BBP photometric systems evaluation

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Abstract

The evaluation of the proposed broad-band photometric systems is presented. This evaluation is done for a set of scientific priority targets and according to a defined figure of merit. The figure of merit is based on the comparison of the estimated posterior errors and the error goals for the astrophysical parameters ($T_{\text{eff}}$, $\log g$, [M/H] and $A_V$) and includes \textit{a priori} information from the trigonometric parallax. A recommendation for the Gaia broad-band photometric system baseline is provided according to the results of the evaluation.

1 Introduction

The procedure to come to a recommendation for a baseline photometric system (PS) for Gaia was decided on at the Copenhagen PWG meeting in April 2004 (Hög & Jordi, 2004a). This procedure is based on earlier discussions that took place at various PWG meetings (notably ESTEC June 2001, Vilnius July 2001, Barcelona November 2001, Tartu July 2002, Leiden November 2003, Torino January 2004) and is fully described in Brown et al (2004). The recommendation is based on an objective performance evaluation of the proposed photometric systems. This evaluation is done for an agreed upon set of scientific priority targets (STs) and consists of:

- Calculating the posterior errors that can be achieved with a PS and comparing those to the error goals. The results are summarized by a figure of merit (FoM).
- Evaluating the global degeneracies of the PS.
- Considering additional criteria such as, for example, the performance with respect to discrete object classification and the technical feasibility.

The set of scientific targets, astrophysical parameters, priorities, error goals and the assumed \textit{a priori} information are detailed in Jordi et al (2004a,b). The scientific targets are single stars belonging to the four main stellar populations of the Galaxy (halo, thin and thick disks and bulge) as observed in several locations of the Galaxy. The posterior errors of the astrophysical parameters ($T_{\text{eff}}$, $\log g$, [M/H] and $A_V$) and the figure of merit were calculated according to the methods outlined in Lindegren (2003a). The value of the parallax and its uncertainty have been included as \textit{a priori} information according to the prescriptions in Lindegren (2004).

The present report deals mainly with the first item, provides some comments on the degeneracies and ends with a recommendation for the BBP baseline.
The information related to the PS optimization, files with FoM values and achieved errors on the astrophysical parameters etc., are available at the PWG website http://gaia.am.ub.es/PWG/ under ‘PS Optimization’.

2 BBP photometric system proposals

There are four strips of CCDs in the Astro focal plane devoted to broad-band photometry. A first evaluation by Jordi & Carrasco in June 2004 (see the summary in Hög & Jordi, 2004b) showed that a PS with five bands yields, in general, higher performance in terms of astrophysical parametrization than a PS with four bands, as was expected. This is not the case for the stars at the faint end, for which four bands are preferred to five.

At the January 2004 meeting of the PWG, Lindegren suggested that a five band system could be implemented by means of four bands with a gap somewhere in between. The gap in combination with the white light photometry from the AF CCDs (the $G$ flux) would constitute a ‘virtual’ filter. The figure of merit computations have subsequently shown that a better performance is obtained by having two bands of a five band system share one of the four BBP strips than by considering four bands and a gap (see summary in Hög & Jordi, 2004b). Therefore, the idea of having a ‘virtual’ filter was not pursued.

Several proposed photometric systems under evaluation contain four bands and are implemented with one band per CCD strip. The PS proposals with five bands are implemented in such a way that two bands share one CCD strip, i.e. at the end of the mission they receive half the number of observations.

We do not include in the present evaluation those PSs considered as obsolete. These proposals are based on the old Gaia design, or they have been replaced by new proposals, or in previous evaluations have been shown to have lower performances than other PSs. They are:

- Asiago proposal (2A, U. Munari, Baltic Astronomy, 8, 123, 1999)
- Genève-Barcelona proposal (1F, Gaia: Concept and Technology Study Report, ESA-SCI(2000)4 Sect. 2.3.2)
- Vilnius proposal (3G, V. Stražys et al., SAG-CUO-78, 2000)
- Lindegren’s proposals derived from chromaticity calibration studies (S4LIN, S4LOG, S5LIN, U5LIN, U5LOG, L. Lindegren, GAIA-LL-39, June 2001)

2.1 Constraints on the BBP bands

Lindegren (2003b) showed that with respect to chromaticity constraints near rectangular filters are acceptable and that the choice of the wavelength separation is more important than the
edge widths of the filter bands. He concluded that four broad bands are enough to match the chromaticity constraints (r.m.s. residuals < 5 μas). Gaps between filters should be avoided or, if they are proposed, no more than one gap is acceptable. In addition, the virtual filter cannot be any of the outer bands. The bands have to cover the whole Gaia wavelength range.

### 2.2 Four band systems

The evaluated four band proposals are (Fig. 1):

- X2B by V. Vansevicius; submitted on 7 June 2004
- H2B and H3B (based on the Heuristic Filter Design) by C. Bailer-Jones; submitted on 16 June 2004 and described in GAIA-CBJ-016
2.3 Five band systems

The evaluated five band proposals are (Fig. 2):

- 4B by L. Lindegren; submitted in December 2003 and described in GAIA-LL-051
- V1B by V. Stražys; submitted in September 2004 and described in GAIA-VILN-002
- F2B-F6B by C. Jordi & J.M. Carrasco; submitted in October 2004 and described in UB-PWG-026

3 Evaluation of the proposals

For the simulation of the synthetic white light flux \( G \), the BBP fluxes and their corresponding errors, spectral energy distributions (SEDs) for the scientific targets in the test population were taken from BaSeL2.2 library (Lejeune et al., 1998). The well known BaSeL library covers the whole HR diagram and \([M/H]\) abundances from \(-5\) to \(+1\) dex, but it does not cover \([\alpha/Fe]\) abundances different from Solar. Because it is unlikely the \([\alpha/Fe]\) abundances can be determined with the BBP, this library is sufficient for the present evaluation.

The end-of-mission magnitude errors were computed taking into account the signal-to-noise ratio, the sky background contribution, the read-out noise and the mean total number of observations. A margin of 20\% was added to account for unknown sources of error. The calibration errors will introduce a minimum error which was assumed to be 3 mmag for the end of mission. The results of the Photometric Data Analysis (Brown, 2003) will provide a better assessment of the value of this threshold.

3.1 Uncertainties of the astrophysical parameters

Following Lindegren (2003a), the astrophysical parameter determination is considered as a linearized least-squares estimation of \( \Delta \vec{p} \), \( \vec{p} \) being the vector of \( K \) astrophysical parameters, where the observation equation resulting for the normalized flux \( \phi_j \) measured in filter \( j \) \((j = 1,J)\) is:

\[
\sum_k \frac{\partial \phi_j}{\partial p_k} \Delta p_k = \Delta \phi_j \pm \epsilon_j , \tag{1}
\]

where \( \Delta \phi_j = \phi_{j,obs} - \phi_j(\vec{p}) \) is the \( O-C \) in flux and \pm indicates the flux uncertainty. The \( \partial \phi_j / \partial p_k \) values constitute the sensitivity matrix, \( S \), consisting of \( J \times K \) elements. Observation equations of unit weight are formed through division by \( \epsilon_j \), whereupon normal equations are formed in the usual manner. Given the variance-covariance matrix \( C_\phi = \text{diag}(\epsilon_j^2) \), the variance-covariance matrix of the estimated AP-vector \( \vec{p}_{\text{post}} \) is given by:

\[
C_{\vec{p}_{\text{post}}} = (B + S^T C_\phi^{-1} S)^{-1} \tag{2}
\]

The matrix \( B \) is a positive definite matrix containing \textit{a priori} information on the astrophysical parameters vector \( \vec{p} \) and it is introduced to avoid infinite or very large values of the elements.
in $C_{\text{post}}$ caused by the degeneracy among the astrophysical parameters. In the absence of any other information, the \textit{a priori} information is determined by the range of possible values of the parameters $p_k$, $B = \text{diag}(\sigma_{k,\text{prior}}^2)$. In the evaluation of photometric systems the information contained in the measured parallax and its error has been introduced in this \textit{a priori} matrix according to the proposal by Lindegren (2004). Other information can in principle be added (e.g., known reddening in a certain Galactic location, ranges of abundances according to Galactic populations, etc.). If the photometric system does not provide any relevant information on a given astrophysical parameter $p_k$ (either because of the flux variances in $C_\phi$ are too large or because the elements of the sensitivity matrix $S$ are too small), then $\sigma_{k,\text{post}} \simeq \sigma_{k,\text{prior}}$.

The calculation of the uncertainties in the parameters, $\sigma_{k,\text{post}}$, assumes that the changes in the measured fluxes of a given star, and hence the changes in its SED, are only due to changes in the parameters $p_k$. In addition it is assumed that the changes of the synthetic SEDs with the parameters $p_k$, i.e. $\partial\phi_j/\partial p_k$, match the changes in true stars. In other words, cosmic dispersion (the effects of rotational velocity, magnetic fields, chemical composition differences on an element by element basis, differences on the interstellar extinction law and so on) and inaccuracies of the SED libraries are not taken into account. In practical situations an additional source of uncertainty will come from the classification and parametrization algorithms themselves (see Bailer-Jones, 2004), which is also not taken into account in the present evaluation formalism. Therefore, the $\sigma_{k,\text{post}}$ values obtained should be interpreted as the maximum precisions that can be obtained in principle. In practice the posterior errors will likely be larger. However, because the unknown sources of uncertainty affect all PS proposals in the same way, the values of $\sigma_{k,\text{post}}$ can be used to compare the performance of one PS to another.

For the broad band photometry we have considered $T_{\text{eff}}$, $\log g$, [M/H] and $A_v$ as the target APs. Thus, $\vec{p}$ is a vector of $K = 4$ elements.

### 3.2 The figure of merit

The performance of a PS is measured with respect to the error goals set for the APs $p_k$ for a given ST $i$, $\sigma_{ik,\text{goal}}$. The figure of merit (FoM) for this ST is given by:

$$Q_i = \sum_k w_k f(\sigma_{ik,\text{post}}/\sigma_{ik,\text{goal}})$$

where $w_k$ indicates the relative weight of each astrophysical parameter and $f(x)$ is a non-linear function of $x = \sigma_{ik,\text{post}}/\sigma_{ik,\text{goal}}$ with a break around 1. The function used is:

$$f(x) = (1 + x^{2n})^{-1/n}$$

We are looking for a PS that is ‘good enough’ over all of AP space and we want to avoid giving a high rank to a system that is extremely good in only one corner of AP space but very bad everywhere else. The latter will be highly ranked for $n = 1$ but not for large $n$. However, for very large $n$ we will not be able to tell the difference between two PSs that are equally bad wherever $x > 1$ but with one PS being better than the other when $x < 1$. A value of $n = 3$ is a good compromise between these two extremes. With $n = 3$, a value of $Q_i = 0.79$ means that $\sigma_{ik,\text{post}}$ (the achieved precision for AP $k$) is equal to the $\sigma_{ik,\text{goal}}$ (the required error for the AP). A value of $Q = 0.25$ means that $\sigma_{ik,\text{post}}/\sigma_{ik,\text{goal}}$ is 2.

The error goals for the APs, as they were defined in Jordi et al (2004b) can be summarized as follows:
• $T_{\text{eff}}$ O-B stars: $\sigma_{T_{\text{eff}}}/T_{\text{eff}} = 2 - 5\%$, A-M stars: $\sigma_{T_{\text{eff}}}/T_{\text{eff}} = 1 - 2\%$

• $A_v$: $\sigma_{A_v} = 0.1$ mag at $A_v \leq 3.0$ mag, $\sigma_{A_v} = 0.5$ mag at $A_v > 3.0$ mag

• $M_v$ (log $g$) for stars with $\sigma_{\pi}/\pi \leq 10\%$: assumed known

• log $g$: for stars with $\sigma_{\pi}/\pi > 10\%$: $\sigma_{\log g} = 0.2$ dex

• [M/H]: $\sigma_{[\text{M/H}]} = 0.1$ dex (not to be determined for OB stars and supergiants)

Some of these goals are unlikely to be achieved in practice with broad band photometry ($\sigma_{[\text{M/H}]} = 0.1$ dex for example), but this does not matter for the present evaluation. We are interested on the relative performances among systems, our primary choice being the system with highest performance. The FoM providing a measure of the $\sigma_{ik,\text{post}}$ with respect to the $\sigma_{ik,\text{goal}}$ yields information on this relative behaviour.

The global FoM for a set of $m$ STs is the weighted mean:

$$\hat{Q} = \sum_i w_i Q_i / \sum_i w_i$$

(5)

It may happen that a PS performs very well for some kind of stars and very badly for others, or very well for a given AP and very badly for another one. Therefore, the overall FoM is a mean measure of the performance of a PS for the set of STs.

Tests to evaluate how much the relative performances among PSs depend on the weighting scheme have been performed and are described in Jordi & Carrasco (2004). The conclusion was that when two systems have a similar performance the ranking may change depending on the assumed weights. However, if the two systems perform very differently, the difference (ranking of the systems) is maintained even though the weights are changed. In the cases of almost equal performance it would be better to consider whether the changes of the $\sigma_{ik,\text{post}}$ values are significant or not. However, in the case of very similar overall performance it is not critical which system is finally chosen.

Tests to evaluate the relative performances when knowledge of interstellar absorption is assumed have also been done. The relative performances among PSs do not depend very much on this a priori information (see PWG website).

### 3.3 Evaluation of the four-band systems

The figure of merit values (FoM) for three of the 4-band BBP proposals are shown in Fig. 3 [the H2B system was not evaluated because of the gaps among the bands]. It can be seen that:

• X2B is superior to H3B in almost all directions for the halo stars, for almost all cases for the thick disk (except at 10 kpc in the Galactic center direction) and for the bulge stars. For the thin disk stars, both systems perform similarly, X2B being slightly better for the orthogonal direction (low reddening).
P1B performs better than X2B and H3B for highly reddened stars (bulge stars and stars beyond 5 kpc in the Galactic center and anticenter directions). It performs significantly worse than X2B and H3B for the halo and thin disk stars closer than 5 kpc and it is similar to H3B in the performance for the thick disk stars.

When the results are grouped by stellar type, P1B performs better than the other two PSs for all AGB and red clump stars and for the late K and M dwarfs of the thick and thin disks. Comparing X2B and H3B, H3B is only superior for the OB-type stars and the HB stars.

The P1B system was designed taking into account only the cool stars. This may explain the good performance for the bulge and at large distances, because then the stellar population is mainly composed of red giants and AGB stars. Looking at the groups of stellar type, we see that P1B performs the best for the very cool stars. We think that it is worth while investigating the PCA approach taking into account all of the HR diagram.

### 3.4 Evaluation of five-band systems

Moving to the 5-band proposals, the comparison among them is presented by groups of PSs differing in a particular feature, such as for example the separation of the red bands.

#### The blue band

4B, V1B and F5B only differ in their blue band. The 4B system was designed when the QE of the CCD was known to be very poor in the range 300 – 400 nm. Results from industry showed (end of June 2004) that the QE is not as low as expected and the V1B system was therefore proposed with an extension of the blue band into shorter wavelengths. At the same time, Straizys modified the red edge in order to match the Johnson B band. V1B was shown to be superior to 4B (see http://gaia.am.ub.es/PWG/meeting_paris/FoM.ppt) except in the case of the HB and A-type stars. F5B was thought up as a hybrid of both systems. Figure 4 shows the comparison between the three systems. It can be seen that the F5B system performs slightly better than 4B in the case of late type stars, but it is not as good as the V1B system. On the other hand F5B performs slightly better than the V1B system in the case of HB and A-type stars but it is not as good for these stars as 4B.

The F4B and F6B systems differ only in their blue band. The F4B system has the same blue band as the V1B system and F6B has the same blue band as F5B. Although the differences between the FoM values for F4B and F6B are smaller than for V1B and F5B, Figure 5 shows that F6B is superior only for the HB and A-type stars. In all other cases, it performs similar to or worse than F4B.

Considering the values of the $\sigma_{\text{post}}$, we see that a blue band as in V1B improves the metallicity and the interstellar absorption determinations, although it decreases slightly the precision of the surface gravity determination. To illustrate this, Figure 6 (top) shows the differences in $\sigma_{\text{post,}[M/H]}$ and $\sigma_{\text{post,}A_v}$ for the 4B and V1B systems and for the F5B and V1B systems. It can be seen that on average the differences are positive, meaning that V1B yields an overall improvement of AP determination. The differences between 4B and V1B are larger than between F5B and V1B. The former are larger than 25% for a significant fraction of the STs.
As a first conclusion we can say that: $V1B > F5B > 4B$ except for the HB and A-type stars, for which $4B > F5B > V1B$. A blue band as in $V1B$ improves the $\sigma_{k,\text{post}}$ of the FGK dwarfs and giants, while a blue band as in $F5B$ or $4B$ is preferred for HB and OB type stars. Given that late type stars are much more numerous and crucial for age determination, we recommend to adopt a blue band as in $V1B$ ($F2B$, $F3B$ and $F4B$).

- **The separation of the reddest bands**

The second set of FoM comparisons deals with the wavelength at which the two reddest bands are separated. The $F2B$, $F4B$ and $F6B$ systems locate this separation at the Paschen jump, while $4B$, $V1B$, $F3B$ and $F5B$ locate it at 815 nm. Figure 7 compares the FoM values of the $F2B$ and $F3B$ systems which only differ in this separation.

$F2B$ yields higher FoM values than $F3B$ in almost all cases, except for the AGB stars and highly reddened areas in the bulge as well as at 10 kpc in the Galactic center direction for the halo and the thick disk. Comparing the $\sigma_{\text{post}}$ values, we see that the differences are larger than 10% for the four astrophysical parameters ($T_{\text{eff}}$, $\log g$, $[M/H]$ and $A_v$) for a large fraction of the scientific targets.

Hence a second conclusion is that $F2B > F3B$, i.e. locating the reddest bands with their separation around the Paschen jump is preferred, except for the aforementioned cases.

- **The width of the central band**

Figure 8 compares the figure of merit values in different galactic directions and grouped by stellar type for the 5-band BBP proposals $F2B$ and $F4B$, which differ only in the width of the central three bands, most notably the band at 655 nm. The two systems have a much more similar performance than the ones in the previous comparisons. They differ clearly only for the A-type stars for which the $F2B$ system ($F2B_{655}$ is narrower than $F4B_{655}$) yields higher FoM values. A narrow filter favours the A-type stars, but is unfavourable in the case of AGB stars and for stars at 10 kpc in the halo, thick disk and bulge.

Therefore a third conclusion is that a narrow 655 nm band favours the A-type stars. In addition, this band combined with a still narrower band around the same wavelength in MBP may provide a temperature indicator for early type stars almost independent of metallicity and reddening.

- **Comparison among all systems**

The $F2B$ and the $F4B$ systems yield the highest FoM values among all systems which have a blue band as in $V1B$, because they also have the separation of the reddest bands at the Paschen jump. Considering the $\sigma_{\text{post}}$ values, we see that the four AP determinations (specially $T_{\text{eff}}$, $\log g$ and $A_v$) are improved by more that 10% for $F2B$ and $F4B$ with respect to $V1B$ (see Fig. 6 bottom). We have seen, however, that $F2B$ and $F4B$, having narrower bands than $V1B$, lose some performance for the faint stars (at large distances or in areas of high reddening). At the same time we have seen that the $4B$ system is better than the $V1B$ system for the HB and A-type stars. Figure 9 compares the FoM values in different galactic directions and grouped by stellar type for these systems. As can be seen, the Paschen jump measurement in $F2B$ compensates the low performance of $V1B$ compared with $4B$ for the A-type stars. In the case of the HB stars, $4B$ is still the best performing system. Given that HB stars are less numerous in the Galaxy, we recommend to adopt $F2B$ or $F4B$.

Figure 10 compiles the FoM values of all the evaluated 5-band BBP systems.
As a general conclusion the narrow bands decrease the uncertainty on the determination of
the astrophysical parameters for bright stars, but increase the uncertainty for faint stars (large
distances and/or high reddening), as expected.

4 Evaluation of degeneracies

As discussed by Brown et al. (2004) there are two important measures of the performance of a
particular photometric system (PS). On the one hand there are the errors (and the corresponding
correlations) on each astrophysical parameter (AP) that can be achieved when the PS is used
for astrophysical parametrisation. On the other hand there is the degree to which the PS is free
of global degeneracies. The latter refers to the problem that very different parts of AP space
can be mapped onto each other in filter flux space. For example, a highly reddened O-star may
to first order look like a nearby unreddened cool dwarf. These global degeneracies are not taken
into account in the figure of merit calculations. The FoM calculations only contain information
for a particular star on the correlations between the errors on the different APs, i.e. the local
degeneracies.

The characterization of the global degeneracies is important because the photometric data will
be used first to classify objects and then to parametrize them. In fact the FoM calculations
assume that one already has available a good classification of the objects in question so that the
linearized equations from which the FoM is derived apply (see Lindegren 2003).

The global degeneracies for the BBP (and MBP) systems were analysed by employing self-
organising maps. With this technique one is essentially looking for natural clusterings of stars
in filter flux space. The analysis of the characteristics of these clusterings gives insight into the
global degeneracies. The analysis is described in a separated report (Brown, 2004) and only the
conclusions are summarised here.

The investigation of the global degeneracies with self-organising maps revealed no obvious dif-
fences between any of the BBP (or MBP) systems. Thus the issue of global degeneracies
effectively has no influence on the recommendation of the baseline BBP system.

However, the self-organising maps have not been exhaustively analysed. A more sophisticated
analysis may yet reveal differences between the various BBP/MBP systems. Brown (2004)
discusses directions for future investigations of the global degeneracies and this should certainly
be done for the proposed baseline photometric systems.

5 Recommendation

Table 1 shows the global FoM per galactic population for all the evaluated 4-band and 5-band
BBP systems.

Considering the tabulated FoM values and the preceding discussion, we proceed to recommend
the following:
Table 1: Figure of merit values for the evaluated 4-band and 5-band BBP proposals

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<th>P1B</th>
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- The 4-band BBP system: we think that the high performance of the P1B system in the bulge does not compensate the loss of performance for all other Galactic populations, and therefore we recommend the X2B system as the 4-band BBP baseline.

- The 5-band BBP system: F2B and F4B are the preferred systems. F2B is superior to F4B in the case of the A-type stars but is inferior in the case of AGB stars and at faint magnitudes. We choose the F4B system because we expect better performance than with F2B when the BBP and MBP photometry are combined for the purpose of AP determination.

Comparing the four (X2B) and five (F4B) band proposals (see Fig. 11), we see that the 5-band proposal yields more precise astrophysical information than the 4-band proposal for most of the stars, as expected, except in the case of highly reddened stars. This latter refers to the highly reddened areas of the bulge, halo and thick disk stars in the galactic center direction beyond 5 kpc. We do not think that the halo and thick disk stars are a problem. The study of the halo and the thick disk can be done avoiding these regions. Thus, considering the halo, thick and thin disks together, we recommend the 5-band option and among these systems, F4B is our choice.

If the BBP system is to be optimized only for crowded areas, the bulge stars become more relevant and in that case, a 4-band system would be preferable and among them, the P1B system is the best performing (for the bulge). However, before accepting any of the current four-band proposals as the baseline, they should be revised to cover the whole Gaia wavelength range in order to be consistent with the chromaticity requirement.

Our proposal is to account not only for the bulge, but for all stellar populations, hence we recommend the adoption of the F4B system as the BBP baseline.

Figures 12 to 14 show the mean achieved precision with the F4B system for the four APs ($T_{\text{eff}}$, log $g$, [M/H] and $A_v$). The mean values of $\sigma_{\text{post}}$ are plotted grouped by stellar type and as a function of the distance (and reddening) towards the Galactic pole, center and anticenter directions. Finally, Fig. 15 shows the $\sigma_{\text{post}}$ for the four APs as a function of $G$ magnitude for a F-type subgiant. This star has been chosen as an example and because the F and G subgiants are the key targets for age and metallicity stellar populations determination.
Table 2 lists the specifications of the filters for the recommended baseline system F4B. Some of the proposed bands are not symmetric. An investigation of the feasibility of manufacturing these is needed.

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<th>Band</th>
<th>F4B431</th>
<th>F4B556</th>
<th>F4B655</th>
<th>F4B768</th>
<th>F4B916</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{blue}$ (nm)</td>
<td>380</td>
<td>492</td>
<td>620</td>
<td>690</td>
<td>866</td>
</tr>
<tr>
<td>$\lambda_{red}$ (nm)</td>
<td>482</td>
<td>620</td>
<td>690</td>
<td>846</td>
<td>966</td>
</tr>
<tr>
<td>$\lambda_0$ (nm)</td>
<td>431</td>
<td>556</td>
<td>655</td>
<td>768</td>
<td>916</td>
</tr>
<tr>
<td>$\Delta \lambda$ (nm)</td>
<td>102</td>
<td>128</td>
<td>70</td>
<td>156</td>
<td>100</td>
</tr>
<tr>
<td>$\delta \lambda$ (nm)</td>
<td>10.40</td>
<td>10.10</td>
<td>10.10</td>
<td>10.40</td>
<td>10.10</td>
</tr>
<tr>
<td>$\epsilon$ (nm)</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>$T_{max}$ (%)</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Type of CCD</td>
<td>AF</td>
<td>AF</td>
<td>AF</td>
<td>AF</td>
<td>AF</td>
</tr>
<tr>
<td>Number of CCDs</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
</tr>
</tbody>
</table>

$\lambda_{blue}$, $\lambda_{red}$: wavelengths at half-maximum transmission
$\lambda_0$: central wavelength
$\Delta \lambda$: FWHM
$\delta \lambda$: edge width (blue, red)
$\epsilon$: manufacturing tolerance intervals centred on $\lambda_{blue}$ and $\lambda_{red}$
F4B431, F4B655 and F4B916: 82 observations
F4B556 and F4B768: 41 observations (both filters share one CCD strip)

Table 2: Specifications of the bands in the F4B system recommended as the baseline for BBP.

The description of the purpose of every band, color-color diagrams, color dependencies on reddening, etc. that may provide insights for the classification and parametrization algorithms are not the subject of this report and will be provided separately.

6 Future tasks

The proposed future steps are:

- analysis of the capabilities of identifying and parametrizing STs that have not been considered here (multiple stars, peculiar stars, emission line stars, etc)
- analysis of performances for Solar system objects
- analysis of capabilities for identifying and parametrizing QSOs
- continuation of the analysis of degeneracies, including $Q$ vs. color diagrams
- assessment of the minimum magnitude error
- assess the importance of having asymmetric filters
- investigate manufacturing feasibility of asymmetric bands, if needed
These tasks are not only related to the BBP design but also to the combined BBP and MBP design.

Acknowledgments

This recommendation is the culmination of an extensive and dedicated effort within the Photometry Working Group to which many people have contributed. Special mention has to be made of L. Lindegren, V. Stražys, C. Bailer-Jones, V. Vansevicius, U. Heiter, M. Grenon and U. Munari for their BBP systems proposals; of L. Lindegren for his proposal of the figure of merit approach; of C. Bailer-Jones and the Classification WG for proposing and running the blind testing campaigns, and of all PWG members that through e-mails and during meetings have contributed with their ideas and comments to the final definition of this BBP baseline. Many thanks to all of them!

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Figure 2: The seven BBP systems with five bands. The V1B and F5B systems are based on the 4B proposal and only differ in their blue band (the three panels on the left). The F2B and F4B systems (top right panel) both have the separation of the two reddest bands at the Paschen jump and differ in the width of their central bands. The blue band is similar to the one in the V1B system. Finally, F3B (middle right panel) and F6B (bottom right panel) are hybrids of the F2B and V1B, and the F4B and F5B systems, respectively. The dashed line shows the response curve of the Astro CCD and the dotted lines represent the spectral energy distributions of unreddened solar metallicity dwarfs of 10 000, 5750 and 3500 K.
Figure 3: Figure of merit values in different galactic directions (top four panels) and grouped by stellar type (bottom four panels) for the three 4-band BBP systems under evaluation. See Sect. 3.3 for a discussion.
Figure 4: Figure of merit values in different galactic directions (top four panels) and grouped by stellar type (bottom four panels) for three 5-band BBP proposals which differ in the location and width of their blue band: 4B, V1B, F5B. See Sect. 3.4 for a discussion.
Figure 5: Figure of merit values in different galactic directions (top four panels) and grouped by stellar type (bottom four panels) for two 5-band BBP proposals differing in the location and width of their blue band: F4B, F6B. See Sect. 3.4 for a discussion.
Figure 6: \textit{Top:} Relative changes in $\sigma_{\text{post},[M/H]}$ and $\sigma_{\text{post},A_v}$ for the 4B and F5B systems with respect to the V1B system. The differences between 4B and V1B are larger than between F5B and V1B, with a significant fraction of differences exceeding 25% for the former. \textit{Bottom:} Relative changes in $\sigma_{\text{post},T_{\text{eff}}}$ and $\sigma_{\text{post},A_v}$ of the F2B and F4B systems with respect to the V1B system. The differences F2B-V1B and F4B-V1B are very similar, meaning that F2B and F4B perform almost equally. The differences are not as large as in the case of the 4B-V1B comparison (top panels).
Figure 7: Figure of merit values in different galactic directions (top four panels) and grouped by stellar type (bottom four panels) for two 5-band BBP proposals F2B and F3B differing only in the separation wavelength of the two reddest bands. The F2B system has the separation at the Paschen jump and F3B at 815 nm. See Sect. 3.4 for a discussion.
Figure 8: Figure of merit values in different galactic directions (top four panels) and grouped by stellar type (bottom four panels) for two 5-band BBP proposals, F2B and F4B, which differ only in the width of the central three bands. The 655 nm band in F4B is 10 nm wider than in F2B. See Sect. 3.4 for a discussion.
Figure 9: Figure of merit values in different galactic directions (top four panels) and grouped by stellar type (bottom four panels) for the 4B system and the 5-band BBP proposals with a blue band as in V1B and with the separation of the reddest bands at the Paschen jump. F2B and F4B yield an overall improvement with respect to 4B and V1B, except for the case of the HB stars for which the 4B system performs better than the others.
Figure 10: Figure of merit values in different galactic directions (top four panels) and grouped by stellar type (bottom four panels) for all the evaluated 5-band BBP proposals.
Figure 11: Figure of merit values in different galactic directions (top four panels) and grouped by stellar type (bottom four panels) for the 4-band and 5-band BBP systems recommended as the baselines.
Figure 12: Estimation of the precisions of the main astrophysical parameters in the Galactic pole direction for several groups of stars, with the five-band F4B system. The interstellar absorption is assumed to go up to 0.3 mag at 1 kpc and to remain constant beyond this distance.

Figure 13: Estimation of the precisions of the main astrophysical parameters in the Galactic center direction for several groups of stars, with the five-band F4B system. Interstellar absorption is assumed to vary from 0.3 mag at 500 pc to 10 mag at 10 kpc. (Class I means luminosity class I).
Figure 14: Estimation of the precisions of the main astrophysical parameters in the Galactic anticenter direction for several groups of stars, with the five-band F4B system. Interstellar absorption is assumed to vary from 0.3 mag at 500 pc to 3.5 mag at 5 kpc and to be constant beyond this distance.
Figure 15: Estimation of the precisions of astrophysical parameters using F4B system for a F-type subgiant as a function of the $G$ magnitude. Top right panel: Metallicity increases from top $[\text{M/H}] = -4$ to bottom $[\text{M/H}] = +0.5$. 