

Comments on Optical Photometry and the Generation of Standard Stars

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Abstract.

Comments will be made on situations encountered in the process of observational optical photometry and the establishing of standard star sequences.

1. Prologue

One of my goals over the years has been to develop, enhance and publish standard star sequences at different brightness levels, and which are needed for a variety of scientific purposes. There occur projected against the celestial sphere a wide range of phenomena for which observers and experimenters need intensity and color information. Therefore there is a long-term need for accurate photometric standard stars, those with known intensities and colors at a variety of optical wavelengths. Use of such standard stars permits the combination and inter-comparison of the brightness and color measurements for various celestial phenomena made by different investigators. Examples of such uses include: the interplay of theory and observation requires accurately calibrated magnitude and color indices of celestial objects to further the understanding of stellar evolution, the determination of the ages and distances of star clusters, studies of variable stars, and to define the distance scale through our Milky Way Galaxy, the local group of galaxies, and onward to the edge of the Universe. Further, one must work toward solving the calibration problems facing the new generations of giant telescopes.

2. Introduction

I begin by mentioning the past. As each of you in your own way continues the beautiful, exquisite, important work of today, you can better appreciate and understand the art of photometry by reviewing the efforts of our predecessors. Required reading, then, is the series of papers, early recollections, by Harold Weaver (1946a,b,c,d,e,f). As astronomers who have a direct interest in the process of standardizing incoming astronomical radiation, a complete history of the topic can be informative. Such a history has been written by Hearnshaw (1996) in his book *The Measurement of Starlight*. Of course, the “two centuries of astronomical photometry” covered by Hearnshaw’s work discusses photometry in the visible part of the electromagnetic spectrum. Authors of similar works today would have a broader and more difficult task since data are acquired, and need to be calibrated, across the electromagnetic spectrum. An early modern collection of information on photometric systems that one might mention ap-

pears in Straižys (1992). A more recent volume of note resulted from the predecessor meeting to this current gathering, Sterken's (2007) *The Future of Photometric, Spectrophotometric and Polarimetric Standardization*. The function of that meeting was to "reflect on the status and on the future of standardization and calibration in photometry, spectrophotometry and polarimetry".

A recent masterful commentary on photometric systems of current usage and great interest may be found in an Annual Reviews chapter by Bessell (2005). Hence, a new overview of the variety of photometric systems currently in use is not necessary.

As one meanders through conversations at meetings, over meals at an observatory's dining room before a night's work, and over drinks during an evening of relaxation, one acquires the sense of the procedures used in acquiring and reducing photometric data. Perhaps the most revealing discussions emanate from these evenings of contemplation, during the long snowy nights when one cannot observe.

The current crop of astronomers, and particularly engineers not a part of the corporate memory of astronomical observing, would do well to remember the importance of having a filter in their modern filter systems easily relatable, transformable, to history: the human eye, the yellow sensitized photographic emulsion, and the V filter of the *UBV* photometric system (Johnson & Morgan 1953), all this to take advantage of a kind of corporate memory from the past.

The goal must be to avoid tie-in problems, at the very least minimizing them, thereby making more accessible and valuable the old published magnitudes and color indices. Observers are not doing experiments in the sense of physics and chemistry research. What they are doing is adding another data point at a particular time in history to the historical record of the intensity and colors of astronomical objects. Even so, even being able to achieve such a goal, observers only have seen a snapshot of the history of the celestial object. These snapshots, acquired over the years, have got to be able to hang together.

3. Setting the Stage

What characteristics should an optical photometric system possess? Irwin (1947) emphasized the observational problem. Harold Johnson described such desiderata in the early days of photoelectric photometry (Johnson 1955), after he and W. W. Morgan had defined the *UBV* photometric system (Johnson & Morgan 1953). The *UBV* photometric system was the first replacement photometric system for the International System of Photographic Magnitudes of the North Polar Sequence (NPS). The NPS had originated at Harvard under Pickering's direction (Hearnshaw 1996, page 161), and served as the basis for the calibration of photographic photometry until mid-twentieth century.

Johnson (1952) described in some detail relations between extant magnitude systems of the day. Johnson (1955) provided further evidence of the uncertainties which arose through use of the International System of magnitudes and the NPS. The NPS was deficient since it did not adequately allow for ultraviolet radiation, thereby preventing proper transformations to be made. There also were too few stars of different spectral types in the NPS, again affecting transformations. Further the NPS stars were placed relatively near the north celestial pole, making them accessible to all northern hemisphere astronomers, albeit at an increasing air mass for observers at temperate latitudes. Johnson stated that a photometric system must contain standard stars which

come from all parts of the Hertzsprung-Russell diagram, from all temperature classes, as well as from all luminosity classes, and reasonably, usefully, distributed over the sky.

Johnson emphasized that a standard photometric system should be defined by a homogeneous set of measures made with one reflecting telescope with an aluminized mirror, on one mountaintop (i.e., one elevation, approximately 7000 feet), one set of specified filters, one specified detector (in his work, a RCA 1P21), and one set of reduction procedures. The ensuing list of standard stars has to include stars of each spectral type and luminosity class, and these stars must be both reddened and unreddened. All these specifications must be met to ensure adequate transformations of the data from future observers' own instrumental arrangements to the photometric system as defined by the standard stars in a given photometric system. Finally, Johnson wrote that a new photometric system should be consistent with previous photometric systems.

Now, a necessary short digression. The MKK system of spectral classification was developed by W. W. Morgan and Philip Keenan and is discussed in Keenan & Morgan (1951). Its initial publication took the form of an atlas (Morgan et al. 1943). Morgan (1988) recalls the history behind development of the spectral classification system which became known as the MK system. The 1943 initial version evolved to that published and described by Johnson & Morgan (1953). It is this latter publication which is of interest to us today since the spectral types and luminosity classes of the stars are tied together with a photometric system, the *UBV* photometric system. The spectral types are correlated with the color indices. This is the initial and most long lasting instance of such affinity, the so-called tie-in.

A strength of the original *UBV* photometric system was the connection between spectral types, effective temperatures, and the magnitudes and color indices as defined by the 1P21 photomultiplier and a prescribed set of filters. This led to the successful list of stars which allowed other observers to calibrate their data relative to the *UBV* system (Johnson & Harris 1954; Johnson 1963). The tie-in was the definition of the color system to be $(B - V) = (U - B) = 0.0$ from the average colors for six identified A0V stars (Johnson & Morgan 1953). And the new photometric system was linked to the past, the International System of Photographic Magnitudes, via the I_{pv} , or m_{pv} and I_{pg} , or m_{pg} magnitudes. The new color index, $(B - V)$, was linked to the past via the photographic based color index (C.I.) = $m_{pg} - m_{pv}$, where m_{pg} equals photographic or blue magnitude and m_{pv} equals photovisual or yellow magnitudes. These magnitudes arose from blue sensitive or yellow sensitive photographic emulsions, respectively.

4. Photometry the Old Way

My Ph.D. thesis involved a photographic study of two galactic (or, open) star clusters, NGC 6087 and IC 4725 = M25 (Landolt 1964a,b), of interest because my thesis advisor, John B. Irwin, had re-discovered the presence of classical Cepheids within the areal confines of the clusters (Irwin 1951) during a sabbatical visit to South Africa. The photographic data were made available through the courtesy of Her Majesty's astronomer at the Cape, Dr. R. H. Stoy. The photographic images were measured with a Cuffey Iris-Diaphragm Photometer (Cuffey 1956). The data were calibrated through use of photometric sequences established in each cluster's vicinity through use of a photomultiplier.

Photoelectric sequences for M25 had been established independently by four different individuals, in fact, leaders in that day and time, of the technique. The sequences

were by Irwin (1958), Sandage (1960), Johnson (1960), and Wampler et al. (1961). Irwin's data (Irwin 1961) were taken with an EMI photomultiplier. The photomultiplier of choice for Sandage, Johnson and Wampler was the 1P21. Johnson's data were taken with the same filters and photomultiplier used to establish the *UBV* system. The reason for recounting this history is to point out that differences exist even among the experts. In this instance, the sequence from Wampler et al. (1961) was chosen as the basic sequence, against which the other three sequences were compared and eventually combined. The Wampler et al. sequence was anchored by Kraft's MK classification of the sequence stars' spectra together with the *UBV* photometry, as well as being an approximate mean of the other three sequences. The scatter between the sequences approached 0.07 magnitude. And, there were color equations between the sequences. The point to be made is that one cannot directly combine data, even from the best practitioners, without incurring systematic problems. Once the Wampler et al. sequence was chosen as the basic sequence, the other photoelectric sequences were transformed onto the Wampler et al. sequence. This average photoelectric sequence then was used to calibrate the photographic data. The final accuracies of the photographic magnitudes and colors were on the order of a few percent.

I was privileged to be the first guest observer in 1959 at the then new Kitt Peak National Observatory (KPNO). At the time, the only telescope available was a 16-inch reflector which had been hauled around from mountain top to mountain top in the southwestern United States, in the search for the best photometric site (Irwin 1952). The standard stars available for calibration purposes were those in the then recently defined *UBV* photometric system (Johnson & Morgan 1953; Johnson & Harris 1954; Johnson 1963). The standard star magnitudes and color indices in Johnson (1963) are the same as those in Johnson & Harris (1954). The 1963 paper was a review paper, whereas the 1954 paper was the original paper wherein the photometry leading to the standard stars was discussed. My project was a study of the massive eclipsing binary system, V382 Cygni, which eventually resulted in a paper (Landolt 1964c). The Johnson & Harris (1954) standard stars were of an appropriate brightness to work well with the 16-inch reflector coupled with a 1P21 photomultiplier as the detector. The data reductions indicated that the accuracy of the magnitude and color index tie-in to the *UBV* photometric system was ± 0.018 mag in *V*, ± 0.011 in (*B* - *V*), and ± 0.014 in (*U* - *B*). These accuracies matched the accuracies of the *UBV* system as defined by Johnson's standard star photometry, on the order of, or just under two percent.

5. Photoelectric Photometry at the Celestial Equator

There had been extended discussion, both privately and in the literature, of the desirability of a faint sequence of standard stars distributed over the sky Blaauw (1955); Greaves (1955); Walker (1959); Stoy (1958, 1961). Therefore an attempt was made by this author to address the perceived problem via establishing a homogeneous set of *UBV* standard stars in the celestial equatorial Selected Areas. By so doing, astronomers in both hemispheres would have access to faint standard stars readily accessible to the telescopes then available.

There were many other fine photometric systems at the time, in the 1960s, but I voted to continue with the *UBV* system because it had a tie to the past, as one could glean from the Weaver (1946a,b,c,d,e,f) series of papers which reviewed astronomical photometry, and from Hearnshaw's book on the history of photometry (Hearnshaw

1996). The tie to the past was Johnson's use of a magnitude defined by a filter whose effective wavelength approximated that of the sensitivity of the human eye. Such a filter allowed a tie to the photographic photovisual magnitudes, and back to the visual photometries, as exemplified by the Harvard Photometry.

An observational program was begun to establish standard star sequences in the 1960s since there were too few sufficiently faint standard stars for the then new telescopes (36-inch and 84-inch) at the new national optical observatories. As in following years, the majority of the data for my standard star efforts were obtained at the national optical observatories. Their existence, together with the telescopes at the national radio observatory sites, allowed the flowering of U.S astronomy, extending observing opportunities to all who could pass the test of a telescope allocation committee. Parenthetically, it will be a great pity if the research community allows this kind of opportunity to diminish in availability now and in the future.

Various procedures have evolved over the years during which standard star sequences have been produced (Landolt 1973, 1983, 1992, 2007, 2009). Initially one needs a technique to identify potential standard stars. The goal is to identify stars of the broadest possible range in color, a non-trivial task since most stars are "yellow." This fact is a plus in one sense. The process is first to discover, to identify, blue stars, the most scarce kind of star by number. One can almost be assured that red stars will be in the vicinity of the blue star since they are more plentiful. There certainly will be sufficient stars of intermediate color, the yellow stars.

Five different procedures have been followed at different times over the years, in the effort to identify potential standard star candidates. Initially, literature searches were carried out by hand, less onerous years ago, when the literature was more manageable. Several stars from the galactic anticenter study by Rubin et al. (1974) were considered. An early prime resource was stars selected from the Giclas catalogs of blue and red objects which Giclas published over the years in the Lowell Observatory Bulletins. Feige (1958, 1959) published lists, with charts, of blue stars. Richard Green forwarded what proved to be most useful unpublished charts and coordinates from the Palomar-Green survey (Green et al. 1986). Other colleagues sent me suggestions as well.

A third effort involved the acquisition of photographic plates through an appropriate combination of emulsion types and *UBVR* filters at the Yale 1.0m telescope at the Cerro Tololo Inter-American Observatory (CTIO). These plates then were iris-photometered and pseudo color-magnitude diagrams were plotted, with the expectation that the redder and bluer stars would stand out in the color-magnitude plot. Unfortunately, this huge task largely was unproductive, as well as being very time consuming. This kind of approach was used in the days prior to the availability of CCDs, modern imaging processing, and powerful computers. At some level the process was useful, but at the cost of huge time consuming effort.

A more successful attempt involved scanning of faint Palomar Sky Survey fields for me by Mike Irwin in the United Kingdom. His efforts identified faint potentially red and blue stars, complete with charts. A number of these fields have been studied over the years, and will result in new sequences. The color extremes picked out via scanning have not always lived up to expectations, sad to say. A considerable amount of time goes into just seeing which stars in which fields may turn out to be useful. Particularly, on occasion the faint red "stars" turn out under good seeing to be galaxies. This is a reminder, again, that when the *UBV* photometric system was formulated, the stars developed as standards had known spectral types and luminosity classes. Now, going

ever fainter, the observer has little idea, at least initially, of the kind of celestial object being photometered.

A most recent useful technique has been to mine Sloan Digital Sky Survey (SDSS) photometry by my colleague James Clem, using modern image processing. The fields possessing stars of the broadest range in color have been incorporated into our observing program. A number of sequences currently are being completed based on this identification effort, with data taken both at the CTIO Yale 1.0m and at the KPNO 2.1m telescopes.

My earliest attempt in providing standard star sequences resulted in Landolt (1973). Those *UBV* data were based on a 1P21 photomultiplier with the data taken at the KPNO. The data were tied into the *UBV* system as defined by Johnson (1963). The majority of the stars that were observed were in celestial equatorial Selected Area fields. The Selected Area fields had the advantage that stars therein already had known brightnesses, positional information, and finding charts (Landolt 1973). Once the data were reduced, it was possible to perform a check on the success of the venture. This check was accomplished by assuming that the newly defined standard stars indeed were of standard star quality, and hence using them as standards, together with using the original Johnson *UBV* standards' measured values as unknowns. One then could re-reduce the data in an attempt to recover the original *UBV* standard stars' magnitudes and color indices. Four long nights of excellent data were chosen for the experiment. After re-doing the reduction process, using the newly defined standard stars as standards, and the original standard stars as unknowns, a comparison was made of the recovered magnitudes and color indices. The original standard star magnitude and color index values were recovered to better than a few tenths of a percent. It therefore was deemed that the reduction process had been a success.

I have striven to adhere to the dictum of one telescope, one photometer set-up, one detector, one mountaintop as my standard star program has progressed. As all of you realize, these desiderata are difficult to meet. Even at the national optical observatories, which have had the advantage of long corporate memory and long continued availability of photometric set-ups, photomultipliers, and currently other detectors, do decide to stop functioning. A more complete discussion is summarized in Landolt (2007).

6. Observational Problems

We know that environmental conditions change from season to season, from night to night, and even throughout any given night. It is imperative that an observer go outside the confines of the console room a number of times each night to ascertain the condition of the night sky. One has the added thrill of the beauty of the night sky! One needs to be appropriately dark adapted to be most effective. One can improve one's acuity by using only incandescent light bulbs to illuminate the console room; fluorescent and similar lighting appreciably slows the human eye's ability to rapidly become dark adapted. At CTIO, for instance, one can readily see the rise and fall of the haze layer on some nights. Given that the observer has noted that the top of the layer was beneath the mountain top. Sometime later the observer cannot see the inversion layer at all. Chances are good that the top of the layer now lies above the mountain top, and the observer is within it. Hence, the extinction has changed; the transparency, too. Such behavior has to be taken into account when analyzing the data.

As one might expect, if forced to switch filter sets during a project, it becomes necessary to determine just how closely the data taken through each filter set matches. In the instance where such a situation happened to me (Landolt 1992) meant that relations between the magnitudes and color indices resulting from one filter set had to be determined. Then the data from the filter set with the fewest data were transferred to the dataset from the filter with the most data. Only then could all the data be averaged together to provide the final magnitude and color indices for the standard sequences.

Similar differences are found when comparing data taken with different individual detectors, but of the same brand. Again, the data need to be compared, and one dataset must be chosen as the basic one. The remaining dataset(s) then are transformed onto the best dataset, with the final compilation being the newly defined set of standard stars.

Another kind of observational problem. Many years ago, the author took data at the 16-inch and 36-inch telescopes at CTIO of a suspected open cluster located at a large southern declination. At best, the air mass of the measurements was large. The carefully standardized photometry taken at the two telescopes did not agree. A star by star comparison showed a constant difference in zero point between the two data sets, something on the order of a few percent. The exact same equipment was used on both telescopes. Which dataset was correct? What caused the difference? Some kind of flexure? Data taken at both telescopes for stars in other programs did agree.

Similar differences between well observed stars, stars observable from both hemispheres, were found between the data sets obtained at northern and southern hemisphere telescopes. In this instance, even though the original data had been reduced in an appropriate manner, more careful attention to details led to eventual compatibility in the results from data taken in both hemispheres. The point in relating this kind of situation is that one always needs to be cognizant of any and all subtleties.

7. The CCD Era

There is a technique used in review tasks, reviewing proposals, or job applicants, etc., where it is useful, using agreed upon criteria to follow a process of an initial pass through the group, thereby eliminating some proposals or candidates. A reasonable approach is to operate with the understanding that at any time during the review process, an earlier rejection can be revisited. It is a method of justifying judgments. On occasion an almost missed gem is recognized.

Similarly, modern data flows have become immense. They will continue to grow in volume and content as the large photometric surveys move forward. The immensity of the task has driven the development of algorithms which attempt to sort out the chaff from the good data. A part of the analysis technique should be to revisit the rejected data points. Just because the data points look to be out of place, to fall appreciably away from the suspected correlation line, does not mean that there is not a physical reason for the point to fall where it does. On occasion an important discovery will be made.

Now to modern and recent observing programs. Suggestions of the past still very much are in order (e.g., Da Costa 1992). Data destined for standardization work still must be taken only under photometric conditions! Extinction stars must be obtained every night. Standard star fields must be taken every night, preferably distributed throughout the night. One technique is to begin the night with standard star fields, adding an additional field every couple hours or so, and finally ending the night with a standard star field.

CCD photometry most often is reduced as a magnitude, as a function of color, as compared to most photoelectric photometry wherein the V magnitude was reduced separately as a magnitude as a function of $(B - V)$, and the color indices were reduced as a function of the color index under consideration. Now-a-days, after one has completed the reductions for each filter, *UBVRI*, say, the standard color indices should be formed. The recovered color indices for the standard stars then must be compared with those same standard stars' published color indices, to ensure that the color transformation was complete and accurate. One still might encounter what amounts to non-linear effects in the transformation process. Those non-linear transformations effects arise from differences between the detector and filters used in the current programmatic data acquisition process, and the photometric system used in defining the standard stars. Those non-linear transformation effects must be removed from the program stars' photometry to ensure that the new data are properly on the published standard system being utilized. A kind of final proof of successful transformation of CCD data would involve separately plotting the derived color indices for both the standard stars and the program stars on a canonical unreddened color-color magnitude diagram for main sequence stars. Unhealthy transformations should be obvious to the practitioner.

Of course, one could reduce the CCD data as color indices, but such treatment normally is not appropriate due to the long integration times for CCD data, in many instances, and the sometimes long read-out times for some CCD cameras, particularly when a set of data for an object involves five filters. The technique was reasonable for photoelectric photometry where integration times were very much shorter and readout times effectively non-existent.

There exist around the sky many photometric sequences; many are in galactic or globular clusters. The author wants to reiterate that using multiple source sequences in clusters is not a good idea, if the most accurate results are needed. As intercomparisons show, some such sequences really are not on the same precise photometric system; again, see the description above for photoelectric data (Landolt 1964b) and the warning for CCD data (Da Costa 1992). Zero point and color equation problems occur. The relatively crowded fields in clusters are a major source of the problems. On the other hand, if the observational program demands only accuracies of three or four percent, or less, then one can relax the quality of the standardization process. However, if accuracies of a few percent are all that are necessary, then one can relax the quality of the standards. Beware, though, of potential systematic problems in the resulting photometry from such a standardization process. And under such circumstances, be careful to not over-interpret the resulting photometry.

8. Results Over Time

Table 1 lists some of the major efforts in defining the *UBV* system, and later, the *UBVRI* photometric system as we know it today. The number in parenthesis in the first column gives the publication year. The number in the second column lists the number of stars in the cited standard star paper. Standard star values in the Johnson (1963) and Landolt (1973) papers were restricted to the Johnson defined *UBV* filters. All other papers in Table 1 in fact included the *RI* filters as described initially by Cousins (1976), and the *UBVRI* filters as described by Bessell (1976, 1979), and formulated for CTIO photometers by Graham (1982).

The author addressed the lack of standard stars of extreme color to some extent in 1983 (Landolt 1983). That paper also added intensity measures at the R (6800Å) and I (8250Å) wavelengths, as defined by Kron et al. (1953) and Cousins (1976). Cousins had set up $UBVRI$ photometric sequences in the Harvard E-regions at declination -45 degrees, and the author's (Landolt 1983) RI measures were tied into those Cousins' sequences. Additional sequences at -50 degrees declination were published by Landolt (2007), and enhanced and expanded sequences around the celestial equator were published in Landolt (2009). A manuscript is in preparation for sequences around the sky at $+45$ degrees declination.

Still fainter $UBVRI$ sequences, with CCD data taken at the CTIO Yale 1.0m and the KPNO 2.1m telescopes, now are under development. The goal is to have a manuscript containing $UBVRI$ sequences approaching 20th magnitude later this year. The sequences will both include an expansion of the author's current equatorial $UBVRI$ photometric sequences as well as several new sequences around the celestial equator. These latter sequences will enable the inter-comparison of photometry between $UBVRI$ filters and the Sloan $ugriz$ filters.

Table 1. Number of UBV standards as a function of time.

Reference	# of Stars	Filters	Sky Location
Johnson (1963)	104	UBV	northern hemisphere
Landolt (1973)	658	UBV	celestial equator
Cousins (1973)	255	UBV	E and F-regions
Graham (1982)	102	$UBVRI$	E-regions
Landolt (1983)	223	$UBVRI$	celestial equator
Menzies et al. (1991)	212	$UBVRI$	celestial equator
Landolt (1992)	526	$UBVRI$	celestial equator
Landolt (2007)	109	$UBVRI$	-50 degree fields
Landolt & Uomoto (2007)	31	$UBVRI$	HST spectrophotometric
Landolt (2009)	595	$UBVRI$	celestial equator
Landolt (2012)	hundreds	$UBVRI$	$+45$ degree fields
Clem & Landolt (2012)	1000+	$UBVRI$	celestial equator

Table 2 summarizes the number of stars in the author's published sequences, the magnitude and color range of the sequence stars, and the average number of measures of each standard star. The sequences planned for 2012a, 2012b, and 2012c will be in fields at $+45$ degrees, intermediate depth fields at the celestial equator, and deep fields around the celestial equator, respectively. The 2012b sequences are an expansion of those sequences in Landolt (2009). A keen eye will note that the number of stars cited for each paper differ between Table I and Table II. That is because Table I includes all stars observed. Table II includes those stars with generally five or more measures each, and hence able to provide more secure transformations.

Table 3 indicates the photometric accuracies achieved over the years. Recall that the Landolt (1973) photometry was UBV only. It is obvious that the accuracies both in the U and I filters are lower in the most recent work. The faintness of the stars being made into standards increased relatively more rapidly than did the size of the telescope with which the data were collected. Hence, the poorer average accuracy, as the author

Table 2. Summary of author's standard star efforts.

Year of Publication	# of Stds.	V Magnitude Range	B - V Color Range	Measures per Star
1973	335	10.5 → 12.5	-0.25 → +2.00	11
1983	223	7.0 → 12.5	-0.30 → +2.00	20
1992	217	11.5 → 16.0	-0.30 → +2.30	29
2009	595	8.9 → 16.3	-0.35 → +2.30	24
2012a	hundreds	~ 9.0 → 16.0	~ -0.30 → +2.20	~ 15
2012b	1000+	~ 10.0 → 16.0	~ -0.30 → +2.00	25+
2012c	1000+	~ 15.0 → 20.0	~ -0.30 → +1.80	25+

pushed the telescope and photometer to their limit. The accuracies for the photometry in manuscripts in preparation are not listed. However, one can state that those accuracies will be under one percent.

Table 3. Photometric Accuracies.

	Mean Errors of a Single Observation				Mean Errors of the Mean			
	1973	1983	1992	2009	1973	1983	1992	2009
<i>V</i>	0.0153	0.0134	0.0160	0.0144	0.0046	0.0029	0.0039	0.0036
<i>B - V</i>	0.0159	0.0124	0.0195	0.0191	0.0048	0.0027	0.0048	0.0051
<i>U - B</i>	0.0250	0.0228	0.0439	0.0492	0.0075	0.0050	0.0125	0.0143
<i>V - R</i>		0.0090	0.0126	0.0115		0.0020	0.0031	0.0029
<i>R - I</i>		0.0095	0.0182	0.0166		0.0021	0.0044	0.0040
<i>V - I</i>		0.0116	0.0228	0.0207		0.0025	0.0055	0.0050

The thread throughout my purely observational photometric program has been a tie into the *UBV* system as defined by Johnson & Morgan (1953) and Johnson (1963), today called the Johnson *UBV*. The *RI* aspect of my observations has been tied into Cousins (1976). As time has passed by, the precision of the data has increased, in part because Johnson took many fewer measurements per star than I, and in part because modern equipment is both more sensitive and more stable.

More complete discussions of some of the topics included herein may be found in related papers (Landolt 2007, 2011, 2012). In summary, *UBVRI* photometric sequences, ultimately tied back into Johnson's *UBV* system, and Cousins *RI* system, are available around the sky at -50 degrees declination, at the celestial equator, and about to be at +45 degrees declination. The goal was, and the hope is, that this photometry all has a lineage back to the human eye.

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