Low-cost BVRI Filters for CMOS/CCD Photometry

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Introduction

CCD cameras have been widely and routinely used in the citizen astronomy community for more than a decade. For photometry a system comprises: CCD camera, filter wheel (FW) and filters. There is a wide range of commercially-available CCD cameras and electronic filter wheels, but many camera/FW combinations cost several thousand dollars or more. Recently, low-cost astro-cameras with CMOS sensors have become available; some of these retail for as little as several hundred dollars. Coupled to the cheaper electronic filter wheels now available, a combined camera and filter wheel assembly can be bought for less than AU$1000 (£600). Commercial photometric filters, however, remain expensive with a set of BVRI filters typically costing as much as a low-cost CMOS camera and filter wheel!

Reducing the cost of equipment is important if we wish to encourage more citizen astronomers to take up photoelectric photometry. The cost of photometric filters currently represents a significant barrier to the realisation of a low-cost photometric system. Consequently, I decided to explore the construction of photometric filters using readily available planetary filters.

Planetary filters are dye-in-glass coloured filters loosely based on Wratten filter prescriptions. These include the #47, #38A and #56 bandpass filters, and the #12, #15, #21, #23A and #25 longpass filters. They are optically flat and come mounted in 1.25-inch cells that screw into most filter wheels. Transmission curves are, however, not readily available.

Background: BVRI passbands

In UBVRI photometry portions of a star’s spectrum are selected using optical filters. For such broad-band photometry the resulting passbands have a full-width half maximum (FWHM) ~ 100 nm (Majewski 2008). The sampling of a star’s spectrum by the passband is, however, a combination of the transmission of the filter and telescope optics, the response of the detector, and the transmission of the atmosphere as a function of wavelength.

The spectral transmission of the telescope optics and spectral response of the detector may change over the long-term but can be considered constant over the course of the night and from night to night. Temperature changes can cause small changes in the transmission of the filters. The change is ~ 0.1 nm per degree Celsius which can give rise to a change of several thousands of a magnitude per degree Celsius (Young 1967). The transmission of the atmosphere is particularly important in the U-band where the atmospheric cut-off at around 300 nm can define the short-wavelength edge of the passband.

In the 1940s and leading into the 1950s astronomical photometry was the domain of a handful of specialists. There was much discussion at the time on what type of system to introduce as a ‘standard’ with no consensus on the type and number of bands to adopt (Hearnshaw 1996). The UBV broad-band photometric system was introduced by Johnson & Morgan (1953) and quickly became the *de facto* standard. The response of the 1P21 photomultiplier (PM) tube defined the spectral region that could be measured and, along with considerations of the existing photographic photometry system, determined the choice of filters to realise the defined UBV bands (Hearnshaw 1996; Johnson 1955).

Kron et al. (1953), Johnson (1966), Eggen (1975) and Cousins (1976) all extended the original UBV system to R and I but they used different R and I filters resulting in different passbands (Bessell 1979; Bessell 2005). The UBVRI system in widespread use today came about by combining the Johnson UBV and Cousins VRI systems. Passbands and filter prescriptions for this contemporary UBVRI system are given by Bessell (1990, 2005), Bessell & Murphy (2012) and Munari *et al*. (2002). Standard stars are provided by Menzies et al. (1989), Landolt (2017) and the AAVSO (standard stars in selected open clusters).

Since about 1980 the Johnson RI system has fallen into disuse, the contemporary system being based on Cousins R_c and I_c bands. Johnson (1966), Bessell (1979) and Taylor (1986) have all noted that transformation between the two systems is non-linear.

Filters used in the standard BVRI system

Johnson's original filters were made of Corning glass. For the V filter he had a Corning 3384 (yellow) filter ground and polished. This defined the 'blue' edge of his V-band and the drop off in response of his uncooled 1P21 defined the 'red' edge. The filter was thus a bespoke filter, not a commercially-off-the-shelf (COTS) one. The U filter was made from Corning 9863 glass and the B filter from a combination of Corning 5030 and Schott GG13 glasses. Filter prescriptions and passbands for the original UBV system are given by Johnson (1955). Subsequently there were some concerns raised about 'replicating' these bands and Johnson noted that the published response curves may be slightly in error as a result of his having switched to a cooled photomultiplier (PM) tube later on (Johnson 1962).

Because of their availability and quality, photometrists that followed Johnson turned to Schott glasses for their systems. Schott has a range of similar (but not identical) filters to Corning so it was possible to match the blue edge of the V band (e.g. with a Schott GG495) and similarly the blue and red edges of the B band. With questions over the red edge of Johnson's original 1P21, and later PM tubes with extended red responses, a Schott blue-green (BG39 or BG38) passband filter was added to define the red edge of the V filter and cut out any infrared leak in the blue glasses used for the B filter. This approximated rather than replicated the original B and V bands. (A similar situation ensued for the U filter.)

For an instrumental photometric band that is sufficiently matched to a standard band there is a linear transformation of the observer's instrumental measurements to published values of standard stars. Typically, this applies over a wide range of spectral types and luminosity classes but may not apply to very red or chemically unusual stars (e.g. Carbon and S-type stars). Perhaps the process of matching filters and detectors to the spectral response of a photometric band is better viewed as mimicking rather than replicating the standard photometric bands, the aim being to match them sufficiently well for a linear transformation to be used over a wide range of spectral type and luminosity class.

A number of manufacturers make dye-in-glass coloured filters. These include Schott, Hoya and Kopp (Corning prescriptions). Wratten gelatine filters sandwiched between glass covers have also been used by photometrists. Types and transmissions of these filters can be found at:

Schott: http://www.schott.com/advanced_optics/english/syn/advanced_optics/products/optical-components/optical-filters/optical-filter-glass/index.html

Hoya: http://www.hoyaoptics.com/color_filter/ir_transmitting.htm

Kopp: http://www.koppglass.com/solutions/colored-filter-glass.php

Wratten: http://www.karmalimbo.com/aro/pics/filters/transmision%20of%20wratten%20filters.pdf

Standard Stars for BVRI photometry

Johnson's original primary standard stars (Johnson and Harris 1954) only defined the UBV system from about B8 to K4 for luminosity classes V to III. The 108 secondary standards extended this somewhat. Later, Johnson (1955) published a catalogue of 382 stars encompassing a wider range of spectral types and luminosity classes. He noted that a list of standard stars must include all kinds of stars and it is for this reason that his list contains nearly 400 stars.

While Cousins (1976) carefully and precisely extended the UBV system to the southern hemisphere, there is a paucity of very cool, very hot or chemically peculiar stars in his list of Harvard E and F-region standard stars. Although in excellent accord with Johnson's original UBV system, the issue of possible limitation on types of stars to which a linear transformation can be applied remains for today's photometrists. For example, measured B-V indices for M giants can vary from one observer's system to another by as much as 0.05 magnitudes (Moon, Otero & Kiss 2008). This arises through a slight shift in an instrumental system's 'sampling' of molecular bands over the broad portion of a star's spectrum measured through a broad-band filter. The B-V index is a useful temperature surrogate for earlier type stars but for M giants becomes more of an indicator of their chemistry. (Astronomers thus turn to other bands for determining the temperature of M giants.)

For the contemporary UBVRI system, standard stars are given by Menzies et al. (1989), Landolt (2017) and AAVSO standard clusters (AAVSO 2017).

Filters

Published prescriptions

Many different filter prescriptions have been used since the introduction of the UBV system in 1953. Changes have been driven by availability, cost and introduction of new detectors. In particular, some filter types have been discontinued or become difficult to source necessitating changes to the original filter prescriptions. The extension of PM tubes into the red and infrared, introduction of photodiode detectors, advent of CCD/CMOS sensors have all had an impact on the practical realisation of the standard UBVRI bands.

The original prescriptions for UBV filters were given by Johnson (1955) along with the spectral response and effective wavelengths of the resulting bands. For the RI bands of the contemporary UBVRI system the original filter prescriptions and responses of the bands were given by Cousins (1974; 1976). Summarised details for the UBVRI and other photometric systems have been usefully assembled into the Asiago Database on Photometric Systems, ADPS, (Munari *et al*. 2002). For convenience published filter prescriptions for the UBVRI system are summarised here in Table 1.

Bessell (1990) and Sung & Bessell (2000) have provided filter prescriptions for the contemporary UBVRI system with a view to other photometrists adopting them thus making the UBVRI system more universally consistent and readily realised. The use of photodiodes, advent of CCD/CMOS sensors and discontinuance of some filter types have, however, necessitated changes to such UBVRI filter prescriptions over time.

Table 1. Published UBVRI filter prescriptions.

Passband	Detector	Published filter prescriptions	Reference
U	S4/S11 PM tubes	Corning 9863	Johnson (1955)
		Schott: UG1 (1mm) + WG320 (2 mm)*	Bessell (1990)
	GaAs/S25 PM tubes	Schott: UG1 (1 mm) + BG39 (1 mm)	Bessell (1990)
	CCDs	Schott: UG1 (1 mm) + S8612 (2 mm) + WG295 (2 mm)†	Sung & Bessell (2000)
B	S4/S11 PM tubes	Corning 5030 + Schott GG13	Johnson (1955)
		Schott: BG12 (1mm) + GG395 (2 mm)	Bessell (1990)
	GaAs/S25 PM tubes	Schott: BG12 (1mm) + BG18 (2 mm) + GG385 (2 mm)	Bessell (1990)
	CCDs	Schott: BG37 (3 mm) +BG39 (1 mm) + GG395 (1 mm)	Sung & Bessell (2000)
V	S4/S11 PM tubes	Corning 3384	Johnson (1955)
		Schott GG515	Bessell (1990)
	GaAs/S25 PM tubes	Schott: GG495 (3 mm) + BG38 (1 mm)	Cousins (1976)
		Schott: GG495 (2 mm) + BG18 (1 mm) *[+ BG38 (1 mm)]*‡	Bessell (1990)
	CCDs	Schott: GG495 (2 mm) + BG40 (3 mm)	Sung & Bessell (2000)
R	S25 PM tubes	Grubb & Parsons interference filter or Schott OG570 (2 mm)	Cousins (1976)
	GaAs PM tubes	Schott: OG570 (2 mm) + KG3 (2 mm)	Bessell (1990)
	CCDs	Schott: OG570 (3 mm) + KG3 (2 mm)	Sung & Bessell (2000)
I	S20/GaAs	Wratten 88A or Schott RG9	Cousins (1976)
		Schott RG9 (3 mm)	Bessell (1990)
	CCDs	Schott: RG9 (2 mm) + WG295 (3 mm)†	Sung & Bessell (2000)

Notes: * To be used with UV glass PM tubes. † Used as a fill glass. ‡ for GaAs PM tubes. S25 is also called extended S20 or Extended Red Multi-Alkali (ERMA).

It is worth noting that the response of the detectors available at the time Cousins introduced his RI system defined the long wavelength cut-off of the I-band (Cousins 1976). This is a similar situation to the UBV system when originally introduced by Johnson (1955) where he used the response of the S4 cathode of an uncooled 1P21 PM tube to define the red edge of the V-band. In both instances the use of a detector to define the red edge of the bands was to later cause problems when new detectors were introduced.

Commercial Filters

Currently (i.e. January 2018) UBVRI filters can be bought from the following companies:

- Andover Corporation: https://www.andovercorp.com/products/astronomy-filters/ubvri/
- Astrodon: http://astrodon.com/store/p10/Astrodon_Photometrics_UVBRI_Filters.html
- Baader Planetarium: http://www.baader-planetarium.com/en/filters/planetary.html
- Chroma: https://www.chroma.com/products/single-bandpass-and-single-edge-filters/application/astronomy
- Custom Scientific: http://www.customscientific.com/astronomy.html
- Optec Inc.: https://optecinc.com/astronomy/catalog/ifw/ifw_wheels.htm

Response or transmission curves are provided but the filter prescriptions used are not included. Generally, filter transmissions have been tailored so that resulting bands match Bessell's prescription for the UBVRI system, a notable exception being the Optec R and I filters used in their SSP3 photometers (Persha 1999).

Ongoing development of UBVRI filters has been necessitated by the introduction of CCD cameras and the discontinuance of some glasses previously used in construction of the filters (Goldman, Hendon & Schuler 2005; Hendon 2009). In particular, the higher infrared response of CCD (and now CMOS) sensors leads to the original prescription for the I filter producing a 'tail' extending past the I-band's specified cut-off at

920 nm. To better match the original I-band (Cousins 1974, 1976: Munari *et al*. 2002), and Bessell's later version of it, a dielectric coating has been added to the recommended coloured glass filter by Astrodon (Goldman, Hendon & Schuler 2005). This increases the price of the I-filter so two I-bands have emerged:

- An I_c band matching the published response for the Cousins/Bessell I-band (dielectric coating added).
- An I_s band using the original coloured glass filter recommended by Bessell (1990).

The addition of a dielectric coating is, however, only important for measurements of the reddest stars (Goldman, Hendon & Schuler 2005). For example, Moon (2013) obtained a linear transformation over a wide range of spectral types using a coloured glass filter only for the I-band and showed that it could also be reliably applied to measurements of red giant branch (RGB) stars.

Dielectric coatings are used by some manufacturers to better match the UBVRI prescriptions. However, Bessell (2005) and Majewski (2008) note that, depending on the f/ratio of the telescope, the bandwidth of an interference filter can change across the field of view introducing systematic differences in the photometry. Any 'tilting' of an interference filter will also introduce changes to its transmission characteristics. Baader (2016) outline some other problems that may occur when using interference filters.

Commercial filter sets are designed to be 'parfocal' (i.e., all the same thickness) and to have a high throughput. Even with parfocal filters some minor refocusing may be needed as a result of temperature changes (Baader 2016). Problems have also been encountered with respect to the chemical stability of Schott BG39 and KG3 glasses. In particular the Schott BG39 can develop a haze on its surface. It has been reported that Hydrogen Peroxide will remove this. Another option is to cover these glasses with a clear window.

Low-cost DIY filters

Astronomical CMOS cameras using sensors like the Sony IMX174 can be used for photometry with an uncooled version retailing for ~AU$800 (£450). As 5-position electronic filter wheels now cost as little as AU$260 (£150), BVRI filter selling for ~ $AU1000 (£600) thus cost as much as the camera and filter wheel. I thus decided to explore a do-it-yourself (DIY) approach to BVRI filters.

Challenges for standardising measurements in the U passband are well documented (Bessell 1990; Moon 2017). This is exacerbated by the typically poor sensitivity of CCD/CMOS sensors in U band. An assessment of return on investment by citizen scientists undertaking photometry with small telescopes, and with limited time and resources, is likely to lead to a decision not to bother making U band measurements. I have thus not explored making a low-cost U filter.

B filter

In contrast to the U and V bands Johnson's original B-band was a combination of 2 filters. The introduction of PM tubes with responses extending to longer wavelengths required the addition of a Schott BG38 or BG39 filter to mimic the original B-band (by cutting out the B-filter's transmission in the infrared). The prescription for B filters then involved cementing together 3 different types of glasses. Modern B filters such as those supplied by Baader Planetarium instead use an interference film on a 'blue' glass to realise the standard B band.

Noting this, I thus decided to explore using a planetary 'blue' filter with a standard UV/IR cut interference filter. The most promising of the available planetary filters was the dark blue #38A. (Planetary filters are dye-in-glass filters based on Kodak Wratten specifications.) The response of the combination of a planetary #38A with a UV/IR cut filter used with a Sony IMX174 (CMOS) sensor is shown by the solid blue line in

Figure 1. Also included is the response of Johnson's original B band as listed in the ADPS (Munari *et al.* 2002), shown as a dashed blue line. For comparison the response of a Baader Johnson B filter is shown as a dash-dot cyan line. Measurements of 24 AAVSO standard stars in NGC 3532 gave a linear transformation (see Figure 2) with a smaller transformation coefficient (~ -0.07) than that measured for the Baader Planetarium B-filter (~ -0.12).

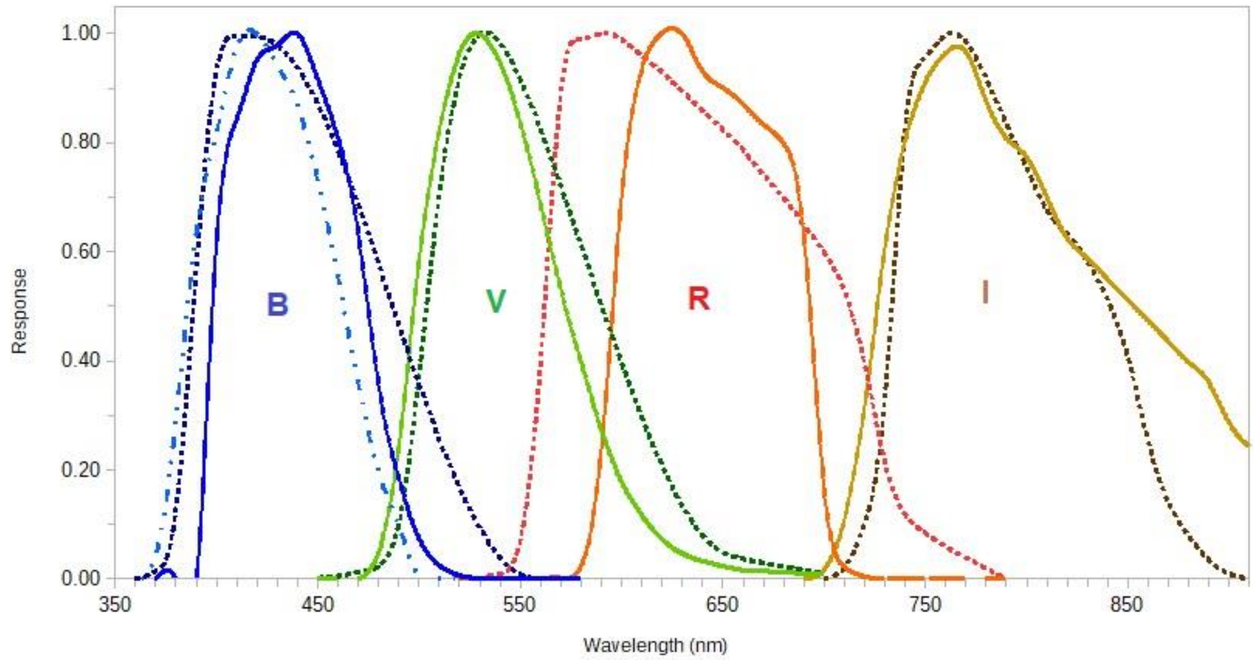

Figure 1: Response of DIY filters used with a CMOS IMX174 sensor (solid lines). Standard passbands as listed in the ADPS are shown as dashed lines. For comparison the response of a Baader B-filter is shown as a dash-dot cyan line.

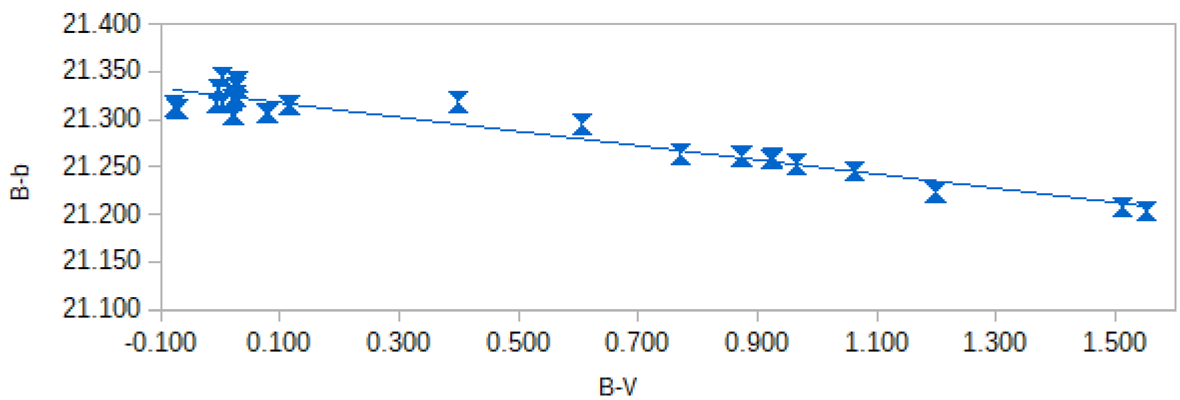

Figure 2: Difference between published and measured B magnitudes as a function of B-V for 24 AAVSO standard stars in NGC 3532.

Combining a planetary #38A with a UV/IR cut filter thus provides a satisfactory B filter for less than AU$50 (~£30).

V filter

To define the blue edge of the V-band I have used a yellow planetary filter (#12) which cost ~ AU$20 (~£10). To define the red edge I originally used a Schott BG39. Thor Labs in the US supply BG39 filters which are 25.4 mm in diameter and 2 mm thick. In cementing the 25.4 mm BG39 to the yellow planetary filter it was necessary to keep the filters concentric. This left a 1.3 mm ‘ring’ of exposed yellow filter which needed to be covered or blacked out with paint.

Combining a #56 planetary filter with the #12 resulted in the response shown in Figure 1. Also included is the response of Johnson V-band from ADPS (Munari *et al*. 2002). Measurements of 24 AAVSO standard stars in NGC 3532 gave a linear transformation (see Figure 3) with a small transformation coefficient (~ -0.02).

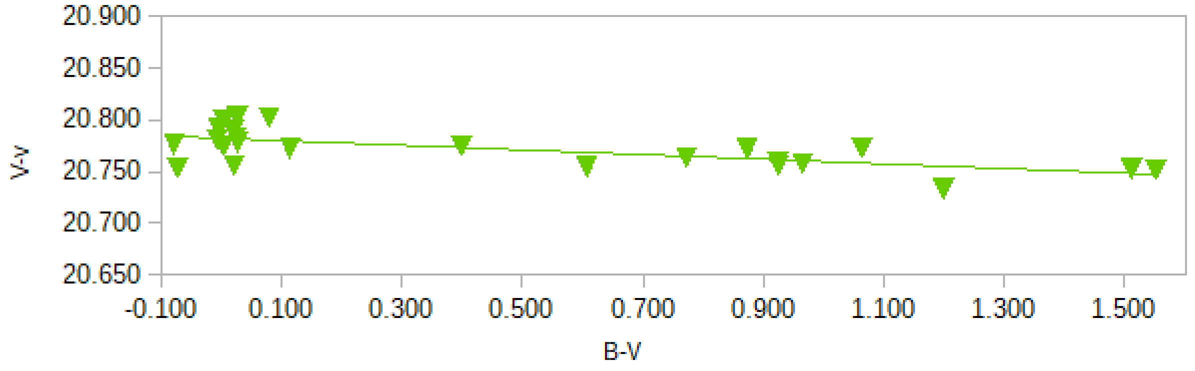

Figure 3: Difference between published and measured V magnitudes as a function of B-V for 24 AAVSO standard stars in NGC 3532.

R filter

For R-band a Schott OG570 is specified for the short wavelength cut-on and a Schott KG3 filter for the long wavelength fall-off. Schott OG570 and KG3 glasses that are 25.4 mm in diameter and 2 mm thick can be sourced from Thor Labs. For DIYers prepared to cement the two glasses together and mount the resulting filter in a suitable cell, there can be a significant saving from buying commercial ones.

The light-red planetary filter (#23A) appears to be a similar longpass filter to the Schott OG570 so I decided to explore its use in making an R filter. For the long wavelength cut-off I used a UV/IR cut filter. These can be purchased on eBay or from telescope retailers for about AU$25 (~£15). The resulting passband is somewhat narrower than the prescribed R-band but has a similar central wavelength (see Figure 1). Measurements of 24 AAVSO standard stars in NGC 3532 gave a linear transformation (see Figure 4) with a small transformation coefficient (~ -0.05).

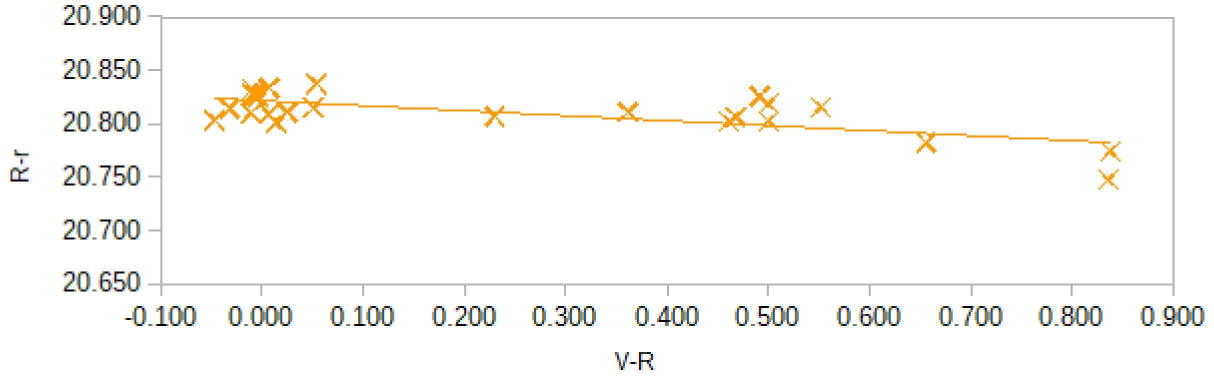

Figure 4: Difference between published and measured R magnitudes as a function of V-R for 24 AAVSO standard stars in NGC 3532.

I filter

For I-band, a Schott RG9 filter is specified (Cousins 1976; Bessell 1990; Sung & Bessell 2000). The RG9 alone is used for the Astrodon I_s band and is also the coloured glass component of Astodon's I_c filter. An I_s filter is thus easy to make with 25.4 mm diameter, 3 mm thick RG9 filters available from suppliers such as Edmund Optics for about AU$65 (~£35). The 25.4 mm diameter, 2.5 mm thick Hoya RT-830 is a similarly priced equivalent with essentially the same spectral response as the RG9 (Moon 2013). The main challenge is mounting a 25.4 mm glass in a cell made for 28 mm glass. (Some of the cheap planetary filter sets sold on eBay use a standard threaded 32 mm cell but have 25 mm diameter glass rather than 28 mm glass and are thus excellent for mounting the 25 mm Schott or Hoya glasses from suppliers such as Edmund Optics.)

An alternative is to combine an orange or red (#15, #21, #23A or #25) planetary filter with a violet filter (#47). As shown in Figure 5 the violet filter has high transmittance in the infrared as well as the violet. The longpass orange or red filter then blocks the violet transmission; cost of the two filters is ~ AU$40 (~£25). For comparison the measured transmittance of a Schott RG9 is also shown.

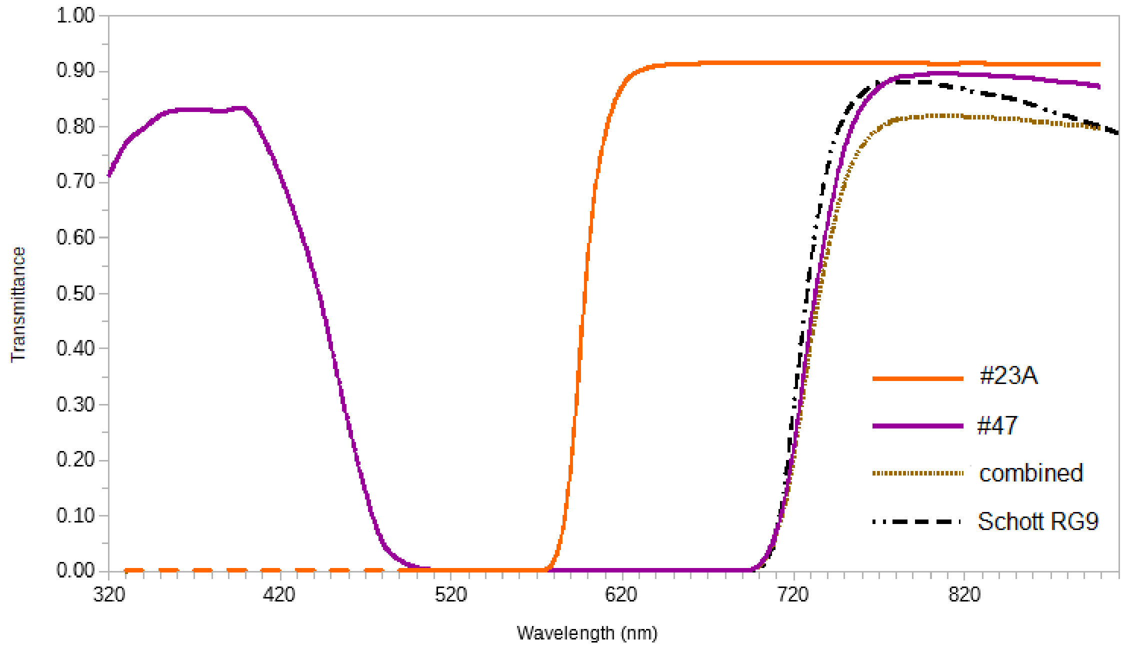

Figure 5: Transmittance of DIY I-filter and its individual components. For comparison the transmittance of a Schott RG9 is also shown.

Figure 1 shows the response of a DIY I-filter when used with a Sony IMX174 sensor and the response of the Cousins I-band as listed in the ADPS. Measurements of 24 AAVSO standard stars in NGC 3532 gave a linear transformation (see Figure 6) with a small transformation coefficient (~ 0.02).

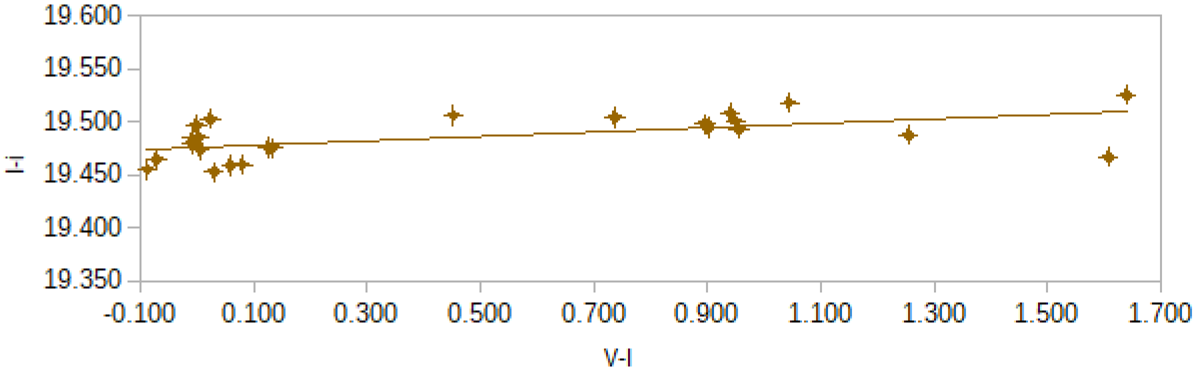

Figure 6: Difference between published and measured I magnitudes as a function of V-I for 24 AAVSO standard stars in NGC 3532.

For DIY filters the individual components can be assembled without cementing them provided they are separated by a thin spacer to eliminate interference fringes (Newton's rings). Cementing the components will increase the overall transmission by about 10% for 2-component filters (Miles 1998). Optical adhesives are available from specialist suppliers but cementing components together can be challenging and is best done by an optical technician.

Discussion & Summary

Current BVRI filter sets retail for around AU$1000 (~£550). A low-cost set of BVRI filters can, however, be constructed from readily available planetary and UV/IR cut filters for around AU$130 (£70).[1] Measurements of AAVSO standard stars in the southern cluster NGC 3532 show that these filters, used with CMOS sensors, give linear transformations from -0.1 < V-I < 1.70 covering a range of spectral types and luminosity classes.

The central wavelengths and FWHM for the DIY filters used with a CMOS sensor are given in Table 2. For comparison the values for the BVRI bands from responses listed in the ADPS are included.

Table 2. Central wavelengths and FWHM for DIY filters used with CMOS sensor and for the BVRI bands as specified in ADPS.

Band	λ_c (nm)		FWHM (nm)	
	ADPS	DIY	ADPS	DIY
B	438	438	98	75
V	547	535	87	76
R	647	644	152	98
I	787	788	110	123

The thicknesses of the DIY filters can vary depending on the brands used. They may thus not be parfocal. My experience is that a minor refocusing when changing filters is not onerous but note this can be an advantage of commercially-available filters over DIY ones.

Filter components can be cemented together using cheap 'super' glue but ensuring there are no bubbles trapped between the components is challenging. The components do not have to be cemented provided a thin spacer is used to eliminate interference fringes (Newton's rings). This results, however, in a throughput loss

1 Planetary filter sets are a popular accessory for citizen astronomers. The dark blue (#38A), violet (#47) and dark red (#25) are typically not used by many observers so lay idle amongst their accessories. They can now be put to good use!

of around 10% for a 2-component filter. Again, throughput has not been an issue for me as I've successfully used DIY filters for measuring stars down to 12th magnitude with a 150 mm f/5 Newtonian and CMOS camera using exposure times no longer than 60 seconds.

Transmission of planetary filters may vary somewhat from one manufacturer to another. In particular I found the Prostar brand of filters to be a lighter tint than other brands and unsuitable for constructing BVRI photometric DIY filters. GSO filters (often re-branded under the retailer's name) seem to provide cheap, good quality planetary filters that are suitable for making BVRI filters.

Finally, for any filter set, it should be remembered that a linear transformation derived from measuring standard stars strictly only applies to the range of colour indices, spectral types and luminosity classes measured. There is no guarantee that such linear transformation can be applied to stars with unusual spectra or very red stars with many molecular bands in their spectra.

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