Stellar Photometry with the FOC

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Abstract

The steps in preparing an FOC image for photometry are described. We have found that the best photometric results come from DAOPHOT fitting of an empirical PSF to the stars in the unrestored image. Deriving a PSF from an image poses problems, solutions for which are discussed, as are procedures for removing unreliable stars after the measurement. Photometry with the post-COSTAR FOC will be much easier, but there will still be special problems. Some of our efforts have gone into calculation of color equations between FOC bands and standard systems. The color equations depend in a surprisingly strong way on metallicity, and they also depend on interstellar extinction. In this paper we will touch upon a number of problems that relate to photometry: how to do some things, other things that are lacking, and some of the characteristics of the results.

I. Preparation of the Image

The first stage is the preparation of the image for measurement. For most observers and images this is done by the RSDP pipeline (although tasks exist in STSDAS that allow the observer to do his or her own preparation—as might be appropriate if improved calibration files become available).

The first step is geometrical correction. This is done in a fairly satisfactory way that is flux-conserving, although the edge regions of an image are not corrected as well as is the middle. There is also one aspect of geometrical correction that remains undone. Each line of the image is produced by a TV scan that oscillates in speed near the beginning, so that the right-hand edge of the image has several bands that differ in sensitivity by about 10 percent. The nature of this defect is still not fully understood, since part of it might be a difference in sensitivity as well as in scan speed, and it has not yet been included in the pipeline. It can be removed by carrying out suitable procedures on the raw (.D0H) image, but the geometrical correction in that part of the image is then no longer appropriate.

Another problem of geometrical correction is that it has not been completely stable with time, particularly in the f/48 camera. From time to time the geometrical correction data file has been changed.

The flatfielding is reasonably good, but not perfect. The only test we have made of it

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(by measuring the same stars as they fall in different parts of the field on two different images) suggested errors of 10 percent or worse, but the test was probably corrupted by use of stars that fell in the non-linear range of the image transfer function. Until now there has been very little material available for such testing, but a number of images have recently been taken that should allow star images to check both the flat field and the nature of the irregularity at the start of the scan.

Two other problems remain in the flatfielding. One is that the flat fields are heavily smoothed and do not contain any features smaller than a dozen pixels or so. Thus all the blemishes remain, and the question of actual small-scale variations in sensitivity remains unanswered. The other problem is the pattern of diagonal striping that shows up in f/96 images, in extended regions of high density (Fig. 1). It is worst in areas in which the count rate is in the non-linear part of the ITF, but these areas can be corrected for non-linearity and used perfectly well if this annoying pattern is removed. For the removal method and its availability, see the previous short paper by King et al. Fortunately this method can be applied to the output image of the pipeline (.C1H), so that it is not necessary to repeat the pipeline processing.

The reseau marks that are used in the geometrical correction are not removed by the pipeline, but they can be dealt with by the STSDAS RREMOVEX task, which interpolates over them.

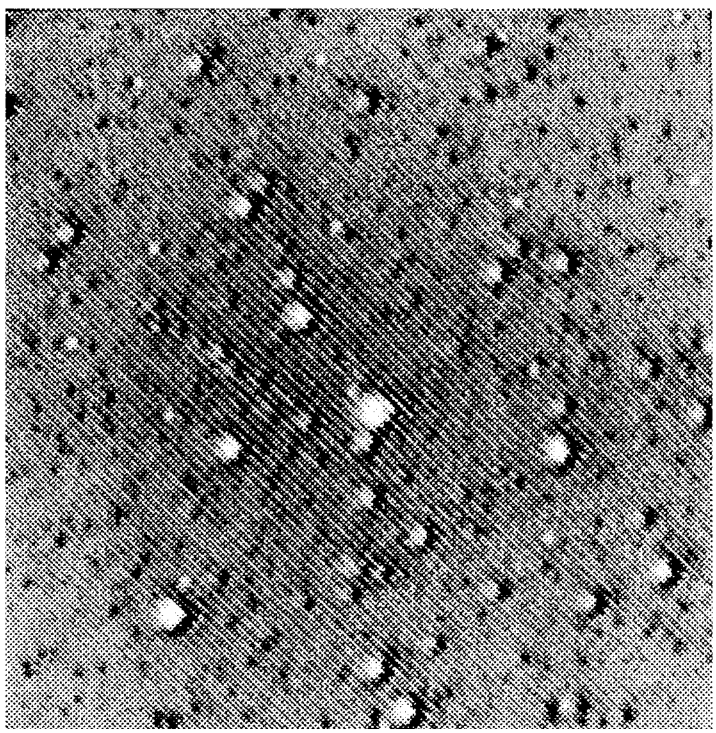

Figure 1: Central part of an FOC f/96 image of the globular cluster M15. Easily seen are the réseau marks, the diagonal stripes, and the white spots at the centers of saturated images

II. The Process of Photometric Measurement

The spherical aberration of *HST* is notorious, and one might think that all images need to be corrected for it. We have found, on the contrary, that we do better photometry on the unrestored images. We do PSF fitting with DAOPHOT. It is definitely superior to aperture photometry on the restored image. One cannot properly use the least-squares fitting of DAOPHOT on a restored image, because the size of the pixel errors has changed and the pixels are now correlated with each other. One of us (I.R.K) has done some exploration of the problem of least-squares fitting of a restored image, but has not carried it through because it did not seem to be needed for the approaches that we were using for photometry. But there has been a great improvement in restoration methods recently, and it may be worth taking this problem up again. A little more information about it is given in a paper by King in the proceedings of the Image Restoration Workshop (Hanisch and White 1994).

In order to use DAOPHOT successfully on an unrestored image, we have had to face two serious problems: (1) saturated stars and (2) getting an adequate PSF.

The problem of saturated stars is that they have extensive halos that need to be fitted and subtracted out, so that neighboring stars can be measured. This was at first a daunting task, because the saturation removes the center of the image in an asymmetric way that makes it hard to tell where the center of the image is. (Figure 1 includes a number of saturated star images, where this effect is easy to see.) We did a great deal of inconclusive work trying to find proper centers and scale factors for saturated images by hand and eye. But finally we figured out how to get DAOPHOT to do it for us. One of us (C.S.) has devised the following method: In each saturated image we delineate the saturated area (and the part near it that is non-linear), and we raise the pixel values in this area to a high number that is above the threshold beyond which DAOPHOT is instructed to ignore pixels. DAOPHOT is then able to take the saturated images in its stride and fit their outer parts, so that their halos can be properly subtracted.

Having an accurate, full-size PSF is essential to the process of DAOPHOT measurement. Even though our use of DAOPHOT fits only the small central part of the PSF that has the highest, and therefore most significant, values, we must then subtract out the whole PSF, out to its outermost edge, and do so accurately. (What we are talking about here is, in the f/96, a radius of the order of 100 pixels.) It is not easy to find a PSF that will fit a particular image. In fact, it turns out to be downright impossible. A PSF library is of no use for this purpose, because the PSF in the library invariably turns out to have been taken at a different setting of the OTA focus. Because of the OTA breathing, in which the focus shifts slightly in the course of each orbit, each image may have a unique PSF. The only recourse seems to be to bootstrap the PSF out of the image that we want to measure.

There are various ways of doing this. In a very few fortunate cases there are enough isolated stars, with enough range in magnitude, that we can piece together a PSF from the radial span in each star image that falls in the narrow dynamic range between saturation at the top and hopelessly low S/N at the bottom. But this is a rare occurrence. Nearly always we have to assemble a PSF from the scraps of numerous star images that are in the right intensity range and have parts that are not disturbed by neighbors. One of us (J.A.) has had some success doing this by an iterative process in which he gets the best PSF that he can, measures the magnitudes of the stars, and then uses the knowledge of the relative magnitudes to fit these good scraps together. Iteration of this process produces a better and better PSF, which can then be fed into a final conventional DAOPHOT measurement.

For this task, it is interesting to note that the image-restoration experts now include in their repertory a process called blind deconvolution, in which the deconvolution process recovers the PSF at the same time as it is doing an image restoration. (For discussion, see various papers in Hanisch and White [1994].) One may hope that some of these algorithms will be capable of extracting a good PSF from a globular-cluster image, for example.

Another area that we should touch on is post-processing. The image that has been measured has had reseau marks and blemishes removed[1], but in so doing some stars may have been corrupted. These stars have to be expunged from the result list, as do faint stars that are hopelessly buried in the halos of brighter neighbors, etc. To do this (which exists equally in ground-based work) we have always used a program that accepts as inputs the result list and the original image, and displays zoomed pictures of the measured stars one by one. Then the observer can judge each individual star and reject the ones that are situated in a position where they could not have been measured correctly. One of use (C.S.) has written a Sun display program that allows examining individual stars at a rate of more than 1000 per hour.

The FOC staff is considering implementing a quality mask in the observer's data package (which exists but has so far been all 1's), but it will probably turn out that the visual check against the original .C1H image is the best way of pruning an output list down to the stars that are really valid.

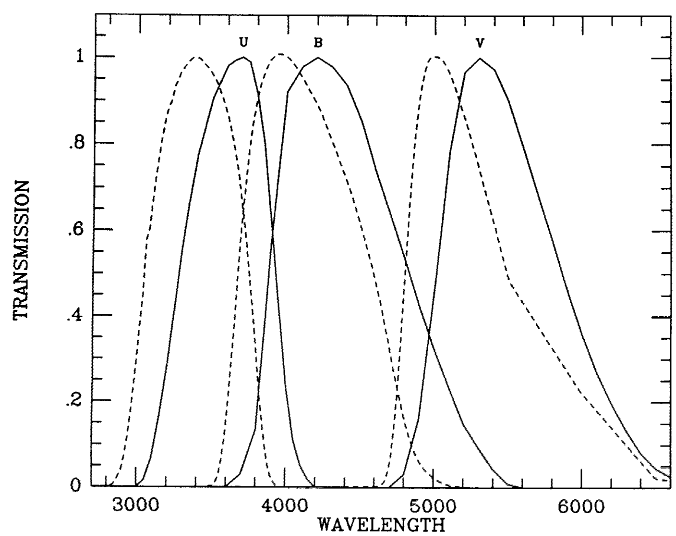

Figure 2: Transmission curves of the FOC *UBV* filters F342W, F430W, and F480LP (dashed) and the Johnson *UBV* (solid). All curves are normalized to a peak value of unity.

Everything that we have said so far applies to the aberrated *HST*. But what about the post-repair era, when COSTAR gives us diffraction-limited images? Certainly photometry will get easier on the whole, but two new troubles will face us. The re-imaging that corrects the spherical aberration can do so only at the cost of a small

1. Reseau marks and blemishes are not removed by the calibration pipeline. The user can remove them in post processing.

amount of astigmatism that varies linearly across the field. This will put us into the unpleasant domain of the spatially variant PSF. Esthetically the differences are hardly noticeable, but for measurement they will have to be taken properly into account. Fortunately, DAOPHOT is already equipped to handle this kind of PSF variation, but it will cost us more effort in PSF construction.

The second problem is that the post-COSTAR PSF will be a diffraction pattern and will therefore have a direct dependence on wavelength. (The present aberrated PSF shows this effect to a small extent, but its form is dominated by the spherical aberration.) In the broad-band filters through which we do most of our imaging, the PSF will be noticeably different for red and blue stars, because of their different effective wavelengths for this diffraction pattern. Another modification will have to be made to DAOPHOT for this effect; and photometry will be a two stage process: first with a color-independent PSF, and then, when approximate colors for the stars are known, a final measurement with color-dependent PSFs.

III. Interpretation of Photometry: the Problem of Color Equations

Finally, we want to take up the problem of color equations, which we need to apply in order to interpret our FOC photometry in terms of known astrophysical quantities. In general, we need to be able to convert measurements made through our filters into the standard Johnson UBV system. This turns out to be an unexpected headache.

Here we rely on calculations by one of us (J.A.), who has carried out synthetic photometry on a wide range of stellar types. For this purpose we have created spectrophotometric curves for stars along the sequences of globular clusters of various metal abundances. This we do by using the Yale isochrones (Green et al. 1987) to get the values of $\log T_e$ and $\log g$ for each star and then producing a spectrophotometric curve for each star by interpolation in a grid of model atmospheres calculated by Kurucz (1979, and private communication). We have not yet published these results, because we still lack model atmospheres for blue horizontal-branch stars, but we would like to present some flavor of the results here.

First, we should note that the FOC F342W, F430W, and F480LP passbands are not a very good match to the Johnson UBV bands (Fig. 2). This makes the effects that we are going to show you worse than they would be if the bands were closer matches.

First let us look at some color equations for F480LP (Fig. 3), which is the best behaved of the three bands. The first thing to notice is that the color equation is considerable, about $0.1(B - V)$. Straight lines do fit the color equations, certainly at any level of photometric accuracy that we can hope to obtain. What is a little disturbing, though, is that the slopes differ noticeably for the three different metallicities shown here. For the other two bands the situation is worse. In Figure 4 are shown the slopes of their color equations as a function of the metallicity of a globular-cluster. As you can see, the F430W has a color coefficient with respect to the standard B that is quite large, and the value of the coefficient has a metallicity dependence that is probably large enough that we should choose the value that is appropriate for the metallicity of the stars that we are working on.

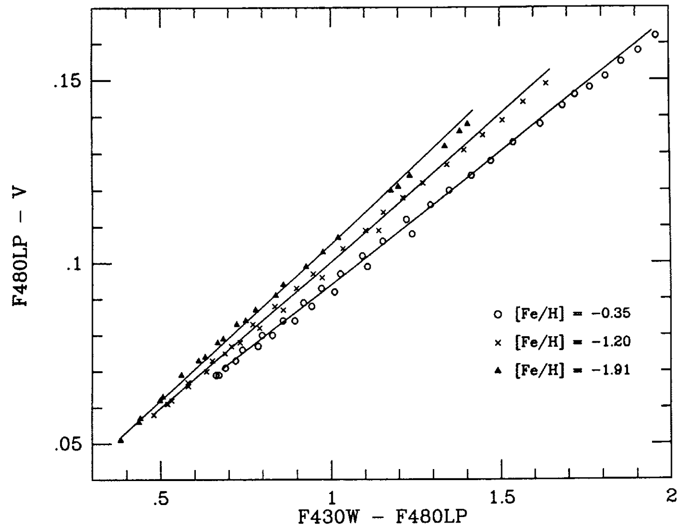

Figure 3: Color equation plots for the F480LP filter. The straight lines are least-squares fits to the stars above the main-sequence turnoff.

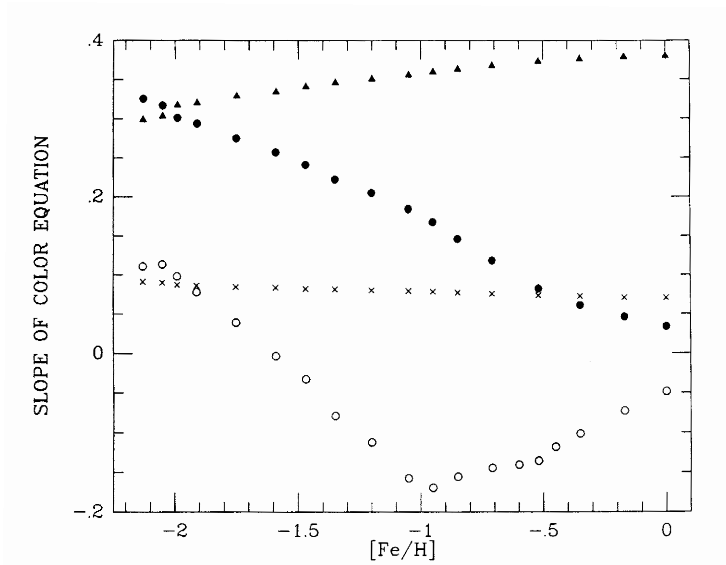

Figure 4: Slopes of color-equation plots as a function of metallicity. Crosses, F480LP (*V*); triangles, F430W (*B*); circles F342W (*U*)—solid circles for fit to stars above main-sequence turnoff, open circles for stars below MSTO.

But it is the *U* color equation that is amazingly ill-behaved. Not only does the color coefficient of the correction to F342W depend strongly on metallicity; it is quite different for stars of the same color above and below the main-sequence turnoff!

Finally, we show in Figure 5 the dependence of color-equation slopes for a constant metallicity but for differing amounts of interstellar absorption. Again the effects are quite noticeable.

The moral that we would like you to draw from this is that color equation depends on just about every possible parameter—especially when systems are not very well matched to the standard systems.

But these magnitudes are only in the computer; what about empirical calibration of the FOC bands? This has not been provided for in any *HST* program. What we will probably have to do in order to achieve an adequate standardization of FOC photometry is to derive empirical color equations for the globular clusters for which CMDs can be derived from FOC material and from the ground, and use our calculations to interpolate in and extrapolate from them.

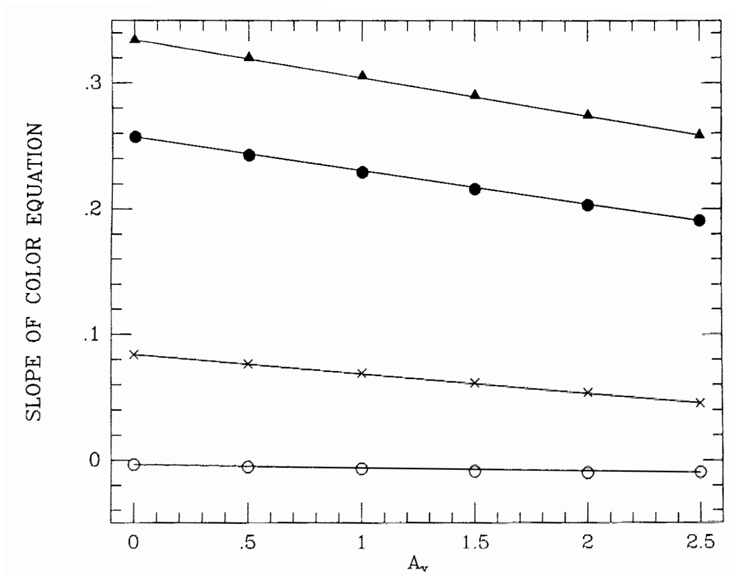

Figure 5: Slopes of color-equation plots as a function of interstellar extinction, all for the globular cluster NGC 6397 ([Fe/H] = –1.91). Symbols have the same meaning as in Figure 4.

Although we have not done similar calculations for the WFPC (and will not do so until we fill in the missing BHB stars in our database), there seems little doubt that similar effects occur for the WFPC, since its filter bands are not perfectly matched either. There one has the problem that color equations have been determined by observing with the WFPC a standard sequence in Omega Centauri, which is rather metal deficient, and that these color equations have then been used to derive colors of stars of solar metal abundance, or even of super-metal-rich stars in Baade's Window.

And we already have a small photometric disaster in one or two WFPC[1] programs, which have used the F336W (*U*) and F439W (*B*) filters to discriminate blue stars. We have found that in a cluster of very low metallicity a color-magnitude diagram made from these two bands has the horizontal branch lying across the subgiant branch, so that the HB stars cannot be separated out. Fortunately the shift is less extreme at metallicities that are less extreme, so that part of the program can be salvaged; but here is another example of the tricks that color systems can play on you.

We should mention in passing that this is not purely an *HST* problem. The filters used with ground-based CCDs differ considerably from the Johnson filters that were used in the photoelectric calibration of the standard stars. So systematic errors

1. For a discussion of WFPC photometric properties the reader is referred to the WFPC section in this volume.

probably exist in the ground-based results too. This is a sobering thought, when a gigayear of age corresponds to such a small difference in the color of the main-sequence turnoff.

IV. Conclusion

Photometry with the FOC presents a number of challenging problems, some of which we have solutions for and some of which clearly need further work.

References

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