Systematic Trends in Sloan Digital Sky Survey Photometric Data

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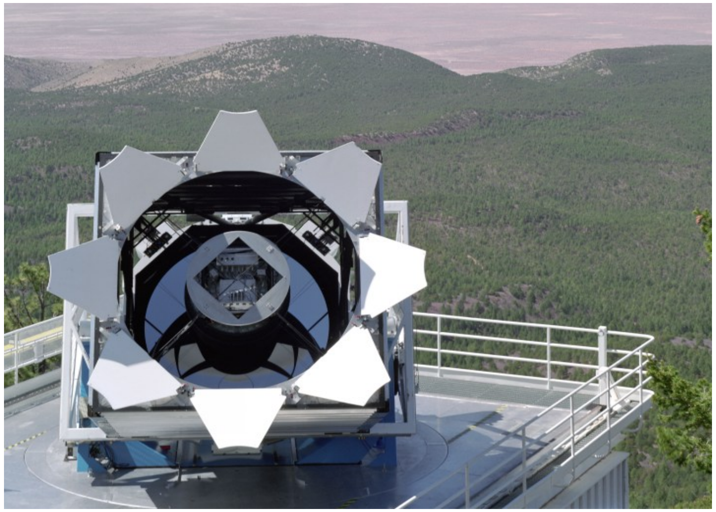
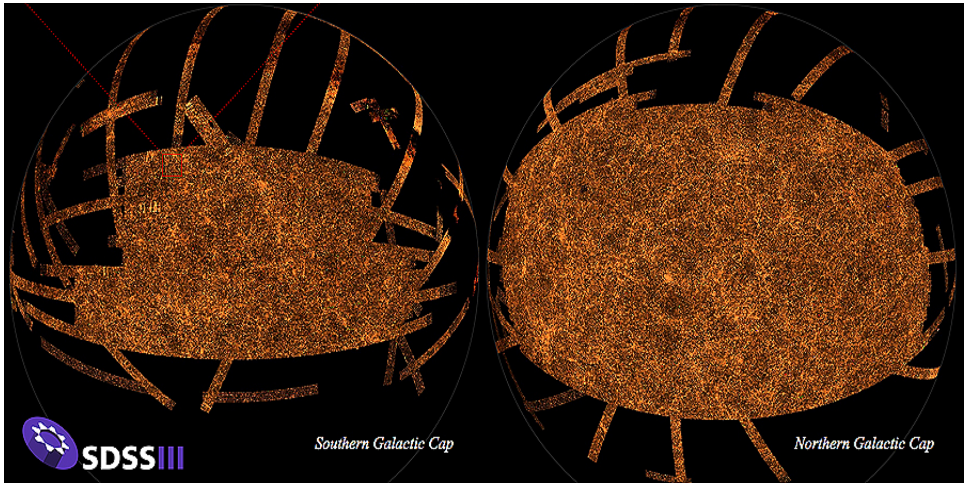
Sloan Digital Sky Survey (SDSS)

Data Release 8:

- Covers 14555 deg^2 (Aihara et al. 2011)
- Photometry in *ugriz* down to 22.5 mag
- Aperture and PSF magnitudes (among others)

Padmanabhan et al. 2008 performed a relative photometric calibration that reaches ~1% for *griz* and ~2% for *u*





Padmanabhan Calibration:

Fitted a single photometric model including terms for:

- Nightly extinction and detector relative zero-points

- Flat field correction vectors (drift-scan) for each "season" between maintenances.

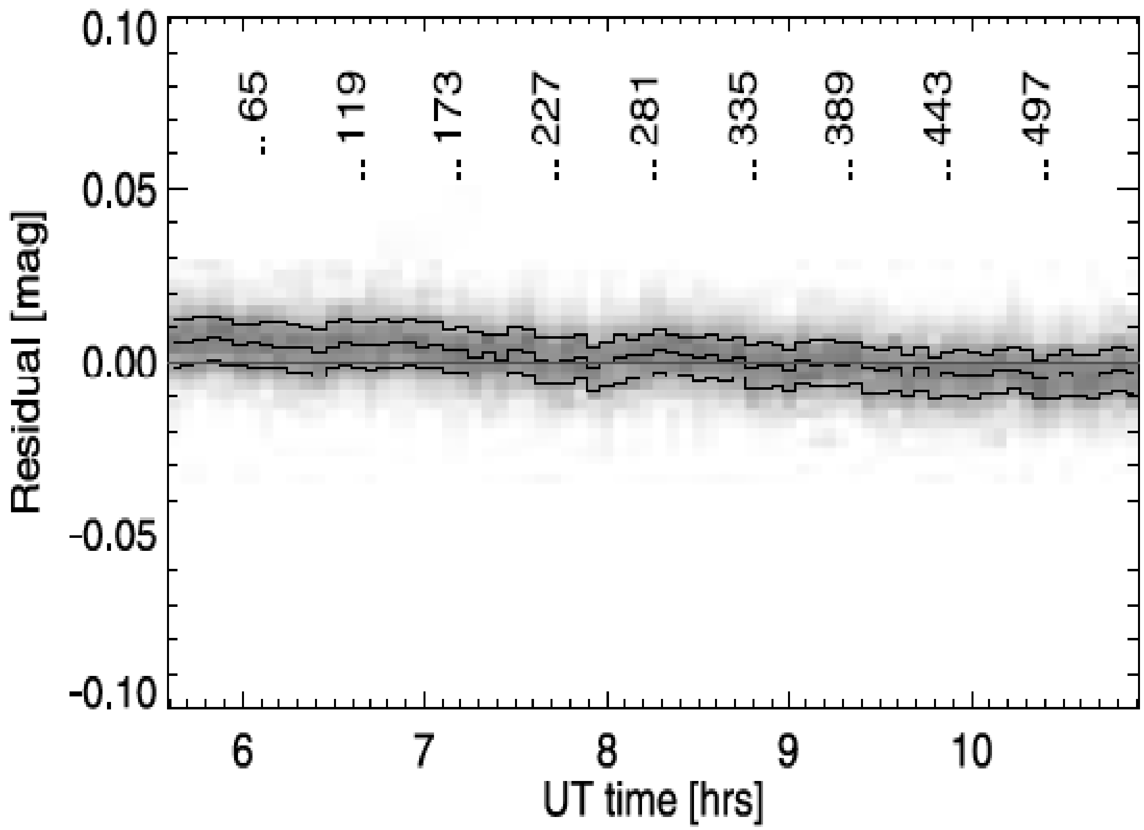
Key point: Relative calibration

Looked at the calibration residuals as a function of:

- Star brightness
- Detector column (for flat field accuracy)
- Celestial coordinates
- Time

Padmanabhan Calibration:

However they noted clear trends as a function of time, manifesting as “coherent errors at the few millimagnitude level”. Figure 9 from their paper:



CAN WE IMPROVE ON THIS?

COULD THESE TRENDS BE FURTHER CALIBRATED OUT?

PROBLEM:

- We don't know *a priori* what trends need modelling *or* what form they take.

Photometric Model:

$$\overline{m}_i = \sum_{p=1}^{N_{\rm obj}} \delta_{jp} M_p + \sum_{p=1}^{N_z} \delta_{kp} Z_p = M_j + Z_k$$

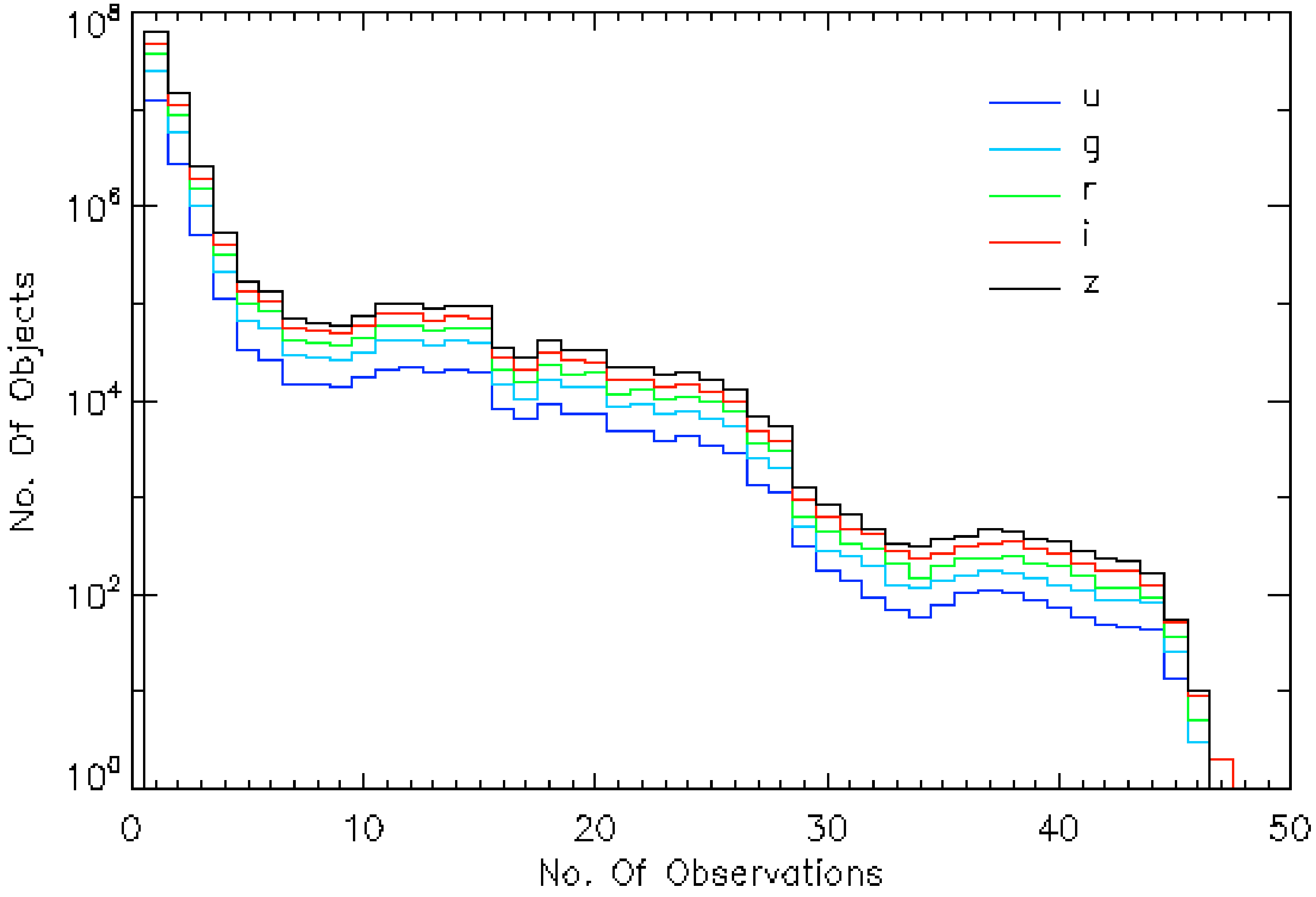
m_i = Model magnitude for *ith* magnitude measurement

M_j = Unknown true instrumental magnitude for *jth* object

Z_k = Magnitude offset for *kth* bin in a quantity X we are interested in probing.

- Construct the normal equations for solving this linear least squares problem for ***REPEAT OBSERVATIONS***.
- Becomes intractable to solve in one step when there are more than a couple of thousand objects........

Repeat Observations:



Normal Equations:

SPECIAL FORM:

$$\begin{pmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B}^T & \mathbf{D} \end{pmatrix} \begin{pmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{pmatrix} = \begin{pmatrix} \mathbf{v}_1 \\ \mathbf{v}_2 \end{pmatrix}$$

<=>

$$\begin{aligned}
A_{pq} &= \sum_{i=1}^{N_{\text{data}}} \delta_{jp}\, \delta_{jq} \,/\, \sigma_i^2 \\
B_{pq} &= \sum_{i=1}^{N_{\text{data}}} \delta_{jp}\, \delta_{kq} \,/\, \sigma_i^2 \\
D_{pq} &= \sum_{i=1}^{N_{\text{data}}} \delta_{kp}\, \delta_{kq} \,/\, \sigma_i^2 \\
v_{1,p} &= \sum_{i=1}^{N_{\text{data}}} \delta_{jp}\, m_i \,/\, \sigma_i^2 \\
v_{2,p} &= \sum_{i=1}^{N_{\text{data}}} \delta_{kp}\, m_i \,/\, \sigma_i^2
\end{aligned}$$

- Symmetric positive-definite
- A,D diagonal (A is diagonal spotted by Regnault et al. 2009)
- B is sparse when few measurements per object

$$\left(\mathbf{D} - \mathbf{B}^T \mathbf{A}^{-1} \mathbf{B}\right) \mathbf{x}_2 = \mathbf{v}_2 - \mathbf{B}^T \mathbf{A}^{-1} \mathbf{v}_1$$

Solve with Cholesky factorisation and forward and back-substitution

If you want the true instrumental magnitudes:

$$\mathbf{x}_1 = \mathbf{A}^{-1} \mathbf{v}_1 - \mathbf{A}^{-1} \mathbf{B} \mathbf{x}_2$$

Covariance on zero-point offsets:

$$\mathbf{C} = \left(\mathbf{D} - \mathbf{B}^T \mathbf{A}^{-1} \mathbf{B}\right)^{-1}$$

Application To SDSS:

Considering each of the 30 CCDs independently:

- Down to 19 mag there are ~3,5,8,10,13 million objects in ugriz, and ~4,8,12,15,20 million measurements.
- Our implementation takes a few minutes to solve for each CCD.
- We only iterate to reject variable stars.

What Did We Investigate?

Aperture Magnitudes:

- Trends as a function of:

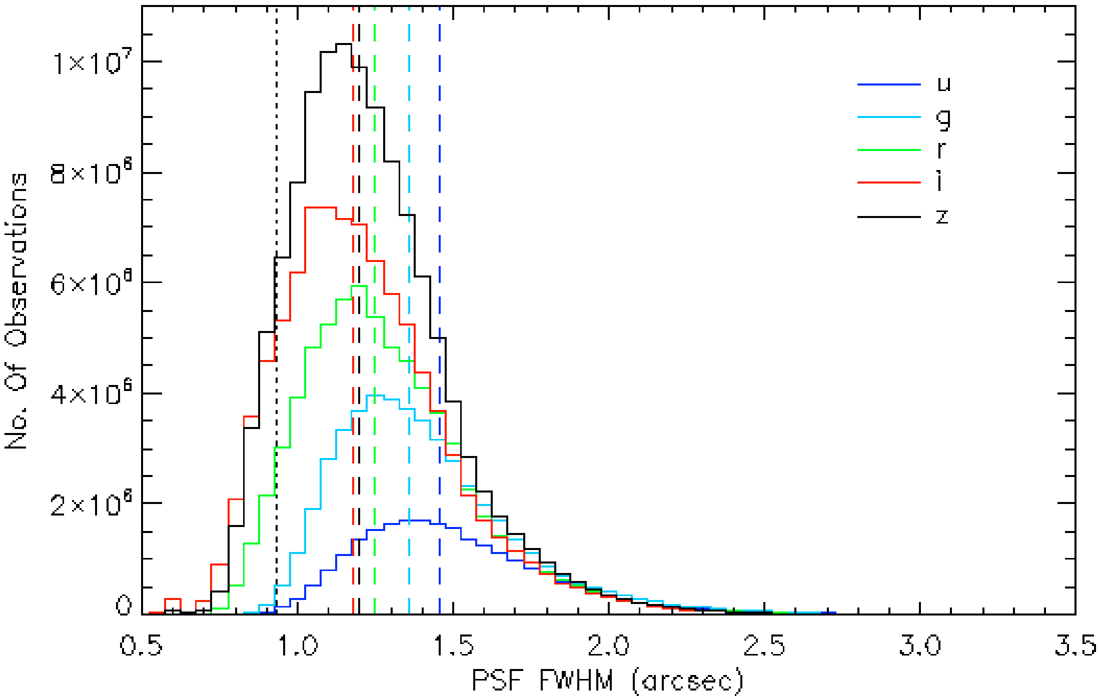
(i) Detector row

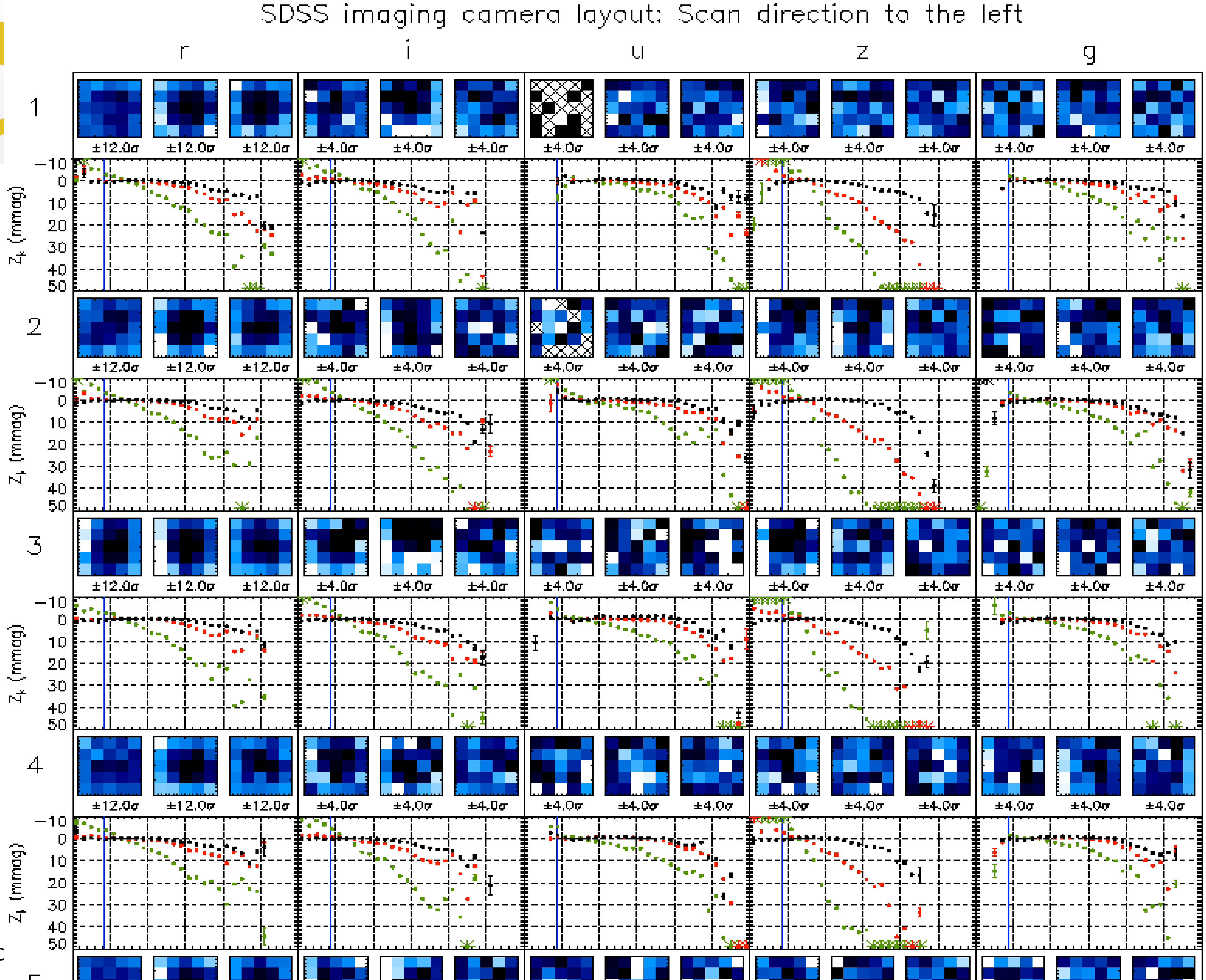
(ii) Detector column

(iii) PSF FWHM

(iv) Subpixel coordinates

[Cannot investigate trends as a function of brightness]




SDSS imaging camera layout: Scan direction to the left
r
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±12.0σ
±4.0σ
z_k (mmag)
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0
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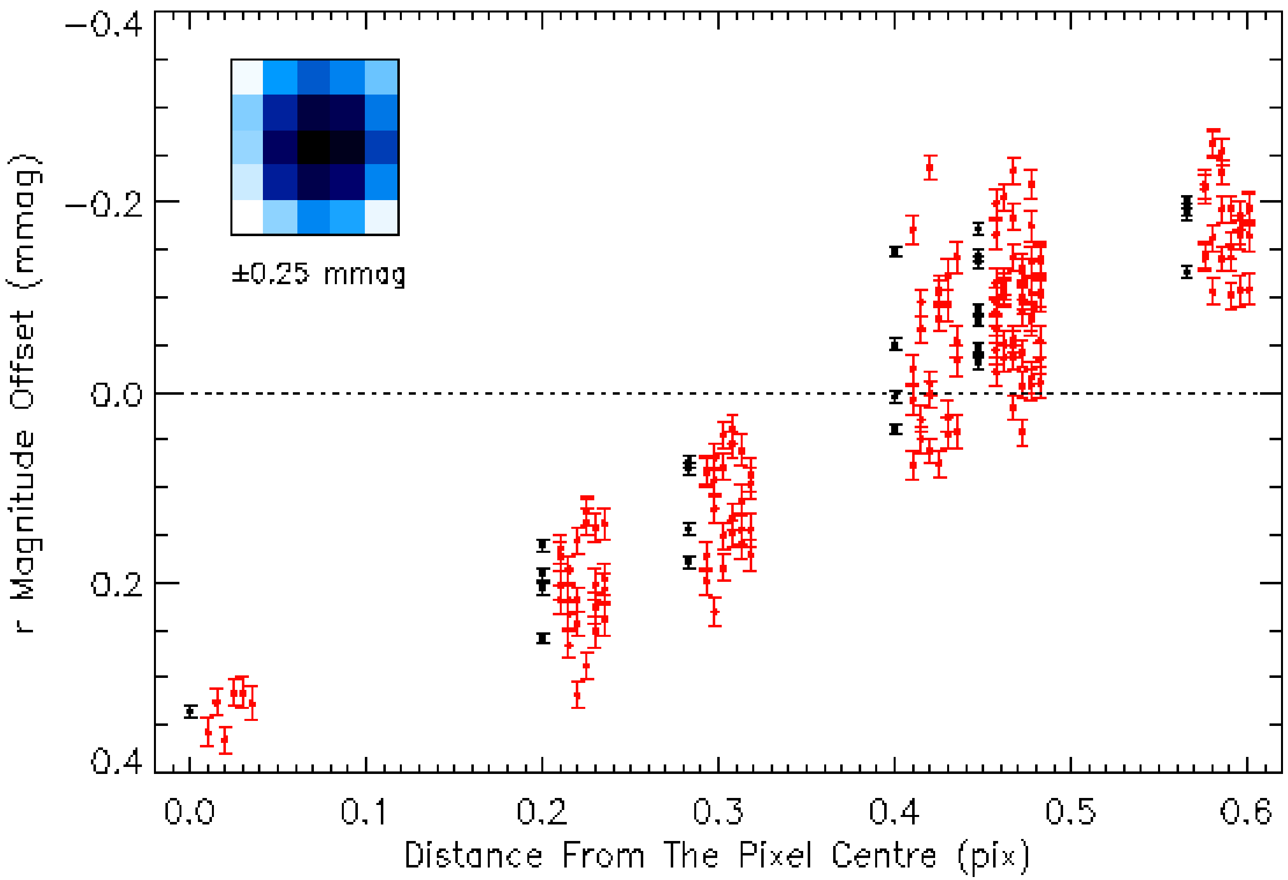
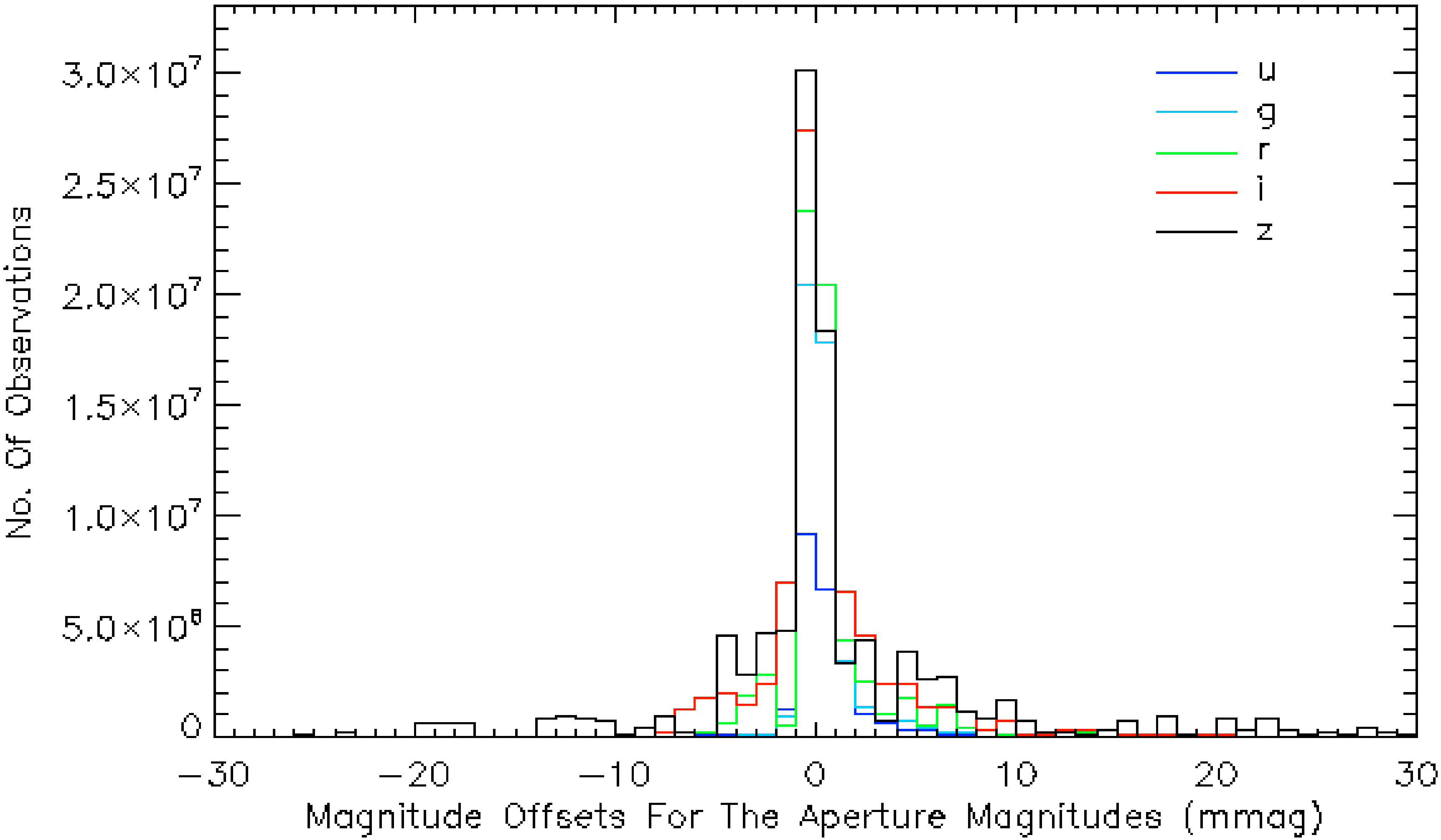
30
40
50
AD

Aperture Magnitudes:

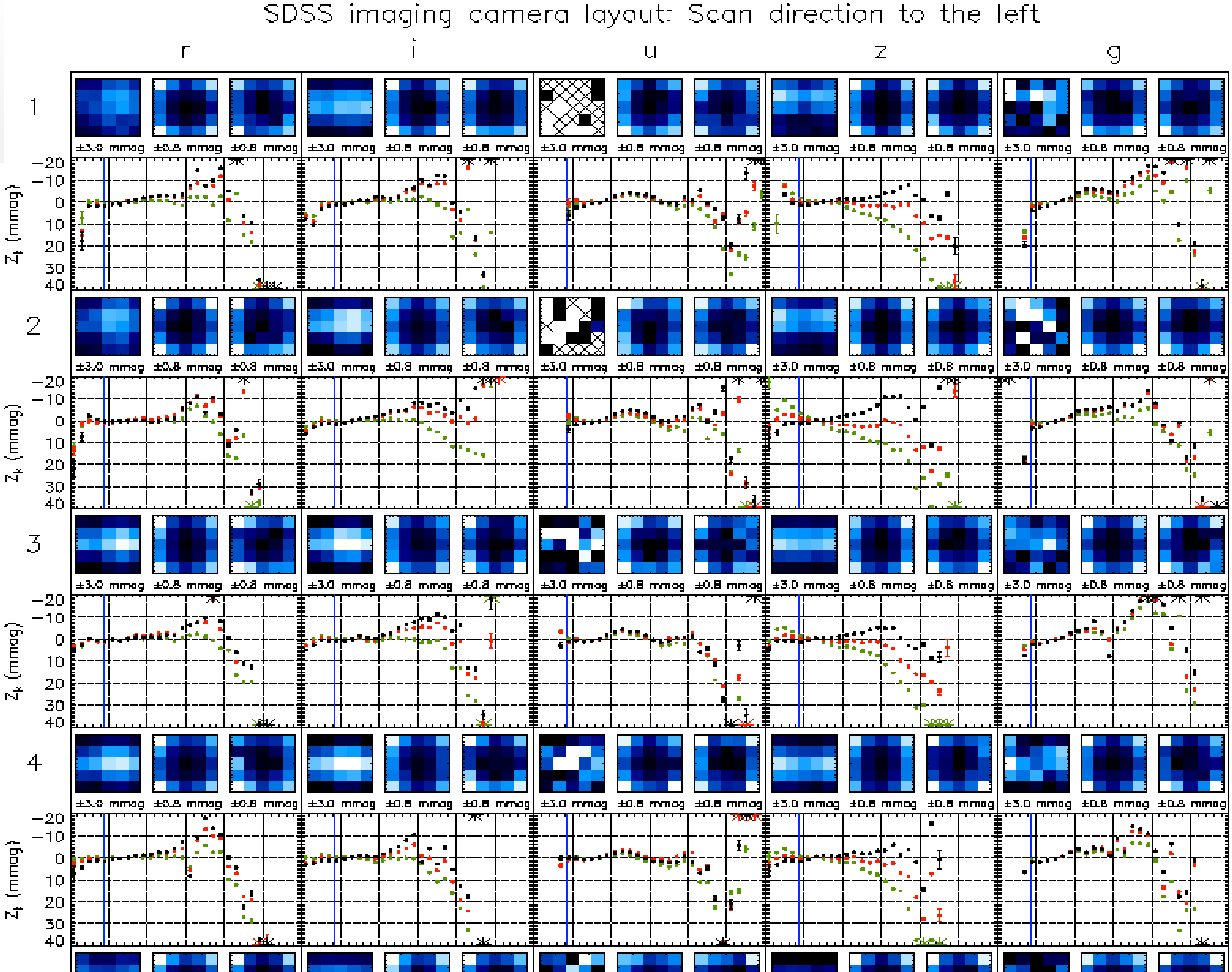


Aperture Magnitudes:



Aperture Magnitudes:

- Systematic trend as a function of PSF FWHM that is of amplitude 7-15 mmag for the brightest objects and 30-170 mmag for the faintest objects (worst in *z* band). Possible sky over-subtraction problem?
- Low-amplitude 0.54 mmag systematic trend as a function of subpixel coordinates for *r* waveband.
- Why is this important? Because the SDSS photometric calibration is *derived* from the aperture magnitudes and *applied* to all other magnitudes!


SDSS imaging camera layout: Scan direction to the left
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±3.0 mmag
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z_t (mmag)
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-10
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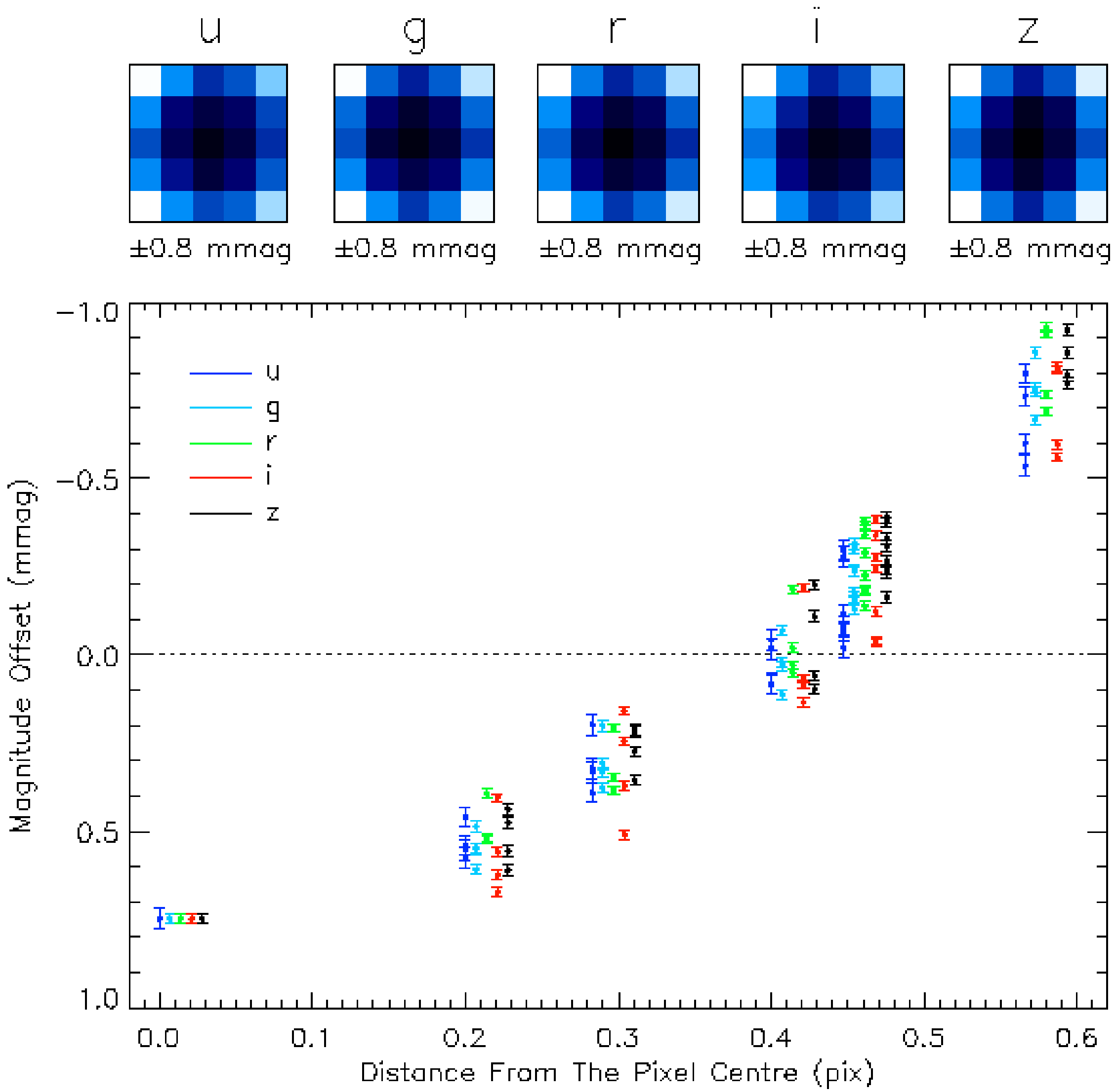
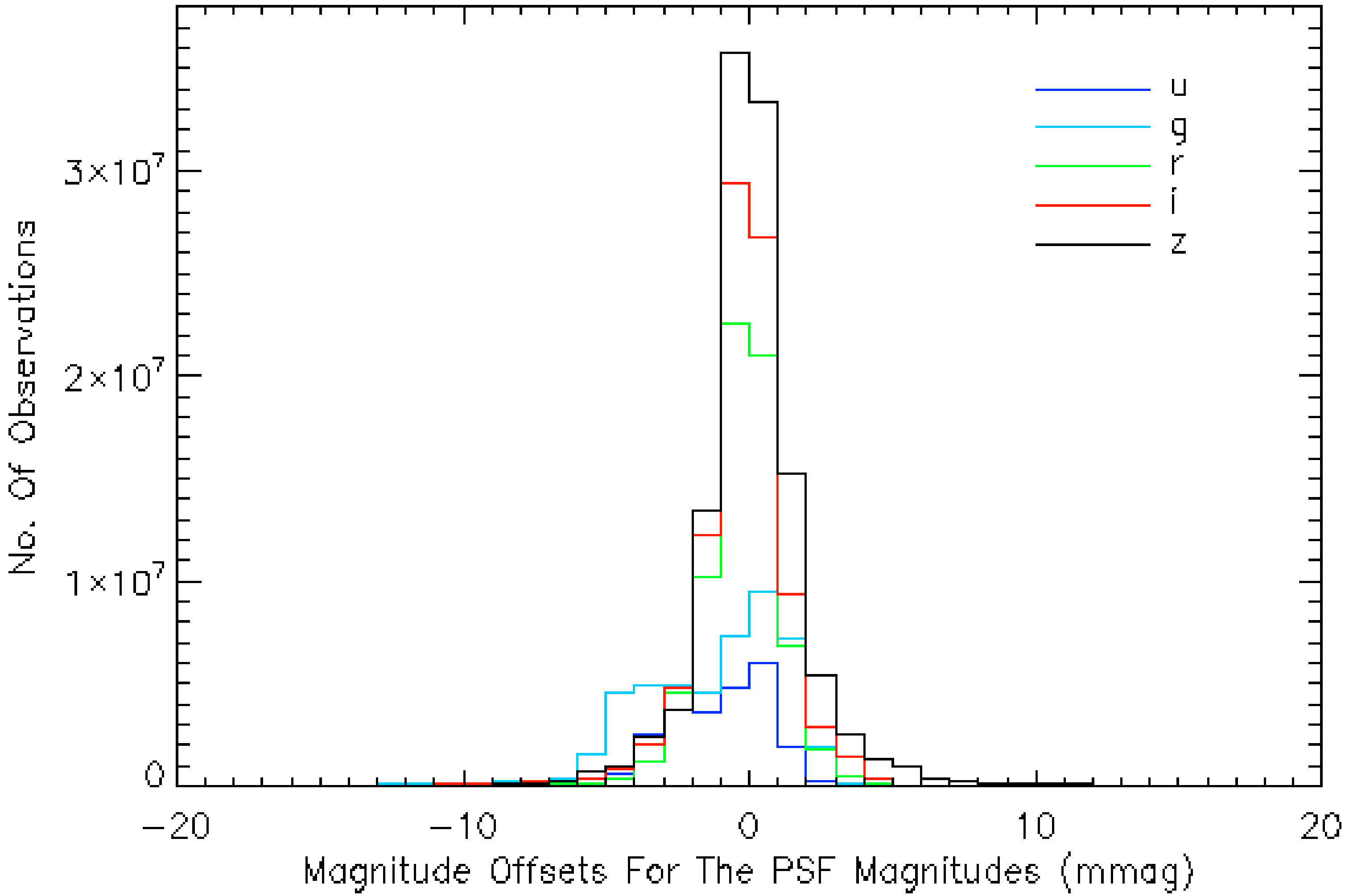
10
20
30
40

PSF Magnitudes:



PSF Magnitudes:



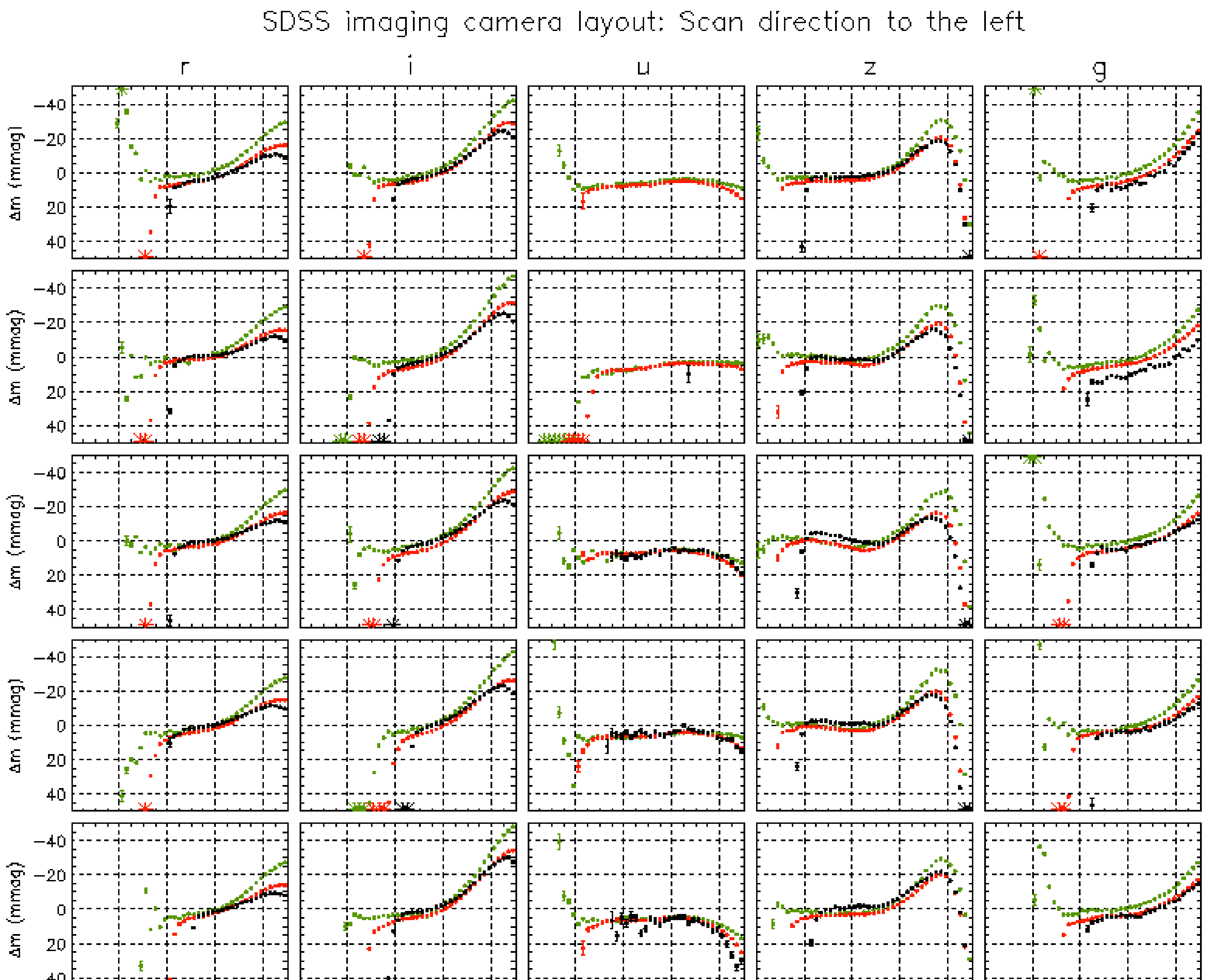
PSF Magnitudes:

- Complicated (wavy) systematic trends as a function of PSF FWHM that is of amplitude ~10-20 mmag for seeing better than 2.5”, and ~20-50 mmag for seeing worse than 2.5”.
- *Software introduced* systematic trends as a function of subpixel coordinates. Amplitudes of ~4-7 mmag for less than critical sampling and ~1.6 mmag for greater than critical sampling.

Aperture And PSF Magnitudes:

- The SDSS photometric calibration is derived from the aperture magnitudes and applied to the PSF magnitudes.
- This procedure is valid if both magnitude scales are related by a simple offset.
- The investigation of how these magnitude scales compare was not investigated by Padmanabhan et al. 2008.

Now we can use the full SDSS data base since we are not restricted to repeat observations. Simply calculate the difference between the aperture and PSF magnitudes as a function of object brightness.


SDSS imaging camera layout: Scan direction to the left
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Δm (mmag)
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AD

Conclusions:

- We have found significant systematic trends in SDSS aperture and PSF magnitudes at the level of the ~1-2% quoted precision of the survey calibration.
- In other words, there is still *room for improvement*.
- Systematic trends as a function of image properties like PSF FWHM, subpixel coordinates, etc. are always worth investigating.
- We detected a ~1-4% non-linearity between the aperture and PSF magnitude scales.
- Important results because SDSS is used to calibrate other surveys.
- We supply a program to correct SDSS photometry using our fitted offsets.
- We have developed a powerful photometric calibration program.