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Star Finding and PSF Determination using Image Restoration

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Abstract. Crowded-field stellar photometry consists of three main phases: locating the point sources, determining the point spread function (PSF) and measuring the point source brightnesses. In earlier work (Lucy 1994; Hook & Lucy 1994) we have described a two-channel restoration method which provides photometric fidelity and addresses the last of these items in a restoration context. Here we describe two further enhancements. First, an experimental method for locating stellar images by enhancing the sharp cores of stars using a multi-channel entropy *minimization* technique is described. In addition an extended version of the two-channel method is given which allows PSFs to be extracted from designated point-sources in images during restoration. A *default* PSF may be used to regularize the result. A simple but accurate model for the form of ground-based PSFs (Saglia et al. 1993) has been implemented and seems a suitable choice of default PSF for ground-based images. Examples using a typical ground-based CCD image of a star cluster are given.

These methods are available in preliminary implementations running within both the IRAF and MIDAS data analysis packages.

1. Introduction

In earlier papers (Lucy 1994; Hook & Lucy 1994) we described a two-channel restoration method in which one channel contains point-sources and the other contains a smooth background to represent the sky or an extended object. The second channel is regularized by the addition of an entropy term to the expression being maximized, but the first is treated as a simple likelihood maximization. This method has many advantages including the suppression of the artifacts often seen around bright stars in conventional single channel restorations and photometric fidelity without the bias found in most restoration techniques (e.g., Cohen 1991).

The technique of multiple channels with different regularization is here extended in two directions of relevance to crowded field photometry. First an experimental three-channel method is described in which one channel has a *neg-*

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ative coefficient for the entropy term. This has the opposite effect to the normal smoothing which follows from positive entropy coefficients and enhances point sources, ultimately to the point where they become δ-functions (single pixels or sub-pixels). Secondly, ways of extracting a PSF from an image containing designated point-sources are described as well as different ways in which such a PSF may be regularized. An implementation of a recently suggested theoretical form for the PSF of ground-based telescopes is available and is suitable for use as a *default* PSF.

2. Star Finding

Maximum likelihood restorations often develop noise "spikes" when large numbers of iterations are used and regularization methods, often based on maximizing an entropy expression, are used to impose smoothness. However, point sources in images are really δ-functions on the sky and hence are the opposite of smooth. This suggests a method for finding point sources using an entropy *minimization* rather than the normal maximization used to impose smoothness. In this case an objective function of the following form is maximized:

$$Q = \sum_i \tilde{\Phi}_i ln \Phi_i + \alpha S + \beta T, \tag{1}$$

where $\tilde{\Phi}$ is the observed intensity distribution, Φ is the current estimate and the summation is performed over all pixels in the image. The first term is the likelihood, and S and T are entropy-type expressions. The second term has positive α and acts as a standard regularization to enforce smoothness on the background channel. The third term has $\beta < 0$ and leads to a minimization of the entropy of a "points" channel. Both entropy expressions are evaluated relative to floating priors, the second term relative to a highly smoothed version of the total estimated intensity in the image and the third relative to a slightly smoothed version of the current estimate for the points channel. It is necessary to choose the parameters α and β, as well as the degree of smoothing applied when creating the floating defaults, so that even faint points are successfully found but noise clumps are not detected. An experimental implementation has been coded as a program called **stars**. Unlike normal star finding methods which seek local maxima this method is global and works on the entire image.

Figure 1 (*left*) shows a typical deep CCD image of a star cluster. This frame is part of an $I-$band image of the cluster M71 taken by F. G. Jensen (Aarhus) using the Nordic Optical Telescope, and used with his permission. Figure 1 (*center*) shows the points (low entropy) channel produced by applying this method to Figure 1 (*left*), and Figure 1 (*right*) shows the smooth (high entropy) background channel obtained simultaneously. All the stars visible to the eye in the input have been found and there are few spurious detections. The background smooth image shows small artifacts caused by the displacements of the stars from the centers of pixels. This map of the star positions may then be used directly as input to the PLUCY two-channel code to obtain *unbiased* magnitudes for the designated point-sources.

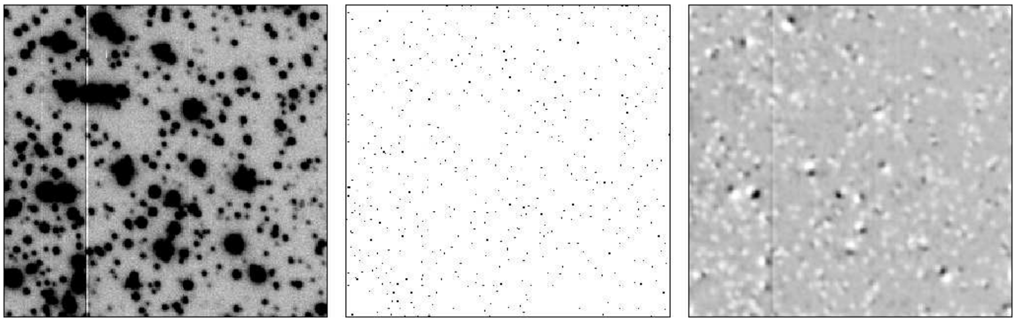

Figure 1. An example of star finding: see text for details.

3. PSF Determination

Successful image restoration and photometry both require a good knowledge of the PSF. Many restoration methods can be generalized to allow simultaneous "blind iterative restoration" in which the PSF is obtained simultaneously with the restored image. Such methods are generally thought to be unreliable and are little used. However, when the additional information of designated point-sources is added much greater robustness and reliability is achieved. Such simultaneous PSF determination can easily be added to the PLUCY two-channel code and a preliminary example of its use on *HST* data is given in Hook & Lucy (1994).

Such results tend to retain noise features from the data frames, particularly around bright stars, and are clearly not optimal. It would be advantageous to use extra information about the PSF expected and also to provide regularization to produce a resultant PSF which is smooth. The code has now been updated to include such regularization and found to be effective. We now need a suitable choice of form for the regularizing, default PSF.

Several models for ground-based PSFs have been proposed and used. These are typically simple analytic functions (such as the Moffat function or multiple Gaussians) which may be conveniently fitted to stars but do not have any physical basis. However, recently Saglia et al. (1993) have investigated another form for such PSFs which can be derived from the theory of atmospheric seeing and they show that this form fits observed PSFs as well as, if not better than, the more traditional ad hoc forms. This new form has only two parameters (one of which is simply the size of the star images as defined by the FWHM) but has the minor disadvantage of not being analytic, being instead the Fourier transform of a simple exponential function. This form for the PSF has been implemented as an IRAF compatible task called "seeing" and seems an excellent choice for a default PSF.

Figure 2 shows the steps in the derivation of a good PSF from the same M71 image used above. First the FWHM of bright (but unsaturated) stars in the frame is measured. This value is then used to produce a default PSF of the Saglia et al. (1993) form (*upper-right*). This in turn is used as the default PSF with the PLUCY code to finally give the required best estimate for the PSF (*lower-left*). A simple circular disc is used as the first approximation for the

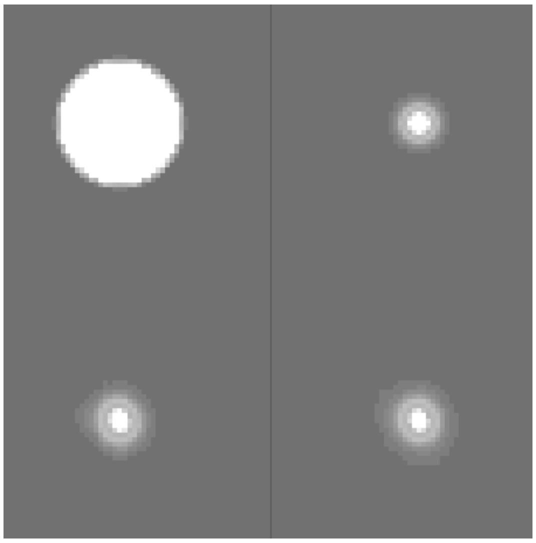

Figure 2. PSF Determination—see text for details.

PSF (*upper-left*). A clear elongation of the images has been well modelled and the result is smooth and free of noise features. The PSF found by DAOPHOT, using the same input data, is given at the lower-right for comparison.

4. Conclusions

We have extended earlier work on multi-channel, regularized image restoration to produce experimental codes which allow both the mapping of point-source positions in an image and the estimation of the PSF during a subsequent photometric image restoration. A recently suggested form for ground-based PSFs has been implemented and found to be a suitable default. Tests have successfully been made using a typical deep, ground-based CCD frame. All codes have been implemented using the F77/VOS interface to IRAF and are available on request.

References

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