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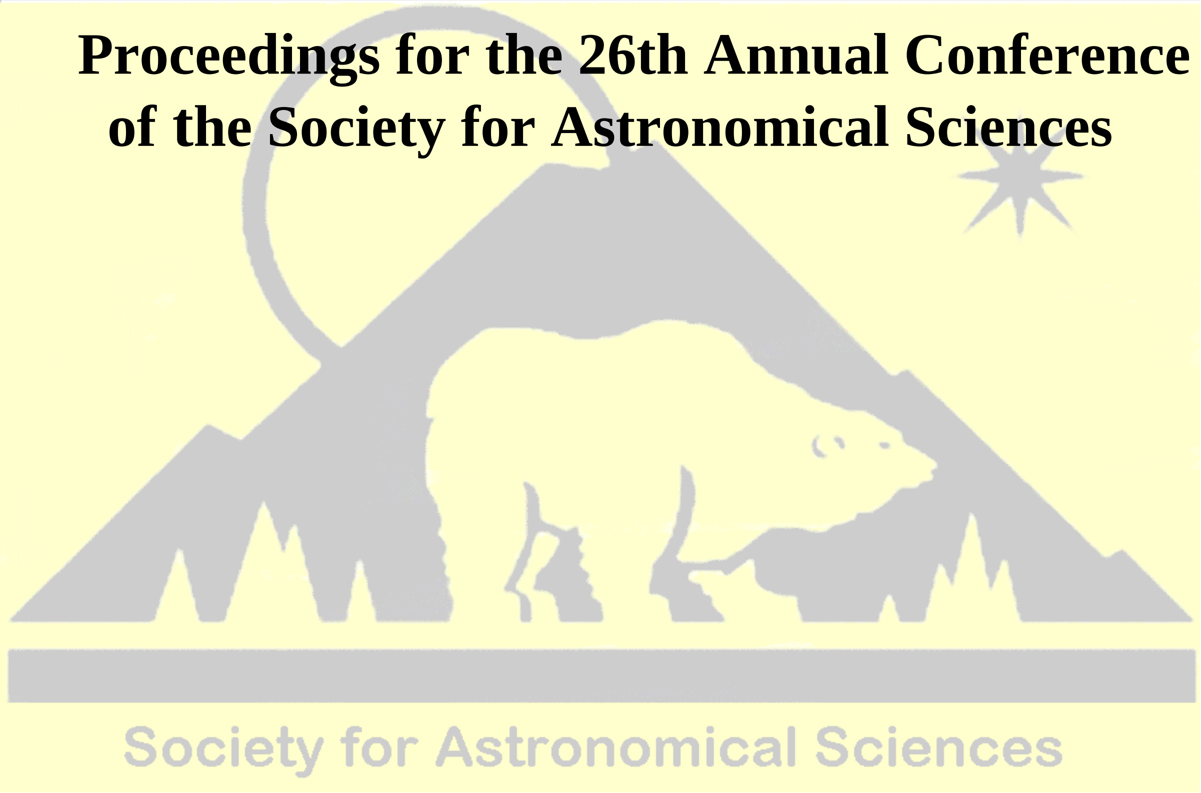

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Photometry With DSLR Cameras

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Abstract

The emergence of DSLR cameras as cost effective astro-imaging tools prompts the author to investigate the use of DSLR cameras in making photometric measurements. The quantum efficiency, dynamic range, linearity and transformation to the standard system are explored. Observational and processing techniques unique to use of DSLRs in quantitative observation are presented. Suitability for particular observing programs is discussed.

1. Introduction

Digital single lens reflex (DSLR) cameras with high pixel counts have become the staple of professional photographers within the last five years. Entry level versions of the latest generation of these cameras are priced below $800 and offer pixel counts of 8 to 10 mega-pixels. Astro-photographs made with DSLRs appearing in popular astronomy periodicals amply demonstrate the capability of these cameras to produce excellent images. Since these cameras employ solid state CMOS or CCD photo detectors, it appeared to the author that DSLRs might be a cost effective alternative to CCD cameras for quantitative work in photometry and astrometry.

This paper presents an analysis of the DSLR camera design, implementation as it pertains to use of the camera in scientific study and presents the results of photometry performed on standard star fields and the transformation of those results onto Johnson-Cousins standard.

2. Unique and Important Characteristics

Consumer DSLRs share two of the key traits of CCD science cameras: They have linear response over a large portion of their range and they are readout digitally, presenting an image representation amenable to quantitative analysis. They also share the less desirable trait of producing electrons in response to thermal excitation of the detector in addition to captured photons.

They differ from scientific CCD cameras in several key respects. Firstly, the cameras are not hermetically sealed and operate at ambient temperatures. The combination of properties leads to the requirement that frequent dark and bias frames must be taken to accurately calibrate images.

The active portion of these sensors is typically smaller than scientific camera. Typical pixel size range from 4.0um to 6.5um. These sensors are typically covered with micro-lenses to improve the quantum efficiency (QE) of the devices. Even so, their normal quantum efficiencies are lower than science cameras. The other consequence of the small pixel sized in these cameras is that the total captured charge capacity of DSLRs is significantly smaller than scientific cameras.

The detectors of DSLRs are universally equipped with “anti-blooming” gates. Anti-blooming limits the charge that can be accumulated by any pixel in the detector by providing a contact to the pixel pulsed with a lower electric potential than the full well potential of the cell. This causes excess current to flow out of the pixel before it spills into adjacent pixels. While this prevents unpleasant aesthetics in photographs, it leads to non-linear response of the detector as the well potential approaches the anti-blooming potential.

R	G	R	G	R	G
G	B	G	B	G	B
R	G	R	G	R	G
G	B	G	B	G	B
R	G	R	G	R	G
G	B	G	B	G	B

Figure 1: Typical Bayer Mosaic Pattern (R=red, G=green, B=blue)

The most striking difference between DSLRs and purpose built science cameras is that DSLRs have filters epitaxially deposited directly on the detector in a “Bayer” pattern. The standard pattern for filter coatings are shown in Figure 1. The presence of filters on the detector is the most significant architectural difference between DSLRs and science cameras. Their presence motivates most of differences in observation techniques discussed below.

If the color filters have pass bands similar to photometric standard filters, then the DSLR is a turnkey multi-color photometric machine.

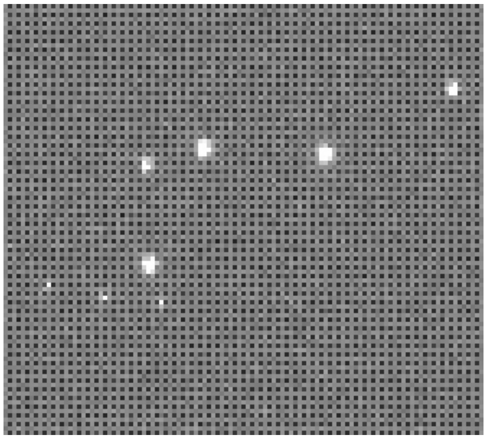


Figure 2: Raw image from Bayer filter mosaic

There are a couple of other characteristics of DSLRs that, while not unique, merit consideration in using the cameras. First, the micro lenses on the detector cause the QE of the camera to vary with the f-Ratio of the optical system to which it is attached. Slower optical systems, beyond about f7, will display lower QE than faster optical systems because the micro lenses are not strong enough to bend all of the shallower light cone into the active portion of the detector pixel.

The other consideration is that larger detectors demand better optical systems. System that performed well with smaller CCDs may display significant field curvature and vignetting when used with larger detectors.

3. Operational Considerations

Using a DSLR for photometric observation is similar to using a standard scientific CCD with the following key exception. DSLR observations are almost always made by taking a multiple sequence of short exposures and combining them. There are a number of reasons for this approach. Primarily, the smaller dynamic range and higher thermal electric response effectively limit exposure times in order to keep the objects of interest within the linear range of the detector. Additionally, depending on the color you are sampling, only one in four, or two in four pixels on each image is of a given color. You want the seeing and tracking errors of many images to “drizzle” together into normal point spread function (PSF).

On the positive side, DSLRs are completely self-contained. No computer or electronics more complicated than an electronic cable release are required for making observation. After working with progressively more complicated software, cabling, cooling, and filter wheels, this is a refreshing change. If you are planning an extended session, extra memory cards and batteries, or an external power supply will be required.

When making exposures with DSLRs, all data should be stored in the camera’s RAW/Uncompressed mode. The default for DSLRs is typically JPEG, an encoding system that discards information to achieve higher compression rates. Even TIF and other lossless encodings may apply non-linear contrast stretch, and noise suppression that discards portions of the image data.

4. DSLR Performance

DSLR cameras offer an extraordinary value in many respects. Because they are produced for the mass markets, manufacturers can, and do, spend phenomenal amount of money on design, development and custom tooling that boutique science camera makers simply cannot afford. The resulting performance numbers support this observation. Figure 3 provides comparison of quantum efficiencies between DSLR cameras and other available cameras.

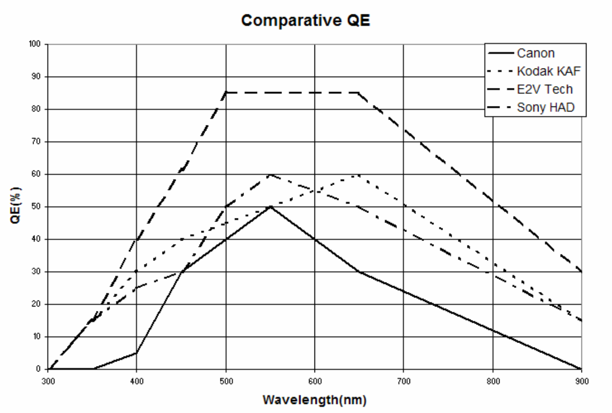
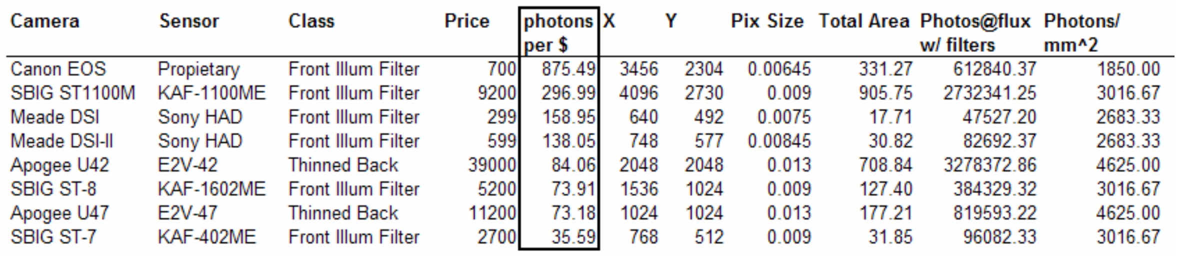


Figure 3: Relative Quantum Efficiencies

These curves show that while the QE of DSLRs falls below other cameras, the QE is still good enough to prove useful. Note that these figures are based on removing the manufacturer’s supplied IR blocking filter. On all commercial cameras, except



Camera	Sensor	Class	Price	photons per $	X	Y	Pix Size	Total Area	Photos@flux w/ filters	Photons/ mm^2
Canon EOS	Propietary	Front Illum Filter	700	875.49	3456	2304	0.00645	331.27	612840.37	1850.00
SBIG ST1100M	KAF-1100ME	Front Illum Filter	9200	296.99	4096	2730	0.009	905.75	2732341.25	3016.67
Meade DSI	Sony HAD	Front Illum Filter	299	158.95	640	492	0.0075	17.71	47527.20	2683.33
Meade DSI-II	Sony HAD	Front Illum Filter	599	138.05	748	577	0.00845	30.82	82692.37	2683.33
Apogee U42	E2V-42	Thinned Back	39000	84.06	2048	2048	0.013	708.84	3278372.86	4625.00
SBIG ST-8	KAF-1602ME	Front Illum Filter	5200	73.91	1536	1024	0.009	127.40	384329.32	3016.67
Apogee U47	E2V-47	Thinned Back	11200	73.18	1024	1024	0.013	177.21	819593.22	4625.00
SBIG ST-7	KAF-402ME	Front Illum Filter	2700	35.59	768	512	0.009	31.85	96082.33	3016.67

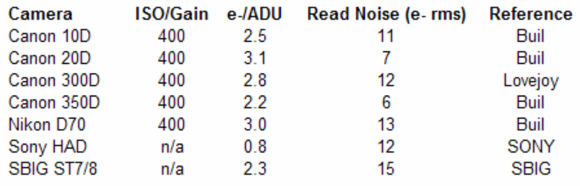
Table 1: Camera effectiveness expressed in Photons/Dollars/Second

the Canon D20a, the manufacturer’s filter has a cutoff point that excludes Hydrogen Alpha emissions.

Clearly, these QE numbers show that if you are looking for a detector to operate at the edge of delectability for your optics, a DSLR is not your choice, but for many other programs, it may be adequate. The real figure of merit for a DSLR camera is Photons/Dollar/Second. If you use this metric to evaluate cameras, the DLSR is hard to beat.

Table 1 shows the analysis of DSLRs vs. a variety of science cameras with filters using the Photons/Dollars/Second metric. It assumes a uniform flux (photons/nm) falling on the detector. Using this metric, you can see that the large detector area coupled with its lower cost propels the DSLR to the top of the list. Even for projects that need to work out at dim magnitudes, the price difference between a large back illuminated detector and DSLR might be more profitably spent on larger optics, at least up to 20” glass.

Another figure of merit for cameras where DSLRs shine is Signal to Noise Ratios (SNR). QE is worthless unless the noise is low enough to make the SNR of the camera superior. Table 2 shows a comparison of readout noise and gain for a variety of cameras. The DSLRs all display very low read noise values.



Camera	ISO/Gain	e-/ADU	Read Noise (e- rms)	Reference
Canon 10D	400	2.5	11	Buil
Canon 20D	400	3.1	7	Buil
Canon 300D	400	2.8	12	Lovejoy
Canon 350D	400	2.2	6	Buil
Nikon D70	400	3.0	13	Buil
Sony HAD	n/a	0.8	12	SONY
SBIG ST7/8	n/a	2.3	15	SBIG

Table 2: DSLR Read Noise Comparison

5. Photometry Performance Tests

The analysis above indicates that DSLRs have excellent potential to perform quantitative photometric and astrometric observations. To ascertain how well the cameras actually perform photometry, I set about making a series of observations of Landolt standard star fields using a Canon EOS 350D camera. The camera has an 8 Mega-pixel detector composed of 6.4um pixels that have a factory applied RGB Bayer filer array deposited on the detector. Observations were made on two separate new moon evenings with near photometric conditions. The observations were made with geometrically increasing exposure times and across a wide range of air masses between 1.19 and 2.0. Landolt fields SA100xxx .. SA105xxx were observed during the program.

Observation data was converted from Canon RAW data format to FITS floating point representation using Canon and Meade image processing software. All subsequent data reductions and analysis were then performed using IRAF 2.13 Beta running under the PC-CygWin environment.

Observation and calibration images were split into 3 separate R, G and B images using flux conserving techniques. Calibration images for each color field were combined and applied to observations. Each field was measured by taking eight exposures and averaging these together after they had been calibrated and co-aligned. For the purpose of data reduction each of these composite images was treated as a single photometric observation with an air mass of that of the middle of the sequence.

Photometric measurements of each field were performed using DAOPHOT point spread photometry. Observational data was taken in each of the color bands. The basic working assumption being that the camera’s native red, green and blue responses would approximate Johnson-Cousins standard R,V, and B band responses respectively.

These observations were then fitted for extinction and zero-points using a “least squares” best fit method. These raw instrumental readings were then plotted against the Landolt magnitudes in Figures 4, 5 and 6.

These instrumental fits have RMS errors of 0.347, 0.134 and 0.236 Mag. for B,V and R bands respectively.

For the V color band an attempt was made to determine a single color correction term to transform the observations onto the standard system. The result was again plotted against the Landolt standard value and shown as Figure 7.

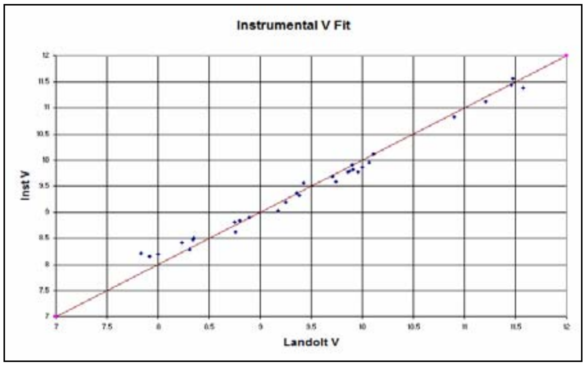


Figure 4: Instrumental V Fit

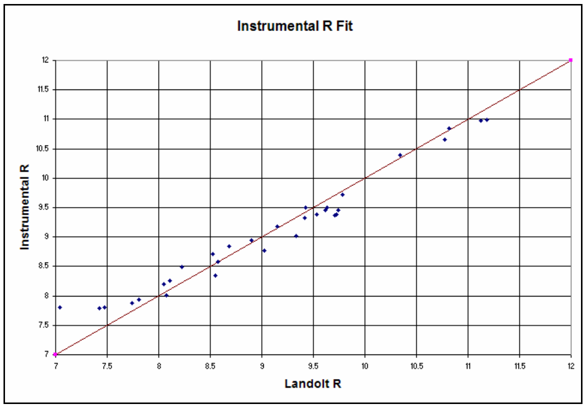


Figure 5: Instrumental R Fit

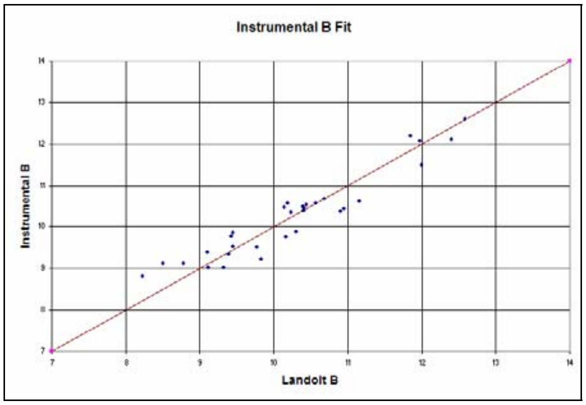


Figure 6: Instrumental B Fit

After refitting the V band magnitudes using the instrumental V-R term for color correction, the RMS error value dropped from 0.134 Mag. to 0.132 Mag.

6. Discussion of Results

The attempt at chromatic correction of the V-Band response must be categorized as a failure given the average statistical uncertainty of the instrumental photometry was 0.003 Mag. and the incremental improvement of the photometry was only 0.002 Mag.

Figure 7: Color Corrected V Fit

I must conclude that the fit problems were more likely a result of another systematic effect. Two separate plots support this analysis. A scatter plot of error vs. color index shown as Figure 8 suggests no significant relationship between color and error. While Figure 9 showing error as a function of magnitude suggests another cause for the low quality of the fit.

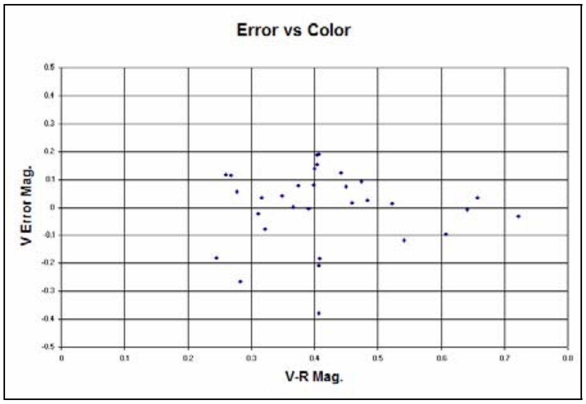


Figure 8: Error vs. Color Plot

Overlaid on Figure 9 is a 3rd order polynomial fit of absolute error as a function of magnitude. It clearly shows that for objects in the range of 9.0 to 11.5 magnitude absolute photometry errors are on the order 0.05 magnitude. But for objects brighter than magnitude 9.0, systematic errors increase rapidly with magnitudes being systematically under estimated. This pattern of errors leads me to conclude that, despite earlier admonitions, I was a victim of non-linear detector response resulting from the presence of anti-blooming structures in the detector.

I have considered reanalysis of this data set after exclusion of observations with fluxes yielding magnitudes brighter than 9.0, but I feel the resulting sample size would be too small to provide strong support of any conclusion.

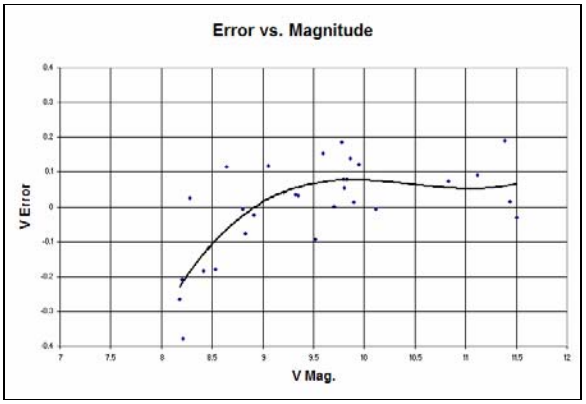


Figure 9: Error vs. Magnitude with 3rd order fit

7. Conclusions

Based on the results above, I think several conclusions can be drawn. Firstly, no single exposure set taken with this DSLR family of camera can accurately span more than 2.5 magnitudes. That particular restriction does not preclude performing very accurate, multi-band differential photometry. All that is required to perform milli-magnitude differential photometry is care to assure that target, check and comparison stars are within a 2.5 magnitude range and that the exposures used keeps all observed stars well within the linear regime of the camera.

Secondly, I would assert based on these results, that, subject to dynamic range limitations, the Green filter set closely approximates the Johnson-Cousins V band.

Third, data would indicate that the instrumental blue filter response may not extend far enough into the shorter wavelengths to easily transform onto the standard system. Still, the presence of color information in single frame exposures provides the tools necessary to select reasonable comparison stars in differential photometry.

Fourth, the work here begs for follow up work using geometrically scaled exposure sets to more fully characterize the chromatic effects of the camera.

With the constraints indicated above, I conclude that DSLRs are very well suited to programs of differential photometry. They also offer excellent opportunities to perform large surveys with modest optical systems.

The key to using the cameras in survey applications will be to take multiple exposures of geometrically increasing duration, where each exposure goes approximately 2.0 magnitudes deeper than its predecessor. By carefully limiting the magnitude selection from each exposure group to 2.0 magnitudes, centered the linear portion of the detectors, wider dynamic ranges can be surveyed without loss of precision.

The practice will lead to more exposure and processing time to reduce data from any survey. As in other survey work, the design of the backend data stream processing will be resource intensive. It will require the same level of automation and online storage as any other program yielding equivalent volumes of raw data.

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