The High Road to Astronomical Photometric Precision: Differential Photometry

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1 The Basics of Differences

One might think from the combination of errors that a difference between equally precise individual magnitudes would result in increased uncertainty, or decreased precision, by a factor of $\sqrt{2}$ in their difference. This is frequently the case in computing a color index from separate magnitudes; in fact some differential photometers have been created to observe only a single star in two or more passbands simultaneously in order to decrease the error in the measured color index. Nevertheless, ground-based observations can be improved by comparing the light of two stars in close proximity because of several conditions:

1. First-order atmospheric extinction (i.e., extinction independent of star color) depends on airmass (roughly $\propto$sec z), therefore if $\Delta z \approx 0$, so is this component of the general atmospheric extinction
2. First-order atmospheric extinction can vary both temporally and spacially; hence, simultaneous or nearly simultaneous observations of two stars in close proximity on the sky can improve the error budget under such conditions
3. Color-dependent extinction (sometimes called "second-order extinction") arises in part from atmospheric Rayleigh scattering but if two stars of similar intrinsic color index are observed, some effects may cancel
4. Effects of errors in transformation coefficients can be reduced somewhat by selection of stars of closely similar apparent spectral energy distributions (SEDs) if observed at low air mass
5. Variations in background flux and sky brightness can be minimized by differential photometry if sampled more quickly than the sky variations
6. When chopping can be applied, the noise at frequencies other than the chopping frequency can be minimized

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We demonstrate these points formally in the following discussion. The total measured power collected from a stellar source can be described in the expression;

$$\mathscr{P}_{\text{obs}} = \frac{\pi}{4} \cdot D^2 \cdot \int_0^\infty \left[\left(\mathscr{F}_* + \mathscr{F}_{\text{bgd}}\right) \cdot t_{\text{atm}}\, t_{\text{tel}} + \mathscr{F}_{\text{sky}} \cdot t_{\text{atm}'}\, t_{\text{tel}'} + \sum_i^n \mathscr{F}_i^{\text{local}} \cdot t_i \right] q_\lambda \, d\lambda, \tag{1}$$

where $\mathscr{F}$ is the flux from the particular source indicated by subscript; t is the transmission coefficient, so that t_{atm} is the transmission through the atmosphere, and t_{tel} through the telescope optics including filter(s) and windows in the optical path, and t_i, transmissions of the various local fluxes; primed transmission quantitities are associated with sky brightness (generally these need not be identical to the corresponding stellar or local values); D is the effective diameter of the light-gathering area of the telescope; q_λ is the wavelength-dependent quantum efficiency of the detector, and λ is wavelength. The integration is taken across the passband, but note that here the explicit passband function is defined by the optical transmission functions. The transmission factors and detector spectral sensitivity are sometimes explicitly combined into an instrumental passband function, S_λ. Background flux is that in the star field itself due to other stars as well as diffuse objects such as galaxies and nebulae. The sky flux includes moonlight, twilight, airglow, and aurora, but the treatment of these diffuse sources can be challenging because the light path may not be identical to that of light from a targeted object. The sources of local flux are the lights within and outside the telescope enclosure. We may assume that the observer can control these nuisance sources satisfactorily so we need not discuss them further. The collected power is readily converted into the number of detected photons per unit time with the expression,

$$n_{\text{meas}} = \mathscr{P}_{\text{obs}} / \left(hc\lambda_{\text{eff}}^{-1}\right) + n_{\text{det}}, \tag{2}$$

where the factor $(hc/\lambda_{\text{eff}})^{-1}$ converts units of power (energy/time) into a photon count rate, and where the quantity λ_{eff} applies to the passband; a more exact treatment would involve division of (1) by the monochromatic factor (hcλ^{-1}) and integrated across the passband. n_{det} is an unwanted contribution from the detector or its associated electronics, again in counts per second. In photoelectric detectors, n_{det} arises from thermal emission within the detector and can be minimized by cooling, either by a cryogen such as dry ice (solid CO_2) or thermoelectrically. In a charge-coupled device (*CCD*) it arises partly from thermal emission, which similarly can be controlled by cooling, and partly from "read-out" detector noise, which can be measured. Read-out noise is usually small in current-day CCDs but may be important under such conditions as very low signal and background flux levels or very short exposure times. We will assume that this contribution, too, is manageable so it need not be discussed further. With (2), the time-integrated number of detected events can be written:

$$\mathscr{N}_{<\lambda>} = \frac{1}{4}\pi D^2 \left[<\mathscr{F}_{*+\text{bkg}}> \cdot <t_{\text{atm}}> \cdot <t_{\text{tel}}> + <\mathscr{F}_{\text{sky}}> \cdot <t_{\text{atm}'}> \cdot <t_{\text{tel}'}> \right] \cdot <q_{<\lambda>}> \cdot \Delta\lambda \cdot \tau \cdot (hc/\lambda_{\text{eff}})^{-1}, \tag{3}$$

where τ is the integration/exposure time of the observation, and the angle brackets ($< >$) indicate averages over τ, or the effective passband width, $\Delta\lambda$. Hopefully most, if not all, of the background flux arrives at the detector through the same optical path as the target flux, although (depending on the design of the optical system) the sky flux may not. The difference in pathways may be important for glass and interference filters because of the dependence of λ on angle of incidence. In principle, the background and sky fluxes can be subtracted once they are measured, although their contributions to the noise remain.

Equation (3) is expressible in terms of magnitude measure but remains inconvenient unless the background and sky terms are subtracted first.

Equations (2) and (3) have useful applications, but it suffices for present purposes to proceed with (1). Over an integration time, τ, we arrive at the radiant energy collected in the interval:

$$\mathscr{E} = \mathscr{P} \cdot \tau. \tag{4}$$

Differential photometry can improve matters by eliminating some sources of noise and by minimizing others, but the detailed treatment determines how effective the differential photometry can be. If we express the passband brightness of one star relative to another by substituting from (1) and then differencing (4), without first subtracting the sky, we are left with several inconvenient terms:

$$\begin{aligned} \mathscr{E}_1 - \mathscr{E}_2 = \frac{\pi}{4} \cdot D^2 \cdot \{ [(< \mathscr{F}_{*,1} > - < \mathscr{F}_{*,2} >) \cdot < t_{\text{atm}} > \cdot < t_{\text{tel}} >] \\ + \left[(< \mathscr{F}_{\text{sky},1} > - < \mathscr{F}_{\text{sky},2} >) \cdot < t_{\text{atm}'} > \cdot < t_{\text{tel}'} > \right] \} \cdot < q > \cdot \tau \cdot \Delta\lambda, \end{aligned} \tag{5}$$

where averages are taken over the integration time interval as well as over the effective spectral bandwidth of the passband, and the background fluxes are assumed to be identical. If the sky fluxes are also identical, the second bracketed term vanishes; if they are not, or if the backgrounds are not identical, lack of detailed investigation of these terms will impact both precision and accuracy. If, on the other hand, the sky is carefully measured and subtracted from the observed radiant energy, so that

$$\mathscr{E}_{\text{target}} - \mathscr{E}_{\text{sky}} = \frac{\pi}{4} \cdot D^2 \cdot < \mathscr{F}_{\text{target}} > \cdot < t_{\text{atm}} > \cdot < t_{\text{tel}} > \cdot q \cdot \tau \cdot \Delta\lambda, \tag{6}$$

for each of two stars, the ratio of the sky-subtracted detected energies becomes

$$\frac{\mathscr{E}_{*1} - \mathscr{E}_{\text{sky},1}}{\mathscr{E}_{*2} - \mathscr{E}_{\text{sky},2}} = \frac{\mathscr{F}_{*1}}{\mathscr{F}_{*2}} \cdot \frac{< t_{\text{atm},*1} >}{< t_{\text{atm},*2} >}, \tag{7}$$

after common terms are divided out. From this, a differential magnitude can be obtained,

$$m_1 - m_2 = -2.5 \cdot log \left\{ \frac{\mathscr{F}_{*1}}{\mathscr{F}_{*2}} \right\} - 2.5 \cdot log \left\{ \frac{< t_{\text{atm},1} >}{< t_{\text{atm},2} >} \right\}. \tag{8}$$

Johnson (1962) states that determining simultaneous sky brightness can produce an improvement of 20–100% in the resulting photometric accuracy depending on the amount of sky variation. Shortly we will consider the sources of noise that can afflict such differential measurements; but first we need to consider the sources of error in photometric measurements generally. These are:

- Scintillation noise
- Target photon noise (sometimes called "shot noise")
- Sky photon noise
- Thermal environment noise
- Detector noise; and, ultimately
- Transformation errors

Scintillation noise is proportional to the signal, increases with airmass, and is dominant for bright stars, but can be minimized by observing with larger telescopes that gather light through a wider column of atmosphere; the dependence varies with the inverse square of telescope diameter. Typical scintillation amplitudes for a 30-cm telescope are about 1% with frequencies of $\sim$1–100 Hz. The signal to noise ratio, *SNR*, for this source is, moreover, independent of signal. Code and Liller (1962) compare the noise contributed by "seeing" with other noise sources over the range of apparent magnitudes $0 \leq V \leq 20$.

Photons follow Poisson statistics, so that $SNR \propto \sqrt{\mathscr{N}}$, where $\mathscr{N}$ is the number of recorded events, as in (3). Because both target and sky shot noise suffer these fluctuations, the noise enters from both measurements. In addition, sky brightness may vary greatly due to scudding clouds before the Moon, aurorae, and merely sky glow. Yes we said "scudding clouds before the moon" because photometric skies are not always photometric from zenith to horizon, as any observer can attest. Thus both the intrinsic variations as well as the shot noise connected with these varying sources of spurious light may contribute to the noise.

The treatment of emission from the thermal environment and noise is important for infrared astronomy, and is usually treated by cryogenic cooling of the detector with liquid nitrogen, or, for the thermal infrared, beyond 2 μm, with liquid helium. The additional sources of impairment of infrared photometry, along with their remedies, are described in the Milone and Young paper in this volume and in the citations of that paper. Instrumental noise these days arises mainly from the detector; amplifier noise, once highly significant in photoelectric photometry, is now relatively insignificant. Although read-noise has been a significant source of noise in CCD observations, as Howell's paper in this volume shows, this source of error has decreased greatly in modern CCD photometry. For completeness, we mention also noise due to transformation error. This is not a source of random error, but of systematic error because it depends on the spectral energy distribution and other factors. It may, however, be rendered less important by careful selection of comparison star. A fuller discussion of errors in differential photometry can be found in Young et al. (1991), who conclude that even with careful selection of comparison stars, manual alternate observations of target and comparison stars can rarely produce precision better than 0.5%. Automated photometry, however, can do better sometimes, as we demonstrate below.

In general, the combination of random noise sources gives the net noise level:

$$\mathscr{N}_{\text{total}} = \sqrt{\left[\mathscr{N}^2_{\text{scint}} + \mathscr{N}^2_{\text{shot}} + \mathscr{N}^2_{\text{sky}} + \mathscr{N}^2_{\text{det}}\right]}. \tag{9}$$

The combination of errors can be applied to (7) in order to find the precision of a differential measurement:

$$e_r = \left\{\left[e^2_{*1} \cdot \left(\frac{t_{\text{a1}}}{\mathscr{F}_{*2}t_{\text{a2}}}\right)^2\right] + \left[e^2_{*2} \cdot \left(\frac{\mathscr{F}_{*1}t_{\text{a1}}}{\mathscr{F}^2_{*2}t_{\text{a2}}}\right)^2\right] + \left[e^2_{t_{\text{a1}}} \cdot \left(\frac{\mathscr{F}_{*1}}{\mathscr{F}_{*2}t_{\text{a2}}}\right)^2\right] + \left[e^2_{t_{\text{a2}}} \cdot \left(\frac{\mathscr{F}_{*1}t_{\text{a1}}}{\mathscr{F}_{*2}t^2_{\text{a2}}}\right)^2\right]\right\}^{0.5}, \tag{10}$$

but we note that $e_{*1,2}$ include sky and background noise contributions.

Now we ask in what ways differential photometry can improve both accuracy and precision. The selection of a non-variable comparison star has much to do with it. By "non-variable" we mean a star found to be not significantly variable at the desired precision level over at least the time interval of the observing run. Three general criteria are followed:

1. Small angular distance from the variable.
   This criterion helps to assure a small atmospheric extinction difference between the stars
2. Greater brightness than the variable (with some exceptions).
   This can improve photon statistics. There are occasions, however, where systematic effects may occur if the comparison star is substantially brighter than the variable, or vice-versa. Normally one would not select, except of necessity, a comparison star that is much fainter than the variable
3. Similarity in apparent SED to the variable.
   Color indices may be more useful than spectral type matching if there is substantial difference in interstellar reddening between the two stars, because such an effect redistributes the spectral energy distribution, effectively changing the effective wavelength of the passband, which leads to a significant color term difference. A second-order effect may remain, however, due to the shift in λ_{eff} introduced by differences in spectral features within the passband. It is the distribution of flux across the passband that gives rise to the color term (sometimes incorrectly referred to as the "second-order" term) in extinction. We discuss this color dependence further, below

Sometimes it is desirable to add a fourth criterion (Milone 1967): Equality in zenith distance at some selected hour angle of the pair so that the differential air mass is near zero when needed. Usually comparison stars are not so numerous that one can fulfil all of these criteria, but in crowded regions, this may be possible. This also may be useful, however, where the best comparison stars are not within a few arcmins of the target star. The required position angle, p, and optimized hour angle can be derived from the equation for the differential airmass. Ignoring corrections for atmospheric curvature and refraction, we obtain

$$dX = -X^2 \cdot (\cos\delta \, \sin\phi \, d\delta - \sin\delta \, \cos\phi \, \cos H \, d\delta - \cos\delta \, \cos\phi \, \sin H \, dH), \tag{11}$$

where $X = \sec z$, δ = mean declination, ϕ = site latitude, and H = mean hour angle. The nulling of this quantity yields

$$dH/d\delta = -d\alpha/d\delta = \frac{\tan\phi - \tan\delta \cdot \cos H}{\sin H}, \tag{12}$$

where, for simultaneous observations, $dH = -d\alpha$, where $d\alpha$ is the difference in right ascension between the two stars.

The position angle can be expressed as

$$\tan p = \frac{d\alpha \cdot \cos\delta}{d\delta}, \tag{13}$$

so that

$$\tan p = -\frac{(\tan\phi - \tan\delta \cdot \cos H) \cdot \cos\delta}{\sin H}. \tag{14}$$

The optimized hour angle can be found from the solution of (12):

$$\cos H = +\frac{\tan\phi \cdot \tan\delta \pm (d\alpha/d\delta) \cdot \left[\left(\tan^2\delta - \tan^2\phi + (d\alpha/d\delta)^2\right)\right]^{0.5}}{(d\alpha/d\delta)^2 + \tan^2\phi}. \tag{15}$$

Given a comparison star that meets the first three criteria, it is an easy matter to use (15), to determine what part of a night provides a minimal airmass difference. A fuller exposition is given in (Milone 1967).

It should be noted that a full characterization of the extinction on any given night is very difficult to achieve with broadband filter systems. Young (1988) suggests that such a determination requires overlapping passbands which can satisfy the sampling theorem, something the *UBV* system alone cannot do; on the other hand, narrower overlapping passbands, such as the Geneva system B_1 and B_2 undersample the spectrum in other ways. Even if two stars are identical in intrinsic color (and spectral type), the slight changes caused by color extinction will results in departures from millimagnitude extinction in the B band. Thanks to the Chappuis bands of ozone, however, there is a very much reduced atmospheric reddening effect within the V passband. This makes highly precise differential photometry possible if still difficult. To cite Young et al. (1991) "... if one is willing to live with fairly exacting contraints" in terms of comparison star selection, air mass, and magnitude and color extinction measurements, "then millimagnitude differential photometry of some stars may be possible with existing systems such as the Johnson-Morgan B and V."

2 Differential Visual Photometry

The idea to compare visually the brightness of one object with another exploits the excellent ability of the human eye to do just this. Probably the earliest such documented use of this principle in astronomy was by Pierre Bouguer in 1725 (Bouguer 1729), of "Bouguer extinction" renown, who used a standard candle to illuminate a surface and compare the illumination with that produced by the Sun and Moon. John Herschel made use of a demagnified image of the Moon to measure stellar brightnesses of Southern stars in 1836. About this time, C. A. Steinheil (1837) developed his prism photometer in conjunction with a refracting telescope, the objective lens of which was split in two. Each half of this lens had the same focal length, but could be independently focused. Consequently, a star imaged with one objective component could be compared with another star imaged by the other objective component (a prism in front of one component introduced a second star from outside the field of view). By separating the two objectives so that the stars' extrafocal (spread-out) images had the same intensity, Steinheil (1837) created a kind of null photometer; the difference in distance of the two objectives from the focal plane provided a measure of the relative stellar brightnesses.

In 1850, F. Arago (1858) suggested that the principle of polarization could be used to measure starlight. This seminal idea led to the most precise and accurate means of determining relative brightness available to visual photometry (see Bastien's paper in this volume). J. C. F. Zöllner (see Hermann (2002) for a recent biography and portions of his work) followed Arago's suggestion to create the first polarizing comparative photometer, with which a focused star's brightness could be compared with that of an artifical star. The light of the artifical star (a kerosene lamp) was polarized by passage through a fixed Nicol prism and then through a rotating analyzer; this allowed the light to be dimmed to match the apparent brightness of a star. As part of a submission for a photometry prize offered by the Academy of Sciences of Vienna, he included the design and a list of 226 stars observed with it. Although Zöllner was not awarded the prize, his work was subsequently published (Zöllner 1861) and proved very influential. Copies of Zöllner's instrument were used subsequently by a number of astronomers: C. Pierce at Harvard (from $\sim$1871), J. Wolff at Palermo and Bonn (from 1869), G. Müller at Potsdam (from 1877) who with P. Kempf produced the *Potsdamer Durchmusterung* survey, and E. Lindemann at Pulkovo (from 1870). The highest precision attainable with these early comparative devices was not great, not better than $\sim$5%, and typically worse.

In the summer of 1877, following in the footsteps of Bond and Pierce, E. C. Pickering (1879) started a new program to carry out visual differential photometry at Harvard, and experimented with a variety of apparatus to develop the best instruments for this purpose. The work was begun with the Zöllner astrophotometer but this was abandoned because the artificial star was considered unsuitable. Pickering and his associates (O. Wendell and A. Searle) found it insufficiently constant, and, moreover, the image could not be reduced to a small enough size to match the stellar seeing disk. There was a certain degree of irony in this; years earlier Zöllner had criticized G. P. Bond (1861) for his use of a highly variable flame that was said to match the color of the moon, in order to obtain differential measurements of the Sun and Moon with the flame, and thus to each other. Pickering's group then tried to use various images of bright stars, dimmed, as had been the artificial star, by a double-edged prism, used in conjunction with a rotatable Nicol prism. The latter acted as a polarization analyzer, and, as it rotated, reduced the light of a star. Most of the instrumental configurations contained two telescopes, with the dimming performed on light through the smaller of the two, which was used for the brighter star. Figure 1 shows one of the earlier two-star instruments in use at Harvard (Pickering 1879, Figs. 5 and 6, p. 7). Instrument "I" used an aperture stop rather than a polarizer to vary light from the brighter star.

Decades later a version of the Pickering polarizing photometer, as the visual two-star instrument was then called, was still in use at Harvard (Wendell 1909) and a copy was being used at Princeton (Dugan 1911). Indeed, the latter was used at Princeton through the 1930s. John E. Merrill reported (private communication to EFM, 1980) that the observations of RW Com that he obtained with the instrument (reported by Russell (1939) and published in Milone et al. (1980)), had a typical mean photometric precision of ∼2%. This was about the maximum precision obtainable with such an instrument.

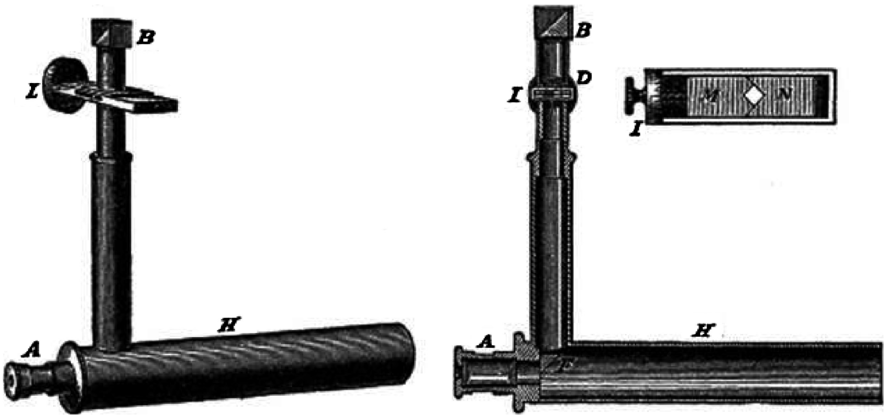

Fig. 1 A version of the visual two–star photometers in use at Harvard in the nineteenth and early twentieth century century. "Photometer I", as illustrated and described by Pickering Pickering (1879) did not include polarizing elements but rather a variable aperture in one of the two telescopes to vary the brightness of one of the two stars. Legend: *A*, eyepiece in larger telescope to view the fainter star; *B*, prism; *D*, objective for the smaller telescope; *F*, prism (near *A* within telescope tube *H*) to bring image of brighter star into field of view; *M, N*, two thin slabs of brass with V-shaped ends, forming a square "cats-eye" opening, adjustable with calibrated knob, *I* (image: courtesy Harvard College Observatory)

3 Differential Photographic Photometry

Although photography was invented in 1837 and first astronomical images were obtained in 1840 by J. W. Draper, only after the invention of dry gelatine emulsions in 1870 did the photographic plate become the primary astronomical detector. The differential visual comparisons made of early type stars near the North Celestial Pole, that had been pioneered by Harvard astronomers, were further extended to the photographic realm, and the use of a visual dye led to the development of multi-wavelength photometry with photographic (m_{pg}) and photovisual (m_{pv}) magnitudes.

As noted in the article by Sterken et al. in the present volume, differential photographic photometry provided the highest possible precision for photographic work; this is evidenced by the work of Jordan (1923) on the short-period eclipsing binary star system RW Com, by Plaut (1940) on WW Dra, the eclipsing brighter component of the wide double Σ2092, and by Wesselink (1941) on SZ Cam, the eclipsing binary component of the visual binary Σ485. Wesselink found that the difference in the $m_{pg} - m_{pv}$ color index of the visual pair was only 0.05. On the plane of the sky they are only 17.9 arcsec apart. The brightness of the comparison star is about equal to the average brightness of SZ Cam, which is the northern component of this pair. Thus the companion satisfies most of the criteria mentioned in Sect. 1. Wesselink showed that any variation of the southern component was within $\pm$0.02 magn., so it was demonstrated to be a suitable comparison star (one can be unlucky in choice of comparison and check stars if these have not been studied previously; Wesselink was fortunate here). To improve the precision of the differential photometry, Wesselink went further than merely having at hand a close and well-matched comparison star. He made use of a diffraction grating placed above the objective of a long-focal length refractor. The 29 cm objective grating produced first order diffraction images removed from the zero-order images by 12 arcsec (corresponding to 0.29 mm on the plates) with known magnitude difference between the zero- and first-order images. A typical procedure was to take 11 (or more) exposures per plate, resulting in 44 stellar images. Wesselink measured the images with the Schilt photometer (see Sect. 3 of the Sterken et al. paper in this volume for a discussion of these instruments). He examined carefully the difference in the constant dispersion produced by the objective grating and the atmospheric dispersion, that varies in both direction and extent, with hour angle; by selecting the dispersions only at 45 and 225°, so that the dispersion did not overlap any star images, and by using a comparison star of similar brightness to the variable, he was able to reduce the effects of systematic error. He found in the end no systematic error in Δm depending on the hour angle. The maximum mean precision attained is $\sim$2%.

4 Differential Photoelectric Photometry

Accurate differential photoelectric photometry became possible only after the appearance of photomultiplier tubes. Although the first photomultipliers were developed already in the mid-1930s, in particular at the RCA laboratories, it took some time before these new devices became widely used in astronomical photometry. This was primarily due to World War II. After the war, the superior properties of photomultipliers were quickly recognized by the astronomical community and many observatories started to develop photometric instruments based on the first generation of commercially available photomultipliers, the RCA 931 and 1P21 type tubes. One of the pioneers in this new field of astronomical instrumentation was Theodore Walraven (1916–2008), whose passing occurred just as the present volume was being planned. In recognition, we will devote this section to his differential photometry work and legacy.

Immediately after his appointment to the Leiden Observatory in November 1946, and while still working on his Ph.D. thesis, Walraven started experimenting with photomultipliers. By the end of March 1947, always assisted by his wife Johanna, he made his first photoelectric observations with an uncooled 1P21 tube on the 48-cm Zunderman reflector (Fig. 2). Extensive series of observations were obtained of RR Lyrae, which resulted eventually in Walraven's classical analysis of the "Blazhko-effect" in RR Lyrae, (Walraven 1949) rediscussed later in the landmark review paper together with Paul Ledoux in Handbuch der Physik (Ledoux and Walraven 1956).

These early photoelectric measurements on rapidly changing variables such as RR Lyr had a decisive influence on Walraven's designs of subsequent photometric instruments. The accuracy that could be achieved with single-channel photometers in the light- and colour-curves of short-period variables was clearly limited by extinction variations. Obviously big improvements could be obtained by

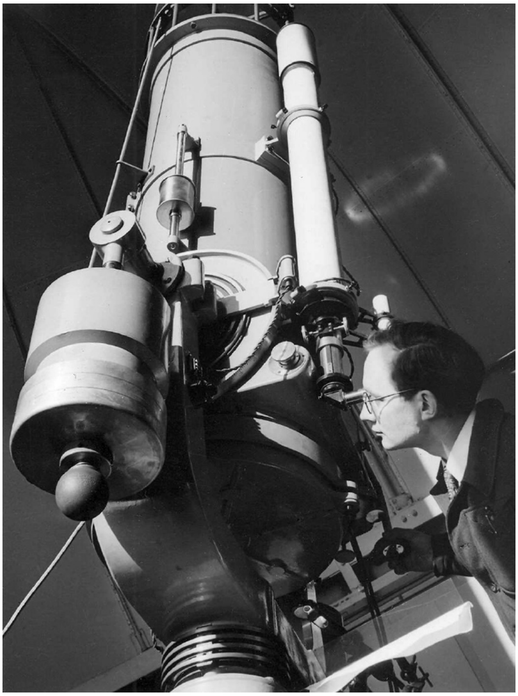

Fig. 2 Theodore Walraven at the 48-cm Zunderman reflector of Leiden Observatory in 1947 (photo: courtesy Leiden Observatory)

applying differential techniques. While the construction of several single-channel photometers (both cooled and uncooled) for the telescopes in Leiden and for the Leiden Southern Station in Johannesburg was going on, the first steps towards differential photometry were made. This was done in two directions: simultaneous measurement of two stars – variable and comparison star – in a given filter passband, and simultaneous measurement in several passbands of one star. Surprisingly, the more challenging of these two techniques, simultaneous multi-passband photometry, had been tackled already in 1949 with the construction of a prototype multi-channel photometer for simultaneous observations in four filters. This development would result eventually in the well-known Walraven five-channel photometer (see below).

4.1 The Walraven Experiments

In parallel with the construction of the other photometers, a "differential nulling photometer" was designed by Walraven in 1950 with the specific aim to observe short-period variables (quasi)-simultaneously with a nearby reference star. Although publication of a full description of this instrument was announced as forthcoming by Walraven on several occasions, this unfortunately never happened. On the basis of the available information (Walraven 1952a,b, 1953, 1955) the principle of the instrument can be summarized as follows. In the first version of the differential photometer the light beams from both stars were directed alternatingly to the same phototube in order to eliminate the problem of sensitivity variations between two phototubes. This light switching was done by means of an oscillating double diaphragm in the telescope focal plane and a set of optics that produced pupil images for both beams on the same spot of the RCA 931A photocathode. The phototube output thus contained an AC component with amplitude proportional to the intensity difference between the two stars. By means of a neutral density wedge in one of the two light paths this intensity difference could be nulled. The setting of this wedge was done automatically by a DC motor in a servo loop driven by the AC amplitude of the phototube output signal. The actual measurement consisted in automatic and continuous registration of the wedge position on a chart recorder. The only necessary human interventions during the observations were checks on the telescope guiding, typically once per 30 min. Due to the nature of the optical transmission of the wedge the nulling-position curve on the recorder multiplied by a scale factor yielded a direct light curve registration in magnitudes, which greatly reduced the photometric reduction effort and allowed on-line determination of light curve parameters. The wedge scale was calibrated by observing the comparison star for different wedge settings in "DC-mode." Figure 3, kindly made available by Adrian A. Disco, who was involved in the construction of this early prototype instrument, shows its installation on the 33-cm refractor of Leiden Observatory in July, 1950. According to Disco, the instrument was tested on the star XZ Cygni.

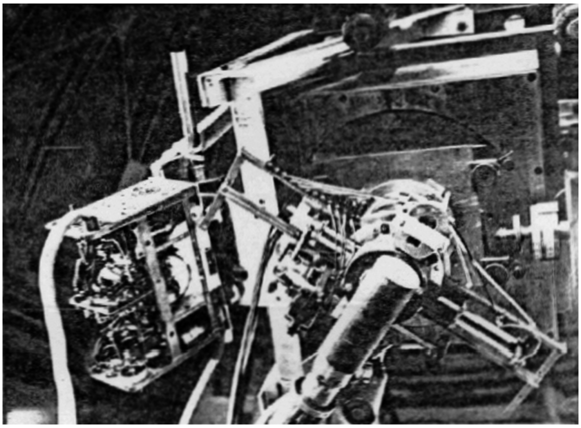

Fig. 3 Prototype of the differential wedge photometer (one cell version) during tests on the 33-cm refractor of the Leiden Observatory, in July, 1950. Courtesy, Adrian A. Disco, who worked on the servo-mechanism

After several modifications of the prototype instrument, including experiments with photon-counting, the Walravens moved to the Leiden Southern Station in Johannesburg, where the new photometer was mounted on one of the twin 40-cm refractors of the "Rockefeller" telescope in March 1951. This equipment was then used for extensive observations of the multi-period variable AI Vel (then called "RR Lyrae–type" variable, but nowadays classified as high-amplitude member of the Delta Scuti family). In the meantime the work on improvements of the photometer continued, resulting in a two-channel version. Once the improved two-channel wedge photometer was completed in the course of 1951 the measurements were resumed with that instrument and AI Vel and SX Phe were intensively monitored until April 1953. Examples of the superb light curves produced by the nulling technique are given in Fig. 4 (from Walraven (1955)). Walraven's papers on the pulsations of AI Vel, SX Phe and RR Lyr (Walraven 1952a,b, 1955) still stand as classics in the variable stars literature.

The two-channel differential photometer used the same optical wedge nulling technique, but this time there was a set of four fixed input diaphragms – two for the two stars and two for nearby sky positions – and the more elaborate optics included pairs of reflecting prisms for centering of the stars in the diaphrams and and two prism sets for beam switching. A brief description of the two-channel instrument was given by Walraven in his paper presented (and read, by Bengt Strömgren) at the small photometry symposium in Philadelphia on December 31, 1951 (Walraven 1953). A schematic layout of the switching scheme is given in Fig. 5.

After the return of the Walraven family to Leiden in 1953 the observations with the differential photometer stopped and the instrument was dismantled. However, Walraven never lost interest in this elegant instrument or in his favourite star. A quarter of a century later, and back in South Africa, the Walravens built a new version of the differential photometer using the original optical wedge and started re-observing

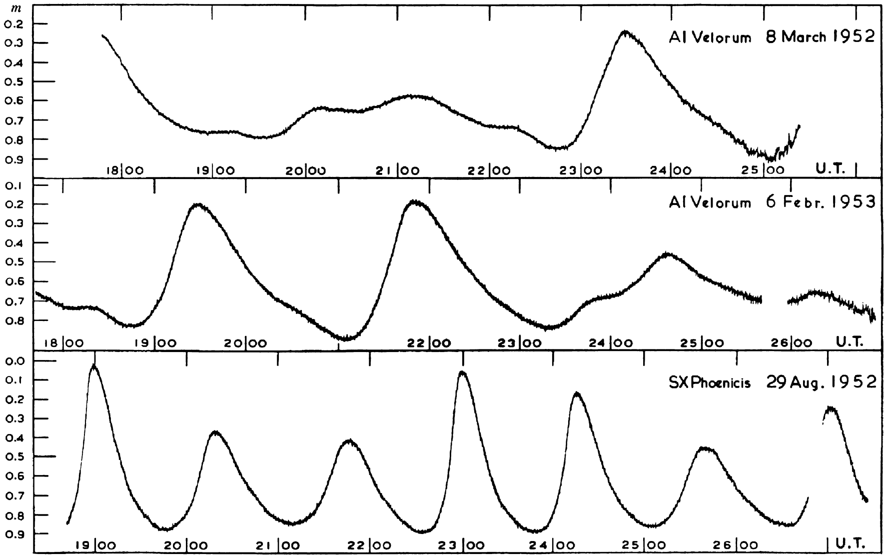

Fig. 4 A sample of the light curves of AI Velorum and SX Phoenicis, obtained with the 2-channel differential wedge photometer and the 40-cm "Rockefeller" refractor of the Leiden Southern Station at Union Observatory, Johannesburg, South Africa (from Walraven (1955))

AI Vel in 1979. After retirement in 1980, when the Walravens moved to the small town of Cornelia in the Orange Free State, these observations were continued with their private, fully automated 40-cm telescope and the novel simultaneous six-colour photometer that Walraven had developed during the last part of his career. The combined dataset of AI Vel photometry spanning a period of 38 years was eventually analyzed in collaboration with Louis Balona (Walraven et al. 1992). This impressive study revealed additional pulsation modes and systematic period ratio changes.

Back in Leiden in 1953, Walraven had taken up the work on the other differential photometry approach: simultaneous photometry in multiple wavelength bands. The prototype four-channel photometer mentioned above eventually evolved into the five-channel (*VBLUW*) photometer that was built for use on the new 91-cm "Lightcollector" reflector. While this telescope was being manufactured by the Rademakers company in Rotterdam, the photometer was developed at Leiden Observatory during 1954–1957.

The *Lightcollector* and its photometer were specifically designed as an integrated system for efficient photometric observations on individual stars (cf. Fig. 6; Walraven and Walraven 1960; Pel and Lub 2007). The telescope had only a small field with good image quality, but it was equipped with fast and accurate electronic presetting. The photometer was based on an ingenious quartz/calcite crystal optics filter that produced five well-defined and ultra-stable passbands in the visual/near-UV. These passbands were separated in a 2-prism spectrograph and measured simultaneously by five 1P21/1P28 photocells and current-integrating amplifiers.

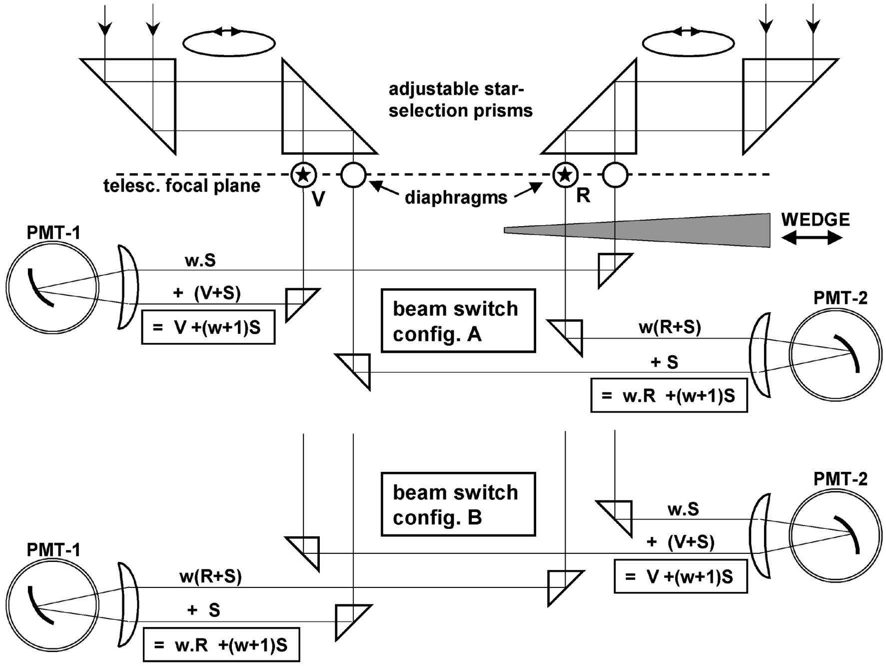

Fig. 5 Schematic layout of the beam switching optics in Walraven's 2-channel differential photometer. The two stars (variable "V" and reference "R") are centered into two of the four identical diaphragms in the telescope focal plane by means of the star-selection prisms. The other two diaphragms select sky background, "s". One pair of beams passes through a neutral density wedge that can be moved by a DC-motor. Two alternating sets of four beam-switching prisms direct the beams to the photomultiplier tubes PMT-1 and PMT-2. By switching between the beam configurations "A" and "B" both phototube signals are modulated in anti-phase with the same amplitude (V - w.R), where *w* refers to the wedge attenuation factor, eliminating the sky background. This amplitude drives the servocontrol loop that actuates the optical wedge until (V - w.R) = 0. The signal modulations in both phototubes are then nulled simultaneously and the wedge position gives the magnitude difference $V - R$

All photometer optics were of UV-transmitting materials (quartz/calcite/fused silica) and, as in all of Walraven's instruments, had been made mostly by Johanna Walraven. With two bands (V,B) longward of the Balmer jump, two bands (U,W) in the Balmer continuum and the L band at the confluence of the higher Balmer lines, the ($VBLUW$) photometry was designed as a photoelectric counterpart of the three-dimensional classification of (photographic) stellar spectra by Barbier, Chalonge and Divan, with which Walraven had become closely familiar during long observing runs at the Observatoire de Haute Provence in 1949–1950.

In 1958 the 91-cm telescope was erected at the new location of the Leiden Southern Station, the Union Observatory Annexe at Hartebeespoortdam. Routine observations with the new telescope and photometer started in 1959 with a massive observing program on OB-stars. For many years the observations remained focused

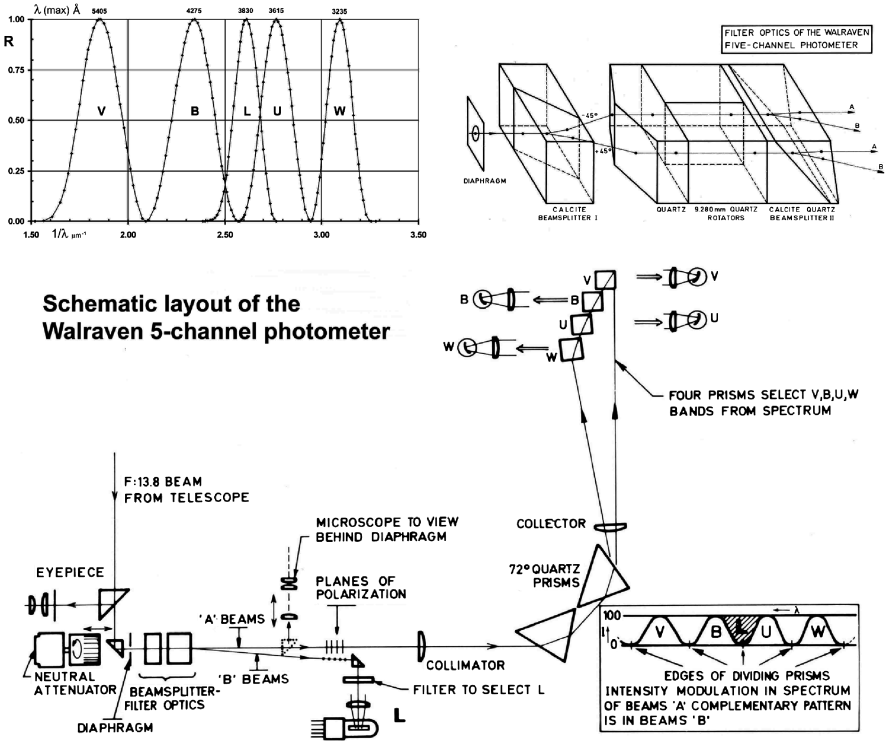

Fig. 6 Overview and schematic layout of the Walraven *VBLUW* photometer (from Pel and Lub 2007)

on early-type stars, but when the (*VBLUW*) system turned out to be very effective also for the determination of ($T_{\rm eff}$, $log\ g$, $[Fe/H]$) of A-F-G stars the scope widened to later spectral types and big programs on Cepheids and RR Lyrae stars followed. A more detailed discussion of the 32 years of productive life of the Walraven five-channel photometer (Hartebeespoortdam 1959–1978, ESO La Silla 1979–1991) is outside the scope of this paper, but some final remarks about the application of differential principles with this instrument are in order.

Already during his first photometric observations Walraven had been struck by the fact that atmospheric extinction variations at different wavelengths were strongly correlated. This implied that the accuracy of colour measurements could be improved greatly by simultaneous measurements in multiple passbands and it explained why Walraven focused so strongly on multichannel instruments and differential techniques. The (*VBLUW*) photometer proved the point very convincingly. Whereas in single-channel photometry the errors in colours were usually larger than the individual filter magnitudes, merely due to the combination of errors, (*VBLUW*) color indices were 2–3 times more accurate than the individual magnitudes, even for the $(U-W)$ colour, with band centers at 360 and 325 nm.

A differential approach was also followed in the calibration of the system of ($VBLUW$) standard stars. When the ($VBLUW$) photometry was first set up in 1958, a standard star system had to be built up 'from scratch'. This was done following a simple and elegant differential method with the following steps:

1. Selection of $\sim$20 suitable standard star candidates, well distributed around the declination circle with DEC=(site geographic latitude): the "ring standards"
2. Frequent observations of pairs of ring standards in quick succession when Δ(airmass) ≈ 0. This yields per pair accurate differential magnitudes in all channels because instrumental gain drifts drop out (Δt very small) and a rough approximation of the extinction coefficients is sufficient for accurate differential extinction correction [$\Delta(sec\ z)$ very small]. In about 6 months all ring standard pairs are observed many times, covering the full 24 h circle, and the mean magnitude differences per pair are known very accurately
3. A least squares "ring closure" solution for the whole network of pairs and careful check on possible systematic effects (as function of time, position, brightness, colour) in the residuals. This fixes all differential magnitudes in all channels very precisely, but leaves the zero-points of the magnitude scales still undetermined
4. Definition of the zero-points, in this case done by choosing HD 144470 as primary ring standard with all four colour indices exactly zero and $V_{Walraven} \equiv V_{UBV_{Johnson}}$
5. The set of ring standards is now completely fixed, so extinction coefficients and instrumental zero-points for all observing nights can be determined
6. Secondary standards can be connected to the ring standards and final (extinction, zero-point)–solutions can be made for all nights with the full set of standard stars

During the 32 years of operation of the ($VBLUW$) photometer this procedure was repeated a few times, most extensively after the move of telescope+instrument to La Silla in 1979. In the latter case the residuals of the least-squares ring solution were extremely small: 0.00045 mag for V and [0.00025, 0.00031, 0.00031, 0.00027 mag] for [$(V-B)$,$(B-L)$,$(B-U)$,$(U-W)$] (Pel 1991; Pel and Lub 2007). This demonstrated beautifully the power of differential measurements. It should be noted that these very small residuals proved only that the internal consistency of the system was very high; systematic errors could still be present. However, extensive cross-checks with photometry in other systems, both ground-based (Johnson, Geneva and Strömgren photometry) and space-based (Hipparcos photometry), showed that the ($VBLUW$) system was truly free of systematics down to the level of 0.001 mag, a beautiful confirmation of the strength of Walraven's differential strategies.

4.2 Development of Other Photoelectric Differential Photometers

In the late 1950s and 1960s, other dual-channel photometers were designed and built at Kitt Peak National Observatory and elsewhere (Crawford 1958; Wood and

Lockwood 1967), the purpose of which was to observe in two passbands simultaneously. Thus the main purpose was to obtain color information.

Baum et al. (1959) describe a six-channel differential photometer which consisted of separate pickoffs for a star and nearby sky and funneled the light from each through separate filters to U, B, and V filters, but which is criticized by Johnson (1962) because of the unsatisfactory U filter available at that time, and because of the use of dichroic filters which would make transformations to the Johnson-Morgan UBV system, as he called it, difficult. The criticism is interesting because Johnson was one of the coauthors on the 6-channel photometer paper.

Beginning in the 1960s, relatively simple photometers were constructed that conveniently and systematically sampled two regions of sky, but not simultaneously. Such instruments were in use at Dyer Observatory (see Fig. 7) in the 1960s and other photometers with sky offsets were described by Visvanathan (1972) and by Kinman and Mahaffey (1974). We will not discuss the pioneering work on differential pulse-counting photometry by W. Blitzstein, resulting in PBPhot, because the latter is discussed extensively by Ambruster et al. in this volume.

An automated double-beam photometer was designed and constructed by McCord (1968). This photometer involved a mirror chopper that passed beams from different parts of the field alternately into the single detector. The chopping frequency was 30 Hz. A mechanical slide mechanism allowed a mirror to shift across the field of view, with a range of 10 arcmin. A similar chopping system but with

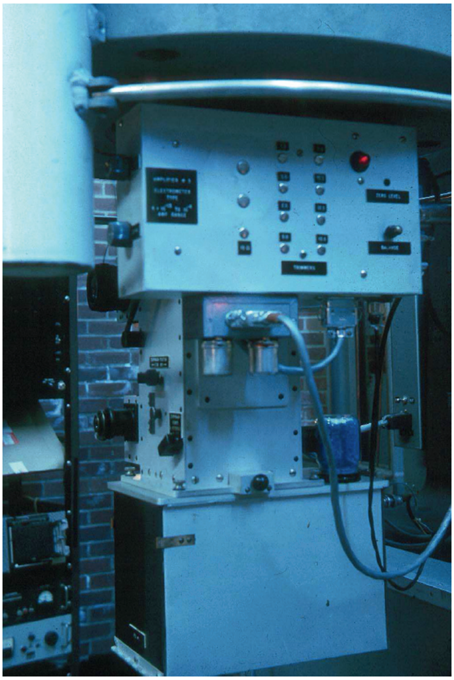

Fig. 7 The well-designed astronomical photometer in use at the Dyer Observatory, ~ *July*, 1965. The rocker switch from star to sky can be seen on the lower right side of the left face, but the operation was purely manual. Note the use of desiccant containers to minimize moisture

a fixed second beam was devised by Myrabø (1979, 1980) for variable star photometry at Trömso, Norway, in the teeth of strong auroral emissions. Two apertures were located in the focal plane, at a separation of 6 arcmins; it was preceded by a rotated chopping wheel (i.e., a wheel with sectors removed) in close proximity. The two beams were imaged, alternately, on a single photomultiplier, and the chopper could be run over a frequency range of 1–20 Hz. De Biase and Sedmak (1974) discuss the principle of a multiplexed adaptive multichannel single-detector photometer that can select among a known source, an unknown source, and the backgrounds for these two sources. These principles, initially discussed by Sedmak (1973) were put to practical use in several photometers, including the twin-beam *URSULA* system (De Biase et al. 1978). Geyer and Hoffmann (1975) describe a two-photometer instrument in use at the Nasmyth focus of a 106-cm telescope at the Hoher List Observatory. This system used reflecting prism diagonals to pick off two objects, or one object and sky in the field. The system as it appeared in 1983 is demonstrated in Fig. 8 by Prof. Geyer.

Grauer and Bond (1981) describe a two-photometer system in which one photometer is located on the arm of an offset-guider and the other is placed in the main beam. The system was fabricated in duplicate for use at both Louisiana State University and the Kitt Peak National Observatory. The photometer system made use of the high-speed design of Nather (1973), but sampled the sky only briefly in about 20-min. intervals. Davidson et al. (1976) describe a two-channel photometer that employed an oscillating flat mirror that provided star and sky fluxes alternately to a single photomultiplier. The optical path was nearly identical, traversing the same diaphragm and filter.

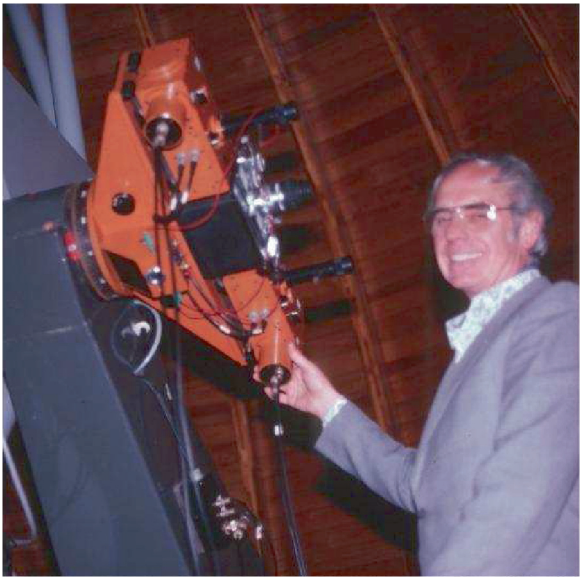

Fig. 8 The two-photometer instrument in use at the Hoher List Observatory along with its developer, Prof. Edward Geyer, ∼ *August*, 1983

A high-speed photometer that employed two photomultipliers to observe both target and reference source was used at the Asiago Observatory by Bernacca et al. (1978), and another, described by Piccioni et al. (1979) was used at the Bologna Observatory.

In the early 1980s, the Rapid Alternate Detection System (RADS) was developed at the Rothney Astrophysical Observatory in the foothills of the Canadian Rockies, to overcome the cirrus-laden skies that plague western Canadian sites most of the year, but especially in the winter. The idea was to compensate for sky transparency variation while correcting for sky brightness variation, and minimizing response differences by avoiding wherever possible electronic or optical path differences. The inspiration for this device came originally from Adriaan Wesselink, who described to EFM the Walraven photometer that he had seen in action in South Africa (see above).

4.3 The Rapid Alternate Detection System

The Rapid Alternate Detection System (*RADS*) combines gated photon-counting techniques with secondary-mirror chopping techniques borrowed from infrared astronomy. The purpose in developing this system was to meet the conditions for precise differential astronomy outlined in Sect. 1.

4.3.1 RADS Hardware

The instrument as originally developed was described in Milone et al. (1982). The base photometer was manufactured by Astrometrix, Inc., of Charlottesville, Virginia, through the good offices of Prof. Laurence W. Fredrick, and was installed on the 0.4-m telescope of the Rothney Astrophysical Observatory late in 1972. Operated solely in DC-mode for about a decade, the photometer per se was described in Chia et al. (1977). Some of its design features were especially valued: the photometer head allowed access to each filter as it was rotated past an access port, and it had an exterior plug-in lamp that illumined the aperture diaphragms with fiber optics. The proposed operation of the RADS was put forward by EFM in July, 1977. Extensive discussions, first with T. Alan Clark, who with EFM co-directed the RAO, with Physics Department technician Charles H. Hanson, and then with technicians at Kitt Peak National Observatory and elsewhere, led first to an analog system, designed by Charles Hanson, whose time was contributed by Prof. Harvey Buckmaster of the Physics Department's Electron Paramagnetic Resonance (EPR) Group; a digital system was then designed and was constructed by Frederick M. Babott. Following initial trials, a pulse-counting system was installed early in 1981. In Fall, 1981, the RADS system came on line.

The flow chart of its operation is illustrated in Fig. 9, and its components can be seen in Figs. 10 and 11.

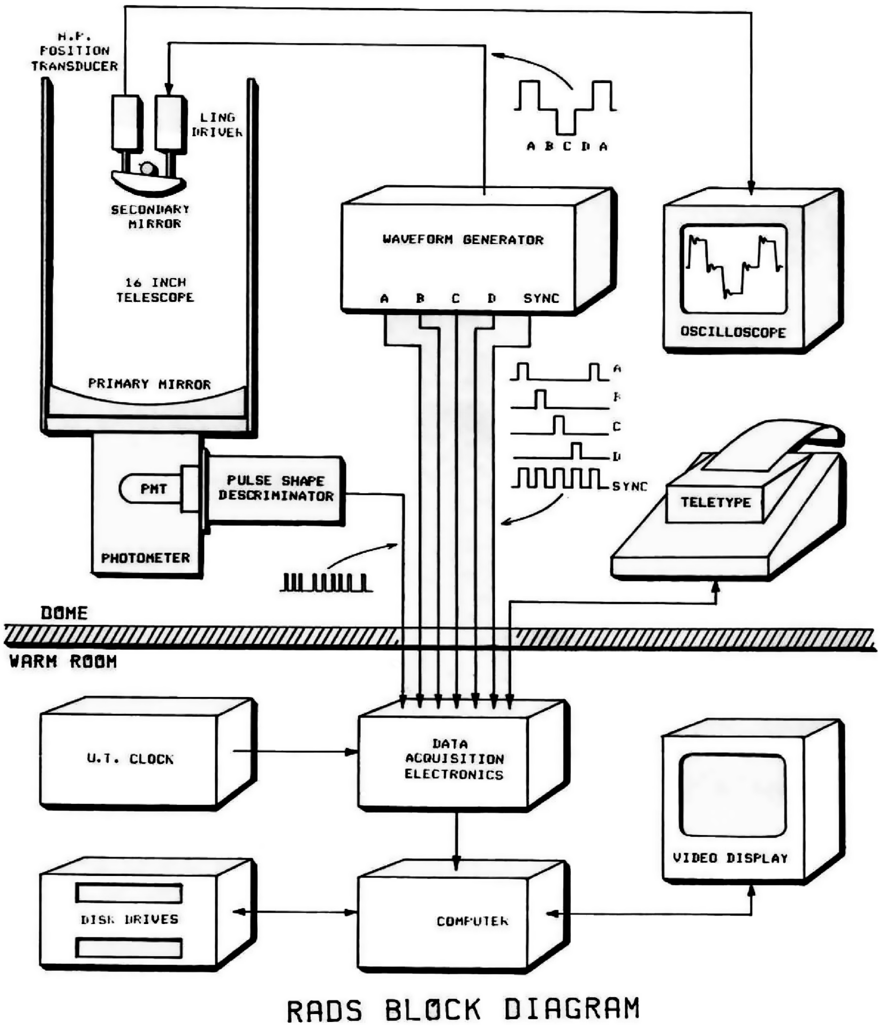

Fig. 9 A schematic and flow diagram of the operation of the Rapid alternate Detection System developed at the University of Calgary in the early 1980s by Milone et al. (1982), and adapted from Fig. 2 of that paper. See text for details

The heart of the system is basically a simple photometer of Sedmak's (1973) class A-a, wherewith the photometric targets and filters are selected sequentially, i.e., in serial mode. However, over the full integration period, the channels are accessed very nearly in parallel, and one may program the filter selection as a symmetric set. This was the usual RADS operation. At the heart of the action, a Ling Electronics electrodynamic vibrator (Model 102) drove the secondary mirror against the restoring force of two Bendix Flexural Pivots. A Hewlett-Packard linear transducer (Model 70CDT-050-B11), mounted opposite the Ling, indicated the mirror's

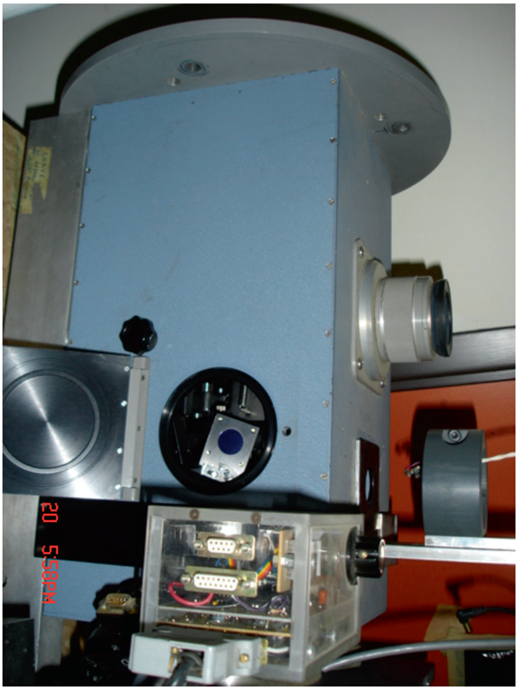

Fig. 10 Details of the RADS photometer head, showing the filter change assembly, the filter compartment through the access hatch, the field eyepiece (*above*) and CCD-imaged aperture (*below*) of the Astrometrix-built photometer

position. A function generator (the "MAC" box, described below) was programmed manually to send an amplitude voltage to the Ling vibrator for each of four mirror positions. It was used also to set the time at each location (the original range was 1–999 ms), and a "delay time" to allow the mirror shake that occurred each time the mirror was stopped, to settle down to negligible oscillation amplitude.

The entire chopping assembly could be rotated 360°, so that the chopping line could be set in any direction for suitable comparison star selection (see Sect. 2); the chop amplitude, when first implemented, achieved a maximum range of ± 10 arcmin on the plane of the sky. The Ling shaker was driven by a closed loop servosystem consisting of MAC and transducer inputs, damping the Ling driver response.

The initial photometer detector, an EMI 6256 photomultiplier, was relatively insensitive (although excellent for tracking the light decline of Nova Cygni 1975 (V1500 Cygni) when it first appeared); it was subsequently replaced by an RCA C31034 (GaAs) photomultiplier, mounted in a mu-metal shield and encased in a Products-for-Research dry-ice cooled chamber, with a chamber thermometer mounted on the exterior to keep track of temperature variations.

The initial data acquisition electronics consisted of a pulse counter, four separate adders, and four time counters accurate to ± 1 μs. In the early 1980s, the results were sent to an Apple IIe computer, which received also timing signals from an AstroComputer Control clock. The first power amplifier and function generator were designed and constructed by Charles H. Hanson. Later versions were constructed and maintained by Frederick M. Babott.

Fig. 11 The third-generation RADS "MAC box" – the multi-function generator that permits selection of duty cycle, delay time, and chop throw (amplitude of spatial variation)

In later versions, the chop amplitude was extended first to ∼±30 arcmin, and then to ∼±45 arcmin. Figure 10 shows the Astrometrix photometer, coldbox, and the filter and diaphragm advancing mechanism, and the CCD attached to the centering eyepiece. Figure 11 shows the Multichannel Ampltude Controller (MAC) box, the function generator that is used to select the four stations (channels) to pick up the main target (usually A), the sky near the secondary target (usually B), the secondary target (usually C), and the sky near the primary star (usually D). The sequence of filters was automated and made programmable after a few years of operation.

The output file list consisted of tables of star identifier, filter, U.T., counts in each channel, integration time in each channel, and a continuation or termination code.

4.3.2 RADS Operation and Efficiency

An observing run setup at the telescope initially required about a half-hour or more, but this decreased with experience to about 15-min under good observing conditions. The usual practice was to place the target object, usually a variable star, in Channel A, a comparison star in Channel C, and the sky in Channels B and D. Channels A through D were selected sequentially to adjust placements in a manual "static" mode and then tweaked in the "run" mode. From time to time, the dome clearance had to be checked and the dome moved; all other operations except for periodic centering checks, were carried out in the warm and lit control room. For setup, the timing controls were set so that maximum time would be spent on each channel (999 ms), to allow visual centering. The setup proceeded as follows:

- Target acquisition. The telescope was set on field of the two objects, centered half way between them. If their separation exceeded the 15 arcmin diameter of the field eyepiece, the telescope had to be moved back and forth to ascertain the position angle of the line separating them; this position angle could be computed in advance to save setup time. The required shift of direction was then noted in the aperture eyepiece.
- Chop rotation adjustment. A mode switch on the controller (MAC – see Fig. 11) would then be set to "run" to find and change the chopping angle. This angle was controlled with a bi-directional switch mounted on the telescope; the rotation was adjusted until the two lines created by the motions of the two objects overlapped, first in the field, then in the aperture eyepiece (for this exercise, the widest aperture would be selected).
- Chop amplitude adjustment. This was accomplished first by moving the mode switch from "run" to "A", and centering the main target in the aperture with the A channel 10-turn potentiometer. Then, setting the switch to "B", a sky field near the secondary object would be selected by turning the B channel potentiometer. This was followed by the selection of "C" by dialing the C potentiometer to center the secondary object in the aperture. Finally, with the mirror position switch on "D", the sky near the primary object was selected by dialing the D 10-turn potentiometer. Practical constraints on sky settings are discussed further below. The sky fields needed to be checked carefully to avoid faint stars.
- Dynamic adjustment and aperture selection. Set on "run", the centering of each channel was checked in the desired aperture diaphragm, and recentered if needed. The aperture was selected to be at least three times the apparent stellar diameter.
- Duty cycle selection. The "dwell time" at each channel would then be selected with the thumb switches for each channel. This and the delay time, discussed next, determined the chopping frequency, which we discuss below.
- Delay time selection. The thumb wheel for setting of the delay time is at the upper right of the MAC box. This time interval determined when no pulse counting was to take place. The delay time was the time allocated to mirror motion, and it included the time for the ringing of the suddenly stopped mirror to decrease to within a fraction of the selected diaphragm before the counter gate for the selected channel was opened. The required delay time could be read from the transducer trace on an oscilloscope located in the dome (see Fig. 12). The largest interval of motion was selected for the delay time. To minimize the effect of ringing, the channel settings were further constrained: The preferred setting for Channel B (sky) was about one aperture diaphragm away from Channel C, and along and within the path separating the two stars. Similarly, the preferred setting for Channel D was along the chopping line, about one diaphragm from Channel A. Because the largest excursions occurred when the secondary mirror moved from star to sky settings, the greater ringing of the secondary mirror at the sky settings resulted in minimal impact on the stellar photometry.

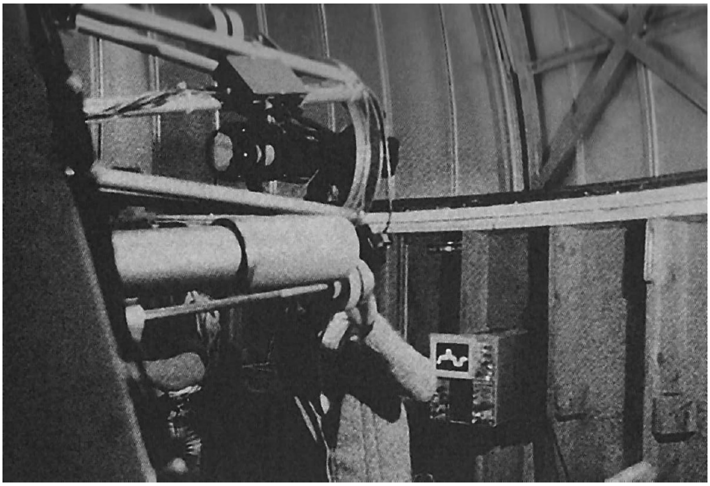

Fig. 12 The RAO 0.4-m telescope secondary mirror assembly and controller, and the oscilloscope trace showing the transducer output. Note the duty cycles of the four chopping stations. Reproduced from Milone (1993)

- Chopping frequency and integration time selections. To avoid sky variations due to, say, rapidly varying cloud or aurora, the highest possible chopping frequency should be employed; however, the higher the frequency, the lower the efficiency, in the sense that a larger fraction of any given interval could be spent collecting photons from the program star and in the other channels. This is because the parts of the cycle in which the mirror is in motion constitute overhead which must be paid in order to achieve the observational precision and accuracy desired. The integration time was set, along with the filter sequence, in the control room as interactive computer input.

Now we discuss the connection between chopping frequency and the system's efficiency. The chopping frequency of the function generator was determined by the period of a cycle, which, in turn, depended on the sum of all duty cycles and overhead settings. Thus to have a 1 Hz chopping frequency and a 1-s integration time, and if one could use a 25 ms delay time, a 225 ms dwell (counting) time for each channel could be used. In this 1 cycle example, 100 ms would be overhead and 900 ms on photon counting, 225 ms of which would be spent observing the object of interest specifically. Thus, photon counting would occupy 90% of the cycle, but only 25% of this on the target, per se. With these parameters, the percentages and system efficiency would be the same regardless of the integration time. However, if one desired to run at a higher frequency, the delay time could not be decreased much without risking signal loss, leaving only the channel duty cycles to adjust. To avoid decreasing the target star duty cycle, one's only options were: to decrease the the duty cycle of the sky channels, feasible only in a dark and nonfluctuating sky; to use only one (central) sky channel (i.e., operation in a 3-channel mode); and, reduction of the comparison star duty cycle, relative to the variable star's. The latter may be a reasonable choice only if the comparison star is significantly brighter. Usually, the duty cycles were kept the same for all channels, and more photons acquired at higher chop frequencies by selection of longer integration times. If the period of the variable star is very short, so that the integration time is phase-limited, the only recourse was to trade precision for time resolution, or move the system to a larger telescope!

For those nights when standardization could be carried out, a list of pairs of standard stars within about 40 arc-mins of each other was produced, first by Bart Milone, in the early 1980s, and later, in the mid-1980s, in a more complete form by astrophysics major Andrew Kyrgoussios; in this form it became known as the "Kyrgoussios List". Still later, pairs of Landolt stars (stars observed by Landolt in the equatorial Harvard Selected Areas) were used for this purpose (Landolt 1973, 1983). Although the RAO had a full set of *uvby* and Hβ filters, in practice these intermediate-band filters were rarely used because the wider UBVRI passbands allowed more flux to be measured per duty cycle, an important constraint for photometry on a 0.4-m telescope.

4.3.3 RADS Software Development

As one might expect, software had to be written to best serve the data as they were gathered. The initial data acquisition program was hard-wired and blasted into an *EPROM* (erasable programmable read-only memory) chip, and underwent several iterations. In the late 1980s, the interactive Data Acquisition Program for RADS (`DAPR` was written, in initial form by Dr. Robert H. Nelson, and later, with added capabilities and more flexibility, by undergraduate astrophysics major, Perry E. Radau. These programs yielded output lists of the data for 1–4 channels, in what was called General RADS mode; a high-speed read-out mode was available for occultation work, although the latter was rarely attempted at the RAO.

The main software reduction program, to produce systemic magnitudes, was written first for an Apple IIe micro-computer in Applesoft Basic by EFM and called `CTOM` (for "Counts to Magnitudes"), and later, in a slightly expanded form, and ported to a Zenith PC, `CTOVMOD`.

The data were then reduced with the aid of several programs. The normal procedure was to input previously determined extinction and transformation coefficients (or determine them) in the equations:

$$\begin{aligned}\Delta y &= \Delta y_0 + k'_V \cdot \Delta X + k''_V \cdot \Delta X(b-y)\\ \Delta(b-y) &= \Delta(b-y)_0 + k'_{BV} \cdot \Delta X + k''_{BV} \cdot \Delta X(b-y)\end{aligned} \tag{16}$$

and

$$\begin{aligned}\Delta V &= \Delta y_0 + \varepsilon \cdot \Delta(B-V)\\ \Delta(B-V) &= \mu \cdot \Delta(b-y)_0\end{aligned} \tag{17}$$

where we used the familiar notation of Hardie (1962), namely, b and b_0 for observed and systemic Johnson B magnitudes, y and y_0 for observed and systemic Johnson V magnitudes, respectively, X for airmass, k' and k'' for first-order and color-term coefficients, ε and μ for transformation coefficients; in these differential formulae, the zero point terms vanish. Expressions analogous to the lower formulae in (16) and (17) were used to transform the other color indices to extra-atmosphere (i.e., systemic) and standard systems, respectively.

Except for the lower of (17), these were the equations of condition used in the least squares determinations of the unknowns. For the transformation of color terms, a variant suggested by Hardie (1962) was used instead:

$$c_s - c_0 = \mu' \cdot c_s + \zeta'_{\lambda 1,2} \tag{18}$$

where c_s and c_0 are the standard and systemic colors, respectively, $\mu' = (\mu - 1)/\mu$, and the zero points are related through $\zeta' = \zeta/\mu$, so that the coefficient to be found, μ', was a number close to zero. The quantities μ and ζ were then computed.

The program contained default values for the Sensitivity Corrections (see below) and Coincidence Corrections (required to compensate statistically for the simultaneous arrival of multiple photons within the response time constant of the photomultiplier system), but values could be read in if new determinations had been made. The k' values were computed with the Bouguer method from the sky-subtracted star data; with these new values, internal iterations could be performed.

Beginning in 1988, `CTOMVMOD` was replaced by the program `REDUCE`. Numbered versions of `REDUCE` evolved over the decade, each version with broadened capabilities and aids to facilitate its use. This work was undertaken mainly by undergraduate astrophysics majors, first James A. van Leeuwen, and later Perry E. Radau, who maintained it through the early 1990s, with some assistance from Dr. Robert H. Nelson, visiting astronomy faculty member from Prince George, B.C.. The software treated either single-channel (unchopped) or differential (RADS) data with two or more channels of output. The program applied both photon coincidence and RADS "sensitivity" corrections (from calibration of the flux through three of the channels to that in the first). The sensitivity corrections were most often determined by observing in full chopping mode the twilight sky both after and, if the system were set up from a previous night, before an evening's observation. The `REDUCE` software required input extinction coefficients unless standard star data were entered along with a list of standard star data. In the latter case, coefficients were then computed with the Hardie (1962) method.

In variable star reduction operations, the comparison star data were used to produce Bouguer extinction coefficients in each passband as well as systemic magnitudes and color indices.

Transformation coefficients were determined via least squares in a separate program entitled `TRANSFRM` which required a list of standard magntudes of the observed stars (usually taken from selected areas in Landolt (1973, 1983) tables). The Hardie method was used to obtain the transformation coefficients and zero points when absolute photometry could be performed. When the skies were photometric, through iteration a consistent set of extinction and transformation and extinction coefficients could be obtained.

The program RADSEXT was specifically written to reduce RADS observations of pairs of standard stars, in order to compute the extinction coefficients, k' and the k'' color terms in (16) and the color-coefficients of (17) and (18). Thus it was used to reduce standard star pairs, but also to provide statistical measures of the variable star and comparison star data. This was made possible because of the ability of the RADS to cancel the effect of the non-color extinction coefficient, k', on the differential photometry. The color effects that were airmass-dependent could be separated somewhat from those that were not, given a significant range of airmass of the observations. The result was such that even if the night were not photometric, in the classical sense, one could still obtain useful data on the photometry system. Examples are given by Milone and Robb (1983).

The statistical information provided by RADSEXT was:

- The mean standard error (m.s.e., or the standard deviation) of a single observation of the comparison star as computed from the differences from the mean, e_1^c, and
- That computed from the differences between chronologically successive pairs of observations of the same star, e_p^c, compared with
- The m.s.e. computed from the mean of the differences between the variable and the comparison star, e_1^d, and
- That computed from the differences between successive pairs of the differences between variable and comparison stars, e_p^d.

The next section provides an example of the usefulness of these quantities.

The Differential Variable Star Program (DVSP) produced phased light curves for further analyses and plotting.

After a light curve was extracted from the reduction programs, a program called PHIMIN, written by EFM and later ported to the PC and called EXTREME, was used to determine times or phases of minimum and sometimes maximum light. The program made use of a variation of the Kwee and Van Woerden (1956) method, in which data from opposite sides of an extremum are reflected about trial midpoints. The usage is discussed and illustrated in Milone et al. (1980). The successive numbered revisions of the PC-adapted EXTREME program were managed by undergraduate astrophysics major and later graduate student Jason R. McVean..

POLYFIT, a generalized polynomial fitting program, was used to obtain Fourier series coefficients for W UMa and pulsating star light curves.

The plotting program DCLIGHT was developed for RADS data light curves by undergraduate astrophysics major Stephen C. Griffiths, after all other software were ported to PCs. Other visualization software was made available by Douglas Phillips of the University of Calgary Academic Computer Services.

Light curves of eclipsing binary stars were analyzed with continually updated University of Calgary versions of the Wilson-Devinney program (Wilson and Devinney 1971) and Josef Kallrath's implementation of the Simplex method (see Kallrath and Linnell 1987). Since $\sim$1998, a package of light curve solvers, WDXY (where Y is a year, i.e., version), has been in use (see Kallrath and Milone 2009 for a description of this package and its evolution). The WDXY software contains its own onscreen and postscript plotting routines. Specialized software has been coded by W. J. F. Wilson to analyze light curves of pulsating stars.

4.3.4 RADS Contributions to Science and Education

The science that can be (and was) explored with this device was described by Milone and Robb (Milone and Robb 1983). Of special interest to photometrists was the possibility to measure second-order and color coefficients because of the effective elimination of first-order extinction effects. Figure 13, adapted from Fig. 1 of Milone et al. (Milone et al. 1982), illustrates the effectiveness of the system against extinction variation. The stars are the close pair HR 1764 and HR 1765. The raw V magnitude is plotted for HR 1764 (labeled "M") and the differential magnitude (labeled "DY" in the Hardie 1962 notation). Figure 14 illustrates the quality of light curve that can be obtained with RADS data. It shows the phased and processed dV light curve and $d(B-V)$ and $d(V-I)$ color indices of IR Cas obtained by RAO observer James A. van Leeuwen in 1988.

Variable star studies carried out with this instrument include that on one of the RAO's binaries-in-clusters targets in Stephen J. Schiller's (1986) doctoral program, notably DS And (Schiller and Milone 1988) in the open cluster NGC 752. Other observed systems for which analyses were completed are:

- The over-contact binaries:

  44i Boo (Robb and Milone 1982),
  TY Boo (Milone et al. 1991), and
  V781 Her (Nelson et al. 1995)

- The symbiotic binary CH Cyg (Milone et al. 1986)

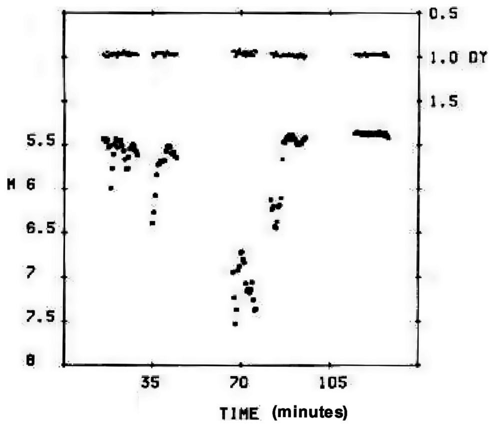

Fig. 13 Differential and single-channel light curves obtained with the RADS, The irregular variation in the latter is due to extinction caused by clouds. The raw V magnitude of HR 1764 (labeled M) and the differential raw V magnitude (labeled DY) between it and HR 1765 is plotted above. These early B stars differ by $\sim$1.0 magn. and are separated by 3.5 arcmins. in right ascension and about 2 arcmins in declination

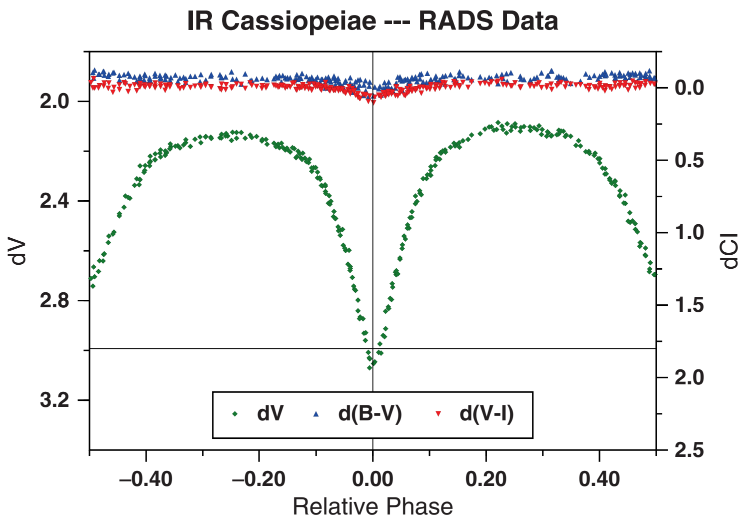

Fig. 14 The reduced and phased differential light and color curves of IR Cassiopeiae obtained in 1988 by astrophysics student and RAO observer James A. van Leeuwen with the Rapid Alternate Detection System installed on the 0.4-m telescope at the RAO

- The large-amplitude delta Scuti stars:

  EH Lib, (Wilson et al. 1993)
  DY Peg, (Wilson et al. 1998) and
  DY Her (Milone et al. 1994)

- The multi-mode delta Scuti Star V369 Sct; (Volk and Milone 2000) and
- The multi-mode RR Lyrae star AC And (Rousseau et al. (1988))

In addition to these, RADS data were obtained on the following objects; although not yet published, most of these data have been analyzed and appeared in student reports, and some of the work has been discussed at conferences.

- The eclipsing binaries QX And (H235 in NGC 752), VW Boo, CV Boo, IR Cas, VW Cep, EM Cep, RW Com, CG Cyg, V444 Cyg, RT Lac, SS Lac, UZ Lyr, and UZ Psc
- RR Lyr
- Nova Cygni 1992 and
- V376 Peg (HD 209458, extra-solar planet transit system)

In the cited paper on CH Cygni, (Milone et al. 1986) the last line of text in the right-hand column of p. 1179 was somehow omitted in the printing. We exploit this omission to make a point about science with RADS-like instruments. The omitted line reads: "May 24 data. This is evidence that the fluctuations on". This line is in the context of a discussion of the usefulness of RADS photometry statistics for RADS observations of this interesting symbiotic binary, and in the teeth of sky background (particularly aurora) and extinction variations. What was concluded in this paper was that $e_p > e_1$ (where e_p is the m.s.e. computed from pairs of consecutive time-ordered observations and e_1 is that for a single observation computed from the mean) for both the comparison star and the variable – comparison star differences. That it was so for the comparison star demonstrated that short-term variations in sky transparency and sky background were dominant compared to longer-term extinction variation (the "airmass effect" as it is referred to in Howell's paper in this volume). The error in the differential data would be expected to be larger by a factor of $\sqrt{2}$, but in the case of CH Cygni,

> "that seen here exceeds that to be expected in both e_1 and e_p for the May 24 data. This is evidence that ... fluctuations on scales of several minutes ... are indeed present..."
>
> (Milone et al. 1986), pp. 1179–1180.

This is the type of science for which RADS-like systems excel.

The RADS instrument allowed observations to be carried out for about 30 years in an environment where portions of at most 1/3, and in bad years, less than 1/5 of the nights could be categorized as photometric. It was used by a generation of astrophysics students who learned how to carry out careful photometry and how to reduce and analyze their results. More than two dozen of these students pursued careers in science and education, and a good fraction of these have become major contributors to astronomy and astrophysics.

4.3.5 RADS Denouement

In 1997, a 1.8-m Honeycomb mirror, purchased earlier from the Mirror Lab of the University of Arizona, was successfully mounted in a support structure designed by T. A. Clark, then the newly-retired RAO co-Director and Project Manager for the ARCT mirror support project. The 1.8-m replaced a 1.5-m metal mirror that the RAO originally leased from the University of Arizona Lunar and Planetary Labs, thanks to the good offices of its director, the Rev. George V. Coyne. The mirror had been figured and polished first at the Norm Cole Workshop in Tucson and then completed at the Kitt Peak National Observatory in a project managed by the Astrophysical Research Consortium (ARC). The 1.5-m Infrared Telescope then became the 1.8-m Alexander R. Cross Telescope (ARCT), after the RAO's benefactor, who supplied the required funding to complete the mirror polishing project. The combined projects extended from 1987, when the IRT was dedicated, to 1997. From 1992–1995, the 1.8-m mirror was used in ARC's Apache Point Telescope while a 3.5-m mirror was completed, under a cooperative agreement between the ARC and the RAO. In 1999, in contemplation of a major upgrade to all the telescope systems, the RADS was moved to one of the several ports affixed to the ARCT backplane. The theory was that it could be used on much fainter objects on the larger telescope; moreover, the 0.4-m telescope was to be fitted with a CCD camera that could be accessed and operated remotely.

Despite major upgrades carried out over the following years, the RADS was never again as productive as it had been when on the 0.4-m telescope. In its new location, it was used to study several variable stars, including RT Lac and VW Cep, and to search for transits by extra-solar planets in solar-like stars. However, competition with programs requiring the infrared, spectroscopic, and CCD instruments and frequent telescope closings due to the difficulties of maintaining the technically challenging alt-alt mounting of the ARCT, diminished the number of available nights for RADS observations. After EFM stepped down as RAO director in 2004, "stare" instruments which may be maintained more easily than dynamic instruments such as the RADS, were favored, so that the RADS effectively became mothballed. F. M. Babott who had maintained the RADS instrument since the beginning retired in 2009, further limiting the liklihood of its further operation.

Despite its great promise, the RADS configuration did not catch on at other observatories, although the many references to "two-star" photometers in this article indicates that the value of differential photometry was understood. Partly the lack of adoption of RADS-like systems was due to the dynamic character of the system which required careful setup and maintenance. The characteristics of the system effectively made RADS photometry as much an art as a science. After a period of non-use, for example, the Ling driver sometimes appeared to "stick" longer than programmed at a setting, and sometimes overshoot the next position (with further use, the system "limbered up"). Moreover, settings that were set up statically, i.e., by moving the amplitude controls on the MAC box successively through the channels by hand, had to be tweaked further after the system was set to "run." Additionally, as the telescope moved across the sky, the settings needed to be checked as the Ling Driver and restoring force of the flex pivots were more efficient at some orientations than others. These and other quirks of the system meant that great vigilance was required of the observer in order to produce light curves of high accuracy and precision.

There were also intrinsic sources of error in the system, although, in principle, these could be determined and removed during analyses. For example, the photometer employed a Fabry lens to image the primary mirror on the photocathode; this is the classical way to minimize the effect of non-uniform photocathodes by having the flux illumine a fixed area. Nevertheless, the slight changes in projection of the secondary mirror at different off-axis settings required "sensitivity corrections" to the counts from three of the channels to have them calibrated to the fourth channel. This correction was typically $\sim 1\%$ but sometimes could be as much as 5%, depending on star separation, orientation, and the characteristics of the sky in which the calibration was attempted. The use of the sky as a calibrating source also begs the question, raised earlier in this paper, about the effects of the sky background entering the detector from slightly different directions than the starlight. However, the most likely reason that the RADS did not become widely used elsewhere was the dawning of the long-awaited 2-D electronic detectors, the CCDs, in which a number (sometimes an enormous number) of comparison stars as well as a very well sampled sky, can be observed truly in parallel, if with less time discrimination.

We note, however, that photoelectric photometers that can provide rapid measurements simultaneously – or nearly simultaneously – in several passbands, are still of value, as we demonstrate in the next section.

4.4 Simultaneous Multi-Passband Photometry

Although the advantages of simultaneous multicolour photometry are evident, multichannel photometers are technically challenging. As a consequence, such photometers were not used as widely as one would expect, so that most photometric programs during the "high season" of photoelectric photometry (1950–1990) were performed with single-channel instruments.

One successful exception was the Walraven five-color photometer, discussed above; another was the Strömgren intermediate-passband *uvby* system. During the 1950s Strömgren had systematically studied and tested many intermediate- and narrow-band indices for photoelectric classification of stellar spectra. After the possibility of three-dimensional classification (temperature, gravity, metallicity) of intermediate-type stellar spectra had been demonstrated, the *uvby* system was conceived by Strömgren at Lick Observatory in 1959 and tested there the same year on the the 36-in.Crossley reflector and the 36-in. refractor. The next year Strömgren made more extensive *uvby* observations with the 20-in. reflector at Palomar. The system was soon augmented with the Hβ index developed by Crawford. The index is the ratio of light through a narrow-band filter and a broader one, both centered on the Hβ line. Large observing programs were initiated in the 1960s at Kitt Peak and a bit later also at ESO, La Silla. Early reviews of this development can be found in Strömgren (1963; 1966). During the 1970s and 1980s *uvby*-Hβ photometry became a standard tool for quantititative analysis of stellar spectra.

It should be noted that this development was not entirely based on multichannel photometers from the beginning. In the early years of *uvby*-Hβ photometry the *uvby* measurements were made with single-channel photometers and the H measurements with dual-channel instruments. The building of four-channel *uvby* photometers started in the late 1960s, notably at the Brorfelde Observatory, where the development of photoelectric instrumentation received a major impulse with Strömgren's return to Denmark in 1967. Like the five-channel Walraven photometer, the four-channel Strömgren instruments were spectro-photometers, where the spectrograph dispersion (in the *uvby* case, from a grating) provided the geometric separation of the wavelengths and the passband shapes were defined by additional filters. The higher dispersion from a grating (as compared with the prism spectrograph in Walraven's case) was needed to reduce the influence of seeing motions on the spectrum position. A complete *uvby*-Hβ measurement could now be obtained with much higher accuracy in two steps: the *uvby* data with the four-channel photometer,and the Hβ narrow/wide measurements with a separate two-channel instrument. The ultimate goal, simultaneous measurement of all *uvby*β indices with

Fig. 15 The fully automated six-channel *uvby*-Hβ photometer on the 50-cm Danish telescope at ESO, La Silla (photo: courtesy ESO)

one instrument, was realized in 1987 in the fully automated six-channel Strömgren photometer on the 50-cm Danish telescope at ESO, La Silla (see Fig. 15). Further discussion of the importance of Strömgren and other system photometry are discussed by Sterken et al. and by Wing, and spectrophotometric systems are discussed also by Adelman, all in this volume.

5 Future Prospects

This paper has concentrated on the advantages of differential photometry to achieve higher astronomical precision and accuracy than would be possible without it. The technique is not flawless, and fundamental sources of inaccuracy and imprecision can still plague the photometry, especially in the presence of nonphotometric skies and ill-conceived passbands. We have focused especially on the work of Walraven and of his differential photometry legacy. We note also that Armbruster et al., in this volume, discuss a particular photoelectric system, the Pierce-Blitzstein Photometer, with which differential photometry had been carried out for more than half a century.

Experimentation can be expected to continue. In the infrared, an *IRRADS* was proposed by EFM in the 1980s, but not funded. Instead, another path to higher precision in the IR was pursued (see the Milone and Young paper in this volume).

It still seems worthwhile to implement a differential IR system such as IRRADS, however, for the highest precision attainable in the presence of partially impaired skies, if one needs to observe under such conditions in the near-infrared, or, more generally, in the mid-infrared where the ambient background is so bright that array instruments must be read out rapidly. With or without an *IRRADS*, however, the use of *IRWG* passbands is the best way to insure improved infrared accuracy and precision.

The current detectors of choice are charge-coupled devices, a separate exposition on which is given by Howell, elsewhere in this volume. The recent development of the orthogonal transfer CCD appears to be capable of producing the highest precision of this class of instrumentation.

The challenge to produce equally great accuracy remains, and to meet this challenge the skills of the observer and analyst are still paramount. We note also the importance of careful selection of passbands to minimize transformation errors.

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