JHK Standards for Small Telescopes

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Presented at the 91st Spring Meeting of the AAVSO, July 2, 2002

Abstract The AAVSO Futures meeting, held in Madison, WI, in May 2001, proposed that the AAVSO support near-infrared research with small telescopes. A photometer, the SSP-4, has been developed to provide *J*- and *H*-band capability for a reasonable cost. However, proper calibrated photometry requires a set of standard stars. This paper describes such a set of stars, suitable for small telescopes, and with accurate coordinates, proper motions, and high-quality magnitudes.

1. Introduction

Amateur astronomical photometry has been almost exclusively confined to the visible window between 300 and 1000 nm. However, modern technology offers the potential of extending the wavelengths available to small telescopes. In particular, the near-IR bandpasses, *JHK*, can be observed from the ground with quite simple systems. Before describing such a new photometric instrument, some photometric background is useful.

In the 1960's, Harold Johnson and collaborators used the 1P21 photomultiplier to acquire precision photometry of many objects. He devised a three-filter setup: one (V) matched the visual response of the human eye, and so its measures could extend the existing database of visual observations; one (B) matched the response of most photographic plates, offering the potential of calibrating existing plates and providing increased measurement accuracy of objects; and one (U) centered on the Balmer jump, offering new astrophysics. This 3-filter set was quickly adopted by other observatories, especially since Johnson and Harris (1954) provided a list of 108 Standard Stars so that calibration was possible.

Later detector development, especially the RCA 31034A photomultiplier tube, extended the red response, and new filters were devised to utilize this new wavelength regime. Johnson created two new filters, R and I, but other astronomers were now observing with photomultipliers and devised their own filters as well. The red system that became accepted was the Cousins R and I (called R_c and I_c), primarily because of the seminal work by Cousins and by Landolt in creating lists of high-quality standard stars for the new system. The Johnson/Cousins $UBVR_cI_c$ photometric system has been the accepted standard wide-bandpass filter system for several decades, even after the advent of new detectors such as the CCD.

The situation in the infrared world is far more uncertain. The original detectors (such as lead sulfide photocells) were very insensitive. The atmosphere has "windows" in the infrared; to use these windows to get the largest flux per object, filters were used that had wider bandwidth than the window. Such filters were first developed by Johnson, and had names such as *J* (1.2micron), *K* (2.2 micron), *L* (3.5 micron), and so on, centered on the known atmospheric windows. Later another window at 1.6 microns was discovered, and a filter (*H*) created to cover that window. Quality photometry was not key, since the primary reason for observing in the infrared was to get crude star colors.

Observatories around the world devised their own infrared systems. There were a multitude of infrared-sensitive detectors (PbS, PtSi, HgCdTe, InSb, etc.) and few good sources of filters. With no concensus of detectors and filters, the only common elements were the atmospheric windows themselves. As sensitivity increased, observers started to narrow the bandpasses so that changes in the atmosphere had less influence on the photometry, in other words, trying to make the photometry filter-defined rather than atmosphere- or detector-defined. However, even here differences arose. For example, in the *K* bandpass, if you use only the blue part of the atmospheric window, you decrease the background by a factor of two since the glowing atmosphere starts becoming important on the red side of the window. Likewise, if you use only the red part of the window, you match a methane absorption feature, meaning images of the outer planets can suppress the planet, enhancing the contrast of cloud features, planetary rings, inner satellites, etc.

Therefore, three main groups formed, each with slightly different filter sets. Each of these groups then developed their own standard star lists, sometimes never publishing them. Infrared photometry in the literature can be quoted with good precision, but you need to know which system was used for the measures before you can intercompare datasets. However, the one bandpass in common between the groups is *K*, so as long as a measure is taken through a standard *K* filter from one of these groups, it is very similar to any other group.

The South African Astronomical Observatory (SAAO) system was defined by Glass (1974), with standard stars given in Carter (1990) and Carter and Meadows (1995). The AAO, MSO, and MSSSO systems are derivatives of the SAAO system. This system has a bluer central wavelength for the *J* filter than the ones described below.

The Caltech/Tololo (CIT) system was first defined by Frogel *et al.* (1978) and extended by Elias *et al.* (1982, 1983). The United Kingdom Infra-Red Telescope (UKIRT) adopted this system and extended it to fainter stars (Hawarden *et al.* 2001). This system has the reddest *J* filter; it almost completely avoids the H_2O band near 1.12 microns as described later. This system was adopted for the HST NICMOS instrument; the standard stars were extended by Hunt *et al.* (1998) for its calibration. This system was also adopted for 2MASS (Persson *et al.* 1998), though 2MASS uses a K_s (K-short) filter that avoids a CO-band feature in the red, which will systematically offset K_s from K for some types of stars.

The third system is from the European Southern Observatory (ESO), defined by Wamsteker (1981) and Engels *et al.* (1981) and extended by Bouchet *et al.* (1991). This system has the bluest *H* filter.

Koorneef (1983) tried to homogenize the various systems, creating a standard star list that was heavily used. This homogenized system was basically on the Johnson system for *J* and *K*, and on the SAAO system for *H*.

The current push is to extend these systems to fainter magnitudes as support for the larger telescopes. A secondary push has been to improve the quality of the photometry. The concept here is to narrow the filters even more to avoid as much of the H_2O absorption as possible. A consortium of large observatories has been formed, and have defined a new filter set (Simons and Tokunaga 2002, Tokunaga *et al.* 2002). Called the Mauna Kea Observatories (MKO) system, it represents a compromise between the competing factors of throughput and photometric performance, and has been endorsed by the IAU.

A plot showing the atmospheric windows and how the MKO filters fit within those windows is shown in Figure 1.

Before we discuss the selection of standard stars, we should first describe a new instrument that can be used by AAVSO members: the Optec SSP-4 solid state near-IR photometer.

2. The Optec SSP-4

The AAVSO entered into an agreement with Jerry Persha of Optec, Inc. to develop an infrared-capable single-channel photometer system. After extensive research, it was decided that the communications industry Hammamatsu G5852 InGaAs PIN photodiode gave the most value. The spectral response curve for this diode is given in Figure 2. It is sensitive from 1.0-2.1 microns, peaking at about 1.9 microns, which means the diode works reasonably well at *J*, quite well at *H*, and could be used for a narrow-band filter at *K* (similar to K_s).

The basic layout of the SSP-4 is shown in Figure 3; it borrows much of its structure from the older SSP-3. A photograph of the prototype unit is shown in Figure 4. This photometer is compact and light, and can be handled easily by just about any amateur telescope.

The initial filter complement is *J* and *H*, manufactured by Spectro-Films. Bandpass for *J* is 1.250microns (0.2micron fwhm); for *H* is 1.650microns (0.3micron fwhm). These are very similar to the MKO bandpasses.

Preliminary tests with the prototype unit suggest that $J = H = 6.0$mag is within range of most amateur telescopes and sites.

3. AAVSO standard stars

As mentioned earlier, there are a variety of *JHK* systems. We have to decide which system to use for the SSP-4.

Since the filters come closest to matching the MKO system, and since the MKO system is similar to the CIT system, it makes sense to use the brighter CIT fundamental standards as the best choice for standard stars. There are no MKO standards available right now, and most professionals using the MKO filters cannot work bright enough to support the amateur/small college using an SSP-4.

In Table 1 are 53 primary standards for the AAVSO. These are mostly from the UKIRT bright standards list (see Joint Astronomy Centre in references), but there are a few additional stars from Elias *et al.* (1982) and also from a careful calibration by Vrba, Joyce, and Strom (1981) at KPNO in the 1970's. The Vrba list overlapped with the UKIRT list; those overlapping stars have agreement within 0.01magnitude, so both lists are on the same basic system. The stars in Table 1 should be good enough for ground-based single-channel all-sky calibration. As we observe these stars, we can possibly refine their magnitudes for the specific filter set in the SSP-4, or link into the fainter MKO standards when they become available.

Table 1 includes accurate coordinates, as well as proper motions, for all stars. The coordinate epoch and equinox are both 2000.0. Note that these are all bright stars, and bright stars tend to be preferentially nearby and therefore high proper motion objects. Be sure to make proper motion corrections if needed.

4. Observing in the near-IR

If you look at Figure 1, you can see that the atmospheric windows are not perfectly transparent. This is particularly true at sea level, where high water vapor content will contaminate the passbands. Working in the infrared is much like looking through light cirrus; only under rare conditions do you get results that are similar to optical photometric skies. As the water vapor content changes nightly, and sometimes even within a night, the effective bandpass also changes and transformation coefficients are not stable. In general, you should expect 0.05mag all-sky accuracy per night under good observing conditions.

The moonless sky background will be higher in *J* and *H* than it is at *BVRI*. At *H*, there is considerable airglow, so the sky is actually brighter at *H* than at *J*. However, scattering is a strong function of wavelength, so observing at *J* and *H* with a moonlit sky is no different than without the moon. You can work within a few degrees of the moon, only limited by scattering within your telescope and your ability to find the program object. Likewise, you will not see much (if any!) sky background due to urban lights; your city lot is just as good as a dark mountaintop.

Extinction coefficients are small, typically 0.10mag/airmass at *J* and 0.06mag/airmass at *H*. Since the sky is constantly changing, it is usually simpler to find standard stars at the same airmass and calibrate fields without making a separate extinction calculation.

Since conditions are constantly changing, you should not stay on an object for long periods of time before moving to the comparison star, even under what appears to be photometric conditions. The usual procedure is to use the pattern SCSPSCSPSCS, where S = sky, P = program object, and C = comp star. This pattern brackets each star measure with sky measures, and further brackets the program object with comparison star measures.

You will be working with bright stars, so they will be easy to see on your flip mirror/reticle viewer. This is not always the case in the near-IR; we are often looking at highly obscured objects and have to blind-offset to find them. For these objects, you can sometimes find them by moving the telescope slowly and seeing where the peak signal occurs.

5. Acknowledgement

The data from Vrba, Joyce, and Strom have been kindly given to me for inclusion in this paper.

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Table 1. The AAVSO near-IR primary standards.

HD	RA (2000)	Dec	pmra mas/yr	pmdec mas/yr	Sp.Cl.	V	J	H	K	L	L'	note
358	$00^{h}\ 08^{m}\ 23^{s}.26$	$+29^{\circ}\ 05'\ 25''.6$	135.68	-162.95	B8IV	2.06	2.30	2.33	2.36	2.39	—	3
1013	00 14 36.16	+20 12 24.1	90.66	1.88	M2III	4.82	1.63	0.81	0.63	0.45	—	3
6860	01 09 43.92	+35 37 14.0	175.59	-112.23	M0III	2.06	-0.92	-1.73	-1.87	-2.01	-2.02	1
12929	02 07 10.41	+23 27 44.7	190.73	-145.77	K2III	2.00	0.09	-0.52	-0.63	-0.74	—	3
14818	02 25 16.03	+56 36 35.4	-0.39	-0.65	B2Iae	6.25	5.58	5.43	5.33	5.32	5.30	1
15318	02 28 09.54	+08 27 36.2	41.72	-14.46	B9III	4.28	4.41	4.42	4.43	4.43	4.41	1
20902	03 24 19.37	+49 51 40.2	24.11	-26.01	F5I	1.82	0.87	0.62	0.56	0.47	—	3
23288	03 44 48.22	+24 17 22.1	20.73	-44.00	B7IV	5.46	5.52	5.50	5.51	-5.64	—	1
29139	04 35 55.24	+16 30 33.5	62.78	-189.35	K5III	0.85	-1.86	-2.64	-2.80	-2.98	-2.93	1
30836	04 51 12.36	+05 36 18.4	-3.62	1.03	B2III	3.69	4.04	4.09	4.14	4.15	4.16	1
31398	04 56 59.62	+33 09 57.9	3.63	-18.54	K3II	2.69	0.21	-0.51	-0.66	-0.85	—	3
34085	05 14 32.27	-08 12 05.9	1.87	-0.56	B8Iae	0.12	0.23	0.22	0.21	0.15	0.08	1
34029	05 16 41.36	+45 59 52.8	75.52	-427.11	G4III	0.08	-1.34	-1.73	-1.81	-1.87	-1.87	1
37763	05 31 53.02	-76 20 27.5	143.19	287.74	K2III	5.17	3.28	2.76	2.66	2.58	—	2
48915	06 45 08.92	-16 42 58.0	-546.05	-1223.14	A1V	-1.46	-1.30	-1.32	-1.32	-1.35	-1.37	1
60178	07 34 35.86	+31 53 17.8	-206.33	-148.18	A2V	1.59	1.55	1.54	1.53	1.51	—	3
61421	07 39 18.12	+05 13 30.0	-716.58	-1034.60	F5IV	0.34	-0.41	-0.61	-0.65	-0.68	—	3
62509	07 45 18.95	+28 01 34.3	-625.69	-45.96	K0IIIb	1.14	-0.51	-0.99	-1.11	-1.15	-1.19	1
69267	08 16 30.92	+09 11 08.0	-46.80	-48.65	K4III	3.54	1.05	0.30	0.16	0.01	—	3
84999	09 50 59.36	+59 02 19.4	-294.44	-151.75	F2IV	3.80	3.14	3.02	2.99	2.97	2.93	1
85444	09 51 28.69	-14 50 47.8	18.68	-21.88	G7III	4.12	2.61	2.12	2.04	—	—	1
87901	10 08 22.31	+11 58 01.9	-249.40	4.91	B7V	1.35	1.57	1.58	1.61	1.61	—	3

(Table 1 continued on following pages)

Table 1. The AAVSO near-IR primary standards, continued.

HD	RA (2000)	Dec	pmra mas/yr	pmdec mas/yr	Sp.Cl.	V	J	H	K	L	L'	note
89484	10 19 58.43	+19 50 28.5	294.9	-154.0	K1III	2.61	0.10	-0.50	-0.58	-0.75	—	3
89758	10 22 19.74	+41 29 58.3	-80.47	34.10	M0III	3.05	0.12	-0.68	-0.82	-0.94	-1.00	1
102647	11 49 03.58	+14 34 19.4	-499.02	-113.78	A3V	2.14	2.02	1.99	1.98	—	—	1
103095	11 52 58.77	+37 43 07.2	4003.69	-5814.64	G8Vp	6.45	4.87	4.46	4.38	4.34	—	2
107259	12 19 54.36	-00 40 00.5	-59.14	-23.13	A2IV	3.89	3.79	3.78	3.77	3.77	3.77	1
113415	13 03 46.12	-20 35 00.6	142.13	5.14	F7V	5.58	4.60	4.28	4.26	—	—	1
114710	13 11 52.39	+27 52 41.5	-801.95	882.68	G0V	4.26	3.19	2.92	2.88	2.87	2.87	1
121370	13 54 41.08	+18 23 51.8	-60.95	-358.10	G0IV	2.68	1.71	1.41	1.37	1.33	—	3
124897	14 15 39.67	+19 10 56.7	-1093.43	-1999.43	K1III	-0.04	-2.21	-2.90	-2.99	-3.10	-3.08	1
128167	14 34 40.82	+29 44 42.5	188.32	132.72	F2V	4.46	3.70	3.51	3.49	3.47	3.47	1
135742	15 17 00.41	-09 22 58.5	-96.39	-20.76	B8V	2.61	2.76	2.79	2.80	2.84	2.85	1
147165	16 21 11.32	-25 35 34.1	-10.03	-18.03	B2III	2.89	2.49	2.44	2.42	2.42	2.41	1
147394	16 19 44.44	+46 18 48.1	-13.15	39.31	B5IV	3.89	4.20	4.27	4.30	—	4.35	1
148513	16 28 33.98	+00 39 54.0	6.97	-67.95	K4IIIp	5.39	2.83	2.16	2.02	1.87	—	1
148786	16 31 08.37	-16 36 45.8	-44.57	-38.04	G8III	4.28	2.76	2.32	2.26	2.18	2.20	1
156014	17 14 38.88	+14 23 25.0	-7.0	31.0	M5Ib	3.48	-2.29	-3.14	-3.37	-3.71	-3.70	1
161096	17 43 28.35	+04 34 02.3	-40.67	158.80	K2III	2.77	0.90	0.40	0.21	0.15	—	1
164136	17 58 30.15	+30 11 21.4	-0.48	3.23	F2II	4.41	3.46	3.25	3.21	3.15	3.17	1
172167	18 36 56.34	+38 47 01.3	201.03	287.47	A0V	0.03	0.00	0.00	0.00	0.00	0.00	1
175190	18 55 07.14	-22 40 16.8	110.34	-30.79	K3II	4.99	2.73	2.10	2.02	1.91	—	1
186791	19 46 15.58	+10 36 47.7	15.72	-3.08	K3II	2.72	0.32	-0.38	-0.55	—	—	1
188947	19 56 18.37	+35 05 00.3	-34.00	-27.60	K0III	3.89	2.16	1.70	1.63	1.52	1.54	1

(Table 1 continued on following page)

Table 1. The AAVSO near-IR primary standards, continued.

HD	*RA (2000)*	*Dec*	*pmra mas/yr*	*pmdec mas/yr*	*Sp.Cl.*	*V*	*J*	*H*	*K*	*L*	*L'*	*note*
197345	20 41 25.91	+45 16 49.2	1.56	1.55	A2Iae	1.25	0.99	0.91	0.89	0.80	—	3
197989	20 46 12.68	+33 58 12.9	356.17	330.28	K0III	2.50	0.73	0.19	0.10	0.02	—	3
202850	21 17 24.95	+39 23 40.9	0.43	-3.61	B9I	4.23	3.87	3.83	3.80	3.73	3.72	1
203387	21 22 14.80	-16 50 04.4	30.83	5.26	G8III	4.28	2.84	2.38	2.24	—	2.18	1
212593	22 24 30.99	+49 28 35.0	-5.12	-3.37	B9I	4.57	4.30	4.27	4.25	4.23	4.22	1
212943	22 27 51.52	+04 41 44.4	77.29	-307.35	K0III	4.79	2.93	2.37	2.30	2.22	2.21	1
216956	22 57 39.05	-29 37 20.1	329.22	-164.21	A3V	1.16	1.04	1.03	1.00	1.00	0.96	1
217906	23 03 46.46	+28 04 58.0	187.76	137.61	M2II	2.42	-1.19	-2.05	-2.22	-2.39	-2.38	1
218045	23 04 45.65	+15 12 19.0	61.10	-42.56	B9V	2.49	2.52	2.52	2.52	2.50	—	3

1 UKIRT bright standard http://www.jach.hawaii.edu/JACpublic/UKIRT/astronomy/calib/bright_stds.html
2 Elias, et al., *1982* Astron. J., ***87****, 1029*
3 Vrba, Joyce, and Strom 1981, private communication

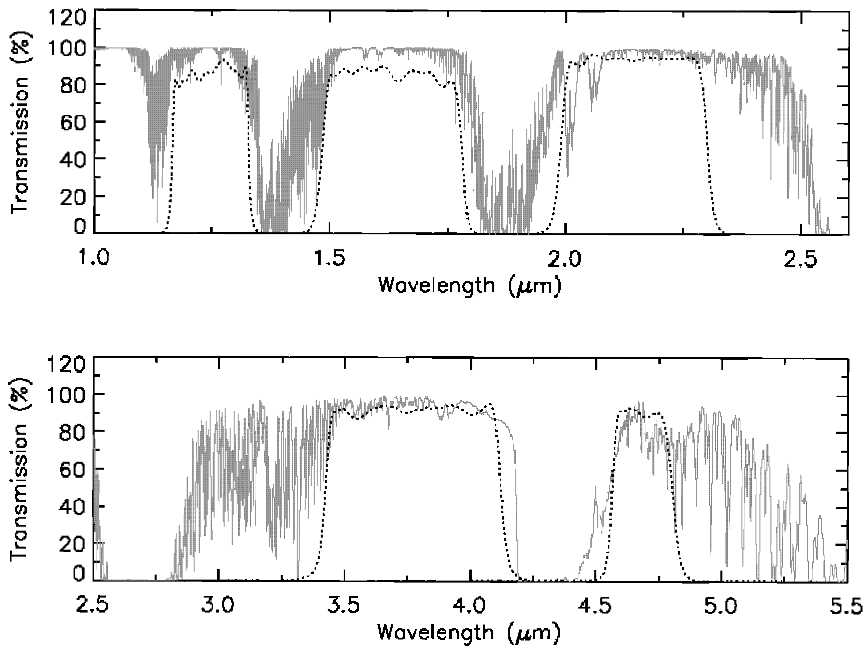

Figure 1. Atmospheric transmission from 1000 to 5500nm. Solid line is atmospheric transmission; dotted line is the filter response curves for the MKO filter system. From Tokunaga *et al.* (2002). *Copyright 2002, The Astronomical Society of the Pacific, reproduced with permission.*

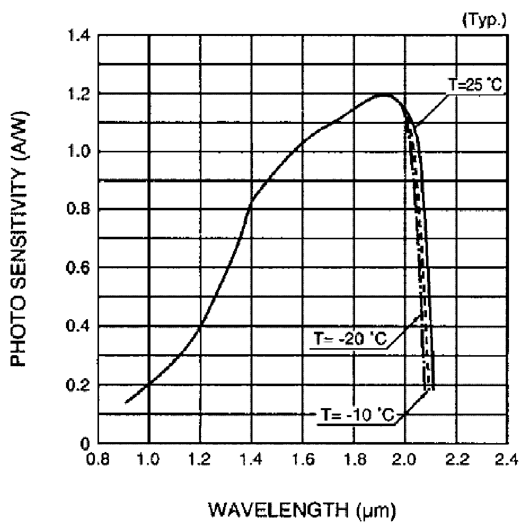

Figure 2. Spectral response curve for the Hammamatsu G5852 InGaAs PIN photodiode. *Courtesy Hammamatsu Corporation.*

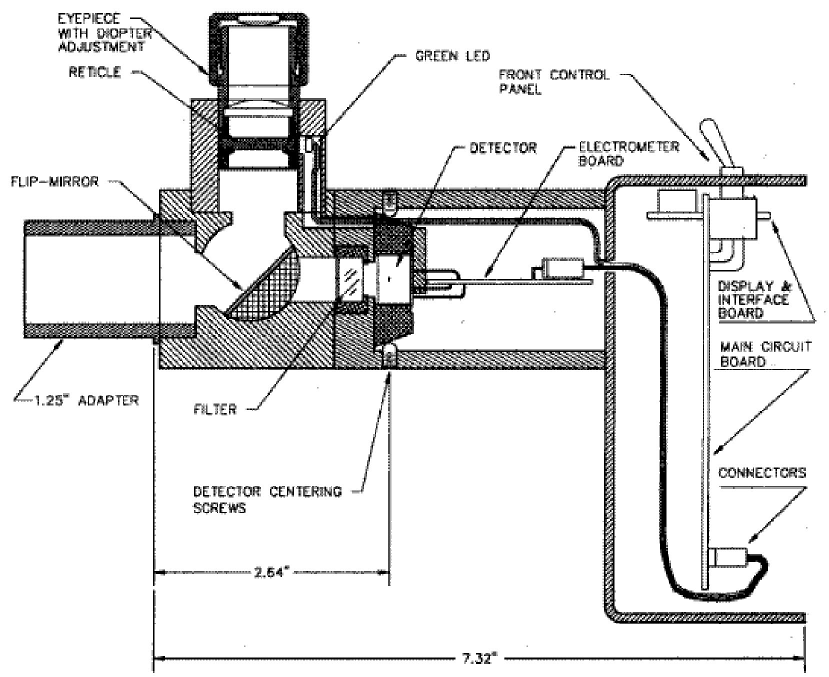

Figure 3. Cross-sectional view of the SSP-4. *Courtesy of Optec Corp.*

Figure 4. SSP-4 Solid-State Infrared Photometer shown with TCF-S Focuser. *Courtesy of Optec Corp.*