Inter-observer Photometric Consistency Using Optec Photometers

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Abstract Four observers, over a wide geographic range, observe slowly-varying stars in Johnson B and V bands using Optec SSP-3 and SSP-5 photometers on telescopes of modest size. Significant corrections for transformation and extinction were applied to their data, and we find very close agreement among them. In paired same-night observations, the median absolute difference between observers was 7 mmag. For the two observers with the most measurements in common, we estimate a systematic difference of 3.2 mmag or less.

1. Background

According to Henden (2017), published evaluations of consistency among photoelectric photometry (PEP) observers practicing differential photometry are difficult to find. Landis *et al.* (1985) describe a two-observer project to determine time-of-maximum of V396 Per. Based upon fitted data, they claim about ± 3 mmag rms deviation from the fit for each observer, and a systematic difference of about ± 1 mmag between observers. However, no documentation for the fit is provided, and the authors note that the exact period (which would affect the fit) is not known. All the authors are now deceased, so no further details are available. This study was conducted in V band only, with transformation adjustments of approximately 1 mmag, and it is not clear if measured or assumed extinction coefficients were employed. In the authors' words, "Differential photometry of this accuracy was possible because every pertinent factor was nearly ideal." Key factors were the small color difference between variable and comparison, minor differential extinction, and small transformation coefficients. It appears that Landis owned a DC photomultiplier photometer at the time of the study (Landis 1984), while Louth had a pulse-counting photometer (Skillman 1980), but it is not certain if these were the instruments used.

Cortesi and Poretti (1993) describe PEP observations of 44 Tau from two sites. They estimate a difference of 8.5 mmag between the observers, again V band only, based upon a fit. Transformations, if applied, would have been very small, on account of Δ(B–V) on the order of –0.007 (Tycho). It is not clear if extinction corrections were applied, and the authors note an ambiguity in the fit.

In Calderwood *et al.* (2015), two photoelectric observers operating simultaneously at the same location with closely-matched equipment achieved V-band measurements of common target stars with a median difference of 0.006 magnitude. Optec SSP-3 photometers were used at a fairly dark mountain location, and transformation corrections greater than those found in the Landis study were employed.

In this study, we step beyond the 1985, 1993, and 2015 projects. Data were taken in both B and V bands, with transformation effected largely using measured color contrast, and extinction corrected largely using measured extinction coefficients. Data are compared on a same-night basis rather than a fit. The participants used a variety of instrumentation as shown in Table 1 (the SSP-3 device has a photodiode sensor, while the SSP-5 uses a photomultiplier tube (Optec 2016)). CTOA was at an altitude of approximately 1,000 m, while the other observers were within 100 m of sea level. All locations had significant light pollution.

Table 1. Observers and equipment.

Observer	*Location*	*Photometer*	*Filters*	*Optics*
CTOA	Oregon	SSP-5	B,V	9.25" Schmidt-cassegrain
KJMB	Vermont	SSP-3	B,V	14" Schmidt-cassegrain
BSO	Maine	SSP-3	V	8.3" cassegrain
BVE	Netherlands	SSP-3	B,V	10" Schmidt-cassegrain

2. Observations

Stars already of interest in the AAVSO Photoelectric Photometry (PEP) program (AAVSO 2016a) were selected for this study. Since simultaneous observations would not generally be possible, targets of modest short-term variability were chosen: α Com, P Cyg, W Boo, ρ Cas, and R Lyr. These were bright enough that observers with small apertures could participate. Data were taken between May and September 2016. Difficulties with weather and equipment limited the number of same-night pairs to 31, which are summarized in Table 2.

Table 2. Observation summary.

Star	B pairs	V pairs
α Com	1	1
W Boo	2	2
P Cyg	0	3
ρ Cas	8	13
R Lyr	0	1

Table 3. Example adjustments to ρ Cas instrumental magnitudes, in mmag.

Obs	RJD	1st ext_B	1st ext_V	2nd ext_B	$xform_B$	$xform_V$	net_B	net_V
CTOA	57645	–4	–2	–16	–4	24	–24	22
KJMB	57634	–3	–2	–16	–42	16	–61	14
BSO	57643	—	–3	—	—	9	—	6
BVE	57693	–2	–1	–14	–57	12	–73	11

Magnitudes were measured differentially using the PEP program comparison stars (AAVSO 2016b). The PEP protocol uses an alternating sequence of multiple comparison/variable samples (AAVSO 2016c), with the variable usually sampled three times, and sky samples accompanying each star sample. Individual differential magnitudes are computed for each variable sample, and the mean is taken as the reduced magnitude. The 1σ error is computed as the standard deviation of that mean. Two-color data were gathered by interleaving B and V samples in a single sequence.

3. Reductions

All data were reduced using a PYTHON program written by one of us. Instrumental magnitudes were adjusted for transformation, first-order differential extinction between the variable and comparison, and, likewise, for second-order extinction in B band. Assumed first-order extinction coefficients were used for BSO and BVE reductions, while CTOA and KJMB reductions almost always used measured extinctions. A priori, it was decided to establish an upper limit for acceptable errors. Any observation with a 1σ error greater than 0.015 was discarded (for the bright stars in this study, 0.015 is a large uncertainty). If either band's measurement in a two-band sequence failed this test, both bands were discarded. Whenever available, the measured Δ(b–v) was used to calculate Δ(B–V) to effect transforms, otherwise a catalog Δ(B–V) was used (Δ(b–v) was always available for second-order extinction calculations).

4. Problems and limitations

CTOA's system showed systematically bright B magnitudes, on the order of 40–60 mmag for R Lyr and P Cyg when compared to other observers. These excesses, as will be seen, are far greater than other inter-observer discrepancies. The B pairs involving CTOA for these two stars have been dropped, which partially accounts for the relative shortfall of B band data in this study.

While the target/comparison pairs collectively exhibited a considerable range of color contrast, no Δ(B–V) was extreme. W Boo and ρ Cas, with contrasts of approximately 0.64 and –0.40, were the most challenging in this respect. The stars were generally measured at low airmass ($X < 1.2$), which minimized the effects of first- and second-order extinction. Table 3 illustrates typical extinction and transformation adjustments for ρ Cas.

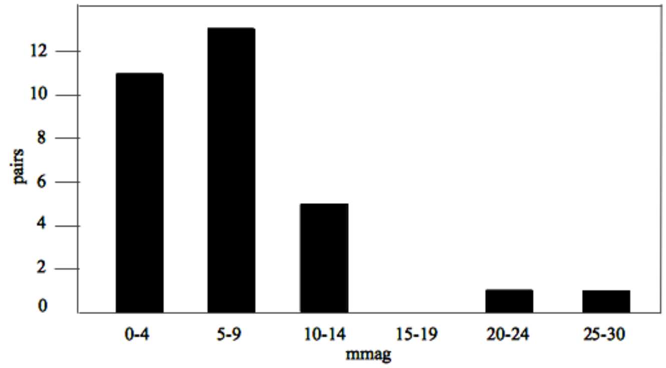

Figure 1. |ΔM| histogram, all observers.

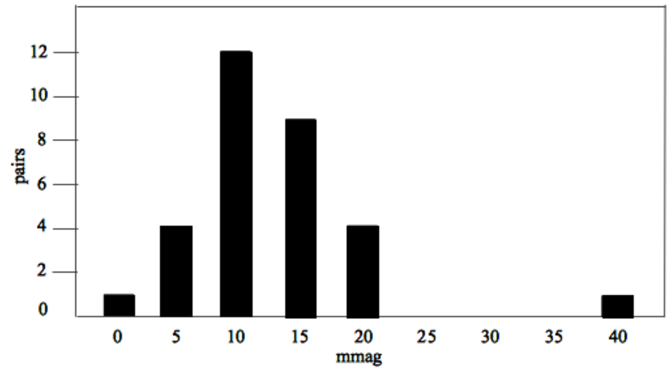

Figure 2. 2σ error budget histogram, all observers.

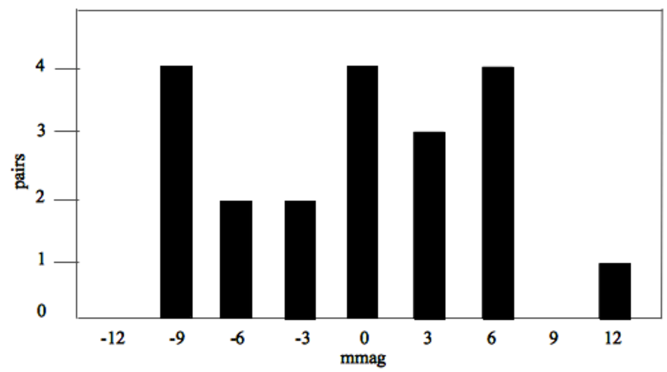

Figure 3. CTOA/KJMB ΔM histogram.

5. Evaluation

For comparison with the 2015 study, we first applied a 2σ overlap as a criterion for inter-observer consistency.

If the difference between a pair of magnitudes was less than or equal to the sum of their 2σ errors, we deemed them to be in agreement. The data are summarized in Table 4 and Figures 1 and 2 (both figures include the pairs that failed to agree). Twenty-nine of the thirty-one pairs achieved agreement, with the median absolute delta being 7 millimags. Note that on 57636 and 57641, all three of CTOA, KJMB, and BSO had V measurements of ρ Cas, and each pairwise comparison is included.

Table 4. Pairwise observation data.

RJD	Star	Band	Obs_1	$JD\ Frac_1$	M_1	err_1	Obs_2	$JD\ Frac_2$	M_2	err_2	ΔM	$2 \bullet err_{1+2}$	agree
57519	α Com	B	CTOA	0.739	4.783	0.003	KJMB	0.623	4.778	0.007	0.005	0.020	Y
57519	α Com	V	CTOA	0.740	4.332	0.004	KJMB	0.621	4.337	0.002	–0.005	0.012	Y
57573	W Boo	B	CTOA	0.761	6.429	0.006	KJMB	0.631	6.438	0.003	–0.009	0.018	Y
57573	W Boo	V	CTOA	0.762	4.744	0.002	KJMB	0.630	4.742	0.003	0.002	0.010	Y
57575	W Boo	B	CTOA	0.756	6.432	0.006	KJMB	0.652	6.429	0.003	0.003	0.018	Y
57575	W Boo	V	CTOA	0.756	4.739	0.001	KJMB	0.651	4.726	0.006	0.013	0.014	Y
57607	ρ Cas	B	CTOA	0.866	5.754	0.005	KJMB	0.676	5.747	0.003	0.007	0.016	Y
57607	ρ Cas	V	CTOA	0.866	4.475	0.002	KJMB	0.674	4.475	0.003	0.000	0.010	Y
57608	ρ Cas	B	CTOA	0.804	5.744	0.004	KJMB	0.825	5.744	0.004	0.000	0.016	Y
57608	ρ Cas	V	CTOA	0.804	4.469	0.004	KJMB	0.824	4.479	0.003	–0.010	0.014	Y
57634	ρ Cas	B	CTOA	0.825	5.692	0.002	KJMB	0.664	5.695	0.004	–0.003	0.012	Y
57634	ρ Cas	V	CTOA	0.825	4.446	0.002	KJMB	0.665	4.448	0.002	–0.002	0.008	Y
57636	ρ Cas	B	CTOA	0.749	5.688	0.001	KJMB	0.737	5.697	0.007	–0.009	0.016	Y
57636	ρ Cas	V	CTOA	0.749	4.451	0.001	KJMB	0.735	4.459	0.005	–0.008	0.012	Y
57636	ρ Cas	V	CTOA	0.749	4.451	0.001	BSO	0.618	4.451	0.002	0.000	0.006	Y
57636	ρ Cas	V	BSO	0.618	4.451	0.002	KJMB	0.735	4.459	0.005	–0.008	0.012	Y
57639	ρ Cas	B	CTOA	0.769	5.685	0.003	BVE	0.455	5.710	0.007	–0.025	0.020	N
57639	ρ Cas	V	CTOA	0.770	4.451	0.001	BVE	0.454	4.441	0.011	0.010	0.024	Y
57641	ρ Cas	B	CTOA	0.772	5.689	0.001	KJMB	0.592	5.682	0.002	0.007	0.006	N
57641	ρ Cas	V	CTOA	0.772	4.446	0.002	BSO	0.638	4.439	0.006	0.007	0.016	Y
57641	ρ Cas	V	CTOA	0.772	4.446	0.002	KJMB	0.594	4.446	0.003	0.000	0.010	Y
57641	ρ Cas	V	KJMB	0.594	4.446	0.003	BSO	0.638	4.439	0.006	0.007	0.016	Y
57643	ρ Cas	V	CTOA	0.798	4.447	0.003	BSO	0.569	4.446	0.007	0.001	0.020	Y
57644	ρ Cas	B	CTOA	0.780	5.691	0.001	KJMB	0.744	5.696	0.003	–0.005	0.008	Y
57644	ρ Cas	V	CTOA	0.781	4.446	0.004	KJMB	0.744	4.446	0.001	0.000	0.010	Y
57645	ρ Cas	B	CTOA	0.695	5.697	0.006	BVE	0.422	5.721	0.015	–0.024	0.042	Y
57645	ρ Cas	V	CTOA	0.696	4.452	0.002	BVE	0.421	4.463	0.004	0.011	0.012	Y
57643	R Lyr	V	CTOA	0.696	3.959	0.001	KJMB	0.585	3.957	0.001	0.002	0.004	Y
57608	P Cyg	V	CTOA	0.763	4.770	0.004	KJMB	0.751	4.765	0.001	0.005	0.010	Y
57641	P Cyg	V	CTOA	0.794	4.788	0.002	BSO	0.602	4.781	0.006	0.007	0.016	Y
57643	P Cyg	V	CTOA	0.717	4.802	0.008	BSO	0.535	4.788	0.001	0.014	0.018	Y

6. Statistical evaluation

CTOA and KJMB had 20 observations in common, which provided an opportunity for statistical analysis through a paired t test. The null hypothesis, H_0, is that the means of the difference of the pairs of observations is zero, or equivalently that the systematic error between the observations is not significant compared to the random error. The variances of the underlying distributions for each observer were not assumed to be the same, so we used the Welch t-test method of determining the t statistic, and degrees of freedom. The resulting p value is 0.80, so we cannot reject the null hypothesis at our chosen significance level of 0.05.

The actual sample mean of the differences between these observation pairs is 0.000 magnitude, with a median value of 0.000 and a standard deviation of 0.006 magnitude. The 95% confidence interval of the mean of the difference between two readings is –0.0032 mag to 0.0025 mag. Our interpretation of the confidence interval is that with 95% confidence the systematic difference between these two observers is less than 3.2 mmag for the stars observed.

We interpret the sample mean value as our best estimate of the systematic error between observations, with the standard deviation as our estimate of the random error. These estimates are with respect to internal consistency between the two observers. We make no estimates of systematic or random errors with respect to magnitudes in the UBV standard system.

Figure 3 summarizes the magnitude deltas for the 20 pairs, the median of which was 0 mmag.

7. Conclusion

It is clearly possible for well-calibrated observers using good technique to achieve highly consistent results using the Optec photometers. We do not wish to attach great importance to the specific value of the estimate of offset between CTOA and KJMB—individual millimags are significant in the calculations and rounding effects come into play. The point is that the number is quite small.

8. Future work

We wish to track down the cause of B band excess in CTOA measurements of the above-noted stars, which we believe are due to a systematic effect in the CTOA instrument. Since the conclusion of the study, weather conditions at the site have not permitted significant investigation of this problem.

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