Photometry & Digital Images

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Scope of this talk

- Emphasis on principles, not prescription
- What is photometry?
  - Physical vs Referential measures & standardization
  - Differential vs systemic needs
- Digital data and what to be aware of
  - What observational material one needs
  - Image processing steps
- Aperture measures & optimizing SNR
- PSF fitting
  - Aperture corrections
  - When PSFs vary
  - Crowded fields
  - Remaining concerns
- Discussion restricted to point sources, but principles apply to all

Need for Photometry

- "Low" dispersion SEDs
  - Colors of objects -> Temp, gravity, abundance, redshift
- Relative Brightness of objects
  - CMDs, distance measurement, extinction, etc.
- Time variability of source brightness
  - Stellar masses, Distances, Pulsation, etc, etc.

Ideal vs Possible

Ideal would be to measure

f_ν in $\underline{\mathrm{erg\ cm^{-2}\ s^{-1}\ Hz^{-1}}}$

for a target of interest.

- but this is hard — not achieved till 1960's.

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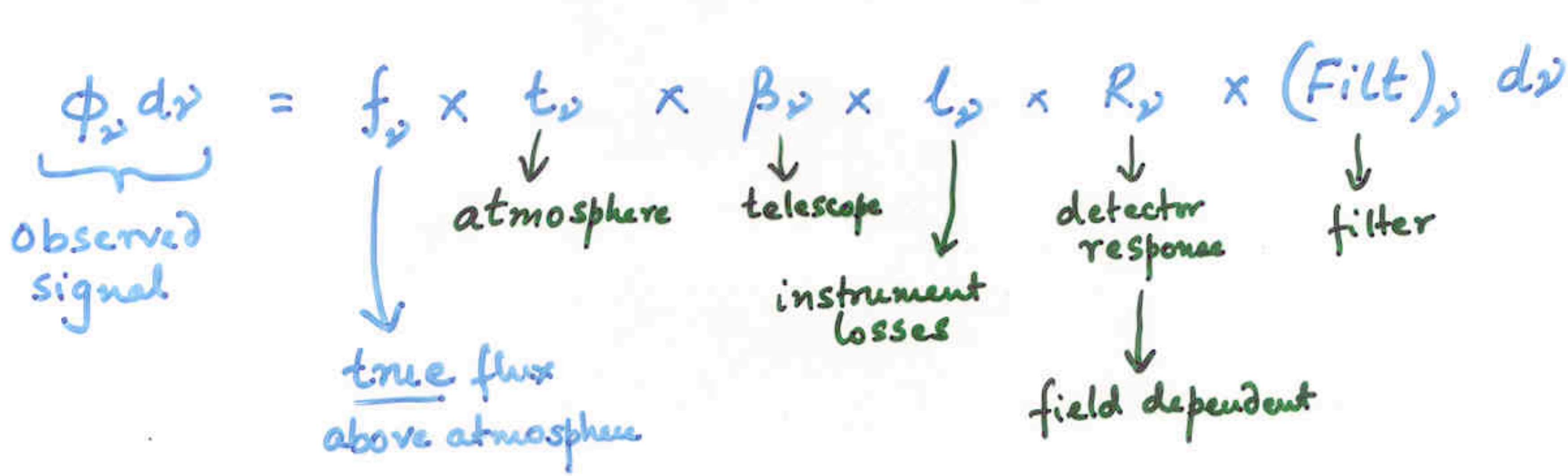
  SPECTROPHOTOMETRY

In practice — observe objects through filters.

— compare signal against that of 'standard' stars — and account for differences from atmospheric extinction and instrument response.

What is measured?



We measure a quantity which depends on extinction and effective bandpass:

A 'passband' is the integration over some 'filter'.

Signal $S' = \int \phi_\nu \, d\nu = S'(X)$

Measure constant objects at various X, and extrapolate to $X = 0$ to get S from S' } time variable?

Ensure stability of all other terms over observing session

Standardization

- Absolute standards
  - In physical units, e.g. ergs cm^{-2} s^{-1} Hz^{-1}
- Relative standards
  - In terms of a reference standard star (or `basket' of stars)
- Sources of Uncertainty
  - Transmission through atmosphere
  - System response: from top of telescope to response data
  - Time dependence in above

Common Formalism

- Measure standard stars at different airmasses X, and in different pass bands, B & V, say.

^

$$b = P + B + \alpha X + \beta(B-V) + \gamma(B-V)^2$$

$$v = Q + V + \zeta X + \eta(B-V) + \theta(B-V)^2$$

Solve coeffs, and apply to "unknowns"

(recall that these are magnitudes, or logs of intensity)

Why the `color terms' ?

Is linear dependence on X ok?

The Effects of System `Drift'

after atmosph. correction :-

$$\phi^{s}_{\nu} = \alpha^{s}_{\nu} f_{\nu} \quad \text{on standard defining system.}$$

Signal → $S^{s} = \int \alpha^{s}_{\nu} f_{\nu} \, d\nu$

for arbitrary setup, $\alpha_{\nu} \neq \alpha^{s}_{\nu}$!!

$$S = \int \alpha_{\nu} f_{\nu} \, d\nu$$

Write $\alpha_{\nu} = C_{\nu} \alpha^{s}_{\nu}$, and expand about central 'ν':

$$C_{\nu} = C_0 + C_1 (\nu - \nu_c) + C_2 (\nu - \nu_c)^2 + \ldots\ldots$$

$$S = C_0 \int \alpha^{s}_{\nu} f_{\nu} \, d\nu + C_1 \int \alpha^{s}_{\nu} (\nu - \nu_c) f_{\nu} \, d\nu + C_2 \int \alpha^{s}_{\nu} (\nu - \nu_c)^2 f_{\nu} \, d\nu + \ldots$$

in ⇓ mags

FUDGE

$$m' = A + m + B.\,\text{colour} + C.\,(\text{colour})^2$$

Other Music to Keep You Awake

- Device/System Linearity?
- CTE or lack there-of, and its effects
- Geometrical Projection of Sky on Detector
- Detector Noise Characteristics
- System Oddities – e.g. cross-talk
- Shutter Performance – timing errors, shading
- Vignetting
- Scattered light and mitigation
- Flat Fielding and Fringing
- ‘Pupil’ Ghosts

Pre-Processing Images

- Source Signal on detector is modulated by device response and artifacts, and accompanied by noise.
- Raw images must be processed to remove instrument signatures
  - Biases, flats (pixel to pixel variations), geometrical distortions, fixed patterns, dark current
- Noise should be tracked to enable:
  - Optimal data extraction
  - Estimate uncertainties
- Pre-processing steps (which mitigate systematic errors) can add random noise. Steps should be designed to add minimal noise.

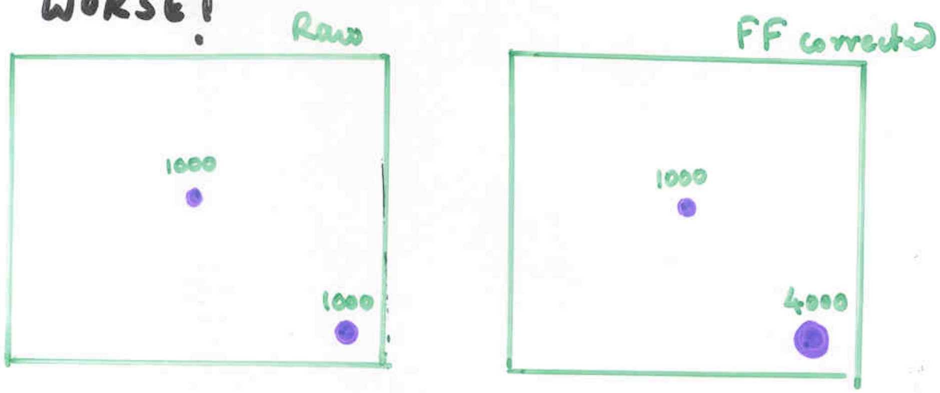
Flat fields

- Flat fields map pixel value to surface brightness on all image scales, iff FF source provides uniform illumination
- `Uniform Illumination' == Constant intensity integral at all relevant incident angles at telescope pupil. Hard to perfect in practice, for wide fields.
- Dome flats vs Sky Flats @twilight vs dark sky flats
- FF correction corrects for surface brightness: when there is geometrical distortion, they do not restore integrated fluxes!

Pixels in different locations of the field see different solid angle of sky.

For point source or stellar photometry,

FLAT FIELDS MAKE THE PROBLEM WORSE!



Consider a perfect detector, but where 1 pix = 1" x 1" in center, and 0.5" x 0.5" in corner.

A star placed at center gives 1000 e⁻ in 1 pix

Same star at corner gives 1000 e⁻ but in 4 pix.

Photometry that includes all the light is same in both locations.

But Flat Field "corrected" image will give 4x higher total counts at corner!

Mitigation for Point Source Photometry

Rectify Image so each pixel projects equal solid angle on sky by resampling.

OR

Apply a correction to image for pixel area, i.e. divide by respective pixel area.9 (useful when images are under-sampled)

0	0	0	0	0
0	2000	5000	2000	0
0	5000	10000	5000	0
0	2000	5000	2000	0
0	0	0	0	0

Perfect star image – no background, no readnoise

Total = 38000

$$S/N = \frac{38 \times 10^3}{\sqrt{38 \times 10^3}} \sim \boxed{200}$$

Noise from Poisson stats only. ….. (Case A)

Noise Domains

Case B (read noise dominated) e.g. 100 electron RDN in every pixel

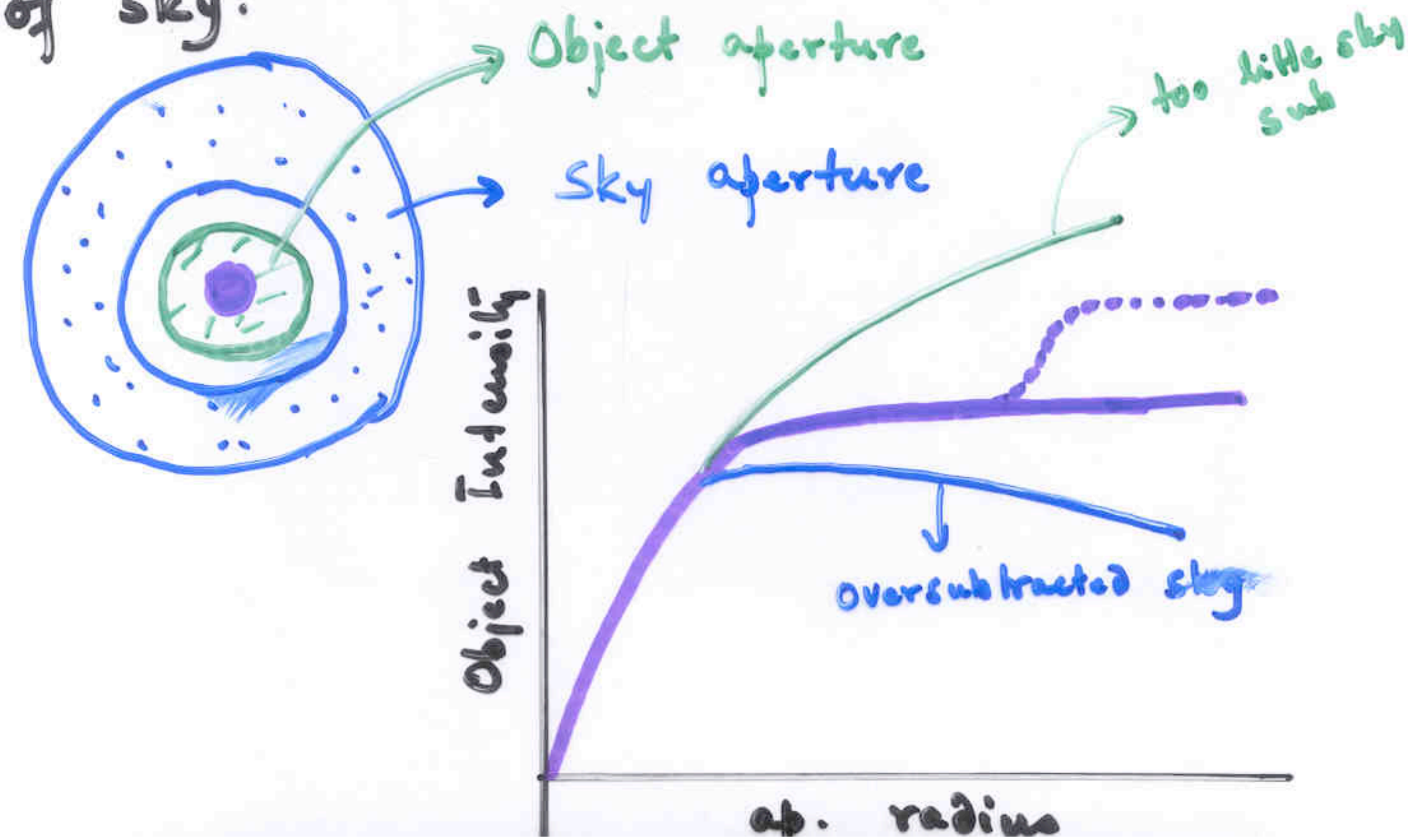
$$S/N = \frac{38 \times 10^3}{\sqrt{38 \times 10^3 + 9 \times 10^4}} \sim 100$$

Case C Background dominated: Add another 10^6 electron sky background in every pixel

$$S/N = \frac{38 \times 10^3}{\sqrt{38 \times 10^3 + 9 \times 10^4 + 10^6 \times 9}} \approx 12$$

If all the light were in 1 pixel, then Case B SNR ~175, and Case C SNR ~ 37 !!

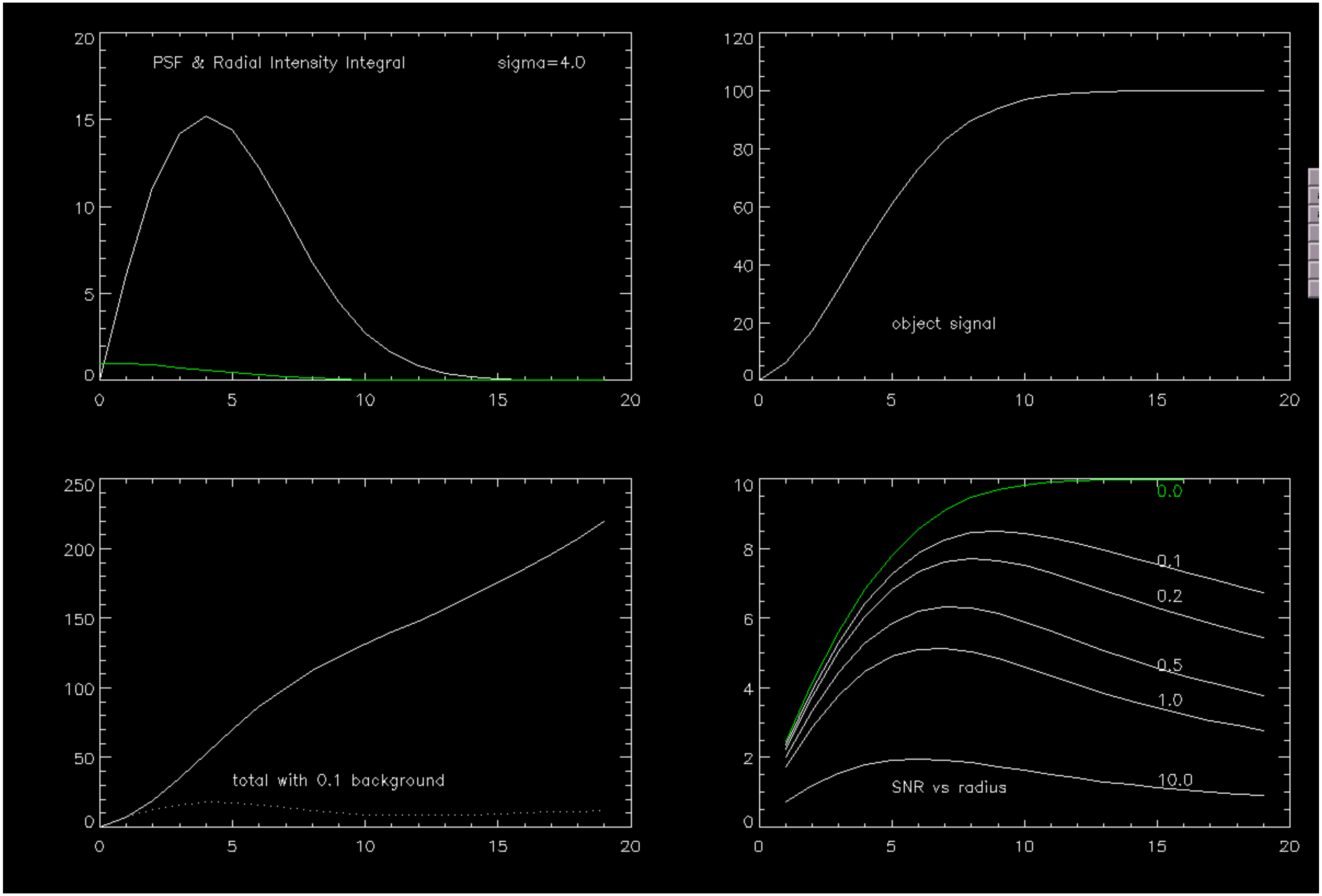
For isolated object — Sky or background estimated ~~by~~ from annular region. Mode of pixel values is the 'most probable' estimator of sky.



Need for `All the Light’

- Not all images have the same seeing – so need all the light to compare brightness in different exposures or even on same exposure if varying PSF.
- Bright stars are less vulnerable to total light
- Even total light needs surrogate in practice: PSF vs. scattered light wings
- But measuring `all the light’ is problematic for faint stars…..

Optimal S/N vs 'All' the light



Things to Consider

- PSF varies from exposure to exposure
- Total light goes to `infinity'
  - How to keep fraction measured const across all images? Or how large must the aperture be?
  - Seeing vs scattering
- Large apertures are bad for faint stars
  - Relative or differential photometry
  - Renormalize to large apertures (if PSF constant) using corrections derived from bright stars

PSF fitting

$$I(x,y) = I_0 f(x-x_0, y-y_0) + I_B(x,y)$$

↓

(PSF)

If $I_B(x,y) = I_B$ is flat over the extent of the PSF,

and

If f is known, and $I(x,y)$ are given, we can solve for

$$x_0, y_0, I_B, I_0$$

(linear in I_B, I_0 ; non-linear in x_0, y_0)

Characteristics of a PSF fit

- A PSF is a model derived from bright stars where SNR is not a concern
- A PSF fit is a maximum likelihood, or most probable characterization of a point source image, if fitting is done **conforming to SNR of individual pixels**: *I_0 is thus the best possible measure of a point source intensity in the sense of optimal S/N.*
- If PSF is constant across the image, then I_0 is best relative photometry on a given image
- Errors can be estimated from fit residuals

Error Estimation

If PSF is perfect, and all noise is Gaussian and = read noise ⊕ Photon noise

$$\frac{1}{S^2} = \sum \frac{1}{s^2}$$

in a weighted fit

For aperture measurement

$$S^2 = \sum s^2$$

Clearly weighted fit is a better estimate

Limitation is that PSF may not be perfect, and all deviations may not be Gaussian

If fit value at a pixel $= F_i$

where $F = I_0 f((x_i - x_0), (y_i - y_0)) + I_B$

$$\chi_\nu^2 = \left(\sum_{i=1}^{n} \frac{(I_i - F_i)^2}{\sigma_i^2} \right) \frac{1}{(n-1)}$$

If Chi-square I unexplainably high, then it may indicate that adopted model is not correct. Non-stellar object?

A basis for classification based on image morphology

Is model for CR better than for point source?

Is model for "galaxy" better than either?

Is 2-star model best?

etc.

The 'Aperture Correction'

- PSF fitted I_0, does not represent all of the light, and so cannot be compared across images unless:
  - I_0 is used in with integral of $f(x\text{-}x_0, y\text{-}y_0)$
    - *Meaningful only if PSF is known exactly*
      - *Not straightforward in practice*
  - I_0 is used with a surrogate footprint in lieu of the integral of $f(x\text{-}x_0, y\text{-}y_0)$,

AND

the result is normalized to the true total intensity via objects with high SNR, i.e. the aperture correction.

Points to ponder:

- What if PSF used is not a perfect match to true PSF?
- What if PSF is not constant across the image?
- How best to determine I_B ?
- What if I_B is not flat across PSF area ? The crowded field problem
- What if positions x_0 , y_0 are independently known?
- Note that pixels are treated as independent – are pixel values really uncorrelated?

Imperfect PSF

- Imperfections in models PSF wrt real one generates `extra' residuals in fit
  - To zeroth order:
    - making same error on all objects
    - degrades fit quality, and overestimates errors
    - poor `subtraction' of fitted objects – affects crowded field photometry
  - Subtler issues:
    - Since S/N vs r is function of brightness, can induce non-linearities with brightness, but seen to work fine in practice unless mis-match is quite severe.

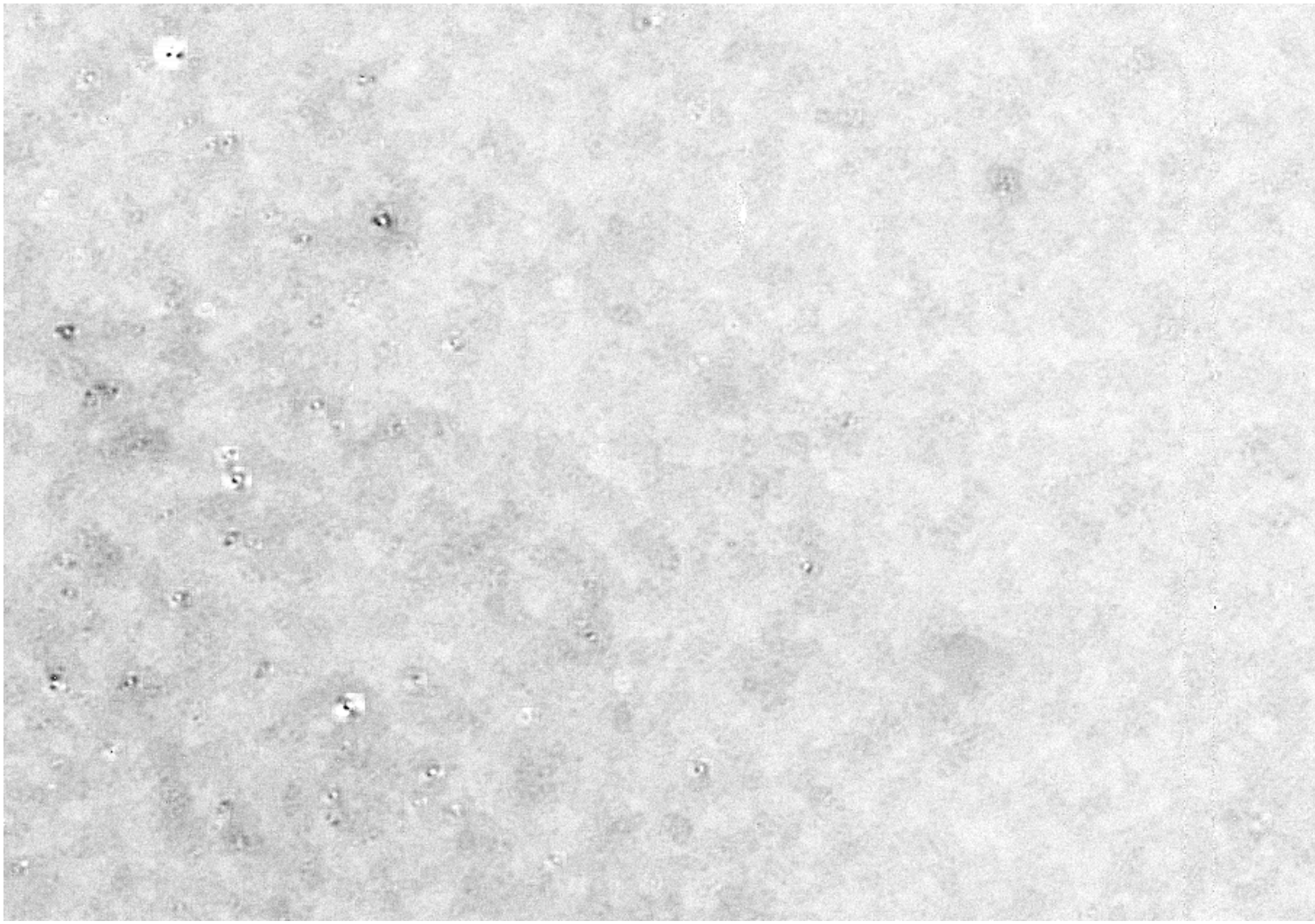
PSF not constant across image

- Can happen in practice, e.g.:
  - especially in wide field imagers, due to field-flattening errors
  - in adaptive optics, due to scale of iso-planatic patches
- Key to mitigation is that \`aperture' integrated brightness should not vary, so
  - map aperture correction as function of position on FOV
    - Easier for wide field imagers than for AO, because method hinges on availability of high SNR objects

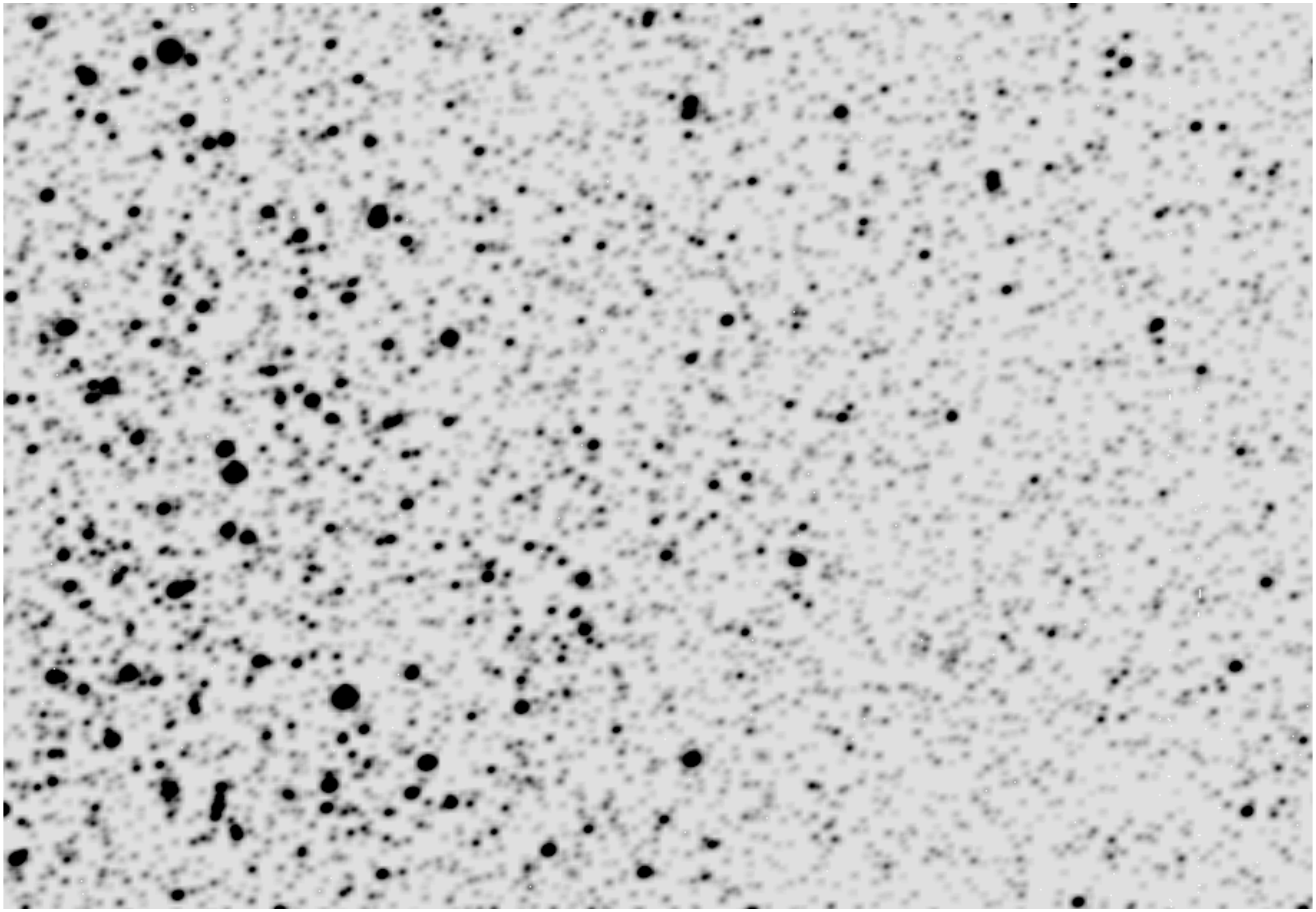
Crowded Fields

- I_B under object A is affected by PSF of neighboring object B. B affected by C, etc. & so on.
- I_B is not constant under PSF
- Mitigation strategies:
  - DAOPHOT way: cluster fit all objects with chain of influence
  - DoPHOT way: iteratively fit objects – brighter ones first

IC1613 (C-band) Image vs Residual



IC1613 (C-band) Image vs Model



Pre-known Positions Fixed

$$I(x,y) = I_0 f(x\text{-}x_0 , y\text{-}y_0) + I_B(x,y)$$

↓

(PSF)

- If x_0 and y_0 are somehow known, then the PSF fit is linear
  - *Faster, easier, and smaller correlations in params.*

Observing Procedures

1. Choosing the right gain

   Noise (sampling) vs. dynamic range

2. Observing bright standards

   problem of short exposures – shutter shading and scintillation

3. Spatial Dithering – getting rid of cosmetic flaws and CRs.

4. Flat fields in Broad Band filters – spectral variation.

5. Making the best of a cloudy night

Making Friends With Your Equipment

Know the following:

Gain (e^-/ADU) – what to choose?

Read noise (other sources?)

Dark Current

Shutter timing – shading

Linearity (light transfer test)

Point Source Transfer characteristics – fat zero

" " – isotropy

Cosmetic Defects

Field Obstructions — vignetting

Scattered Light — baffling

Total throughput – (how many ADU/sec at m_0)

Filter Transmission – Choice of filters

focus offsets between filters

How good are your flat-fields?

Fringe Correction needed?

Geometrical mapping – corrections needed?

Saturation behaviour of the CCDs.

DON'T PANIC, but hold on to towel!

1. Observe standards
   – OFTEN
   – Cover range of colors and airmasses
2. Get adequate flat fields (and fringe frames) so as not to add noise
3. Check Sky conditions
   – OFTEN
   – Watch for con-trails
4. Get bias frames throughout the night
5. Make use of cloudy/shut time
   – Verify shutter corrections
   – Verify linearity