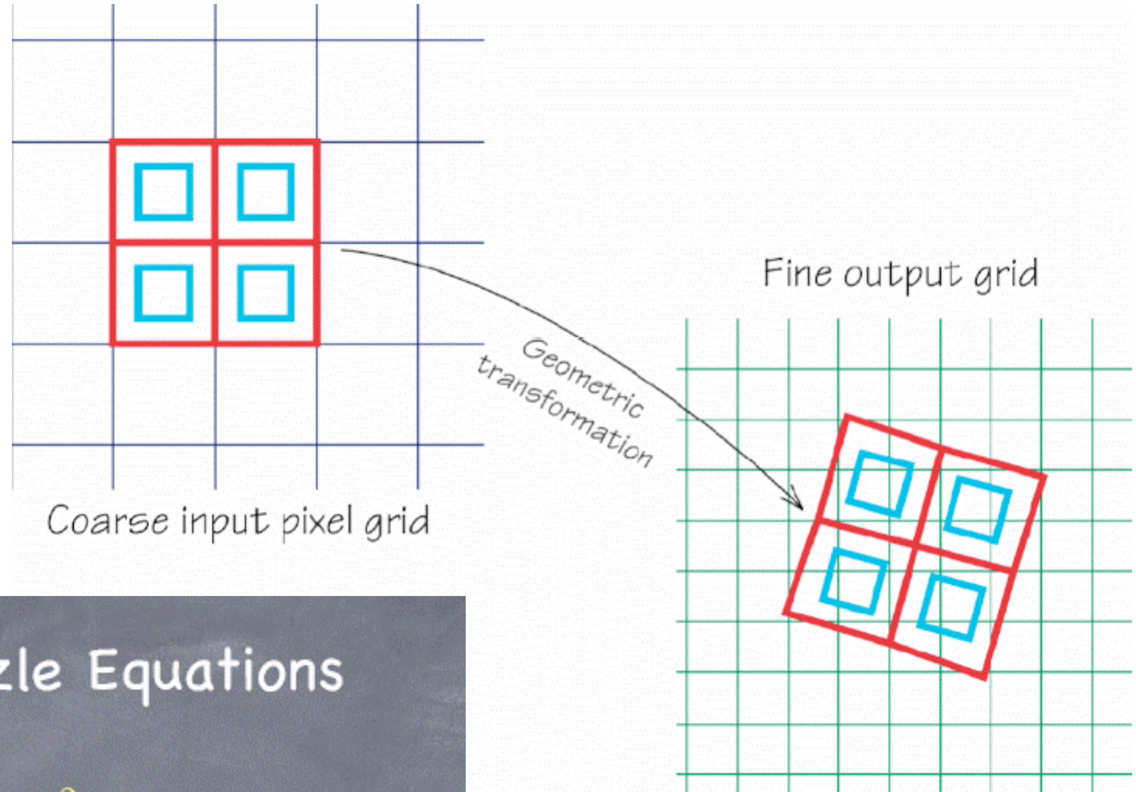
No noise correlation, very fast and easy. But - doesn’t work with geometric distortion and requires perfect sub-pixel dithers.



Drizzling

- A general-purpose image combination method
- Each input pixel is mapped onto the output, including geometric distortion correction and any linear transformations
- On the output pixels are combined according to their individual weights - for example bad pixels can have zero weight
- The "kernel" on the output can be varied from a square like the original pixel (shift-and-add) to a point (interlacing) or, as usual, something in between
- Preserves astrometric and photometric fidelity
- Developed for the Hubble Deep Field, used for most Hubble imaging now
- Other good alternatives exist (eg, Bertin's SWarp)

Drizzling



The Basic Drizzle Equations

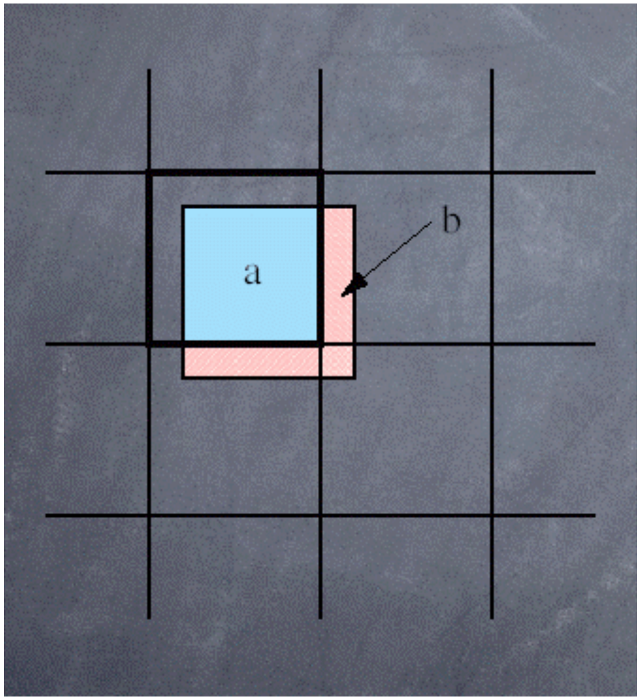
$$I'_{x_o y_o} = \frac{d_{x_i y_i} a_{x_i y_i x_o y_o} w_{x_i y_i} s^2 + I_{x_o y_o} W_{x_o y_o}}{W'_{x_o y_o}}$$

$$W'_{x_o y_o} = a_{x_i y_i x_o y_o} w_{x_i y_i} + W_{x_o y_o}$$

Noise in drizzled images

Drizzling, in common with other resampling methods can introduce correlated noise - the flux from a single input pixel gets spread between several output pixels according to the shape and size of the kernel. As a result the noise in an output pixel is no longer statistically independent from its neighbours.

Noise correlations can vary around the image and must be understood as they can affect the statistical significance of measurements (eg, photometry) of the output.



The Effects of Resampling Kernels

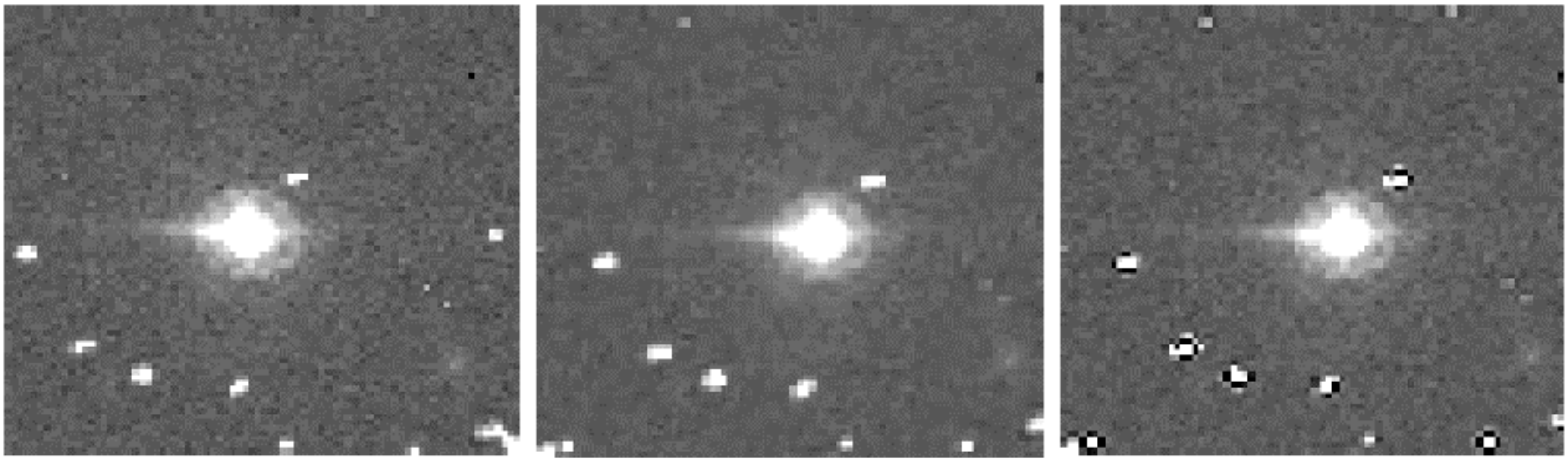
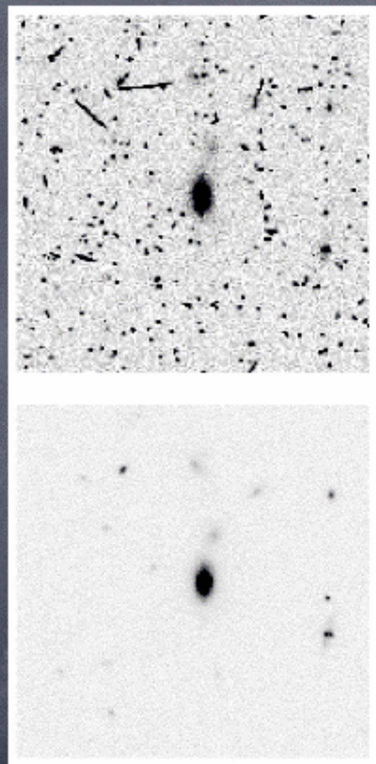


Fig 1: Star in an ACS image through the F814W filter. Left: the original image, the FWHM of the star is 1.78 pixels. Centre: the result of drizzling the original image with kernel=square and pixfrac=1.0, the FWHM is now 2.18. Right: the result of the same drizzling with the newly implemented Lanczos kernel. The FWHM is now 1.93 pixels and there is less apparent correlated noise. Note the dark artefacts around the cosmic rays.

Cosmic Ray Removal Recipe



- Drizzle each image onto a separate sub-sampled output image using pixfrac=1.0
- Take the median of the resulting aligned drizzled images.
- Map (blot) the median image back to the input plane of each of the individual images
- Take the spatial derivative of each of the blotted output images.
- Compare each original image with the corresponding blotted image; mask pixels showing excessive differences
- Repeat on adjacent pixels with stricter criteria
- Drizzle all images onto a single output using cosmic-ray masks

Implemented as MultiDrizzle for HST
- www.stsci.edu/pydrizzle/multidrizzle

FITS format and Metadata

- FITS is an almost universal data exchange format in astronomy.
- Although designed for exchange it is also used for data storage, on disk.
- The basic FITS file has an ASCII header for metadata in the form of keyword/value pairs followed by a binary multi-dimensional data array.
- There are many other FITS features, for tables, extensions etc.
- For further information start at:

http://archive.stsci.edu/fits/fits_standard/

FITS Header elements (Hubble/ACS):

```
SIMPLE  =                    T    / Fits standard
BITPIX  =                   16    / Bits per pixel
NAXIS   =                    2    / Number of axes
NAXIS1  =                 4096    / Number of axes
NAXIS2  =                 2048    / Number of axes
EXTEND  =                    T    / File may contain extensions
ORIGIN  = 'NOAO-IRAF FITS Image Kernel December 2001' / FITS file originator
IRAF-TLM= '09:10:54 (13/01/2005)'
NEXTEND =                    3    / Number of standard extensions
DATE    = '2005-01-13T09:10:54'
FILENAME= 'j90m04xuq_flt.fits' / name of file
FILETYPE= 'SCI      '             / type of data found in data file

TELESCOP= 'HST'                   / telescope used to acquire data
INSTRUME= 'ACS   '                / identifier for instrument used to acquire data
EQUINOX =               2000.0 / equinox of celestial coord. System

......
CRPIX1  =                512.0 / x-coordinate of reference pixel
CRPIX2  =                512.0 / y-coordinate of reference pixel
CRVAL1  =       9.354166666667 / first axis value at reference pixel
CRVAL2  =              -20.895 / second axis value at reference pixel
CTYPE1  = 'RA---TAN'           / the coordinate type for the first axis
CTYPE2  = 'DEC--TAN'           / the coordinate type for the second axis
CD1_1   = -8.924767533197766E-07 / partial of first axis coordinate w.r.t. x
CD1_2   = 6.743481370546063E-06 / partial of first axis coordinate w.r.t. y
CD2_1   = 7.849581942774597E-06 / partial of second axis coordinate w.r.t. x
CD2_2   = 1.466547509604328E-06 / partial of second axis coordinate w.r.t. y

....
```

Fundamental properties: image size, data type, filename etc.

World Coordinate System (WCS): linear mapping from pixel to position on the sky.

Image Quality Assessment: try this!

(IRAF commands in ())

- Look at the metadata - WCS, exposure time etc? (imhead)
- What is the scale, orientation etc? (imhead)
- Look at images of point sources - how big are they,what shape? Sampling? (imexam)
- Look at the background level and shape - flat? (imexam)
- Look for artifacts of all kinds - bad pixels? Cosmic rays? Saturation? Bleeding?
- Look at the noise properties, correlations? (imstat)

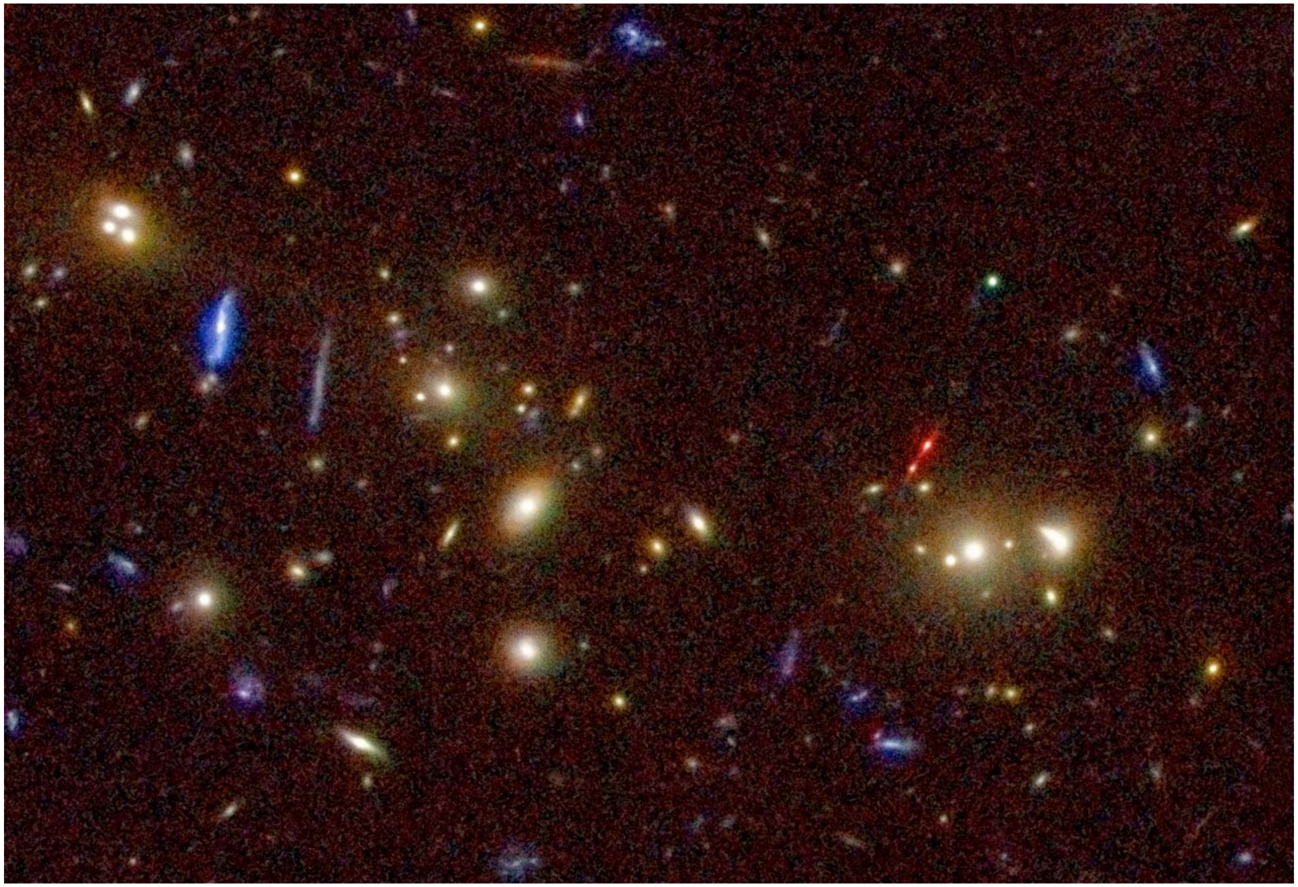
A Perfect Image?

What makes a fully processed astronomical image?

- Astrometric calibration
  - Distortion removed (0.1pix?)
  - WCS in header calibrated to absolute frame (0.1”?)
- Photometric calibration
  - Good flatfielding (1%?)
  - Accurate zeropoint (0.05mags?)
  - Noise correlations understood
- Cosmetics
  - Defects corrected where possible
  - Remaining defects flagged in DQ image
  - Weight map/variance map to quantify statistical errors per pixel
- Description
  - Full descriptive metadata (FITS header)
  - Derived metadata (limiting mags?)
  - Provenance (processing history)

Colour Images

- For outreach use
- For visual scientific interpretation



The Lynx Arc

A region of intense star formation at z>3 gravitationally lensed and amplified by a low-z massive cluster.

This image is an Hubble/WFPC2 one colourised with ground-based images.

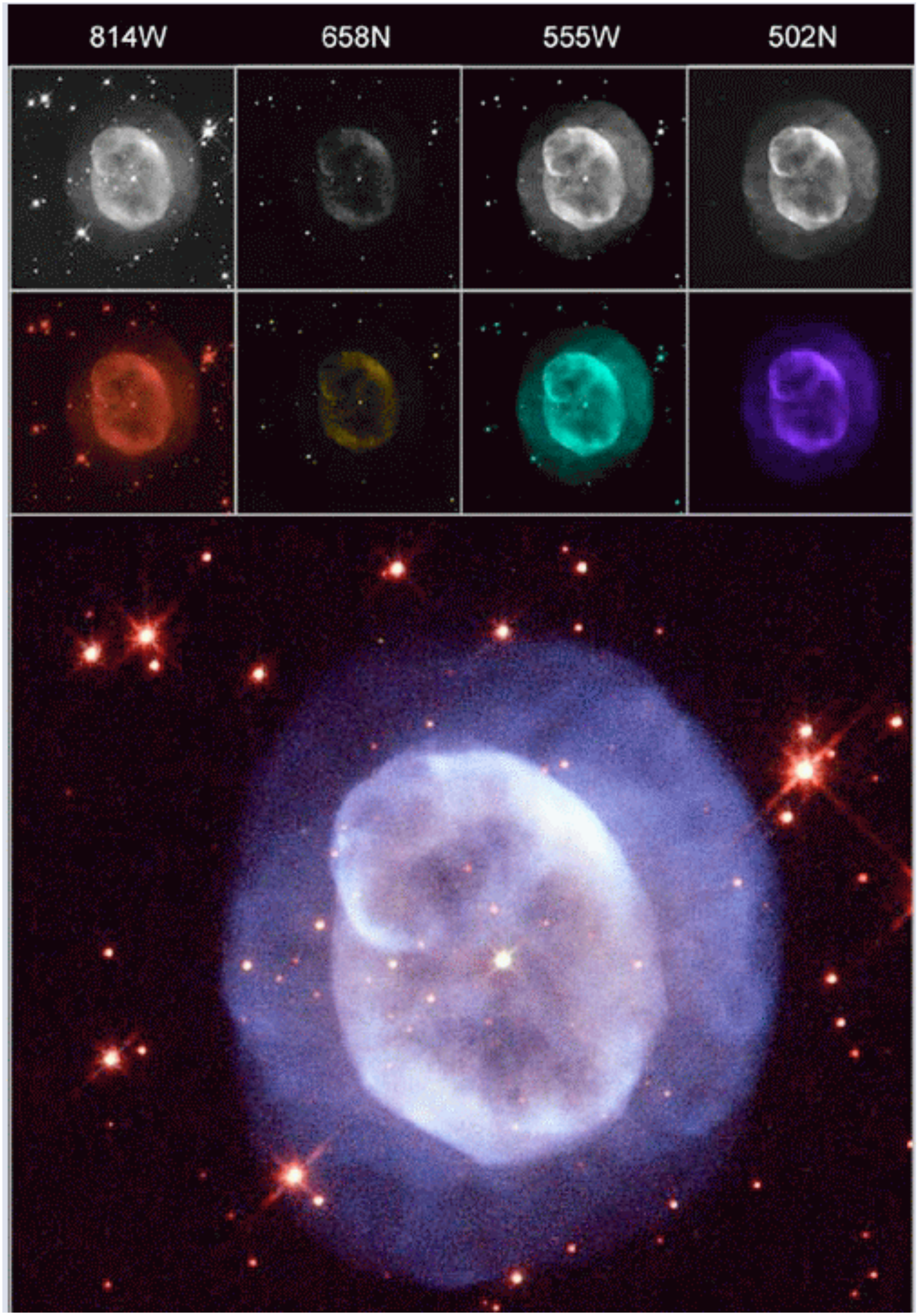
Making Colour Images - a new product…

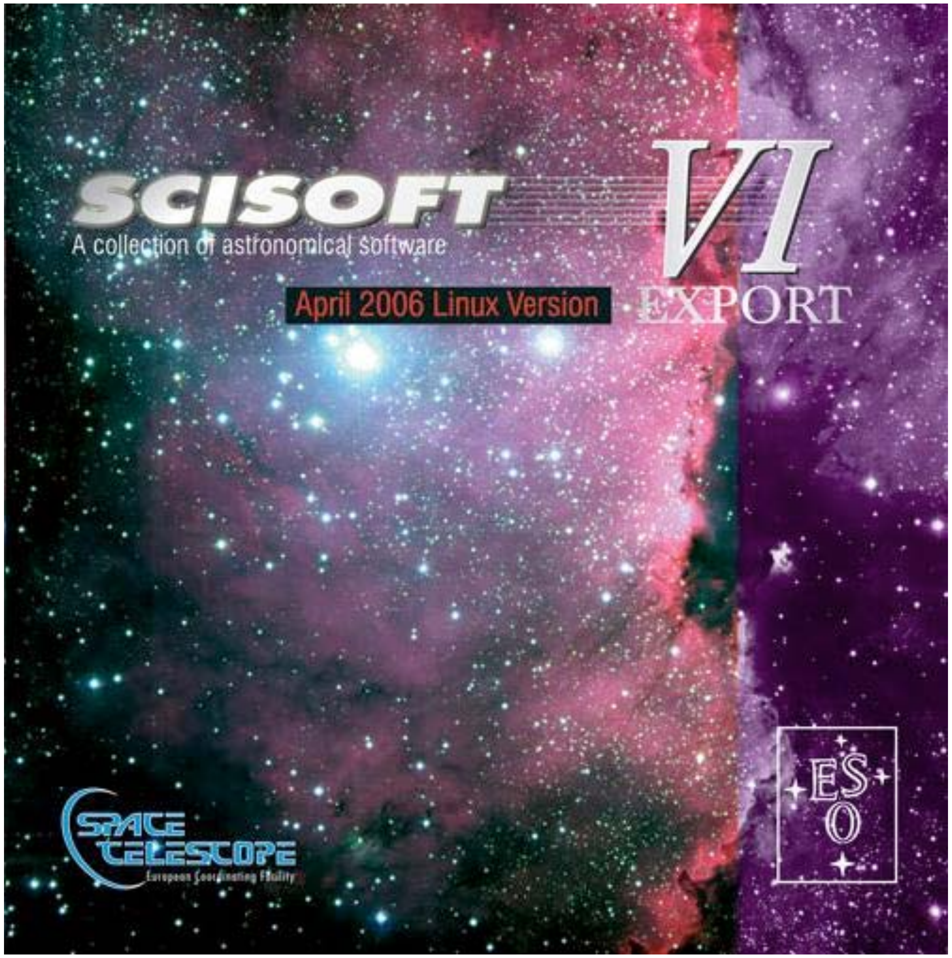
Developed by Lars Christensen and collaborators:
www.spacetelescope.org/projects/fits_liberator

Original input images from FITS files

Colourised in Photoshop

Final combined colour version:





Software

Scisoft is a collection of many useful astronomical packages and tools for Linux (Fedora Core 3) computers. A DVD is available for free…

Most of the software mentioned in this talk is included and "ready to run".

Packages on the DVD include:

IRAF,STSDAS,TABLES etc

ESO-MIDAS

SExtractor/SWarp

ds9,Skycat

Tiny Tim

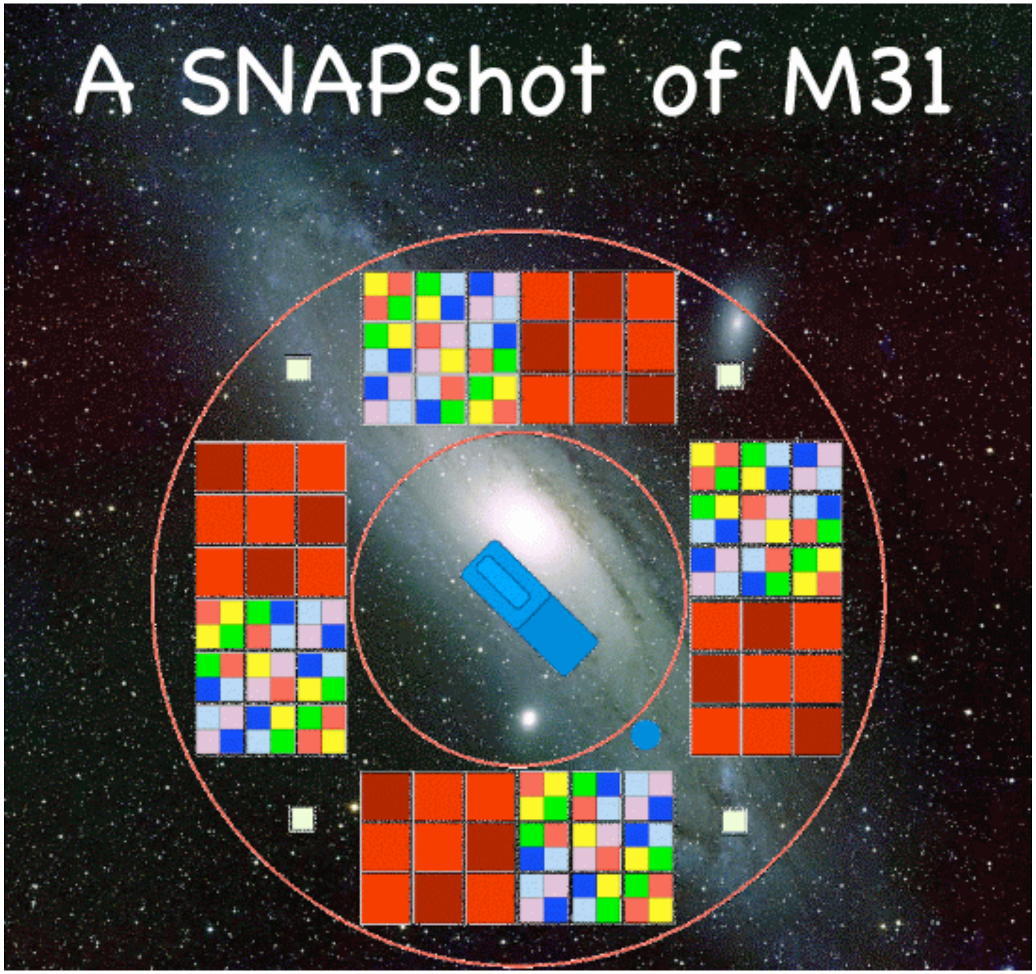
Python …

That’s all - any questions?

The Future of Space-based optical imaging?

SNAP (SuperNova Acceleration Probe) = JDEM (Joint Dark Energy Mission)

Possible next wide-field optical imager in space.



Introduction and Scope

- Optical imaging is the oldest form of astronomical data gathering, and in some respects the simplest.
- Although astronomy has expanded into many other wavelength realms and instrumental techniques optical imaging is still very important - many of the most important recent discoveries, such as dark energy, come from direct images in optical bands.
- This talk will introduce the subject and try to show some of the subtleties of the imaging process and the processing of images.
- I will mostly talk about direct imaging onto array detectors, such as CCDs and will be biased to Hubble Space Telescope and groundbased imaging. Mostly optical, but much also applies to near IR.
- I will NOT discuss “indirect imaging”, adaptive optics imaging or the measurement of images - photometry will be covered in detail in the next talks.
- Finally I will introduce the Scisoft software collection.