Crowded Field Photometry using Post-Exposure Image Sharpening Techniques*

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Abstract

The technique of image sharpening which allows high resolution images to be produced from ground-based telescopes is applied to the problem of photometry in crowded field regions - such as close to the cores of globular clusters. The conditions for image sharpening are discussed and the technique is demonstrated using simple objects (close double stars). Preliminary results from image sharpening of M15 are presented.

1. Image Sharpening

Plane waves (from distant objects) become distorted by refractive index fluctuations while passing through the atmosphere, limiting the resolution which can be obtained by even small telescopes at sea level and modest-sized telescopes at the best high altitude sites. The resolution of a large telescope is entirely determined by atmospheric effects and by its optical quality rather than by diffraction. Refractive index fluctuations are generated by temperature fluctuations in the atmosphere arising (a) from convective motion and/or turbulence locally and in the atmospheric boundary layer, and (b) the dissipation of turbulent energy arising from high-altitude atmospheric wind shears. Collectively the effects are known as seeing. It has proved possible recently, by site selection, careful attention to local thermal effects and by improving optical performance, to produce substantial improvements in average seeing. Nevertheless, atmospheric distortion remains the limitation to high resolution imaging.

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The quality of the atmospheric seeing is usually expressed by a characteristic scale R_0 (Fried's parameter) and time scale τ_0. One definition of R_0 is the diameter of a diffraction-limited telescope producing seeing-limited resolution, ω_{eff} ;

$$R_0 \simeq 1.22\lambda / \omega_{eff}$$

R_0 has a value of a few cm to perhaps 0.5 m, and τ_0 lies in the range of a few milliseconds to 50 milliseconds for the best high altitude sites. The probability of an image having less than 1 rad^2 rms phase error is; (Fried[1978]):

$$prob \approx 5.6 \exp[-0.1557 (D/R_0)^2]$$

Strikingly different behaviour can be observed through small ($D \simeq R_0$) and large ($D > 6R_0$) aperture telescopes. For a large aperture there is little image motion, and the image is always blurred - many bright "cores" can be observed moving about within the image, if the star is sufficiently bright, and only occasionally coalescing into a single "core". For a small aperture one may frequently observe a single bright "core" in constant motion. Figures 1 and 2 express this graphically, and underline the importance to image sharpening of the correct choice of pupil.

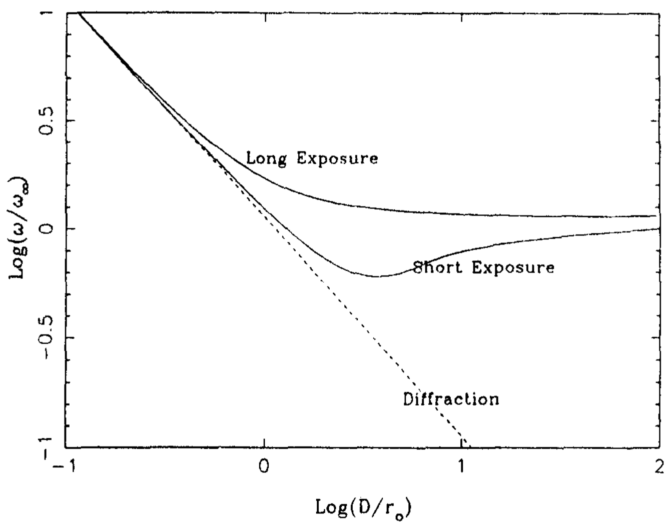

Figure 1: Image width, ω, normalised to that of a large aperture, ω_∞, as a function of aperture, for long and short exposure images (Roddier[1981]).

ω corresponds to the diffraction limit only for small apertures. The short exposure image width (where short means that all image motion is frozen, say 1 millisecond) follows the diffraction limit more closely and shows a minimum at $D/R_0 \sim 3.7$ which is a factor 2 smaller than the long term limit. What is happening is that for values of

$D/R_0 \leq 4$ the dominant term in a polynomial expansion of the wavefront distortion is the linear one (tilt). A gain of a factor 2 can be achieved by removing tilt alone. For values of $D/R_0 > 10$ the dominant terms are of a higher order - removing tilt does not produce any improvement. Figure 2 predicts that it ought to be possible to make large improvements in resolution by using choosing those (few) moments of diffraction-limited seeing for a large aperture.

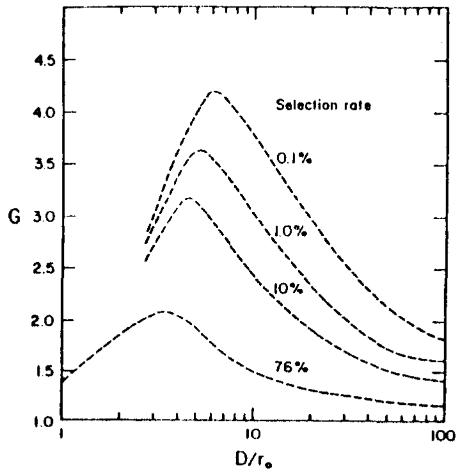

Figure 2: Expected gain in resolution, G, using selection in addition to re-centring, as a function of D/R_0 for different selection rates. (from Hequet & Coupinot [1985].

The technique of image sharpening exploits these effects, and in post-exposure image sharpening image data (usually single photon addresses) are collected in "frames" which are short compared with τ_0. Image motion and quality may be assessed by considering the image of a bright unresolved star or stars in the field of view. **The minimum required reference brightness directly affects the fraction of the sky which is accessible and hence determines to usefulness of the technique.** The crucial trade-off in image sharpening is between small apertures which allow a large fraction of the images to be selected, but have a limited maximum resolution and produce few counts in the reference star(s), and larger apertures which require more severe selection criteria but do, in principle, produce sharper images, and do produce more reference counts.

So, the recipe for (post-exposure) image sharpening is:

1. Choose a site with excellent seeing, a telescope and system resolution with resolution $\ll$ the resolution of a $3.5R_0$ telescope, and focus the telescope to a similar order
2. Choose a telescope sub-pupil $\approx 3.5R_0$, and fill the telescope aperture with sub-pupils to make efficient use of the total area.

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3. Record photon address data with a time resolution $\ll \tau_0$
4. Choose a field with identifiable star(s) producing $\approx$ several x 1000 cps - for a field containing many unresolved stars this may mean >100,000 cps for a detector field containing many sub-pupils.

2. TRIFFID[2]

The image sharpening camera built in Galway and Dublin (TRIFFID) has:

1. An 18.2 mm collimated beam (for f/11 telescopes) within which are placed colour filters, polarising filters, etc., and in which a mask defines sub-pupils in a pupil-plane conjugate to $\approx$5 km altitude (roughly within the high altitude turbulence causing the seeing.)
2. 2 photon counting detectors imaging the same set of sub-pupil images, each sub-pupil image separately. The light is split up using a dichroic filter to allow wide (B) band imaging on an event counting detector[3] (to produce the image sharpening reference signals) and V, R, or narrow band (Hα, for example) imaging onto a framing detector[4] unsuitable for image sharpening by itself.
3. (Remote) data collection system capable of framing photon event into short (>500 μs) frames and storing 450 Kbytes/second directly onto optical disk from up to 3 photon counting detectors of different types.
4. Absolute time-tagging of events to 10 μs to enable phase-resolved high resolution images to be produced.
5. Hardware and software to enable (a) the telescope to be focused to <0".1 and (b) R_0 to be determined.
6. Software to enable image sharpening to be performed with <1000 reference star photons per sub-pupil per second (each sub-pupil being essentially independent)

3. High Spatial Resolution Photometry in Crowded Field Regions using TRIFFID

TRIFFID was used for the first time in June 1992 in the GHRIL Laboratory (Noordam [1985], Redfern[1991]) on 4.2m Herschel Telescope in a programme of study of the post-core-collapse globular cluster M15. A MAMA camera, belonging to ESO, was used as the straight through event-counting detector and the RAL-PCD was used as the sidearm detector. The RAL-PCD was used mostly for narrow band (Hα) imaging. Figure 3 shows both raw and sharpened images of a small region, almost central, to the core of M15, resulting from 5 minutes data accumulation with the ESO MAMA detector. The pixel scale was 0".074 per pixel so that the displayed region is $\approx$4" square, taken from a 14".0 diameter original image. The raw data, 3(a), displays excellent resolution of

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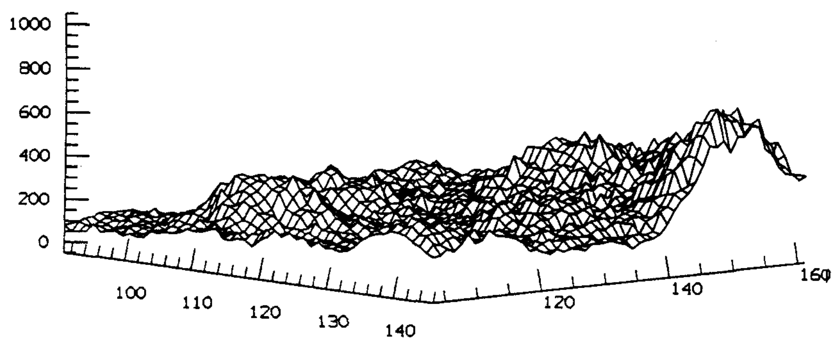
[2] TRansputer Instrument For Fast Image Deconvolution

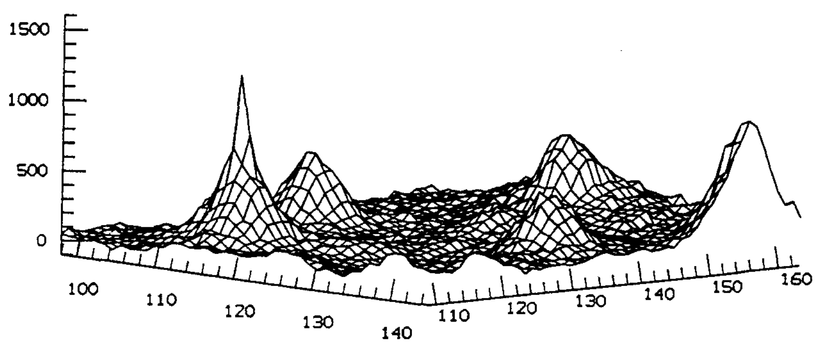
[3] MAMA (Timothy et al [1985]), PAPA (Papaliolios et al [1985]), IPD (McWhirter et al [1982])

[4] RAL-PCD (Carter et al [1990])

0".65. The positions and sharpnesses of 12 stars (in the whole image) were used to form a composite reference and ≈25% of the data was selected and accumulated to form image 3(b). The numerical algorithm used for image sharpening is still under development and image 3(b) represents a preliminary analysis only. Nevertheless, it reveals information which cannot be seen in 3(a). Features can be distinguished down to a resolution of ≈0".25. At least 50% of the dataset displays a final resolution as good or better than this.



3(a) Raw Image



3(b) Sharpened Image

Figure 3: Image Sharpening of the Core of M15

One of the several objectives of this particular study was to obtain a detailed light curve of AC211, the optical counterpart of the binary X-Ray source X2127+11, which displays an 8.5 hour periodicity (Ilovaisky et al [1987]). Photometry of AC211 has difficult heretofore because it is close to a much brighter star and superimposed on a steeply sloping background ≈ 2" from the core of the cluster. The position of AC211 is indicated in figure 3(b) - it is clearly resolved, and photometry can be performed by normal means on this image. Whilst in its bright phase AC211 is known to be bright in Hα (Naylor et al [1988]), so that narrow-band imaging in Hα is likely to be particularly useful.

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Discussion

W. Tobin: *How many big telescopes actually focus well enough for your technique?*

Redfern: The number may be small, but the next generation of telescopes should be better. We are very happy to have access to the NTT which has an outstanding measured image width of 0″.18 (80% energy enclosed). The Nordic Optical Telescope in La Palma is also reputed to be very good.

The problem is, of course, alleviated by taking independent sub-pupils since many abberations reduce as the square of the pupil diameter.

T.J. Kreidl: *Can you quantify to what precision the sharpening process will conserve flux, hence photometric precision?*

Redfern: There is no reason to suppose that the image sharpening process produces any systematic change in the relative intensities of the reference stars and other parts of the field. In the double star images shown the relative intensities remained constant within statistical accuracy.

P.A. Wayman: *Your M15 example is of how many apertures, and how may apertures were you using altogether?*

Redfern: The data which I showed is very preliminary - we have had access to the data for less than three weeks in all. In this data one aperture only, out of four, was used and only 5 minutes total from more than 10 hours of data. In order to produce final images we must address the problems of flat-fielding and image rotation in addition to co-adding the four images.