Publications of the Astronomical Society of the Pacific, 112:691–702, 2000 May

Calibration of the BATC Survey: Methodology and Accuracy

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Received 1999 December 6; accepted 2000 January 29

ABSTRACT. We describe in detail the extinction correction procedures used for the Beijing-Arizona-Taiwan-Connecticut Sky Survey (BATC Survey). The survey covers the spectral range 3200–9900 Å by utilizing a set of 15 intermediate-band filters. These filters are specifically designed to exclude most of the bright and variable night-sky emission lines. We also present extinction coefficients for the filter passbands for typical photometric nights at the Xinglong Observing Station, Beijing Astronomical Observatory (where the observations of the survey are being carried out). Time-dependent, low-amplitude (∼1%), nightly extinction variation has been observed. Such variation is demonstrably independent of filter bandpass and air mass, with amplitudes ranging from ∼0.01 to ∼0.03 mag. The variation is plausibly caused by slowly varying (at ∼1%) atmospheric extinction, possibly related to changes in air pressure/temperature/humidity that occur during the night. An iterative fitting scheme has been developed to take this time-varying component into account. We conclude that the survey can achieve its stated observational goal, namely, an absolute photometric calibration that is tied to the AB_ν system to an accuracy of 1% in all filters.

1. INTRODUCTION

For any large photometric project done with one telescope, it is wise to establish the photometric behavior of the site + telescope combination. In this paper, we use the data we have collected with the 60/90 cm Schmidt telescope of the Beijing Astronomical Observatory (BAO) to establish the photometric behavior of the observing site, the Xinglong Observing Station (longitude: −117°34′42″; latitude: 40°23′47″; altitude: 970 m).

Our methodology for establishing the photometric behavior of this site has been influenced by the experience of one of us (D. B.), who has found nightly, gray (i.e., independent of passband), air-mass–independent changes to occur in atmospheric extinction on otherwise well-established photometric nights. This has been seen on several different sites (Kitt Peak, Cerro Tololo, La Palma; Burstein et al. 1987; Colless et al. 1993; Saglia et al. 1997). As we show here, the nightly atmospheric extinction variations we see are also independent of passband and air mass. If adequately monitored, such "diurnal" changes in nightly atmospheric extinction can be removed from the data to produce ∼1% photometry. Thus, we made monitoring such effects an integral part of our observing procedure on nights anticipated to be photometric in the Beijing-Arizona-Taiwan-Connecticut (BATC) Color Survey of the sky (cf. Fan et al. 1996; Shang et al. 1998; Zheng et al. 1999). In this paper we present the first results of such monitoring and, with these data, the mean extinction coefficients from 3200 to 9900 Å for the Xinglong Observing Station.

Section 2 of this paper describes the survey's photometric system, which is primarily determined by the BATC intermediate-band filter transmissions, and the systematic problems for which we will test in this paper. Section 3

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TABLE 1

Parameters of the 15 BATC Filters

		$\lambda_{\rm eff}$ (Å)		FWHM (Å)	
Filter No.	Code	Wavelength Weighted	Frequency Weighted	Measured	Gaussian Fit
1	a	3371.5	3360.0	359	271
2	b	3906.9	3897.6	291	260
3	c	4193.5	4179.6	309	327
4	d	4540.0	4531.9	332	259
5	e	4925.0	4916.4	374	280
6	f	5266.8	5258.2	344	290
7	g	5789.9	5784.9	289	231
8	h	6073.9	6068.6	308	245
9	i	6655.9	6645.5	491	359
10	j	7057.4	7054.9	238	179
11	k	7546.3	7544.7	192	151
12	m	8023.2	8019.7	255	228
13	n	8484.3	8482.6	167	166
14	o	9182.2	9180.2	247	182
15	p	9738.5	9736.3	275	200

explains the extinction correction procedures in full detail and explicitly tests for these problems. Section 4 states our conclusions.

2. PHOTOMETRIC SYSTEM

The BATC Color Survey's photometric system is defined by 15 intermediate-band filters (cf. Fan et al. 1996). Two, 2 inch sets of these filters are now being used by various members of our collaboration. For completeness, the filter transmissions published in Fan et al. (1996) are reproduced here in Figure 1, with one minor revision. The previous filter 10 has been replaced by two narrower filters (*j* and *k*) to further exclude strong and variable night-sky lines. Also superposed is a typical night-sky emission-line spectrum (from Mount Hopkins, Arizona), so one sees that the filter design avoids most of the known bright and variable night-sky emission lines. One of the advantages of these filters is that the sky background is greatly suppressed in the red, as demonstrated by the discovery of a ring of very faint surface brightness ($R \sim 28$ mag arcsec^{-2}) around the edge-on

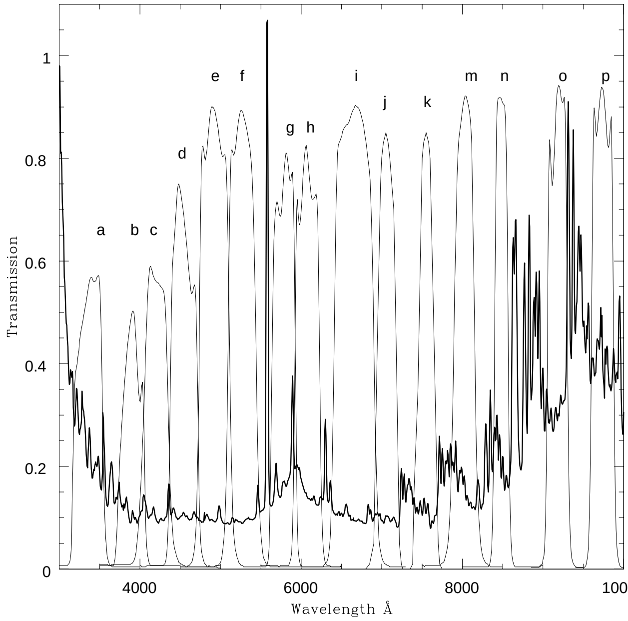

Fig. 1.—Transmissions of the 15 BATC filters. The filter codes (see Table 1) are labeled on top of each filter. Also superposed is a typical night-sky emission-line spectrum. The filter design avoids most of the bright night-sky emission lines.

TABLE 2

BATC Magnitudes of the Four Primary Standard Stars

Band	HD 19445 (C001)	HD 84937 (C002)	BD +26°2606 (C003)	BD +17°4708 (C005)
a	9.234	9.486	10.933	10.726
b	8.653	8.800	10.299	10.057
c.......	8.447	8.626	10.095	9.841
d	8.294	8.505	9.962	9.693
e.......	8.187	8.429	9.848	9.592
f	8.072	8.338	9.743	9.488
g	7.969	8.259	9.652	9.396
h	7.935	8.232	9.617	9.365
i	7.885	8.205	9.576	9.318
j	7.851	8.171	9.541	9.273
k	7.826	8.165	9.522	9.255
m......	7.800	8.150	9.501	9.238
n	7.790	8.144	9.489	9.226
o	7.784	8.149	9.489	9.226
p	7.801	8.173	9.507	9.244

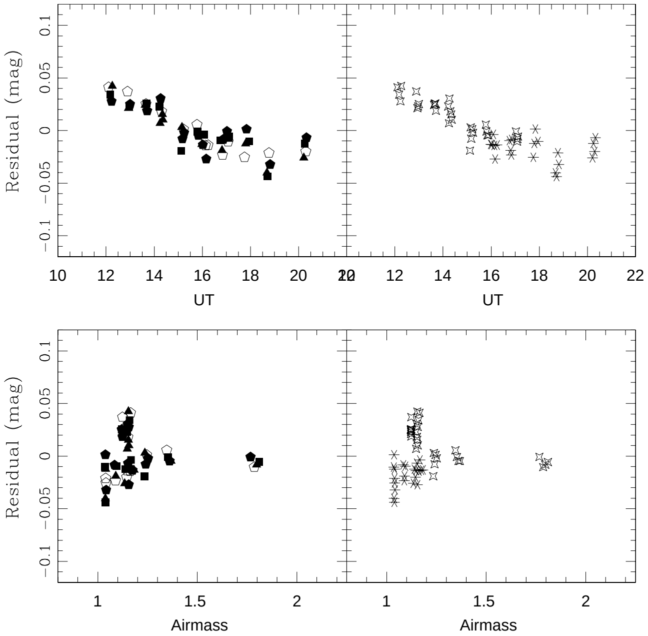

FIG. 2*a*

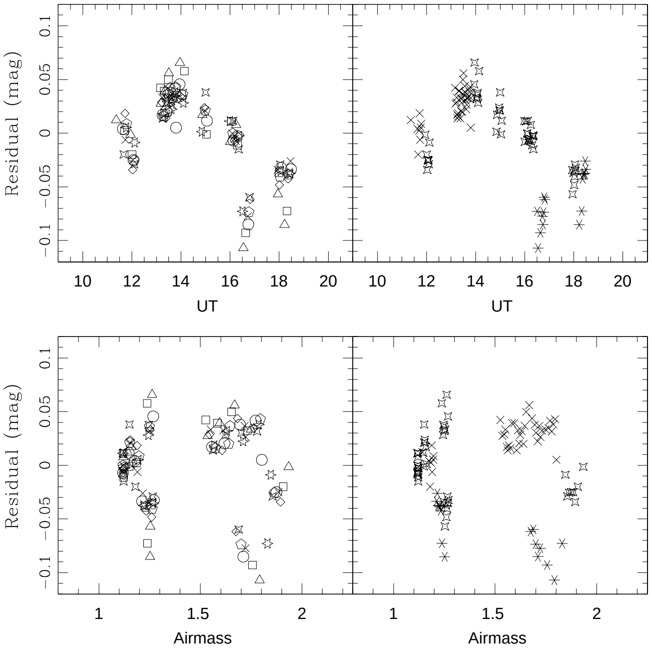

FIG. 2*b*

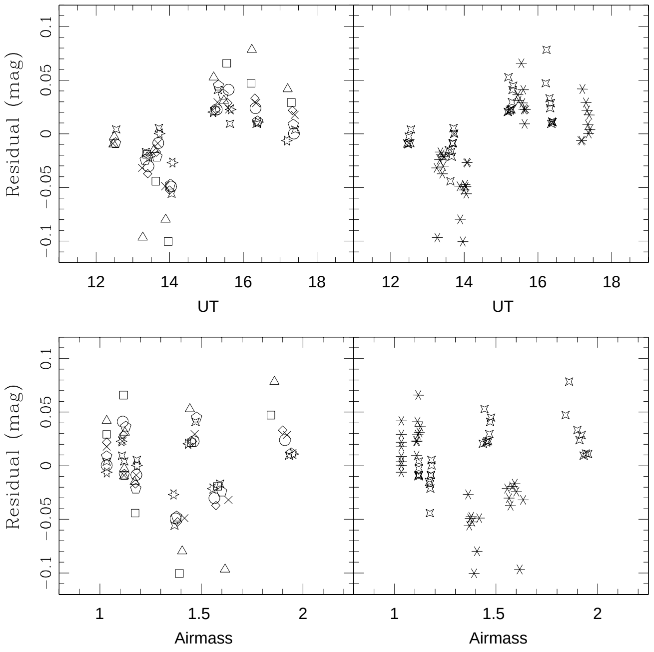

FIG. 2*c*

FIG. 2.—(*a*) For JD 10,175. First-order fitting residuals show strong correlation with both time and air mass. A grade A [after taking off *f*(UT) term, see text] night is shown here, with upper panels used for residual vs. time and lower panels used for residual vs. air mass. In either panel different symbols are used to indicate different filters in the left figure and to indicate different standard stars in the right figure. The passbands used at this night are g (*open pentagons*), m (*filled triangles*), o (*filled squares*), and p (*filled pentagons*). The stars used for this night were C002 (*four-pointed stars*) and C003 (*six-pointed stars*). It is clear that the residuals do not depend on color or on use of different standard stars. (*b*) For JD 10,499. Same as (*a*), but with a grade B night. The passbands used are b (*triangles*), d (*squares*), f (*diamonds*), g (*pentagons*), h (*circles*), i (*crosses*), j (*four-pointed stars*), and k (*six-pointed stars*). The stars used for this night were C001 (*crosses*), C002 (*four-pointed stars*), and C003 (*six-pointed stars*). (*c*) For JD 10,555. Same as (*b*), but with a grade C night. The passbands used are b, d, f, g, h, i, j, and k. Symbols are the same as in (*b*).

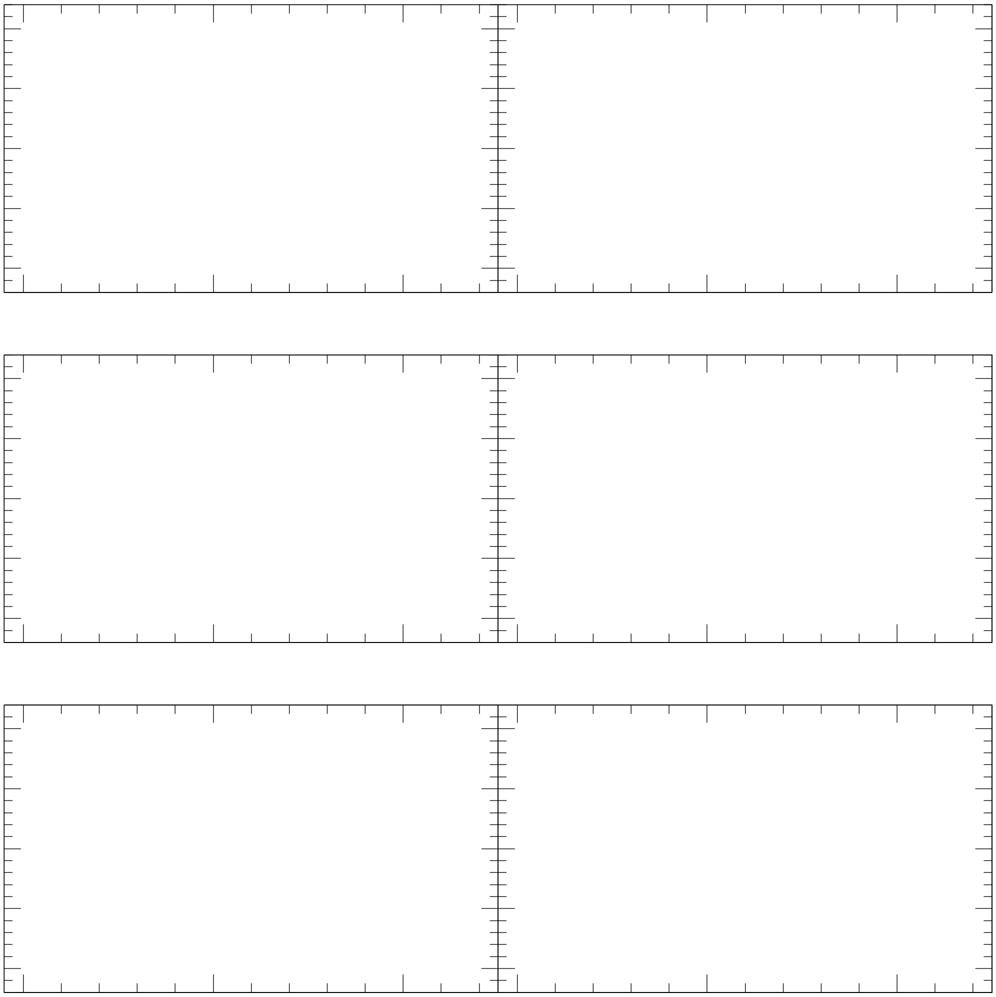

FIG. 3.—We divide the first-order fitting residuals into appropriate "time segments" and fit(UT) terms using straight lines. Refer to Fig. 2 legend for filters used.

galaxy NGC 5907 (Shang et al. 1998; Zheng et al. 1999). The well-known advantages of using these filters is that intermediate bandwidths do not require color terms for atmospheric extinction corrections, as opposed to such a necessity for broadband filters. The passband parameters of these filters are given in Table 1. Two kinds of effective wavelength are given: wavelength-weighted average and frequency-weighted average (written as Two kinds of FWHMs are also given: measured FWHM and the FWHM of an effective Gaussian profile. The definition of magnitudes for the BATC Survey are in the system of Oke & Gunn (1983): AB'm $= -2.5 \log f - 48.60$, (1) where is the appropriately averaged monochromatic flux (measured in ergs s^{-1} cm^{-2} Hz^{-1}) at the effective wavelength of the specific passband (following Fukugita et al. 1996). One way of defining is to take the system response average of the flux, where $R(\lambda)$ is the system's response, is the spectrum

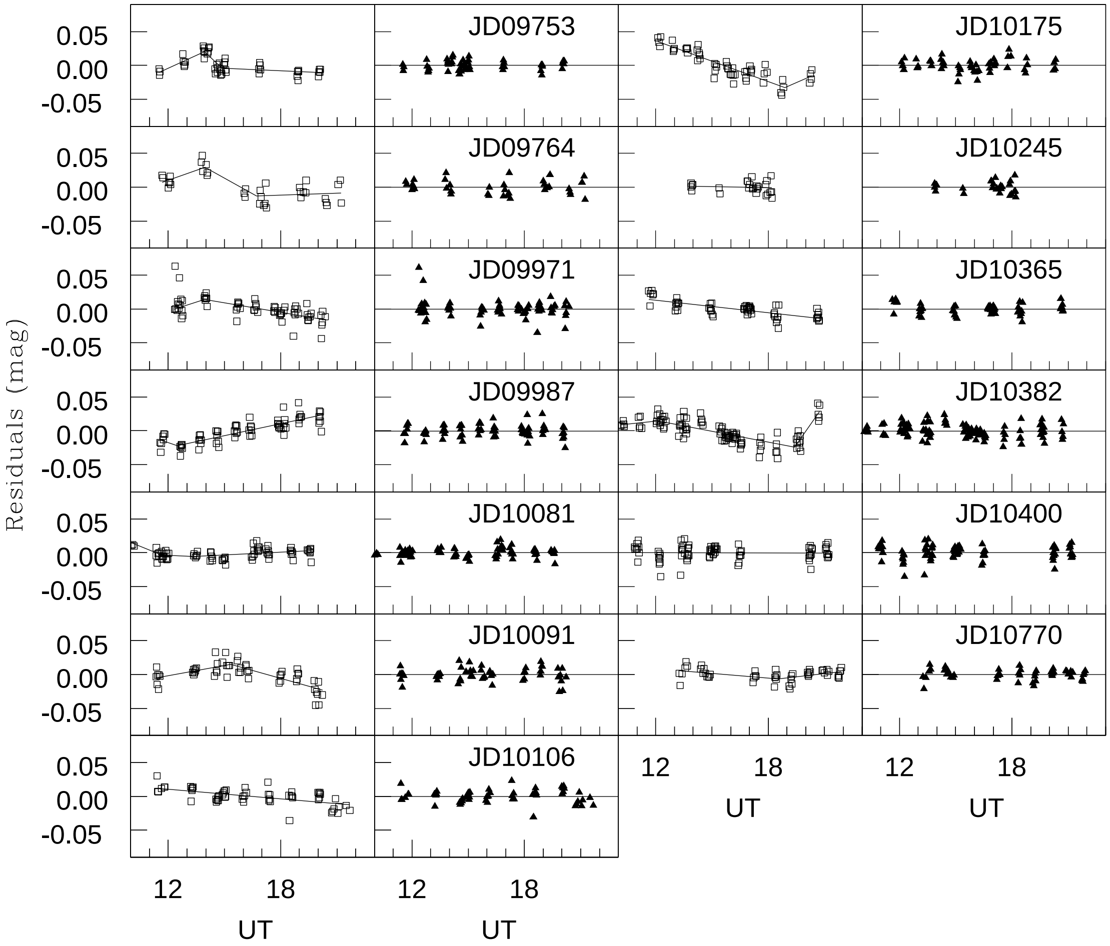

FIG. 4*a*

FIG. 4.—(*a*) f(UT) fitting results for all the 13 A nights. The residuals both before (*left*) and after (*right*) the fit are shown. Note that the vertical scale on this figure is different from those used for B and C nights. Each night uses filters with as wide a wavelength range as in Figure 2. (*b*) Same as (*a*), but for all the 15 B nights. Note that the vertical scale on this figure is different from those used for A and C nights. Each night uses filters with as wide a wavelength range as in Fig. 2. (*c*) Same as (*b*), but for all the four C nights. Note that the vertical scale on this figure is different from those used for A and B nights. Each night uses filters with as wide a wavelength range as in Fig. 2.

energy distribution of the source, and λ_1 and λ_2 are the lower and upper cutoff wavelengths of the passband, respectively (cf. Fan et al. 1996). We noticed that for a photon-count detector such as a CCD, $\tilde{F}_\nu$ can be more naturally written as

$$\tilde{F}_\nu = \frac{\int d(\log\nu) f_\nu R_\nu}{\int d(\log\nu) R_\nu} = \frac{\int d\nu R_\nu \, f_\nu/h\nu}{\int d\nu R_\nu/h\nu} ,$$

which ties the magnitude to the number of photons detected by the CCD, rather than to the input flux (cf. Fukugita et al. 1996). The difference for the BATC filters is trivial (at the ~0.001 mag level), due to the relative narrowness of the BATC passbands.

The system response $R(\lambda)$ actually used to relate f_ν and $\tilde{F}_\nu$ includes *only* the filter transmissions. Other effects, such as the quantum efficiency of the CCD, the response of the telescope's optics, the transmission of atmosphere, etc., are ignored. This makes the BATC system filter-defined. We can do this because the bandwidths are intermediate in size and all the other responses vary little within a specified passband. This issue will be fully addressed in a separate paper, through photometry of stars with a wide range of color. To give a rough idea of to what extent our assumption is true, we note that the effective wavelengths are affected only at the ~6 Å level after taking CCD quantum efficiency and aluminum reflection into account.

The primary standard stars used by the survey to define the photometric zero point are four of the five spectrophotometric standard stars of Oke & Gunn (1983): BD +17°4708, BD +26°2606, HD 19445, and HD 84937.

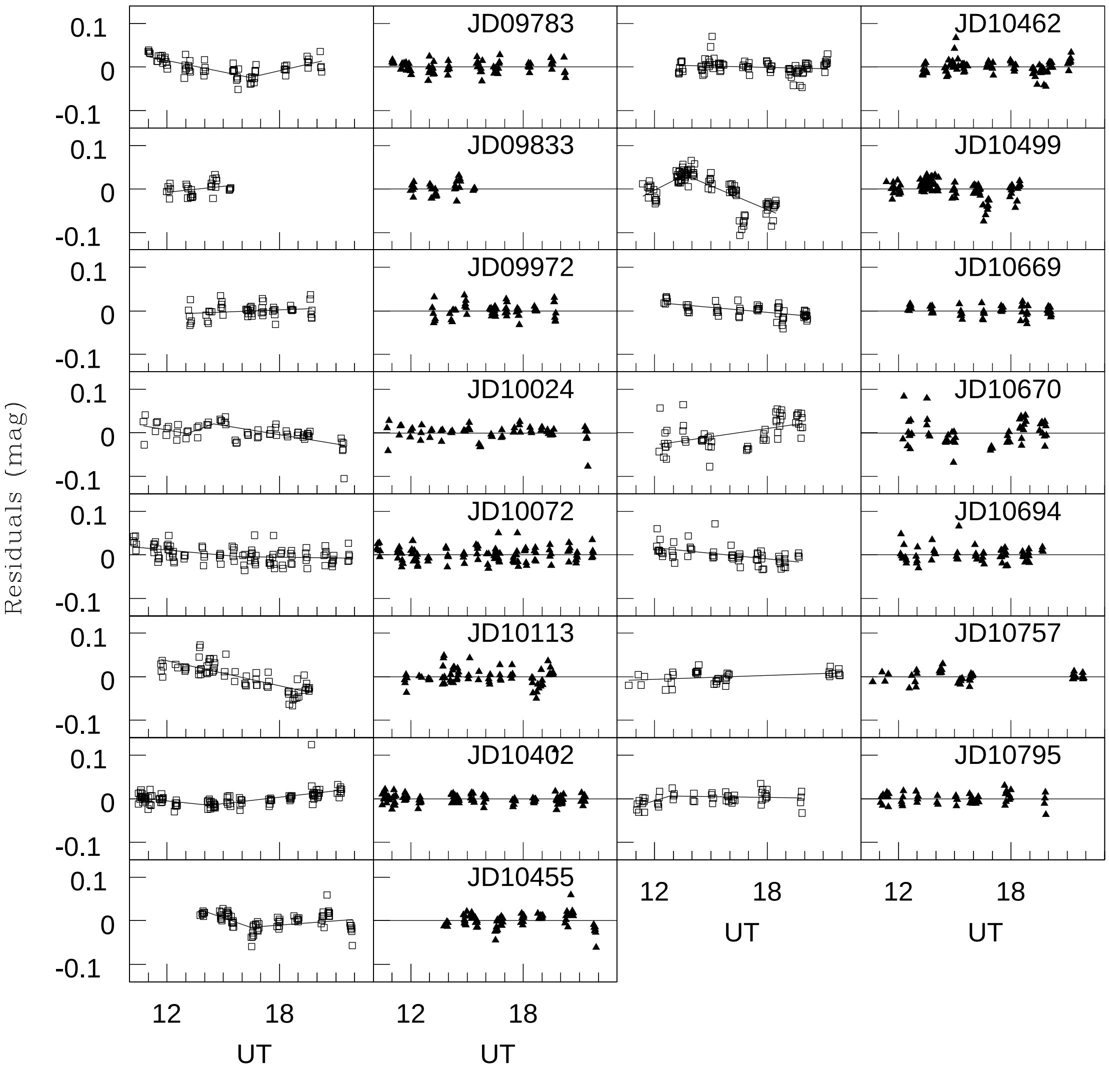
JD09783
JD10462
JD09833
JD10499
JD09972
JD10669
JD10024
JD10670
JD10072
JD10694
JD10113
JD10757
JD10402
JD10795
JD10455
0.1
0
-0.1
Residuals (mag)
12
18
UT

FIG. 4*b*

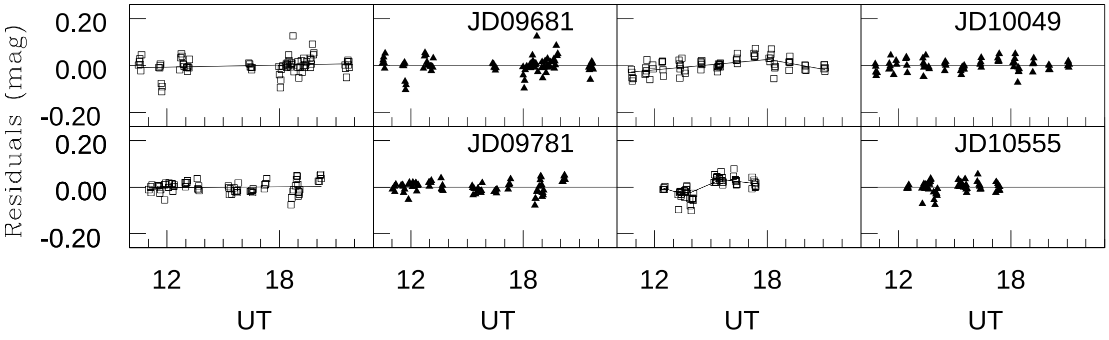
JD09681
JD10049
JD09781
JD10555
0.20
0.00
-0.20
Residuals (mag)
12
18
UT

FIG. 4*c*

TABLE 3

GRADES OF THE 32 PHOTOMETRIC NIGHTS BEFORE AND AFTER f(UT) FITTING

	rms			GRADE			rms			GRADE	
JD (2,440,000+)	Before f(UT) Fitting	After f(UT) Fitting	Flag[a]	Before f(UT) Fitting	After f(UT) Fitting	JD (2,440,000+)	Before f(UT) Fitting	After f(UT) Fitting	Flag[a]	Before f(UT) Fitting	After f(UT) Fitting
9,681	0.028	0.028		C	C	10,175	0.021	0.009	X	C	A
9,753	0.013	0.007	X	B	A	10,245	0.008	0.008		A	A
9,764	0.019	0.010	X	B	A	10,365	0.011	0.007	X	B	A
9,781	0.025	0.025		C	C	10,382	0.017	0.009	X	B	A
9,783	0.020	0.013	X	B	B	10,400	0.010	0.010		A	A
9,833	0.013	0.011		B	B	10,402	0.015	0.011	X	B	B
9,971	0.013	0.009	X	B	A	10,455	0.018	0.015	X	B	B
9,972	0.015	0.014		B	B	10,462	0.014	0.013		B	B
9,987	0.016	0.008	X	B	A	10,499	0.037	0.017	X	D	B
10,024	0.021	0.016	X	C	B	10,555	0.034	0.021	X	D	C
10,049	0.028	0.022	X	C	C	10,669	0.015	0.011	X	B	B
10,072	0.018	0.015	X	B	B	10,670	0.032	0.027	X	C	B
10,081	0.009	0.006	X	A	A	10,694	0.018	0.015	X	B	B
10,091	0.014	0.008	X	B	A	10,757	0.013	0.012		B	B
10,106	0.011	0.008	X	B	A	10,770	0.008	0.007		A	A
10,113	0.030	0.018	X	C	B	10,795	0.014	0.012		B	B

[a] An “X” is marked if f(UT) fitting decreases rms significantly.

Their BATC magnitudes are listed in Table 2. The absolute fluxes of these stars are taken from Fukugita et al. (1996), in which the latest flux measurements of these stars (denoted as AB_{95}) are given. Note that the magnitudes of these standard stars used in Fan et al. (1996) were on the AB_{79} system, which has been superseded by the AB_{95} calibration. The new standardization changes the $b-i$ standard colors (3890 − 6600 color in Fan et al. [1996] notation) by −0.064 mag. These bluer colors remove the discrepancy between the main-sequence colors and predicted reddenings that were found in Fan et al. for the open cluster M67 by using the older standard-star calibration.

3. EXTINCTION CORRECTION

3.1. The Four Observational Issues

The observational goal of the BATC Color Survey is to obtain spectrophotometry in the 15 filters to an accuracy of 1% per passband. To do this, we have to account for four separate observational issues: (1) air-mass dependency of atmospheric extinction; (2) slowly varying atmospheric extinction through the night; (3) possible errors (at the 0.01–0.03 mag level) in either the transformation of the standard-star fluxes to filter-defined magnitudes or the standard-star spectral energy distributions themselves; and (4) determination of the zero point of mean extinction for a given night.

As the first three effects can influence the determination of each other, as well as the value of the fourth, one tries to obtain as many observations as possible in as many filters, over as wide a wavelength region, over as wide an air mass, using as many of the four primary standard stars as possible. Clearly, this is hard to do with just one photometric night (if one also wants to take program observations), but it is possible with many nights, spaced out throughout the year, such as we have for the present analysis.

3.2. The Photometric Observing Procedure

When a night, or a portion of a night, is thought to be photometric by the observers, two or three standard stars are observed seven to nine times with five to nine filters between air masses 1–2. Filters used on a given night span as wide a range as possible in wavelength, modulo bright moon constraints. Only short exposures of the survey program fields are made on photometric nights, so that as many program fields as possible can be observed close their meridians.

The standard stars are put near the CCD center to minimize any systematic errors due to the shutter effect (since only very short time exposures can be made for these stars) or flat fields. The wide dynamic range of the CCD camera ($1.5 \times 10^5\ e^-$) makes it possible to always observe these bright standard stars in focus with a minimum exposure time of 1 s. The photons from the stars are measured within an aperture radius of 15 pixels (25″.05 at 1″.67 pixel scale). The sky backgrounds are measured within an annulus of 20 pixels (33″.40) inner radius and 30 pixels (50″.10) outer radius. In this way we include essentially all the light coming from the star, even if the seeing is variable. Because the stars are bright, Poisson photon errors are at a level of ∼0.0001 mag, negligible for this analysis.

Of the 423 nights of usable observations for the BATC Survey during 1994–1997, 32 nights (7.6%) were deemed to be photometric by the observers, and it is these nights that provide the data we will consider here.

3.3. The First-Order Extinction Correction

To first order the extinction equation for a given filter can be written as

$$m_{\rm inst} = m_{\rm batc} + KX + C\ , \qquad (2)$$

where $m_{\rm inst}$ is a star's instrumental magnitude, $m_{\rm batc}$ is its actual magnitude in our system, here termed "BATC magnitude," K is the extinction coefficient for the filter, X is air mass, and C is the instrumental zero point.

Both K and C in equation (2) are determined nightly. By making the zero point C a free parameter, the nightly determined zero point incorporates any changes in the combined optical response of the detector quantum efficiency, telescope optics, average level of nightly extinction, etc. Although K and C may be determined simultaneously, likely cross-talk between possible air-mass residuals and possible time-dependent extinction variations suggests that an iterative procedure is preferred. By taking the average of both sides, equation (2) gives

$$\begin{aligned}\overline{m_{\rm inst}} &= \overline{(m_{\rm batc} + KX + C)}\\ &= m_{\rm batc} + K\overline{X} + C\ . \qquad (3)\end{aligned}$$

Here we have $C = \overline{C}$ because we define the mean zero point to be held constant for a specified night. Subtracting equation (3) from equation (2), we define the parameter Δ per observation as

$$\begin{aligned}\Delta &= m_{\rm inst} - \overline{m_{\rm inst}}\\ &= K(X - \overline{X})\ , \qquad (4)\end{aligned}$$

with K as the only free parameter in this equation. Fitting Δ versus $(X - \overline{X})$ (or effectively just X alone) we get K and bypass the problem of fitting two parameters at the same time.

Now we can substitute K back into equation (3) and determine the average nightly zero point C,

$$C = \overline{m_{\rm inst} - m_{\rm batc}} - K\overline{X} \ . \tag{5}$$

After K and C have been derived, we can examine the fitting residuals for each night. Substituting K and C into both equations (2) and (3), we define the fitting residual per observation, δ, to be

$$\delta = (m_{\rm inst} - m_{\rm batc} - KX) - \overline{(m_{\rm inst} - m_{\rm batc} - KX)} \ .$$

The root mean square (rms) of the residuals, δ, found in determining K for each passband, are averaged over all filter passbands observed on a given night. This rms is our measure of the quality of the photometric nights: nights are graded as "A" [rms ≤ 0.01 mag (air mass)$^{-1}$], "B" [$0.01 < \text{rms} \leq 0.02$ mag (air mass)$^{-1}$], "C" [$0.02 < \text{rms} \leq 0.03$ mag (air mass)$^{-1}$], or "D" [rms > 0.03 mag (air mass)$^{-1}$]. A, B, and C nights are assumed to be photometric; D nights are assumed not to be photometric.

As can be seen from equations (2) and (3), if the extinction behavior were exactly what equation (2) describes, and if there were no error in the photometry, the rms residual would be zero. Typically, however, the residuals on most nights are found to be of low but nonzero amplitude (0.01–0.03 mag), which are much higher than photon statistics for the standard-star data, and show systematic time dependency. We find that the residuals are more positive in the first part of the night, decrease smoothly for much of the night, then become more positive again in the last part of the night. All these time-dependent terms are replicated in all filters observed over the same period of time, at different air masses. This demonstrated lack of passband dependency in the time-dependent terms indicates a gray (i.e., wavelength independent) variation in the observed standard-star magnitudes. This is consistent with what we and others have seen for nightly extinction variations at other observing sites. Figure 2 explicitly shows how this component varies in terms of air mass and time for different filters and different standard stars for three nights of different preliminary (i.e., before time-dependent variations are removed) photometric qualification.

3.4. Iterative Extinction Correction

To incorporate the time-variable gray extinction component, we introduce a time-dependent term into the extinction equation and rewrite equation (2) as

$$m_{\rm inst} = m_{\rm batc} + KX + f({\rm UT}) + C \ , \tag{6}$$

where we define the time dependency of atmospheric extinction on a given night as f(UT). Consequently, equation (4) becomes

$$\begin{aligned}\Delta &= (m_{\rm inst} - m_{\rm batc}) - \overline{(m_{\rm inst} - m_{\rm batc})} \\ &= K(X - \overline{X}) + f({\rm UT}) - \overline{f({\rm UT})} \\ &= K(X - \overline{X}) + f({\rm UT}) \ .\end{aligned} \tag{7}$$

Note that we take $\overline{f({\rm UT})} = 0$ because the nonzero part of this component is absorbed into the zero point C. The major contribution to the extinction is still the air-mass term. Using the values of K and C determined from the first-order fit in the previous section, and substituting the revised extinction equation, equation (6), into the definition of δ, we find

$$\begin{aligned}\delta &= (m_{\rm inst} - m_{\rm batc} - KX) - \overline{(m_{\rm inst} - m_{\rm batc} - KX)} \\ &= f({\rm UT}) \ .\end{aligned}$$

Thus, by examining δ versus UT we can determine f(UT). Examination of the values of δ versus time shows that a whole night can be divided into several time "segments." A straight-line fit thorough the values of δ within each time segment is sufficient to determine f(UT) for this segment. We therefore express f(UT) as

$$f({\rm UT}) = a_i + b_i {\rm UT}, \quad ({\rm UT}_{i-1} \leq {\rm UT} < {\rm UT}_i) \quad (i = 1, \ldots, n) \ ,$$

where a_i and b_i are constants defining each straight-line segment. We substitute this definition of f(UT) into equation (7) and then redetermine K [C remains unchanged because $\overline{f({\rm UT})} = 0$ by definition, cf. eq. (5)]. To increase the reliability of the fits, we take advantage of the gray behavior of the extinctions and combine all δ residuals for all filters together for each night. The whole reduction process is fully automated except that it requires human interaction to determine the beginning and end of each time segment. To avoid a completely arbitrary determination of f(UT), a maximum of four straight-line segments per night is allowed.

In principle, we can iterate this procedure as many times as necessary. In practice, one iteration provides a satisfactory fit. In Figure 3 we show the residuals (δ) "before" and "after" f(UT) corrections for the three nights illustrated in Figure 2. In Figure 4, we show the before and after residuals versus time relationships for each night, divided into A, B, and C quality categories based on ending photometric quality (i.e., no D nights). One can see how the f(UT) correction procedure improves the quality of the photometric calibration for almost every night.

Note that it always takes at least several minutes to complete the observations of each standard star through all

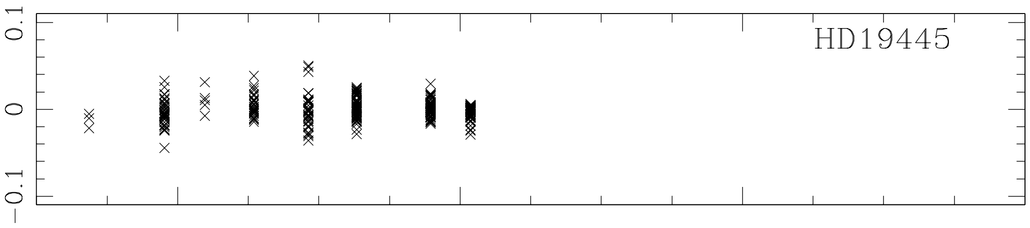
HD19445
0.1
0
−0.1

TABLE 4

FILTER-BY-F

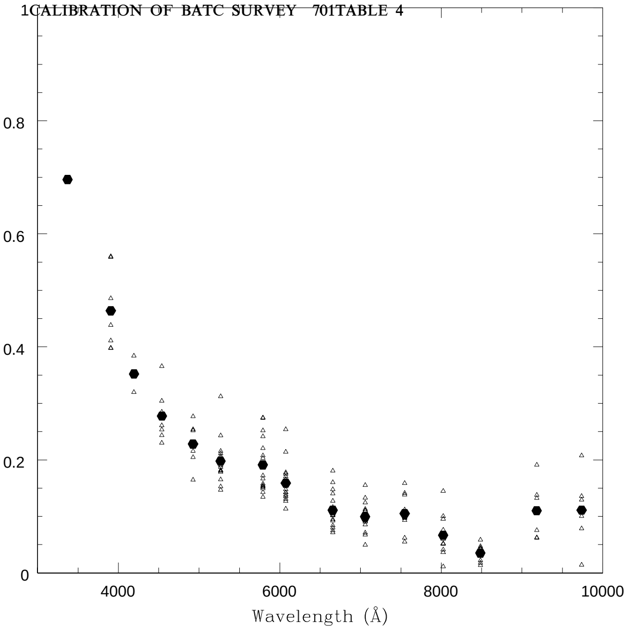

Table 4 gives the mean residuals per filter per standard star as observed on A and B nights, including 1 σ scatter and number of observations. To examine possible star-to-star systematics in m_{BATC}, we again use only the observations from A and B nights. For each filter, we determine

ences versus filter effective wavelength for each of the four standard stars. As is evident from both the table and the figure, the scatter per filter per star is consistent with the predicted BATC magnitudes for most filters for these stars to 0.01 mag. There is, however, some indication that the bluest filters for two or three of these stars might need their because of the filter transmission convolutions. This is especially true for the spectral region near and below the Balmer jump, where stellar flux varies very strongly with wavelength. However, the present data are too few to make a convincing case that such corrections are needed.

For completeness, Figure 6 plots the atmospheric extinction values versus BATC filter effective wavelength for the 28 A and B nights. These data provide the average atmospheric extinction on photometric nights for the BAO Xinglong Observing Station during the period 1995–1997. The mean extinction coefficients (K in eq. [6]) are given in Table 5. It is possible that the nonmonotonic wavelength dependence of extinction in the near-infrared might be due to the effect of stronger night-sky *absorption* in some filters than in others.

4. SUMMARY

The BATC Color Survey utilizes a set of 15 intermediate-band filters mounted at the 60/90 cm Schmidt telescope at Beijing Astronomical Observatory to do degree-sized CCD imaging down to $V \sim 21$ mag with spectral coverage from 3200 to 9900 Å. Our spectrophotometry is standardized to the AB_ν system through the four primary spectrophotometric standard stars of Oke & Gunn, as modified by the study of Fukugita et al. (1996). One of the observational goals of our survey is to obtain spectrophotometry that is tied to AB_ν system to a zero-point accuracy of ~ 0.01 mag for all objects in each of our survey fields. We discuss in detail the atmospheric extinction correction procedure used in our survey when a night is expected to be photometric.

From 1994 to 1997, 32 nights (of 423 possible) were selected by the observers at the telescope to be of possible photometric quality. On a typical photometric night we make ~ 50 observations of two or three of these standard stars in five to nine filters, through air masses between 1.0 and 2.0, both east and west of the meridians of the stars. We explicitly show that there is a component in atmospheric extinction which varies smoothly, at low amplitude, throughout each photometric night, in a manner that is independent of passband effective wavelength and air mass. We suggest that these small ($\sim 1\%$), gray, air-mass–independent variations are linked to the changes in atmospheric air pressure, temperature, and humidity known to occur between day and night. By incorporating a time-dependent correction to the atmospheric extinction for each night into the photometric reduction procedure, 13 nights show 0.01 mag or less scatter in their standard-star measures, 15 others have scatter between 0.01 and 0.02 mag, and only four have scatter between 0.02 and 0.03 mag. However, while we can obtain our observational goal of 1% accuracy in our spectrophotometry on photometric nights at the Xinglong Observing Station, the current low percentage of photometric nights (7.6%) means that, for calibration of our survey, we will likely have to provide supplemental observations at other sites.

The research done with the BATC Survey is supported by the Chinese Academy of Sciences, the Chinese National Natural Science Foundation, and the Chinese State Committee of Sciences and Technology. It is also supported in part by the National Science Foundation (NSF grant INT-93-01805 to R. A. W.), Arizona State University, the University of Arizona, and Western Connecticut State University. W. S. Sun gratefully acknowledges the support from the NSC under grant NSC87-2112-008-033. We thank the referee, Michael Richmond, for his helpful comments.

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