Problems of CCD flat fielding

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Abstract

CCD flat fielding using an illuminated dome screen is discussed. Rings of reduced response caused by dust specks on the cryostat entrance window indicate the required uniformity of screen illumination but may not divide satisfactorily because of telescope flexure. Illumination colour is important for shorter-wavelength, broad-band filters. Flat fields can be distorted significantly by light scattered off telescope baffles. Special precautions are needed for uv flat fielding. The Mt John TH 7882 CDA chip is slightly sensitive to polarisation. Dome flat-fielding accuracy of 0.3% would seem achievable.

1. Introduction

The system sensitivity is nonuniform across an astronomical CCD image because of factors such as interpixel sensivity variations intrinsic to the chip, shadows cast by dust specks on the cryostat window and other optical surfaces, filter inhomogeneities, streaky or bubbly optical cements, and telescope vignetting. A flat-field (sensitivity-map) image attempts to represent the combined effect of these variations. Before photometry can be extracted from CCD science images they must be corrected to uniform sensitivity through division by the appropriate flat-field image. (The process of flat fielding cannot of course correct for any intrapixel sensitivity variation.)

Correct flat fielding is crucial for the observer who seeks precise and accurate photometry. This paper discusses aspects of flat-fielding attempts made using the Photometrics Ltd. cryogenic CCD system which has been in use at the Mt John University Observatory (MJUO), Lake Tekapo, since late 1989 (e.g. Tobin, 1991). Because MJUO is a private facility, it has been possible to conduct more tests than is practical for a visiting observer at an international facility. While I have yet to achieve the ~0.3% flat-fielding accuracy desirable for my scientific programme (photometry of eclipsing binaries in the Magellanic Clouds), I hope my experience so far will provide useful guidance to others, especially those at smaller observatories. The reader should also study the articles by Djorkovski (1984), Djorkovski & Dickinson (1989) and Stetson (1989), and Chapter 5 of the book by Buil (1991).

To obtain a flat-field map it is only necessary to image a uniform, extended source. The twilight sky may be a suitable source for the small fields of view of many CCDs, but twilight flats are difficult to obtain because the sky must be unambiguously clear

https://doi.org/10.1017/S0252921100007697 Published online by Cambridge University Press

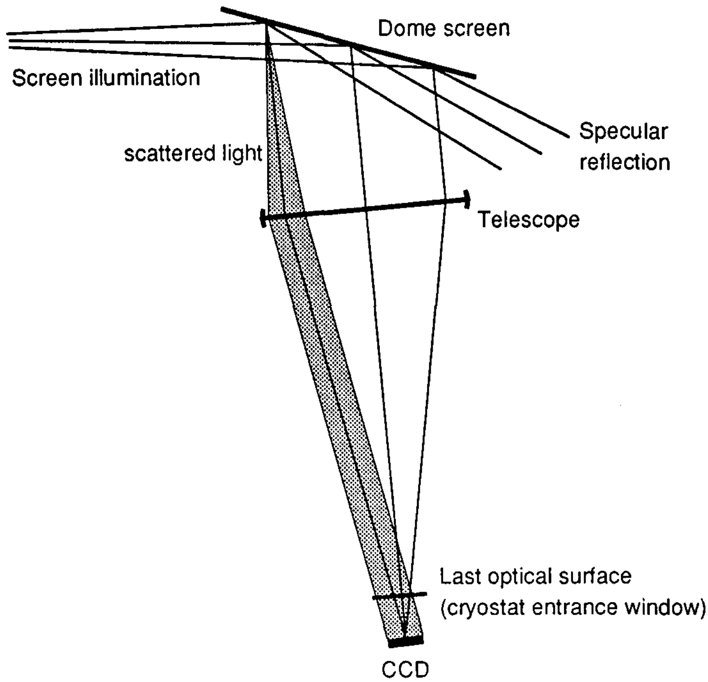

Figure 1 Schema of dome flat fielding. Each element of the screen illuminates the whole CCD, and each point of the CCD is illuminated by all elements of the screen.

and the signal strengths are appropriate for only a few minutes. Another, easier option is to use an illuminated screen within the dome: with the telescope focused at infinity, the claim is that the screen is so far out of focus that the telescope focal-plane illumination is nevertheless uniform.

At MJUO resident technician-observers do much of the variable-star observing. They cannot routinely be asked to extend their working night by the 1–2 hours needed to obtain sky flats (nor can clear twilight be assumed in New Zealand). On a nightly basis dome flats must be used at MJUO, so this paper concentrates on the question of dome flatting.

The tests reported here have been made with either the 0.61-m or the 1-m cassegrain telescopes at MJUO. The CCD is an overcoated 384×576-pixel Thomson TH 7882 CDA chip. On both telescopes its field of view is ~3.8×5.8 arcmin.

2. Dome flat fielding.

Can dome flatting be satisfactory? I think so, if properly arranged. Figure 1 sketches an arrangement. So long as one avoids angles at which the dome screen scattering function is changing rapidly (i.e. close to specular reflection) each elemental area of

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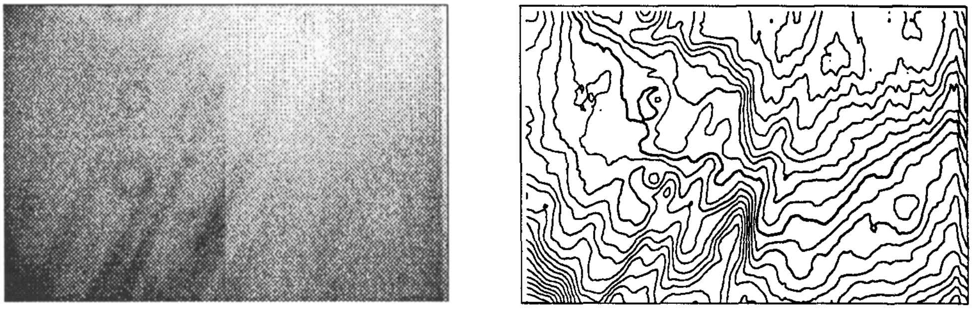

Figure 2 A MJUO V flat field represented *left* as a positive intensity-coded image and *right* in smoothed form as a contour map in which the heavy line represents the mean and the contour spacing is 0.5%. The r.m.s. variation of the flat field is 3.1% with a range of ~12%. In U, B and I the r.m.s. variations are respectively 3.6%, 3.5% and 2.5%.

the dome screen provides uniform illumination within the few arcminute spread of the ray directions which the telescope focuses to differing points on the CCD. The chip is thus uniformly illuminated (and its sensitivity variations correctly mapped) whatever the illumination pattern of the dome screen.

The uniformity of the screen illumination is however important for mapping the throughput variations caused by optical elements in front of the detector. The most obvious of these variations are rings of reduced response resulting from the occultation of the hollow core of the telescope beam by dust specks on the cryostat entrance window. Three examples are clearly seen in the sample MJUO flat field shown in Figure 2, which also shows sensitivity variations on all spatial scales. If the telescope beam is not uniformly filled because the screen is unevenly illuminated, the shadow ring is modulated and differs in intensity from that caused by a star. At MJUO these dust shadow rings depress the level of the flat field by ~3%, and this furnishes an indication of how uniform the scattered light from the dome screen must be. For 0.3% flat fielding the scattered light across the board must be uniform to ~0.3%/3% or ~10%. This can probably be checked with a light meter.

The relative insensitivity of MJUO dome flats to the details of the screen illumination is illustrated in Figure 3 which presents a ratio image in which a dome flat obtained with only *half* the screen illuminated has been divided by a dome flat obtained with a fully-illuminated screen. This severe modulation of the illumination generally only affects the flat field at the ~4% level. These variations principally derive from the glue that holds together the individual glasses in the filter some 50 mm in front of the CCD chip. The dust rings, being caused closer to the chip, are more severely affected and show more obviously the effect of the half-illuminated beam.

So long as the telescope is properly focused at infinity MJUO dome flats seem reproducible at the ~1% level irrespective of telescope orientation and small differences of screen illumination (e.g. illuminating lamp to east *vs.* lamp to west). However,

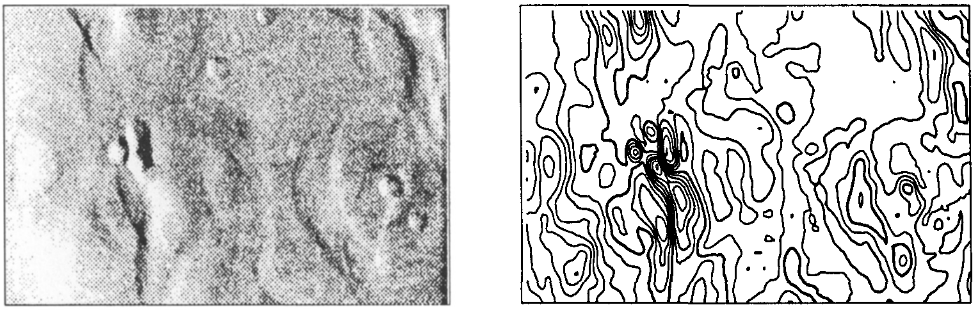

Figure 3 Ratio of two MJUO B flat fields. One was obtained with the dome screen illuminated in the normal way, the other with only half the screen illuminated. The ratio image is presented in the same two ways as in Figure 2.

because of flexure, the position of the dust rings on the chip varies with telescope orientation. For the best photometry dust rings should not impinge upon target stars.

Sky flats in B, V and I obtained from the dusk sky were compared with dome flats. The high spatial frequency variations agree very well, but the (sky flat/dome flat) ratios show large-scale systematic effects in all three bandpasses at the 1.0-1.5% level (Figure 4 gives an example). The filter bandpasses are weighted differently by the red illumination of the dome flats and the blue illumination of the sky flats. To investigate whether this could be the cause of the (sky/dome) differences, dome flats were obtained with the regular $UBVI$ filters, and then with cut-on or cut-off filters which bisected the $UBVI$ bandpasses placed in front of the screen-illuminating lamp. Linear combinations of the full and bisected $UBVI$ responses were made which more-or-less matched the responses to sky illumination, and corresponding synthetic (sky flat/dome flat) ratios were calculated. These show systematic differences of ~1.5% in U, ~1% in B, ~0.5% in V and ~0.1% in I. Figure 4 presents the results for B. The predicted (sky/dome) variation is sufficient to explain the observed (sky/dome) variation in B, but not in I (with V an intermediate case). Conversely, colour effects are likely to be important in the shorter-wavelength broad-band filters at the ~0.5% level in V, increasing to ~1.5% in U. Appropriate colour-balance filters are desirable to match the dome screen illumination to the colour of the stars being observed for short-wavelength, broad bands.

With dome and sky flats agreeing at the ~1% level one might think that MJUO flat-field images are flat at this level. To check this, observations were made of two E-region standards which are ~1 arcmin apart on the sky. The magnitude difference between the stars varied in a reproducible way by ~4% depending on their location on the chip. Despite their similarity, the dome and sky flats are warped.

I believe the cause of this systematic error is scattered light. The telescope baffles prevent sky light from reaching the CCD chip directly, but as Figure 5 shows, considerable light is scattered off the inside of the primary mirror chimney baffle. The

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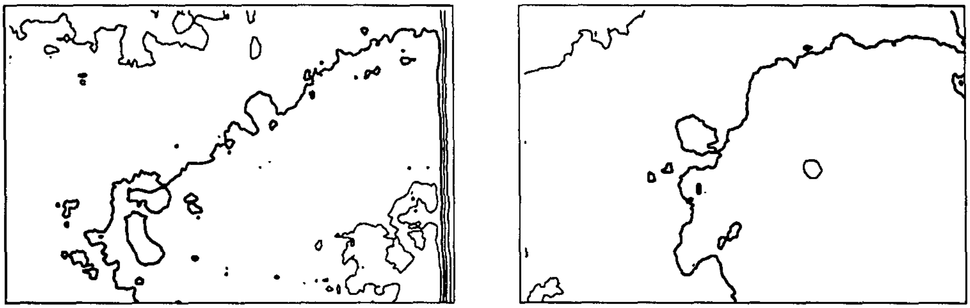

Figure 4 Contour plots of smoothed B (sky flat/dome flat) ratios (0.5% contour intervals). *Left* observed ratio, *right* model ratio synthesized from dome flats obtained with full and bisected bandpasses. The plots are very similar.

dome and sky flats agree because both derive from an extended source (the sky or the rectangular dome screen and reflective pale green dome interior), but both are wrong. Support for this explanation comes from dome flats obtained after the dome screen had been painted down with black paint to the size of the telescope beam. These flats are curved by several percent compared to earlier dome flats.

Annuli, which are very effective at curtailing scattered light, will now be installed in the baffles. Non-flatness of dome and sky flats can probably better be tested using not a pair of stars but observations of an extended open cluster taken at various different chip positionings. Pairwise magnitude differences can then be fitted to a 2D polynomial to check for and to model any remaining curvature of the flat field images, as suggested by Djorgovski (1984).

With the understanding of flat-fielding now obtained, I believe that the prospects are good for achieving the desired 0.3% flat-fielding accuracy.

3. Screens and lamps for dome flat fielding

Until recently slide projectors were used to illuminate rectangular screens of white-plasticized wood composite. In future I wish to extend observations to Strömgren u, and for this the spectral reflectance of the plasticization has been checked since many modern white materials contain 'optical brighteners'. These fluorescent dyes absorb from 300-400 nm and re-emit at longer wavelengths. The reflectance of the MJUO board drops by ~50% from 420 nm to 380 nm, which may cause colour-balance problems not so much for uv filters as for B and Strömgren v. Teflon sheet would seem a possibly more suitable screen material.

A uv-rich lamp is required to illuminate the screen. Mercury lamps show strong emission lines. Deuterium lamps are spectrally smooth and very blue from 300–400 nm, but are intrinsically faint. Xenon lamps have good and smooth uv output but necessitate precautions against explosion, ozone—and sunburn. Because of its safety, simplicity, low light spill, filter slots, easy availability and low cost a 1200 W theatrical

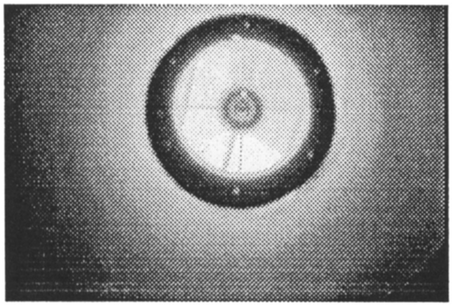

Figure 5 Scattered light in the chimney baffle of the MJUO 0.61-m Boller & Chivens cassegrain reflector. This image was acquired by placing a 50-mm camera lens in front of the CCD. The scattered light in the image is 11% of the light in the beam.

spotlight with mains-operated quartz-halide bulb has now been purchased for MJUO dome flat illumination. Its glass fresnel lens has been removed and a tube collimator installed to restrict its beam to the dome screen (rings within this tube dramatically tightened the beam). Using this spotlight, a dome flat with 0.5% statistical noise can be obtained in U in 40 s, and, it is estimated, in u in 4 min. For colour balancing or attenuation theatrical filters are readily available and can stand proximity to a 1200 W bulb. Further, filter sample books now include spectrophotometric tracings (though only to ~700 nm). The 1200 W spotlight is far too bright for red and ir flat fielding, so a 5 W lamp is under construction for this.

4. Polarization sensitivity

An attempt has been made to check the commonly-made assertion that CCDs are insensitive to polarization. Polaroid sheet was placed in a 1-m diameter rotatable holder located between the telescope and the dome screen. Dome flats obtained at different angles of polarization were compared for U, B and V. (Polaroid sheet is ineffective at I.) For a 90° rotation of the plane of polarization there is evidence of pixel-to-pixel sensitivity variations of at least 0.7%, but less than 3%.

Acknowledgments:

I thank Stephen Duncan, Murray Forbes and John Pritchard for assistance with various aspects of this work.

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Discussion

T.L. Kreidl: *I would contend that sky flats are particularly important when weather conditions are variable. In certain bandpasses, the night sky lines can be quite variable and hence, affect the flat fielding significantly.*

Tobin: This applies for sky-limited images. It will be less of a problem if you are observing brighter stars.

A.T. Young: *The gradient pictures you showed, in comparing flats taken with different pupil illuminations, illustrate those angular effects I mentioned after Peter Stetson's talk. The stray light is in part due to scattering from dust on optical surface.*

W. Tobin: Quite so.

R. Florentin-Nielsen: *What kind of data acquisition system do you use, i.e where do the data go from the CCD controller.*

A. Walker: The data go into a SUN computer. This is presently a VME-bus SUN, but we are changing to use S-bus SUN's.

R. Florentin-Nielsen: *Did you try to let daylight illuminate your dome board for your dome flats.*

Tobin: No, but I may, once I've reduced the scattered light.

J. Tinbergen: *The last three talks bear out what I said (hoping it was true): Imagers are receiving sufficient attention. However, even better results can probably be achieved by experimentation, such as described by Tobin, but with an optical engineer looking over your shoulder. In particular, improvements might be expected from a pupil image within the photometer, by putting filters and a shutter in (cf. Walker, review) and a properly designed calibration light system to supplement the sky flat field information. It is worth looking at the TAURUS II optical system (La Palma Observers' Guide or AAO equivalent).*