The WFPC Photometric System

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Abstract

WFPC passbands differ substantially from those of other photometric systems. This paper deals with (1) the calibration of those passbands, (2) the choosing of filters for a photometric system, (3) transformability to other photometric systems, (4) hazards in astrophysical interpretation of WFPC photometric data, and (5) in–flight calibrations of WFPC2 needed to deal with those problems.

For color–magnitude and color–color diagrams of stellar populations, the three recommended WFPC2 filters are F336W, F555W, and F814W. What is needed in addition to conventional flat fields and photometric calibrations is a simple test of the system to see whether those calibrations yield correct astrophysical results. A few short exposures on an already well studied population such as 47 Tucanae would be a very valuable part of the in–flight calibration process.

I. Calibration of the Passbands

Standard star sequences were calibrated from Chile in 1985 using a CCD camera in which the chip and filters were identical in type to those now aboard the *HST*. Results are contained in Harris et al. (1991; 1993) and can be found in data files accessible through the Space Telescope Science Institute.

These ground-based observations included 15 of the potentially most useful WFPC passbands, ranging in nominal wavelength from 336 nm to 1042 nm. The 15 selected passbands are identified in Harris et al. (1991). Following tradition, the zero points of the magnitude scales were adjusted to make A0V stars be of equal magnitude in all passbands, and they were made consistent with Johnson–Cousins *UBVRI* zero points by fitting to Landolt's (1973, 1983) *UBVRI* standards in Kapteyn Selected Areas around the equator.

Standard WFPC sequences were then created in two fields to which the *HST* can be pointed for periodic in–flight calibration. They are located in the outskirts of the globular clusters Omega Centauri and NGC 6752, and are described in Harris et al. (1993). Each calibration field is about 4 arcmin in diameter, and each provides magnitudes in the 15 WFPC passbands for more than 60 standard stars, including a few that are blue. The standard stars lie mainly between 15th and 19th magnitude

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in the F555W passband. That magnitude range was chosen to ensure high signal–to–noise data, without saturation, for conveniently short exposures in all 15 passbands. With the exception of data for F336W and F1042M, the standard stars have internal errors averaging less than 0.02 mag. WFPC2 retains 14 of the original 15 calibrated WFPC1 passbands. F725LP is the only one that was dropped.

Most of these selected WFPC passbands are wider than their counterparts in other standard color systems, because the WFPC team decided early–on to seek the highest possible signal level while accepting a slight reduction in astrophysical purity. For example, F555W (the most popular WFPC filter) is 1.9 times wider than Johnson *V*, and F569W (the purported substitute for *V*) is 1.4 times wider than Johnson *V*. There is, however, a medium–width filter, F547M, which is only 0.8 as wide as Johnson *V*, and which transforms to *V* with almost no color–index dependence.

II. The WFPC Photometric System

As a practical matter, a photometric system should be based on only a few filters — not 14. We therefore need to consider what subset of the 14 should be chosen for a WFPC Photometric System. For many of our GTO programs, including the study of stellar populations with color–magnitude diagrams and color–color diagrams, the filters originally preferred by the WFPC1 team were F336W, F555W, and F785LP. But, because of the spherically aberrated PSF, most of the WFPC1 team's stellar population programs were postponed. In reviving those programs using WFPC2, we now recommend F814W in place of F785LP, because the infrared response of the WFPC2 chips differs somewhat from that of the WFPC1 chips. Thus, the filters of choice for stellar populations are now those shown in the following table:

Table 1: The WFPC Photometric System

	WFPC2 Passband	$\bar{\lambda}$ (nm)	$\delta\bar{\lambda}$ (nm)	$\int QTd\lambda/\lambda$ (percent)
Ultraviolet	F336W	334	38	0.33
Blue	F439W	430	47	0.47
Visual	F555W	541	124	2.50
Red	F675W	671	88	2.16
Infrared	F814W	794	153	1.96

These five passbands are WFPC analogs of *UVBRI*, but are certainly not equal to them. In some *HST*–WFPC programs, only F555W and F814W are being called for. In others, F336W is included. If a blue band is to be added, F439W is the only available candidate. For adding a red band, the choice of F675W may be more debatable. A popular alternative to F675W for red is F702W because of greater width and higher throughput, but F702W much more strongly overlaps F814W and is therefore more redundant with it. Another popular passband of great width and high throughput is F606W, which is being used for deep surveys.

There has been much thrashing about in reviewing the choice of F336W for the ultraviolet, because F300W (a new option available with WFPC2) will be more sensitive for the detection of hot stars. On the other hand, F300W cannot be directly tied to ground-based photometry nor be easily linked to existing color–magnitude relationships. Moreover, a theoretical color–color diagram using F300W does not appear to offer any astrophysical advantage over one using F336W. In addition, F300W may be inherently harder than F336W to calibrate accurately, because the calibration of F300W will depend on the photometry of WFPC2 frames containing only a single spectrophotometric standard star. The current majority view of the WFPC1 team is to use F300W for detecting the presence of hot stars, but to retain F336W for color–magnitude and color–color diagrams.

That may change. The ultraviolet imaging capability of WFPC2 adds another dimension to the exploration of stellar populations and star–forming regions. Passbands like F300W, F255W, and F160W may thus be candidates for incorporation into an extended WFPC Photometric System, despite calibration problems. Indeed, more than one such system may evolve.[1]

III. Transformations

We have calculated transformations between the 15 calibrated WFPC passbands and the five standard Johnson–Cousins *UBVRI* passbands by plotting our ground-based WFPC–system observations (Harris et al. 1991) against Landolt's (1973, 1983) data for the same Selected Area stars. The internal consistency of repeat observations clearly indicates that part of the scatter in those plots (particularly for the ultraviolet) must be due to intrinsic differences in stellar spectra. Least–squares quadratic fits to the data yield transformation formulae that probably represent abundances near solar values, while discordant stars differ somewhat in metallicity. To help quantify the second–order terms of the transformations, we also calculated theoretical magnitudes based on Gunn–Stryker (1983) spectra. The following quadratic transformation formulae pertain to the range $0.0 < (B - V) < 1.0$ for dwarfs, and to $0.0 < (B - V) < 1.0$ for giants. The exception is the transformation for F336W, which is not valid for stars bluer than $(B - V) = 0.4$.

$$\mathrm{F336W} = U + 0.077\,(U - B) + 0.018\,(U - B)^2 - 0.114$$

$$\mathrm{F439W} = B - 0.092\,(B - V) + 0.017\,(B - V)^2$$

$$\mathrm{F547W} = V - 0.009\,(B - V) + 0.001\,(B - V)^2$$

$$\mathrm{F555W} = V + 0.077\,(B - V) - 0.025\,(B - V)^2$$

$$\mathrm{F569W} = V - 0.087\,(B - V) - 0.001\,(B - V)^2$$

$$\mathrm{F606W} = V - 0.322\,(B - V) - 0.004\,(B - V)^2$$

1. Users preparing *HST* observing programs should contact a WFPC2 instrument scientist at STScI for information on recommended filters and be aware of information in the Handbook and Newsletter.

$$F622W = R + 0.200\,(V-I) + 0.013\,(V-I)^2$$
$$F675W = R - 0.163\,(V-I) + 0.023\,(V-I)^2$$
$$F702W = R - 0.153\,(V-I) - 0.006\,(V-I)^2$$
$$F791W = I + 0.050\,(V-I) - 0.008\,(V-I)^2$$
$$F814W = I + 0.058\,(V-I) - 0.027\,(V-I)^2$$
$$F725LP = I + 0.029\,(V-I) - 0.033\,(V-I)^2$$
$$F785LP = I - 0.055\,(V-I) - 0.034\,(V-I)^2$$
$$F850LP = I - 0.032\,(V-I) - 0.066\,(V-I)^2$$
$$F1042M = I - 0.064\,(V-I) - 0.116\,(V-I)^2$$

The dependence of these transformations on the nature of the stellar population (i.e., the dependence on abundances) is theoretically predictable but has not yet been observationally checked. Existing ground-based observations of some open clusters, particularly M11, may help. M11 has roughly solar metallicity, whereas [Fe/H] is –1.5 in NGC 6752, and it ranges from about –2.2 to –0.8 in Omega Centauri (Noble et al. 1991).

A second set of transformations is needed to connect in–flight WFPC observations to the established ground-based WFPC system, and the problem is very complicated. No two CCDs are exactly alike. Spectral response may vary across the CCD surface, and flat–field errors may also be significant. Even in the absence of quantum efficiency hysteresis, the throughput of a channel may vary with time, temperature, and contamination history. For stellar photometry with WFPC1, there have been additional complications due to the spherically aberrated PSF, to its non–uniformity over the field, and to its dependence on telescope focus and collimation. These problems and the sources of error are dealt with in other papers at this Workshop.

The zero points of the magnitude scales are consequently much less well known for WFPC1 observations than for the ground-based calibration. Attempts to pin down the zero points of WFPC1 were reported by the WFPC team in Chapter 12 (Hunter et al. 1992) of the *Final Orbital/Science Verification Report* and by Holtzman et al. (1991). Efforts are continuing, as for example, by Phillips et al. (1993).

Although most sources of error will be less for WFPC2 than for WFPC1, we will still have to cope with some residual PSF variation over the field, with flat–field errors, and probably with residual secular effects. Except for differential measurements, the desired accuracy of 0.02 mag for WFPC2 photometry will not come easily.

IV. Hazards in Astrophysical Interpretation

Although transformations have to be made in order to compare *HST*–WFPC results with existing *UBVRI* data in the literature, it is a serious mistake to transform WFPC observations to *UBVRI* at the start, before performing astrophysical analysis. One potential pitfall has to do with the dependence of transformations on stellar abundance differences, which I have already mentioned. It is therefore important to use theoretical isochrones and luminosity functions associated with the *WFPC Photometric System* itself, such as those investigated by Edvardsson and Bell (1989). However, those models need to be expanded to provide a broader choice of Z and Y, and they particularly need to include metal–rich populations.

Another potential pitfall has to do with the ratio of interstellar extinction to color excess. It is incorrect to transform WFPC observations to Johnson–Cousins *UBVRI* and use the canonical extinction ratios associated with *UBVRI* passbands. One must instead use the ratios that pertain to the passbands of observation. The importance of this extinction pitfall caught our attention in the analysis of WFPC1 observations of the Galactic bulge, where the interstellar extinction is very large and regionally variable (Baum et al. 1992, Holtzman et al. 1993). We can use passband data from the *HST WFPC2 Instrument Handbook* (Burrows et al. 1993), together with the relations given by Cardelli et al. (1989), to evaluate this effect for WFPC2 observations. We find that the extinction for F555W will be nearly 2.5 times the color excess E(F555W–F814W), whereas the extinction for Johnson–Cousins is only about 2.0 times the color excess E(V – I).

V. Augmentation of the WFPC2 Calibration

The flat fields and standard–star calibrations that are already planned for WFPC2 will probably be adequate for much of the proposed WFPC science but could be improved for stellar population studies. Many WFPC2 programs are affected. Stellar population targets lie in star clusters, the Galactic bulge, the Magellanic Clouds, dwarf spheroidals, dwarf irregular galaxies, M31, M33, and various other nearby galaxies. The problem is that age and metallicity determinations are sensitive to having the zero–points of the magnitude scales be precisely the same as those assumed in constructing the theoretical isochrones. Consider, for example, an old metal–rich population such as one finds in the Galactic bulge, and assume exposures suitable for the turnoff region. The isochrone fit then depends to a large degree on the color indices of the turnoff and the subgiants. Using the WFPC isochrones of Edvardsson and Bell (1989), we see that an error of only 0.01 mag in the color index scale corresponds to errors on the order of 1 Gyr in age and/or 20 percent in metallicity.

The best way of improving confidence in WFPC isochrone fitting is for the calibration program to include some WFPC2 observations of a population whose age and metallicity we already have some confidence in and are willing to adopt for reference. An ideal isochrone reference target would be the exceptionally well studied globular cluster 47 Tucanae (NGC 104). A field of suitable star density in 47 Tuc would have to be selected, and approximately the following exposure times would be needed:

WFPC2 Passband	F336W	F439W	F555W	F675W	F814W
47 Tuc exp. (sec)	700	135	20	25	30

At least two such exposures should be taken in each of these passbands in order to deal with cosmic rays.

There may be alternatives to 47 Tucanae, but our calibration field in Omega Centauri cannot be used for this purpose, because of the spread in its metallicity (Noble et al. 1991).

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