Realization of BV photometry with Starmappers

L Lindegren, 1981 Sept 21

Why BV photometry?

The scientific value of the photometry obtained with the Starmapper(s) is greatly enhanced if collected at two different effective wavelengths so as to permit one-dimensional classification of objects according to colour. This will be true also if TYCHO is rejected, since colours of most of the 100,000 programme stars could still be obtained. These will be valuable also for the HIPPARCOS data analysis, e.g. to eliminate chromatic effects.

The B and V magnitudes of the UBV system (by Johnson and Morgan, 1953), or some similar system, seem to be the natural choice for a number of reasons:

(a) The UBV system is by far the most generally utilized photometric system. More than 50,000 stars have been measured in UBV to this date, so there will be no lack of photometric calibration stars for TYCHO.

(b) The magnitude difference B-V is a good measure of the colour or apparent temperature of a (normal) star, in the sense that there is an almost one-to-one correspondence between B-V and the overall spectral energy distribution in the interval 375 - 800 nm.

(c) UBV is a broad-band system, so that a sizeable fraction of the light is transmitted. The combined passbands of B and V cover the interval 380 - 650 nm, which fits very well with the limits imposed by a partly dioptric system on one hand, and typical PMT sensitivity curves on the other.

B and V response curves

The apparent magnitude $m$ (= B or V) of a star is defined in terms of its spectral energy distribution, $F(\lambda)$:

$$m = \text{const.} - 2.5 \log \left[ \int F(\lambda) S_m(\lambda) \, d\lambda \right],$$

where $S_m(\lambda)$ is the system response curve (transmittance x quantum efficiency). This is primarily characterized by the effective wavelength

$$\bar{\lambda}_m = \int S_m(\lambda) \lambda \, d\lambda / \int S_m(\lambda) \, d\lambda$$

(other definitions are also used), and the effective bandwidth $\Delta \lambda_m$, e.g. the FWHM.

The response curves for B and V are shown in Fig. 1. The main parameters are:

$$\bar{\lambda}_B = 450 \text{ nm}, \quad \Delta \lambda_B = 100 \text{ nm};$$

$$\bar{\lambda}_V = 555 \text{ nm}, \quad \Delta \lambda_V = 90 \text{ nm}.$$
Transformation from instrument system to B, V

Thanks to the almost unique relation between B-V and spectral shape in the region 375 - 800 nm, it is not necessary that the response of the Starmapper follows the B and V curves, or even that the main parameters (3) are closely reproduced, provided there is negligible response outside this interval.

Let \( S_b \) and \( S_v \) be the response curves of the instrument, defining magnitudes \( b, v \) according to (4). (The magnitude zero points are irrelevant here.) There exists then an almost unique transformation between \( b, v \) and \( B, V \), which can be written in the form

\[
\begin{align*}
V &= v + f(b-v) \\
B-V &= g(b-v)
\end{align*}
\]

where \( f \) and \( g \) are functions to be determined from Starmapper observations of stars with known UBV data. The transformations will in practice be nearly linear, i.e.

\[
\begin{align*}
V &= v + c_0 + c_1(b-v), \\
B-V &= c_2 + c_3(b-v),
\end{align*}
\]

where \( c_0, c_1, c_2, c_3 \) are constants.

\( c_3 \) and \( c_2 \) depend on the chosen magnitude zero points and are irrelevant to the present discussion. If the effective wavelengths of \( b, v \) are close to those of \( B, V \), we will have \( c_1 \approx 0 \) and \( c_3 \approx 1 \). In terms of the effective wavenumbers, \( n_m = 1/\lambda_m \), it can be shown that

\[
\begin{align*}
c_1 &\approx (n_v - n_V)/(n_b - n_V), \\
c_3 &\approx (n_B - n_B)/(n_b - n_v).
\end{align*}
\]

For good determination of colours (B-V), it is essential that \( c_3 \) is not much greater than unity, i.e. that the wavenumber baseline of the instrument, \( n_B - n_V \), is not much smaller that that of the BV system, \( n_B - n_B \).

Realization of \( b, v \) system

Fig. 1 also shows some typical instrument response curves without filters. These were obtained as the product of MATRA's transmission curve (curve 3 in Fig. 4.7.1 of their Phase A Report) and the quantum efficiency of three PMT sensitivity types (bialkali, Super S-11, S-20).

Also shown is the schematic spectral energy distribution (in photons per unit wavelength interval) of a B-V = 0.5 star (colour temperature 6320 K). Note that the response is low shortward of the Balmer jump (375 nm), which is necessary for a well-defined transformation (4) to exist.

Since the short wave edge of the B curve and the long wave edge of the V curve are quite similar to the corresponding parts of the S-11 response curve, it is clear that \( S_B \) and \( S_V \) could be quite accurately reproduced by means of suitable blue and yellow filters, respectively. The overall throughput would however be rather low if the sloping edges around 500 nm were to be reproduced.
It seems to be more economical simply to split the instrument response curve in two halves by means of a steep cut somewhere in the interval 470–500 nm. This could be achieved with a short-wave pass interference filter for b and a long-wave pass filter (interference or dye filter) for v, with the 50% transmission points of both filters at approximately the same wavelength. A dichroic beam splitter could obviously be used to the same effect.

It is worth pointing out that very good rejection in the stop bands is not required; a few per cent transmission may be quite acceptable.

A few different grid/filter/PMT configurations are sketched in Fig. 2. It is assumed that two active and two redundant (cold) PMTs are required.

Configuration (A) has some clear disadvantages, e.g. that it may be difficult to accommodate the filters immediately behind the grid, and that spatial inhomogeneities of the filters will directly affect the observations.

In (B) and (C), on the other hand, the angle of incidence varies with position in field, causing some variation of effective wavelength. This effect is much greater with the dichroic mirror than for transmission filters with near-normal incidence.

It is advantageous if a given PMT operates in one passband only (b or v), since its sensitivity type can then be optimized for the relevant wavelengths.

Table 1 gives effective wavelengths, FWHMs, the relative throughput, and the transformation coefficient $c_3$ for some PMT/filter combinations. From the $c_3$ values it appears that any of these combinations would give adequate determination of $B-V$ colours. However, the uniqueness of the resulting transformations (4) should be tested with actual stellar energy distributions for a wide range of spectral and luminosity types. Such spectral data are available (in machine-readable form) at Lund Observatory, and it would be comparatively simple to compute $b$, $v$ magnitudes for a large number of stars, once the instrument response functions are better defined.

<table>
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<tr>
<th>PMT sensitivity</th>
<th>$\lambda_x$ (nm)</th>
<th>$\lambda_b$ (nm)</th>
<th>$\lambda_v$ (nm)</th>
<th>$\Delta \lambda_b$</th>
<th>$\Delta \lambda_v$</th>
<th>$\int S(\lambda) d\lambda$ (relative)</th>
<th>$c_3$</th>
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<td>bialk bialk</td>
<td>470</td>
<td>428</td>
<td>518</td>
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<td>78</td>
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<td>127 128 255</td>
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<td>580</td>
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<td>110</td>
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<td>171 133 304</td>
<td>0.77</td>
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</table>
FIG. 1.

Response curves for B and V (short dashes)
Response curves for MATRA transmission x QE (solid lines)
Spectral energy distribution of B-V = 0.5 star (long dashes)
Conf. (A)

Conf. (B)

Conf. (C)

(Active) b

(Redundant) PMT's

(Active) V

(Redundant) PMT's

(Redundancy by switching mirrors)