Baltic Astronomy, vol. 12, 476–483, 2003.

FLATFIELDING ERRORS IN STRÖMVIL CCD PHOTOMETRY

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Received November 15, 2003

Abstract. The importance of determining the error of the flat field in CCD photometry is detailed and our methods of doing this are described. We now have reached a precision of 1–1.5 % in our photometry. Color-magnitude diagrams of the open cluster M 67 (ours and Laugalys et al. 2003) are compared.

Key words: methods: observational – techniques: photometric – CCD photometry, flat field errors – clusters: individual: M 67

1. INTRODUCTION

The CCD provides panoramic exposures of star fields at a telescope. Usually, the dynamic range of CCD chip is linear over the order of six magnitudes. A 2000 by 2000 pixel CCD has four million contiguous pixels which need to be calibrated to provide the resulting unit response to unit of stellar input radiation. Causes for non unit response of the pixels are: the relatively varying quantum efficiency of each pixel in itself, gradients of varying transmission across a filter and across the camera dewar window, and attenuating dust specks on the filter and window.

Measurement of these variations of relative sensitivity of each and all pixels provides a means to calibrate the CCD and so to remove its effect on in-focus stars. This measurement constitutes the so-called flat field calibration measurement. If the assumption of unit illumination input to the optical system of the telescope (primary, secondary mirrors, filter, dewar window and CCD itself) is a valid assumption, then the flat is the measurement of relative sensitivity response. To name this as the flat is somewhat misleading, because they are not flat in appearance. They appear very non-uniform, non-flat precisely because they are the measurement and display of the relative response of the optical system to unit input.

The assumption of providing unit input illumination to the optical system is very important. To the extent that this assumption is invalid, so the suitability of the flat is compromised in its application to star-field exposures. And the second violation to the suitability of a flat is having added forward-scattered light not parallel to in-focus star beams arriving in the focal plane. This is so because scattered light added to the flat cannot be subtracted; and, it is indistinguishable from the light proper to the flat which will be used in a multiplicative manner (by division).

2. FLATFIELDING

A "flat" is a measurement of the instrumental signature of the telescope-plus-CCD optical system. The telescope mirrors, primary and secondary, the filters, the dewar window of the camera, and the CCD make up this optical system. Flats are not flat, nor uniform in their appearance. Gradients over small, pixel to pixel, and large spatial scale appear in a flat due to dust on the filters and dewar window, and due to variation in transmission in the filters and dewar window, and due to variation in sensitivity across the pixels of the CCD.

Any CCD camera needs to be calibrated for the optical system of the telescope. The basic assumption is that we can provide a uniformly illuminated source to the camera. To the degree that this assumption is violated, we call this the error of the flat over the field of view. The calibration over the pixel-to-pixel scale is easily done by exposures on a not necessarily uniformly illuminated source. In our case we take multiple exposures of the interior of the aluminum dome. We need to make an illumination correction to such a dome flat. The goal is to learn the instrumental signature of the optical system to an accuracy more precise than the limit of uncertainty set by photon statistics in the object frames.

For our early runs we took twilight flats (evening and dawn) and when we compared the two sets we found differences of up to fifteen percent. The problem was traced to scattered light in the telescope. On later runs we encouraged the support staff to investigate the cause, and they added black velvet to the metal "top-hat" which reduced the scattered light. We took pinhole pictures by replacing a filter with a pinhole we made. The resulting frames showed a central image of the secondary mirror and then other areas, away from the secondary that represented the effect of scattered light. Thus we are able to track the state of the scattered light problem. In IRAF it is possible to take an average dome flat and correct it with a sky flat which gives the illumination correction.

On the pixel-to-pixel scale it is easy to calibrate the relative sensitivity to a very high signal-to-noise measurement. Averaging multiple flat exposures made from an illumination source not necessarily uniform, for example, just the inside of the dome, and just keeping the CCD counts in the linear response range, accomplishes this. However, calibration over the full spatial scale field of view is much more difficult to do very accurately, e. g., to 1 or 2 percent. Scattered light probably contaminates most telescopes. And being added to the focal plane, if not somehow subtracted out, this added scattered light will be used in a multiplicative way and thus will compromise the desired constancy of the zero-point magnitude scale needed to some accuracy for the photometry.

At VATT (Vatican Advanced Technology Telescope on Mt. Graham, Arizona) we have done several steps to suppress the scattered light. First, it is better to block its arrival into the focal plane. Baffles must be in place to block stray light, i.e., light directly from the sky to the focal plane. The baffle tube holding the secondary mirror, a top-hat baffle tube suspended above the primary mirror, and the hole of the primary mirror all block the stray light. But the interior cylindrical walls of these baffle tubes provide a forward-scattering surface for stray sky and dome light. It is most important to suppress scattered light in the top-hat and hole of the primary. Currently we do this by placing black velvet on the appropriate surfaces. But pinhole camera exposures (pinhole aperture placed in a slot of the filter wheel) reveal that the interior forward scattering tube surfaces are not entirely black.

If a uniform extended light source passes through the optical system, the flat is the resulting image giving the instrumental signature. It is assumed that no other light arrives in the focal plane extraneously. To the extent that off-axis scattered light is added to the flat, the usefulness of such a flat is compromised.

Over several subsequent runs we have resorted to making dark sky exposures in all filters. These are on sky fields where there are practically no stars and none bright enough to be of concern for our purpose. Although, of course, the light-scattering properties of surfaces don't change from day to night, we can expect much less scattered light to arrive in the focal plane on a moonless astronomical twilight time than proportionately does at bright twilight time. And to some satisfaction we have found that, with the suppression of scattered light by the black velvet, twilight flats ratio to a constant more closely to a few percent rather than 15 percent, and that the dark sky flats do even better.

For some observing runs we have been using valuable moonless nighttime, about two of a nine night run just to get these dark sky flats in eight filters. Their data-number level runs only about to 700 counts for the two ultra-violet filters from hour long exposures and to about 1800 counts for the other six filters with 30 minute exposures. But these levels per pixel are sufficient for the purpose of extracting a spatially smoothed illumination correction for a flat. We take about 12 ten second exposures rapidly off the aluminum dome lit by lights or daylight from the sky. The average of such a set of dome flats with count levels just below saturation levels gives a very high S/N measurement per pixel, of better than a few tenths percent uncertainty. But lacking a properly set up white spot source, we expect these dome flats will require an illumination correction. That correction can come from the dark sky flats. We can call this resulting flat, the averaged dome plus dark sky correction, an initial super-flat. But the error of the flat is unknown at this stage.

We suspect that suppression of this scattered light can never be complete. So we have now turned to a quite different solution. And we pose the question: what difference will it make for their photometry where they fall in focus over the field of view? If tests show no difference, then the perfect flat has been used. But if a difference exists then that is the error of the flat.

3. MEASUREMENTS TO REVEAL THE FLAT ERROR

What measurements are necessary and sufficient in the instrumental system to learn systematic effects and so to be ready to remove them?

The constancy of a set of stars can be used to probe the instrumental system for determining instrumental effects. Take a set of dome flats in each filter to measure the relative sensitivity of each pixel at a high precision. With a high S/N per pixel for the flat measurement, the use of it by dividing it into an object frame will have negligible increase in the uncertainty or noise for the object frame. The noise or uncertainty for the star signal itself will be dominated by the photon statistical error or by background (sky) noise or even by readnoise. In conclusion, take enough flats so the uncertainty of this measurement of relative sensitivity per pixel is much less (10 to 100 times less) than the uncertainty in the star signal. If the Noise/pixel in the flat is 0.001, which is less than the Noise per pixel for the bright star, then the uncertainty in the flat measurement will not significantly increase the uncertainty in the star measurement.

Why take any more flats, other than dome flats? Most likely, the dome flat will not satisfy the requirement of unit source illumination input to the optical system, and so the dome flat will need some illumination correction to be applied to this dome flat. If the source for the dome flat is simply lights in the dome shining on the aluminum dome inner surface, most likely this source is not providing a uniform input to the optical system. An illumination correction for such a dome flat might be extracted from a twilight flat or better from a dark sky flat. One can use the IRAF task, MKSKYFLAT. But even here, the resulting "super" flat might be contaminated by added scattered light occurring somewhere in the optical system, e. g., by forward scattered light off the inner vertical surface of the top-hat baffle or hole in the primary mirror. So maybe the initial, illumination-corrected "super" flat might not be the correct, near "perfect" flat suitable for the starbeams.

So we have turned to the following method to obtain the near "perfect" flat. We use the stars themselves to self-calibrate the CCD. Using the well-grounded assumption that for a rich star field, e. g., the open cluster M 67, the magnitudes of stars remain constant during the short period of calibration measurements, we take various exposures to give enough information to answer the question: using an initial flat, what difference does it make for the magnitude measurements of the stars dependent on where they fall in the CCD field of view? If differential photometry shows no difference, then the initial flat is already the perfect flat. But if the differential photometry shows non-zero differences as a function of position (x, y) on the CCD, then this systematic variation of the zero-point over the field can be used to correct the initial flat and make a near "perfect" flat.

Two exposures are necessary and maybe sufficient to determine the error of the initial flat. Either offset the telescope 1/3 of the field of view (for an equatorial telescope) or rotate the camera 180 degrees (for an Alt-Az telescope). The Alt-Az rotation, however, will not detect a radial error in the flat. The offset method gives differential photometry for only a subset of the stars.

For the differential photometry to reveal real trends due to the error of the flat and not to be confused with other errors, more than two exposures are needed. First take a set of three exposures with the telescope offset just a small amount, e. g., 10 arcsec, so stars maybe falling on bad columns are moved off. Also, the three exposures allow one to obtain a mean magnitude per star and thus show a dispersion to discriminate between bright stars that can show a real systematic trend in the error of the flat and fainter stars having magnitude uncertainties from low S/N and thus too faint to reveal the error of the flat. Second, take three additional exposures dithered at the large offset or rotated position. Then, calculate mean magnitudes in the first and second data sets, and a mean of the first and second, and differential photometry as dependent on x, y coordinates of the mean (of the six measurements) minus the mean of the first and second.

Use this differential photometry table to make the correction to the error of the flat. The non-zero differential magnitudes as $f(x, y)$ indicate that with respect to the mean of six measurements, the various stars were systematically slightly too bright when at $(x1, y1)$ and too faint at $(x2, y2)$. So the "offending" flat can be simply corrected correspondingly just enough to remove its error and on use of the corrected flat, the differential photometry will show near zero values. We use several different methods to make a corrected, nearly "perfect", "super-super" flat.

QTUNE is our custom task for use within IRAF. It takes the differential photometry data per star and maps box areas for specific stars where the initial flat must be modified precisely enough to reduce the error of the flat to zero. The more difficult solution to removing the error of the flat is to make from the box map a smoothed illumination correction image such that it corrects the offending flat (making use of only the brighter stars) for use not only on the calibrating star field, e. g., M 67, but also is an excellent flat for other object fields having single exposures. Use of IRAF task IMSURFIT on the box map image, using the sections parameter, gives good results.

XYZTOIM is a task in the STSDAS package. Use the differential photometry table to create the illumination correction image and apply it to the offending flat by use of IMEXPR. Use of a Chebyshev or Legendre fitting function, 2nd order with cross terms is adequate to fit real trends in the error of the flat. Avoid over-fitting.

QAUTO is our custom task for IRAF that quickly processes all the frames involved in getting new differential photometry after using the corrected flat.

QSF and QSIMPLEX are our custom tasks for minimizing errors and can be programmed to minimize the error of the flat. For example, use QTUNE within QSIMPLEX where the function for smoothing the "box" map illumination correction is optimized such that it gives good results not only for the M 67 calibrating field but other object fields. These tasks were designed by Janusz.

Our present routine is to take twilight or dark sky flats to make preliminary "super" flats by combining the dome flat and the sky flat (by IRAF MKSKYFLAT). We take multiple exposures on a rich starfield, e.g., M 67). Then the telescope is moved about 1/3 field of view, e.g., north and east, or the camera is rotated, so one can determine from the differential stellar photometry what difference there is from constancy of the magnitude zero-point over the field. Such photometry can be used to map the error of the flat and to make an illumination correction to the initially used offending flat. Correct that flat by this illumination correction to make a super-super flat with then very little error of the flat. The illumination correction can be created by QTUNE, or XYZTOIM.

4. COLOR-MAGNITUDE DIAGRAMS OF M 67

As we have discussed, we now have high precision CCD photometry of M 67. In Figure 1 we show our $(b-y,\, y)$ color-magnitude diagram (left panel) and a $(Y-V,\, V)$ color-magnitude diagram in the *Vilnius* system by Laugalys et al. 2003 (right panel). Even though different photometric systems are used, the color-magnitude diagrams show reasonable agreement in the locations of the main sequence, giant branch and blue stragglers.

5. CONCLUSIONS

The purpose of this paper is to show that careful attention to the determination of the error of the flat allows us to do photometry to an accuracy of 1 to 1.5 %, depending on the filter. In Section 4 we show good agreement to the color-magnitude diagram of Laugalys et al. (2003). The most important part of the data reduction is the determination of the error of the flat and then correcting for it in the super flats that we create.

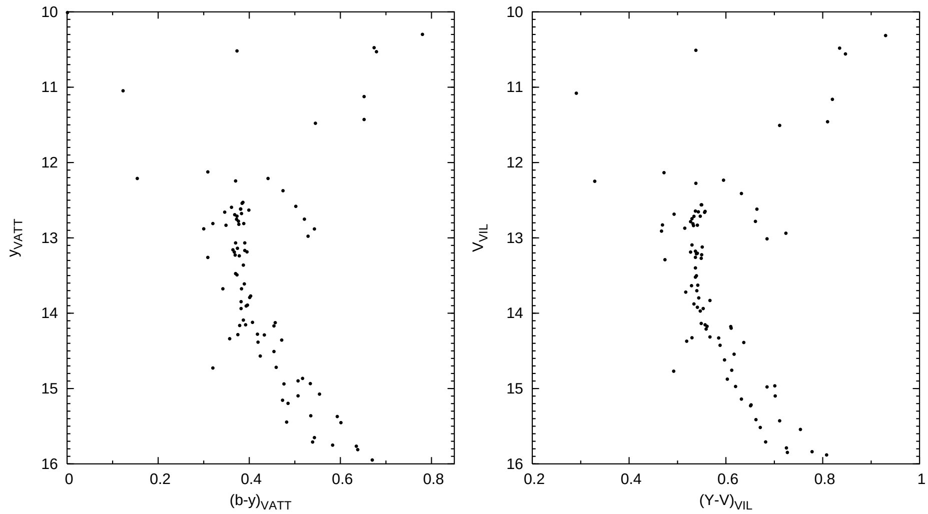

Fig. 1. Comparison of color-magnitude diagrams from VATT and Laugalys et al. (2003) in the *Vilnius* system. Only common stars are plotted.

REFERENCES

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