

# A Calibration Method for Wide-Field Multicolor Photometric Systems<sup>1</sup>

XU ZHOU, JIANGSHENG CHEN, WEN XU, MEI ZHANG, ZHAOJI JIANG, ZHONGYUAN ZHENG, AND JIN ZHU

Beijing Astronomical Observatory, Chinese Academy of Sciences, Beijing 100080, China; National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; and Beijing Astrophysics Center (BAC),<sup>2</sup> Beijing 100871, China; zhouxu@vega.bac.pku.edu.cn

*Received 1999 March 3; accepted 1999 April 16*

**ABSTRACT.** The purpose of this paper is to present a method to self-calibrate the spectral energy distribution (SED) of objects in a survey based on the fitting of a SED library to observed multicolor photometry. We adopt, for illustrative purposes, the Vilnius and Gunn & Stryker SED libraries. The self-calibration technique can improve the quality of observations which are not taken under perfectly photometric conditions. The more passbands used for the photometry, the better the results. This technique has been applied to the BATC 15 passband CCD survey.

## 1. INTRODUCTION

Multicolor photometry can provide accurate spectral energy distribution (SED) information of low spectral resolution for a large sample of objects and is a very powerful tool to deal with many important astrophysical problems. It can be used to measure the photometric redshift of quasars and galaxies and to select quasars and other interesting objects based on their characteristic SEDs. One can also use SEDs for stellar population synthesis, an important tool for studying the structure and evolution of galaxies. The more passbands in which one observes, the better one can determine the SED.

The Beijing-Arizona-Taipei-Connecticut (BATC) multicolor photometric survey is designed to obtain as much information on the SED of celestial sources as possible. It combines the Beijing Astronomical Observatory's 60/90 cm f/3 Schmidt telescope with a Ford Aerospace CCD with  $2048 \times 2048$  pixels (recently replaced by a thinned Loral CCD, thanks to the Steward Observatory) and 15 intermediate-band filters ranging from 320 to 1000 nm to obtain the SEDs for all objects down to  $B = 21$  mag in a field of  $1 \text{ deg}^2$ . A crucial problem in the survey is accurate calibration on the SED of our objects. The standard procedure of SED calibration is as follows: on photometric nights, we observe through the 15 BATC filters both Oke & Gunn (1983) spectroscopic standard stars (HD 19445, HD 84937, BD +26°2606, and BD +17°4708) and the target fields. We convolve the known fluxes of the standard stars with the transmission curves of the BATC filters to deter-

mine magnitudes in BATC photometric system (Fan et al. 1996; Zheng et al. 1999). In practice, however, this method is not very efficient for two reasons. First, the calibrations are not always taken on perfectly photometric nights. This results in systematic troughs or bumps in the SED for all objects in a field. Second, in order to obtain accurate SED calibration for 15 passbands, we need many photometric nights, which could take a very long time at our present site. In order to solve these problems, we are developing a technique we call "SED self-calibration." This is a statistical method, based on applying a stellar SED library to a large sample of observed stellar objects. In § 2 we describe our method of SED self-calibration. In § 3 we present some results from tests of the method. We discuss the method and give our conclusions in § 4.

## 2. METHOD

The BATC survey covers regions at high Galactic latitudes. In a typical field, several thousand objects are detected per square degree. Among them are several hundred unsaturated, bright stars with high signal-to-noise ratios. These "good" stars with highly precise photometry form a large sample which is the observational basis for the SED autocalibration method. In order to make the description concise, we will use, in the following presentation, the term  $\text{SED}_{\text{obs}}$  to express the SED of an object which is calibrated by observations and the term  $\text{SED}_{\text{match}}$  to express the SED of the object in the SED library which best matches the SED of the program star. We assume that most of these "good" stars are normal, nearby stars; therefore, most of these "good" stars should have very close matches in the SED libraries. If the field has been well calibrated by observations, the rms of the differences between the  $\text{SED}_{\text{obs}}$

<sup>1</sup> The work is supported partly by the National Sciences Foundation under contracts 19833020 and 19503003.

<sup>2</sup> BAC is jointly sponsored by the Chinese Academy of Sciences and Beijing University.

and the  $SED_{match}$  for most of the “good” stars should be roughly the size of the photometric precision. If the rms of the residuals is considerably larger than the photometric precision, then either some of the “good” stars might not actually be normal stars or observations in some passbands might not have been made during truly photometric nights. In the former case, we can reject those stars with abnormal residuals from the data sample and repeat the process. In the latter case, we can shift the zero points for some passbands which show systematic deviations of  $SED_{obs}$  from  $SED_{match}$ . We iterate these processes until the rms of the residual reaches the level of the photometric precision, which is about 0.01 mag for “good” stars. This self-calibration method is based on the following assumptions:

1. Most bright stellar objects in the field are normal stars whose SEDs can be found in the SED library.
2. The interstellar extinction for these bright stars is small, and the differences in extinction between stars in the same CCD field are negligible.
3. The SED library is reliable and covers all the required types of spectral and luminosity classes to fit the  $SED_{obs}$ .

We now briefly describe details of the observed and model SEDs.

### 2.1. $SED_{obs}$

First, we must obtain  $SED_{obs}$  for all the objects in the target field. Once a target field has been observed in several passbands, we obtain the instrumental colors of the stars in the field by using standard photometry packages, such as DAOPHOT. The zero point for each passband is obtained through observations of Oke & Gunn standard stars during photometric nights. As long as the zero points are well determined, the instrumental magnitudes can be transformed into the calibrated magnitudes of the BATC system. The instrumental color index can be defined as in Table 1, where  $Co_{j,s}^i$  is the instrumental color index of  $j$ th band minus  $s$ th band of the  $i$ th object. Here we use the  $s$ th band as the reference band.

To calculate the flux-calibrated color index  $C_{j,s}^i$ , the color-index zero-point correction  $Cc_{j,s}$  is added to the

instrumental color index  $Co_{j,s}^i$ :

$$C_{j,s}^i = Co_{j,s}^i + Cc_{j,s}.$$

### 2.2. SED Libraries

The stellar SED library used for this method is a hybrid one, including the theoretical SEDs of Kurucz (1992, 1993) and the observational SEDs of Gunn & Stryker (1983) and Straizys & Sviderskiene (1972, henceforth referred to as “Vilnius”). We transform spectral fluxes into the BATC photometric system using the following equation:

$$m_i = -2.5 \log \hat{f}_v - 48.6,$$

where  $(f_v)_i$  is the monochromatic energy at the central wavelength of  $i$ th filter, in units of  $\text{ergs cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$  (see Fan 1995; Fan et al. 1996). The Vilnius library has 49 spectra covering spectral types from O to M6 and luminosities from the main sequence to giants. The library of Gunn & Stryker contains 74 spectra with the same coverage of spectral types and luminosities. The SED libraries given by Kurucz cover temperatures from 3500 to 50,000 K with a range of stellar surface gravities and metallicities. Using these SEDs we can build a table of model color indices  $Cm$  (Table 2). In Table 2,  $Cm_{j,s}^i$  is the color index between the BATC  $j$ th and the  $s$ th filter bands of the SED library for the  $i$ th spectral type and luminosity.

If the  $SED_{obs}$  is well determined by the observations, it can be matched to one of the model SEDs with a residual at the level of the photometric precision. Mathematically, we search for a minimum of  $\sigma$ :

$$\sigma = \sum_{i=1}^n \min \left[ \sum_{j=1}^m (Co_{j,s}^i + Cc_{j,s} - Cm_{j,s}^k)^2, k \in 1, N \right].$$

Here,  $n$  is the number of the “good” stars,  $m$  is the number of the color index, and  $N$  is the total number of

TABLE 1  
INSTRUMENTAL COLOR INDEX

	$f_1$	$f_2$	...	$f_m$
$s_1$	$Co_{1,s}^1$	$Co_{2,s}^1$	...	$Co_{m,s}^1$
$s_2$	$Co_{1,s}^2$	$Co_{2,s}^2$	...	$Co_{m,s}^2$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$s_n$	$Co_{1,s}^n$	$Co_{2,s}^n$	...	$Co_{m,s}^n$

TABLE 2  
MODEL COLOR INDEX

	$f_1$	$f_2$	...	$f_m$
$s_1$	$Cm_{1,s}^1$	$Cm_{2,s}^1$	...	$Cm_{m,s}^1$
$s_2$	$Cm_{1,s}^2$	$Cm_{2,s}^2$	...	$Cm_{m,s}^2$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$s_n$	$Cm_{1,s}^n$	$Cm_{2,s}^n$	...	$Cm_{m,s}^n$

entries in the model SED library.  $Co_{j,s}^i$ ,  $Cc_{j,s}$ , and  $Cm_{j,s}^k$  are the instrumental color index, the color-index zero-point offset, and the color index of model SED, respectively. We look simultaneously for the nearest match to each star in the library and a value for  $Cc$  which leads to a minimum in  $\sigma$ . In our algorithm, we call subroutines of the MINUIT package (James 1994) from the CERNLIB software. The process converges on the correct values of the color-index zero-point corrections  $Cc_{j,s}$ . During the iteration process, a different weight is given to each star according to its instrumental magnitude. The program can subsequently reject those stars having abnormally high differences between  $SED_{obs}$  and  $SED_{match}$ . At the start of the iteration, we must provide initial values for the color-index corrections. The effect of different initial values on the final converged result is less than 0.01 mag. We take the mean instrumental color index and the mean model color index as the initial corrections:

$$Cc_{j,s}^0 = \frac{(\sum_{i=1}^n Co_{j,s}^i)}{n} - \frac{(\sum_{k=1}^N Cm_{j,s}^k)}{N},$$

Because most nearby stars are spectral type F, G, and K, we employ only these types of model SEDs to estimate the initial color correction constants.

### 3. TESTING

#### 3.1. Empirical Comparison of the Two Methods

We can test the method as follows: If we observe one of the Oke & Gunn standard star fields, we acquire the instrumental SED for the standard star. Since we know the real SED of the standard star, we can determine exactly the SED corrections for each passband. In other words, for this particular field, the zero-point color corrections can be derived directly. If we use our method on the same data set, we can compare its values for the zero-point corrections to the correct ones.

We observed the field of HD 84937 through 13 filters on 1998 January 22. The transparency was good, but it was not photometric. Two exposures were taken for each filter: a short one of a few seconds to avoid saturating the bright star HD 84937 and a long one of 300 s. The short and the long exposures for each filter were taken in quick succession in order to guarantee that both shared the same weather conditions. The short exposure was used to determine the SED corrections for the field via HD 84937 directly, and the long exposure was used to determine the SED corrections via our method. In the following, we use this data set to do several tests of our method.

As mentioned above, we obtained the instrumental SED of standard star HD 83927 (MAG\_std\_instr) from the short-exposure images. Using the known SED of HD 83927 in BATC system (MAG\_std\_BATC), we calculated the differences in each passband  $i$ :

$$dMAG\_std_i = MAG\_std\_BATC_i - MAG\_std\_instr_i .$$

If the SED self-calibration method is successful, it should yield corrections for the SED of the long-exposure images  $Cc_i$  which differ from  $dMAG\_std_i$  only by a constant  $K$ , due to the difference in exposure time:

$$K = Cc_i - dMAG\_std_i .$$

The results are listed in Table 3. It shows that the constant  $K$  is indeed the same in each passband, except for the BATC2 filter. The rms of the variation of  $K$  in color is  $\sim 0.016$  mag. We give two reasons for the large difference in the near-UV band BATC2: First, our thick CCD has very low quantum efficiency in the blue, causing low signal-to-noise values in all stars. Second, the SED template in this region of wavelengths is available only for some stellar types.

#### 3.2. Cross-checking between Two Spectral Libraries

We can test our method in a second way. Suppose the SED libraries, either Gunn & Stryker or Vilnius, represent the SED well for most types of stars. Having computed synthetically the BATC magnitudes in all passbands for the stars in each library, we can apply our method to calculate the corrections between the two sets of spectral models. If (1) both libraries provide accurate stellar SEDs, (2) each library covers an equal range of stellar types, i.e., any SED in one library has a corresponding SED in the other library, and (3) the method developed here is correct and effective, then after the iteration process, the final SED corrections between the two sets of spectral models should be close to zero.

In the following test, we use Gunn & Stryker library as  $SED_{match}$  and the Vilnius library as the  $SED_{obs}$  catalog. The results are shown in Table 4. Column (1) is the filter name, column (2) its central wavelength, and column (3) the correction for each band. The BATC9 passband (6660 Å) is used as the reference band and is kept fixed during the iterative process. The final values for the zero-point corrections are indeed very small. The mean deviation of zero-point corrections except BATC1 is  $\pm 0.015$  mag; however, the BATC1 band shows much larger deviations than the other bands. This result shows that the two SED libraries in

TABLE 3  
RESULTS OF A TEST OF THE SED SELF-CALIBRATION METHOD, USING LONG AND SHORT EXPOSURES  
FOR THE FIELD OF STANDARD STAR HD 84937

Filter (1)	Wavelength ( $\lambda$ ) ( $\text{\AA}$ ) (2)	MAG_std_instr (3)	MAG_std_BATC (4)	Cc (5)	K (6)	K - 1.14 (7)
BATC2 .....	3890	14.475	8.800	-4.3842	1.2908	+0.1508
BATC3 .....	4210	12.196	8.626	-2.4336	1.1364	-0.0036
BATC5 .....	4920	10.342	8.429	-0.8022	1.1107	-0.0293
BTAC6 .....	5270	10.118	8.338	-0.6453	1.1346	-0.0053
BATC7 .....	5795	10.329	8.259	-0.9308	1.1391	-0.0008
BATC8 .....	6075	10.089	8.232	-0.7147	1.1422	+0.0023
BATC9 .....	6660	9.321	8.205	+0.0000	1.1160	-0.0240
BATC10.....	7050	10.500	8.171	-1.1891	1.1399	-0.0001
BATC11.....	7490	10.756	8.165	-1.4294	1.1616	+0.0216
BATC12.....	8020	10.591	8.150	-1.2792	1.1618	+0.0218
BATC13.....	8480	11.685	8.144	-2.4008	1.1402	+0.0002
BATC14.....	9190	12.317	8.149	-3.0111	1.1569	+0.0169
BATC15.....	9745	13.087	8.173	-3.7746	1.1394	-0.0006

general can be well matched to each other, but two points call for further discussion:

1. There is a systematic deviation for both SED libraries in the blue versus the red: below 4550  $\text{\AA}$ , the Vilnius SEDs are flatter than those of Gunn & Stryker; above 4550  $\text{\AA}$ , the Vilnius SEDs are more depressed those of Gunn & Stryker.
2. The large deviation in the UV band indicates that either one or both of the SEDs does not represent the stellar SEDs in this region very well.

### 3.3. Stellar Classification

The process of matching  $SED_{obs}$  to  $SED_{match}$  produces as a by-product a spectral classification for each star or, if a library of theoretical models is used, the stellar atmospheric parameters of each star. It provides us with an indirect way to test the method presented in this paper. Figure 1 shows a good correlation between the original spectral class of stars

TABLE 4  
RESULTS OF CROSS-CHECKING BETWEEN VILNIUS AND  
GUNN & STRYKER MODEL SPECTRA

Filter (1)	Wavelength ( $\lambda$ ) ( $\text{\AA}$ ) (2)	Model Calibration (3)	Note (4)
BATC1 .....	3360	-0.041	
BATC2 .....	3890	-0.019	
BATC3 .....	4210	-0.029	
BATC4 .....	4550	-0.009	
BATC5 .....	4920	0.003	
BATC6 .....	5270	0.025	
BATC7 .....	5795	0.010	
BATC8 .....	6075	0.008	
BATC9 .....	6660	0.000	Fixed
BATC10.....	7050	0.005	
BATC11.....	7490	0.018	
BATC12.....	8020	0.008	
BATC13.....	8480	0.008	
BATC14.....	9190	0.010	
BATC15.....	9745	0.007	

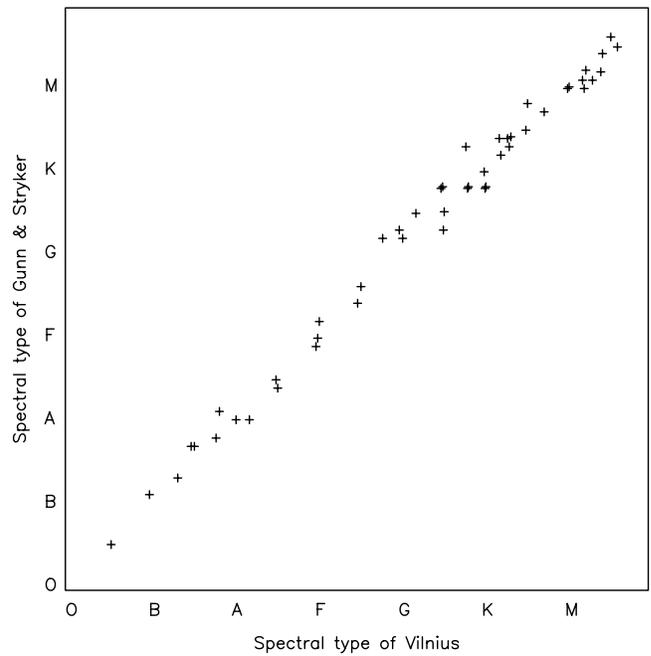


FIG. 1.—Spectral type of Vilnius vs. spectral types obtained from Gunn & Stryker (1983)

in the Vilnius catalog and the spectral class determined for those stars via our method, using the Gunn & Stryker library for SED<sub>match</sub>.

#### 4. DISCUSSION AND CONCLUSIONS

1. Our method is a statistical one, so it can be effectively applied only to a large stellar sample. The BATC survey satisfies this condition. Each BATC field covers about 1 deg<sup>2</sup>. Typically, there are more than 4000 objects detected in each image. We are guaranteed several hundred bright and unsaturated stars with reliable instrumental magnitudes to use as a “good” star sample.

2. The basis of our method is fitting the observed stellar SED to a library of stellar SEDs. Our assumption that most of our “good” stars are normal stars appears firm, and their SEDs can be found from the SED library. Most of the abnormal stars are rejected during the iteration process.

3. The SED library is crucial for the method. There is a great demand in the astronomical community for reliable SED libraries which cover a wide range in wavelength and stellar types. The theoretical libraries (e.g., Kurucz 1993) are limited by our knowledge of stellar physics. The theoretical SEDs for late-type, low-temperature stars are not as reliable as those for hot stars. There are many observational stellar libraries (Gunn & Stryker, Straizys et al., etc.), but differences exist among them. It is not easy to judge which one is the best. After comparing various stellar SED libraries we have collected from the literature, we are at present using mainly the Gunn & Stryker library in our calculations. Further work on making good libraries of SEDs is necessary.

4. In principle, interstellar extinction must be considered in the final result. Our method of SED correction takes into account not only terrestrial atmospheric extinction but also interstellar reddening. If standard stars or spectral models suffer from systematically more or less (or different) extinction than a survey’s target stars, our method will yield systematically incorrect zero-point corrections to the photometry of target stars. This is because the method uses a fitting process to fit the observational SED affected by the reddening to the theoretical SED unaffected by the reddening. In the BATC survey, the fields are located at high Galactic latitudes, where the interstellar extinction is reduced. We also use only bright stars, which are nearby and little affected by interstellar extinction, as standards for the survey fields.

5. We have made several tests to see if the method works:

*a)* We have tried different filter bands as the reference band to see if the change in the reference band affects the

results. Our results show that the difference in the final constant corrections is less than 0.01 mag. This means that the choice of reference band in color index is not important. Normally, we select the band with the deepest exposure as the reference band, since it has highest signal-to-noise ratio. This also allows the measurement of color index for as many stars as possible.

*b)* We wanted to know if the number of filters used affects the results and what is the minimum number of colors required to make the SED self-calibration work effectively. In order to do the test, we reduced the number of filters by taking off some of the color indexes. We found that the method still yields reasonable results. Obviously, the results improve when one uses a larger number of the filter bands and a wider range of wavelengths.

*c)* We wanted to know if the final results depend on the characteristics of the “good” stars which we used for the SED self-calibration. For this purpose, we used various randomly selected subsets of the “good” stars in each image. We obtained very similar color correction constants. Furthermore, we divided the “good” star sample into several subgroups according to their apparent magnitude. The results show that the differences among different groups are about 0.03 mag. One possible reason is the low signal-to-noise ratio of faint stars.

*d)* Does the choice of the initial value of the iteration affect the results? Our tests show that different initial values normally affect only the convergence time of iteration. The difference on the final result is less than 0.01 mag. In some cases, there are several minima, and the process may not iterate to the correct one; this is an open issue. The best way to solve this problem, from our experience, is that if one or a few color indexes are very well determined from observations taken during photometric nights, then we keep these indexes fixed. This causes the iteration always to converge to the correct minimum.

After many tests and applications to real data, we conclude that, although there are still some problems requiring further development (such as creating larger libraries of stellar SEDs), the method presented here can work well; the accuracy of the SED calibration is comparable to the precision of the CCD photometry. A by-product of our method is the automatic classification of the stellar types or the determination of the stellar parameters, which is very useful for the studies of Galactic structure via large-field multi-color CCD photometric surveys.

The authors would like to thank Licai Deng and Rogier A. Windhorst for many helpful comments on this work. We are grateful to Michael Richmond for his help in improving the English and the presentation of the manuscript. This work is supported by members of BATC, especially Zhao-

hui Shang, Hao-jing Yan, Hong Wu, and Xiao-hui Fan, who provided their data sets for testing the method and for discussions. We also thank Yao-Hua Li for his management and support of the instruments, and Ray Chen, Hao-tong

Zhang, Bing Zhao, and Zheng Zheng, who obtained many of the observations for BATC and shared their experience with us. We also thank the assistants who helped with the observations for their hard work and kind cooperation.

#### REFERENCES

- Fan X.-H. 1995, master's thesis, Beijing Astron. Obs.  
 Fan, X.-H., et al. 1996, *AJ*, 112, 628  
 Gunn, J. E., & Stryker, L. L. 1983, *ApJS*, 52, 121  
 James, F. 1994, MINUIT: Function Minimization and Error Analysis (CERN Program Libr. Long Writeup D506) (version 94.1; Geneva: CERN)  
 Kurucz, R. L. 1992, in *IAU Symp. 149, The Stellar Populations of Galaxies*, ed. B. Barbuy & A. Renzini (Dordrecht: Kluwer), 225  
 Kurucz, R. L. 1993, CD-ROM 13, ATLAS9 Stellar Atmosphere Programs and 2 km/s Grid (Cambridge: Smithsonian Astrophys. Obs.)  
 Oke, J. B., & Gunn, J. E. 1983, *ApJ*, 266, 713  
 Straizys, V., & Sviderskiene, Z. 1972, *Bull. Vilnius Astron. Obs.*, 35  
 Zheng, Z. Y., et al. 1999, *AJ*, in press