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DATA REDUCTION TECHNIQUES

FOR DIFFERENTIAL PHOTOELECTRIC PHOTOMETRY

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I. INTRODUCTION

This paper is a compilation of the fundamental techniques used in the reduction of photoelectric photometry (PEP) data. Its purpose is to point out, and hopefully clarify these fundamentals. Much is left unsaid, little theory is presented, and the derivation of the equations are not shown. However, if the reader intends to reduce his/her own data, and you should if you want to gain deeper understanding of PEP, then this paper will provide an overview and foundation upon which to build. It is highly recommended that the works contained in the reference section be studied as well, particularly Hall and Genet (1988), and Henden and Kaitchuck (1982).

It is important that you recognize that the observation of variable stars, and the subsequent reduction of the data you obtain, is not the end product of the scientific process. In order for this data to yield its full scientific meaning it has to be analyzed, and then synthesized with the theoretical, or hypothetical, physical processes occurring in the stars observed. The reader of this paper should be congratulated. You are taking an initial step towards furthering your understanding of this scientific process, and by doing so, your observations will become significantly more rewarding. However, after you become familiar with the data reduction process you should go a step further and try to learn something about the physical processes which are causing the variations you observe. Do not get anxious when you see the equations. They are really quite simple, and can be easily solved with an inexpensive scientific calculator. Further, they will be explained as fully as space allows.

II. DIFFERENTIAL REDUCTION PROCEDURES

There are two fundamental PEP observation and data reduction procedures, both of which vary from observer to observer, depending upon the program of stars one is investigating, and to a certain extent personal prejudices. Typical examples include: when and how often sky readings are taken; when averages are determined; and how extinction coefficients are determined. As you begin to read the literature in the field you will undoubtedly see how these techniques vary among investigators. Do not be overly concerned with these variations at this point. Simply choose a methodology that you are comfortable with, and begin observing and reducing your data. Experience, and the help of the observing program coordinator, will be the best teachers. You will soon find yourself developing your own variations on the basic technique.

DIFFERENTIAL PHOTOMETRY REDUCTIONS ◊

With a few exceptions, the procedure and techniques presented in this paper are intended to clarify certain points and to present a classical methodology based upon the techniques given by Hall and Genet (1988), Hardie (1962), and Henden and Kaitchuck (1982).

As stated earlier, there are two fundamental techniques used in PEP. The first, "all-sky" or "absolute photometry" is the most demanding, and it is very observing-site dependent. It is best attempted only at excellent site with clear, steady skies, conditions uncommon to the sites used by most part time astronomers. The second technique, the one addressed in this paper, is called "differential photometry". As the name implies, differential photometry is simply the determination of a magnitude (brightness) difference (Δm) between a nonvariable star and a star of unknown magnitude. The latter is usually referred to as the program or variable star. Additionally, it is often advisable to observe a second nonvariable star of known magnitude as a check to insure that the comparison star you have selected is not, in fact, a variable itself. This third star is referred to as the check star.

Differential observation and data reduction techniques are not only simpler than "all-sky" techniques, but they are more accurate as well. If you apply a disciplined scientific approach to your observing and data reduction process, differential techniques can result in measurements accurate to at least 0.01 magnitude, and in unusual cases even 0.005 magnitude. The foremost goal that you should have in mind as you begin PEP is that *quality* observations and data reductions are far more important than *quantity*. To paraphrase Dr. Douglas Hall of Vanderbilt University, "There is no such thing as amateur photometrists, only good data and bad data".

For the purposes of this paper, the differential reduction algorithm has been divided into eight steps which are:

(1) Determine average (mean) readings for each object in the observing sequence. Instead of averaging, at this point some observers will simply sum the three integrations (readings).

(2) Subtract the averaged (or summed) sky readings from the averaged (or summed) star readings.

(3) Determine instrumental magnitudes (m). If you have to determine extinction corrections, then it is necessary to determine instrumental magnitudes-- more about this later.

(4) Determine an instrumental magnitude average for the comparison star readings taken just before and just after the variable star reading.

(5) Determine instrumental magnitude differences (Δm) by subtracting the average comparison star instrumental magnitude, determined in step (4), from the variable star instrumental magnitude.

(6) Determine an average instrumental magnitude difference ($<\Delta m>$), color index (Δ(b-v)), if required, and standard deviations (σ).

(7) Apply extinction corrections if necessary.

(8) Transform the results of step (6), or (7), to the standard *UBV* system.

Before beginning a detailed discussion on the data reduction process let's make sure you understand the assumptions used in this paper, and acquaint you with some of the symbols normally encountered (see Table 1):

(1) The photometer is a standard SSP-3 which uses a voltage-to-frequency converter. It is not a photon counter, therefore we will not need to consider "dead-time" corrections. Additionally, if the comparison star has been carefully chosen there will usually be no need to correct for different amplifier gains.

(2) Two-color photometry (*B* and *V*) is assumed.

(3) The observational sequence is: Comparison, Variable, Comparison, Sky, with three ten-second readings taken in each filter for each object.

(4) An observational run consists of the repetition of the above sequence as many times as necessary for your particular program. However, as will be pointed out later, if the comparison star and variable star are separated by more than ~0.5-1.0° you will have to determine extinction corrections. To do this you will have to extend your run for the comparison star over a period of time long enough that the star can be measured at a wide variety of airmasses, that is, a wide variety of zenith distances, or hour angles, if you prefer to think of it in those terms.

TABLE 1.
Symbols and Subscripts Used

b	Instrumental magnitude for the *B* filter
c	Comparison star
d	Photometer reading (e.g., number of counts)
k'	Primary extinction coefficient
k"	Secondary extinction coefficient
m	Generalized instrumental magnitude
o	Indicates magnitude corrected for atmospheric extinction
v	Instrumental magnitude for the *V* filter
x	Variable star
y	Check star
B	Standardized magnitude for the *B* filter
V	Standardized magnitude for the *V* filter
X	Airmass
Δ	Any difference between two quantities
ε	Transformation coefficient

STEP ONE. Determine the average readings for each object in the observational sequence:

$$\langle d \rangle = (d_1 + d_2 + d_3) / 3 \qquad (1)$$

	V Filter				B Filter			
	d_1	d_2	d_3	$\langle d_v \rangle$	d_1	d_2	d_3	$\langle d_b \rangle$
Comparison:	1095	1093	1096	1094.667	0989	0987	0989	0988.333
Variable:	1172	1174	1171	1172.333	1022	1025	1023	1023.333
Comparison:	1093	1093	1092	1092.667	0986	0988	0985	0986.333
Sky:	0504	0504	0505	0504.333	0502	0500	0501	0501.000

STEP TWO. Subtract the sky averages from the star averages:

$$d = \langle d \rangle_{star} - \langle d \rangle_{sky} \qquad (2)$$

	V Filter $\langle d_v \rangle$	B Filter $\langle d_b \rangle$
Comparison:	1094.667 - 0504.333 = 0509.334	0988.333 - 0501.000 = 0487.333
Variable:	1172.333 - 0504.333 = 0668.000	1023.333 - 0501.000 = 0522.333
Comparison:	1092.667 - 0504.333 = 0588.334	0986.333 - 0501.000 = 0485.333

STEP THREE. Determine the instrumental magnitudes:

$$m = -2.5 \log d \qquad (3)$$

	d_v v	d_b b
Comparison:	-2.5 log (509.334) = -6.768	-2.5 log (487.333) = -6.720
Variable:	-2.5 log (668.000) = -7.062	-2.5 log (522.333) = -6.795
Comparison:	-2.5 log (588.334) = -6.924	-2.5 log (485.333) = -6.715

STEP FOUR. Determine an average instrumental magnitude for the comparison star readings taken immediately before and after the variable star reading:

$$\langle m \rangle = (m_{c1} + m_{c2}) / 2 \qquad (4)$$

$\langle v_c \rangle = [(-6.768) + (-6.924)] / 2 = -6.846$ $\qquad$ $\langle b_c \rangle = [(-6.720) + (-6.715)] / 2 = -6.718$

STEP FIVE. Determine an instrumental magnitude difference, in the sense of the variable minus the comparison:

$$\Delta m = m_x - \langle m_c \rangle \qquad (5)$$

$\Delta v = (-7.062) - (-6.846) = -0.216$ $\qquad$ $\Delta b = (-6.795) - (-6.718) = -0.077$

STEP SIX. Determine an average instrumental magnitude difference, standard deviation, and color index. Let's say you have determined the following instrumental magnitude differences for each observing sequence in your run:

$\Delta v =$	-0.216	-0.220	-0.224	$\langle\Delta v\rangle = -0.220$
$\Delta b =$	-0.077	-0.073	-0.075	$\langle\Delta b\rangle = -0.075$

$$\Delta(b\text{-}v) = \langle\Delta b\rangle - \langle\Delta v\rangle \quad (6)$$

$$\Delta(b\text{-}v) = (-0.075) - (-0.220) = 0.145$$

The standard deviation is calculated as follows:

$$\sigma = [\Sigma(x - \langle x\rangle)^2 / (N - 1)]^{1/2} \quad (7)$$

where x is an instrumental magnitude difference, <x> is the average instrumental magnitude difference, determined in step (6), and N is the total number of magnitude differences:

$$\sigma_{\Delta v} = \pm\, 0.004 \qquad \sigma_{\Delta b} = \pm\, 0.002$$

STEP SEVEN. Apply the extinction corrections, if necessary. When the comparison and variable star are separated by more than ~1°, then an extra-atmospheric instrumental magnitude difference should be determined using the following equation:

$$\Delta m_o = \Delta m - k'\,\Delta X - k''\,\langle X\rangle\,\Delta(b\text{-}v) \quad (8)$$

where ΔX is in the sense of the variable's airmass minus the average of the comparison star's airmasses from the readings taken just before and just after the variable star's reading, and <X> is the average of the variable star's airmass and the average of the comparison star's airmasses from the readings taken just before and just after the variable star's reading. The determination of the extinction factors k' and k" is discussed in Part III.

STEP EIGHT. Transform the results of step (6), or step (8), to the standard *UBV* system:

$$\Delta M = \langle\Delta m\rangle + \varepsilon\,\Delta(b\text{-}v) \quad \text{or} \quad \langle\Delta m_o\rangle + \varepsilon\,\Delta(b\text{-}v)_o \quad (9)$$

Let's say you have determined $\varepsilon_v = -0.001$ and $\varepsilon_b = 0.064$. Then:

$$\Delta V = -0.220 + -0.001(0.145) = -0.220 \pm 0.004$$
$$\Delta B = -0.075 + 0.064\,(0.145) = -0.066 \pm 0.002$$
$$\Delta(B\text{-}V) = (-0.066) - (-0.220) = 0.154$$

III. DETERMINATION OF EXTINCTION COEFFICIENTS

Even on the most stable and clear of nights the Earth's atmosphere plays a significant role in our observations. The net effect of the atmosphere on PEP is to cause an extinction (reduction) in the light that reaches our telescopes. This extinction is primarily caused by two phenomena. The first, absorption, is a quantum phenomenon which results in a loss of the amount of photons that would have otherwise reached our instruments. The second, scattering, causes light to be redirected in a variety of different directions. The size of the effect that these two phenomena have on the light of the star we wish to measure is dependent upon the amount of air (atmosphere) that the star's light must travel through to reach our telescopes. Therefore, the height (altitude) of the stars we are measuring above the horizon is of principal importance. As the altitude of the star increases (zenith distance decreases), the amount of atmosphere that the light must pass through decreases. This is why photometry is best accomplished when a star is near the zenith.

Anytime you are conducting photometry on a comparison star and a variable star which are separated by ~1° or more, the atmosphere affects the light received from these two stars appreciably differently. These differences must be accounted for in the reduction process. Though the process to do this is only moderately difficult, it is both time consuming and fraught with chances for mathematical error. Hall and Genet (1988) maintain that, through experience, extinction factors may be arrived at by educated guess. However, for many observers without extensive experience, extinction coefficients must be calculated. This paper presents the basic outline for this process, but it is highly recommended that you consult Hall and Genet (1988) and Henden and Kaitchuck (1982) for a detailed description. Also, Duffett-Smith (1981) presents excellent algorithms, with examples, for basic astronomical calculations used as part of the extinction correction process, such as precession, zenith distance, hour angles, and time and date conversions.

There are two observational methods which may be used to determine a primary (k') extinction coefficient. The first requires that the observer measure a series of standard stars at different altitudes, i.e., different airmasses. The second method, and the one addressed here, is to use the comparison star to determine k'. To do this the observer must extend the run so that the comparison star is measured over a wide number of different airmasses. The secondary, or color dependent extinction coefficient (k") does not change nightly, and can be determined at the same time that you are determining your transformation corrections by the process outlined in Part III.

The algorithm for determining k' is given below. Details for the calculations of the basic observational astronomical functions in steps (1) - (3) are contained in Duffet-Smith (1981).

STEP ONE. Precess the coordinates of the comparison star to the current epoch, that is, to the night of observation.

STEP TWO. Determine the local sidereal time (LST) for each time that you observed the comparison star.

STEP THREE. Determine the hour angle (h) for each of the times determined in step (2):

$$h = LST - \alpha_{precessed} \qquad (10)$$

STEP FOUR. Determine the secant of the zenith angles (z):

$$\sec z = (\sin\phi\ \sin\delta + \cos\phi\ \cos\delta\ \cos h)^{-1} \qquad (11)$$

where ϕ is the latitude of the site in decimal degrees, δ is the precessed declination of the comparison star in decimal degrees, and h is the hour angle at the time of each observation, converted to decimal degrees ($h^{\circ} = h^{h} \times 15^{\circ}$).

STEP FIVE. Determine an airmass for the comparison star at each observation, that is, at each zenith angle (sec z):

$$X = \sec z\,[1 - 0.0012\,(\sec^2 z - 1)] \qquad (12)$$

STEP SIX. A quantity call k is now determined by plotting the individual instrumental magnitude (m) of the comparison star versus the airmasses of the comparison star. The slope of this line is k. For a more precise mathematical way to do this see Simon (1989).

STEP SEVEN. k' is now determined by the equation:

$$k' = k - k''. \tag{13}$$

If you have not determined k" previously by the process outlined in Part IV, then you are probably safe using the values: $k''_v = 0.00$ and $k''_b = -0.02$.

IV. DETERMINATION OF TRANSFORMATION COEFFICIENTS

Even the very best of PEP equipment, regardless of whether you buy commercial equipment or build your own, will not exactly match the standard Johnson *UBV* equipment. Therefore, in order for your data to be usable by others it must be transformed (corrected) to match the standard *UBV* system. To do this, transformation coefficients for each filter, and the color indices, must be determined for your particular instrumental combination. Once determined, these coefficients remain relatively stable over time, and need only be checked (updated) once or twice yearly, unless you change something in your instrumental system.

There are two methods used to determine transformation coefficients. The first, like "all-sky" photometry, is both time consuming and relatively complex, requiring the measurement of a number of standard stars at various locations in the sky. The second, and the one addressed here, is based upon the observation of a close, red-blue pair of stars. This method is detailed by Hardie (1962). A listing of red-blue pairs is given by Henden and Kaitchuck (1982), and Hall (1983a,b).

The advantages of using the close pair method is that the data reduction procedures closely parallel those for a regular differential observation run, and the fact that these selected red-blue pairs are usually within 1° of each other allows us to disregard primary extinction corrections. Further, if the observational run is extended over a period of time so that the pair can be measured over a wide variety of airmasses, then a secondary, or color-dependent extinction coefficient (k") may be determined at the same time.

The procedures given below are based upon the following assumptions:

(1) The blue star, though it is obviously not a variable, is considered to be the "variable" for the purpose of the data reduction, while the red star is considered to be the "comparison" star. This is simply a useful convention.

(2) The observational sequence is red, sky, blue, sky, red, sky.

(3) An observational run should consist of at least six observations of the blue star. While this number of measurements has only a marginal effect on the standard deviation it does reduce the mean error. If you wish to determine secondary extinction coefficients then the run must be extended so that measurements may be taken at a wide variety of airmasses.

STEPS ONE THROUGH SIX. These steps are the same as steps (1) - (6) of Part II (above) for a regular differential data reduction treating the red star as the comparison star and the blue star as the variable.

STEP SEVEN. Determine transformation coefficients without determining a secondary extinction coefficient (k"). If you are not going to determine k" then your transformation coefficients ε_v, ε_b, and ε_{bv} are calculated as follows:

$$\varepsilon_v = (\Delta V - \langle \Delta v \rangle) / \Delta(B-V) \qquad \varepsilon_b = (\Delta B - \langle \Delta b \rangle) / \Delta(B-V) \tag{14}$$

$$\varepsilon_{bv} = \varepsilon_b - \varepsilon_v \tag{15}$$

where V, B, and B-V are the catalog (given) values for the red and blue stars, and ΔV, ΔB, and $\Delta(B-V)$ is in the sense of the variable (blue star) minus comparison (red star).

STEP EIGHT. Determine transformation coefficients and secondary extinction coefficients (k"). Use the same procedure as given in Part II, steps (1) - (6), and Part III, steps (1) - (5), except that airmasses must be calculated for both the red and blue stars at each zenith distance:

$$k''_v = \text{slope of } \Delta v \text{ versus } \Delta(b-v)\langle X \rangle \text{ plot} \tag{16}$$

$$k''_b = \text{slope of } \Delta b \text{ versus } \Delta(b-v)\langle X \rangle \text{ plot} \tag{17}$$

$$k''_{bv} = k''_b - k''_v \tag{18}$$

where $\langle X \rangle$ is the average of the variable star's (blue) airmass and the comparison star's airmass at the time that Δm is determined.

Once k" has been determined you use the following procedure to determine your transformation coefficients:

$$\Delta v_o = \langle \Delta v \rangle - k''_v \langle X \rangle \Delta(B-V) \tag{19}$$

$$\Delta b_o = \langle \Delta b \rangle - k''_b \langle X \rangle \Delta(B-V) \tag{20}$$

where $\langle X \rangle$ is the same as above. Also:

$$\varepsilon_v = (\Delta V - \Delta v_o) / \Delta(B-V) \tag{21}$$

$$\varepsilon_b = (\Delta B - \Delta b_o) / \Delta(B-V). \tag{22}$$

V. REFERENCES

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