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An Absolute Calibration of DENIS (Deep Near Infrared Southern Sky Survey)

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Abstract. An absolute calibration of the DENIS photometric system is presented. It includes the determination of the overall transmission profiles in the 3 bands, namely i, J and K_s, combining contributions from atmosphere, telescope mirrors, instrument lenses and dichroics, filters, and detectors. From these normalized profiles, isophotal and effective wavelengths are computed, using the same synthetic Vega spectrum as that used to support the absolute calibration of many other ground-based and spaceborne photometric systems. Flux densities at zero magnitude are derived, and integrated to give in-band fluxes, which are used to compute theoretical zero-points and compare them to observed ones, yielding estimates of the overall throughput of the whole system.

Key words: Surveys – Infrared: general – Instrumentation: miscellaneous

1. Introduction

The main goal of the DENIS survey (Deep Near-Infrared Southern Sky Survey, see Epchtein et al. 1994 for a complete introduction to DENIS) is to bridge the gap between the optical surveys on Schmidt plates and the far-infrared IRAS survey. Many aspects of astrophysics will benefit from such a survey, particularly studies of cool stars and heavily obscured regions.

Each night, roughly 1 million stars are detected by at least one of the 3 cameras of the DENIS instrument. Photometric calibration is derived by observation of standard star fields. In order to compare our magnitude system to published ones, we need a precise definition of our photometric bands and an absolute calibration of the DENIS photometric system.

In Section 2, we describe the DENIS instrument and show the response curve for the complete system in the three bands. In Section 3, we estimate the conversion factors (ADUs to electrons) from the typical characteristics of DENIS images. Absolute calibration, based upon a synthetic Vega spectrum, is performed in Section 4, and observed and theoretical zero-points are compared.

2. Instrument characteristics

The DENIS instrument has been described in detail by Copet et al. (1999). A sketch of its main optical components is displayed in Fig. 1. It is located at the Cassegrain focus of the ESO 1m telescope at La Silla Observatory (Chile). After reflection from the two telescope mirrors, the light beam goes through a field lens at the telescope focus, covered

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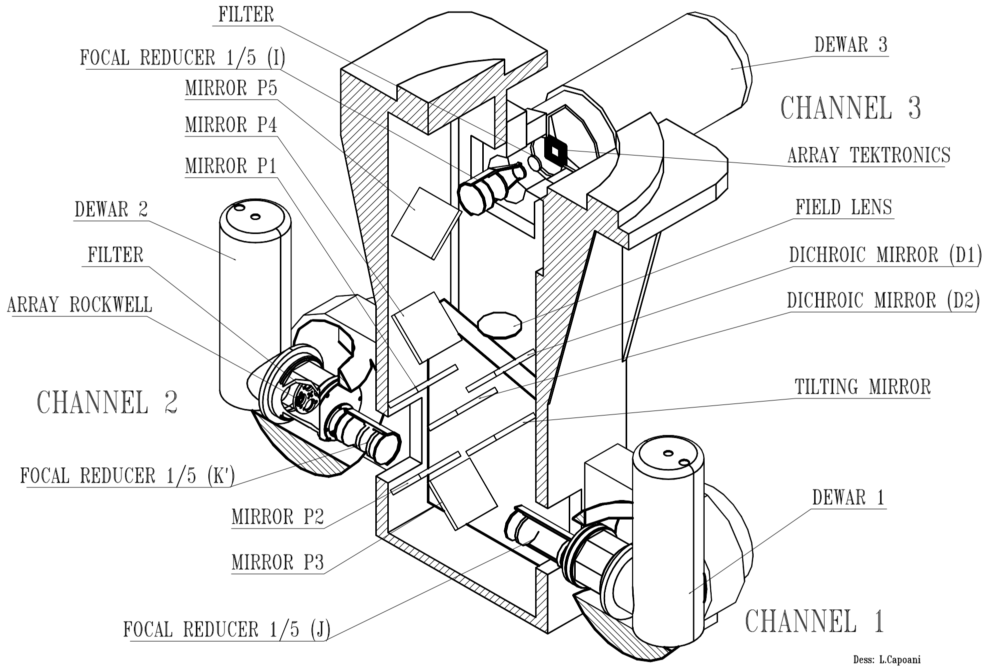

Fig. 1. Optics of the DENIS instrument

by a protective blade, both of CaF_2 and uncoated. Then a dichroic splits the i beam in reflection from the J/K_s beam in transmission.

The i beam has two more reflections from coated mirrors before entering the objective (3 CaF_2 and 2 silica coated lenses), then goes through the Gunn i filter, a shutter, the cryostat entrance window (BK7) and arrives at the Tektronix 1K CCD detector, cooled to 180 K.

The J/K_s beam is reflected off a microscanning mirror (uncoated Al), then J is reflected by a second dichroic and a coated mirror before entering the J objective (3 CaF_2 and 2 fused silica coated lenses), then the cryostat entrance window (coated fused silica), the filter and finally the NICMOS-3 detector, both cooled to 80 K.

The K_s beam is transmitted by the second dichroic, then reflects off two more coated mirrors, passes through the K_s objective (4 ZnS-Cleartran and 1 fused silica coated lenses), the cryostat entrance window (coated fused silica), the filter and the other NICMOS-3 detector.

We have tried to obtain response curves for all these elements. When this was not possible, a reasonable estimate of the transmission was adopted. Filter response curves as provided by Barr Associates (USA) for J and K_s, at the nominal detector temperature (77 K), and by MTO-France for the Gunn i filter (at ambient temperature) are displayed

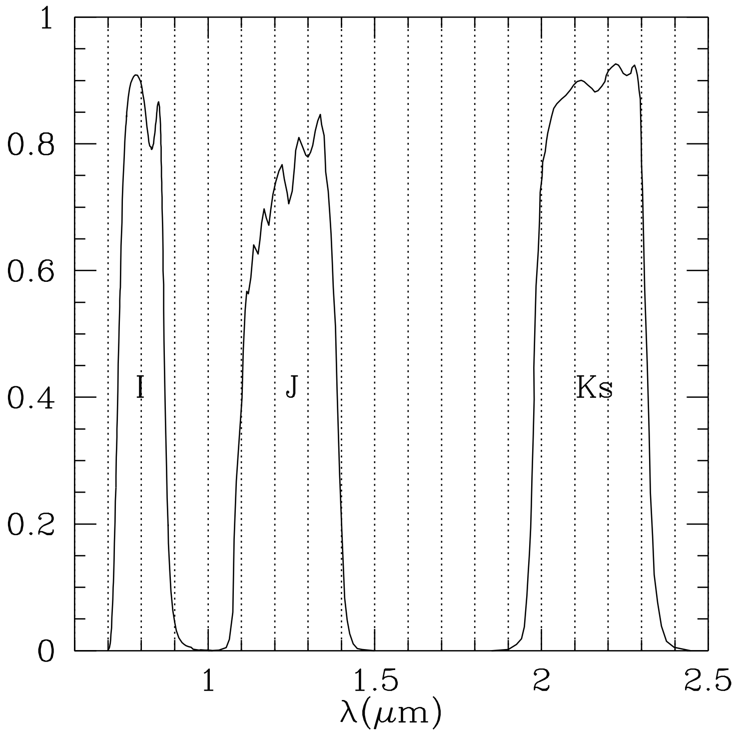

Fig. 2. The 3 DENIS filter response curves

in Fig. 2. The full system response curves (atmosphere, optics, filter and detector) are shown in Fig. 3.

3. Characteristics of DENIS images and conversion factors

The first characteristics generally measured on astronomical images are the "sky emission" level (which includes telescope and instrument background in the K_s band), and the noise on sky images and darks.

Variations in sky level are observed in all three bands. In i, they are related to the distance to, and phase of, the Moon. In J, they are due to variations in the hydroxyl radical's emission intensity (OH^- Meinel bands), connected to the passage of density and temperature perturbations through the upper atmosphere (Ramsay et al., 1992). And in K_s, they come from the temperature variations. Also note that, in crowded fields, the background value is set by the confusion level (background of faint undistinguishable stars).

From these variations, the conversion factor between ADU (analog-to-digital units) and electrons can be deduced. Table 1 compares the result of these gain measurements with the expected values, calculated from the electronics characteristics of the chips, the preamplifiers gains, and the analog-to-digital conversions. Table 2 gives for each band the median value of the read-out noise in electrons, the median and faintest values of

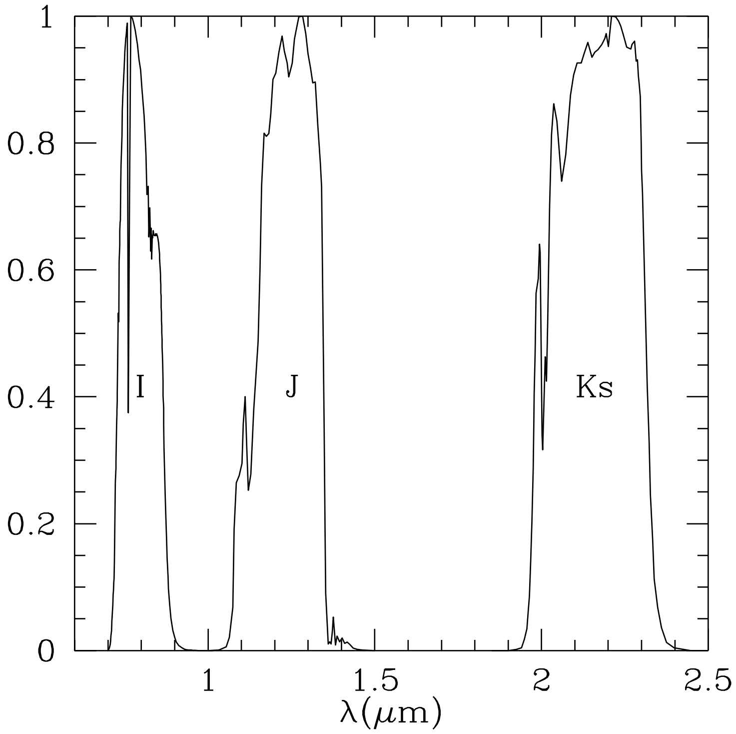

Fig. 3. The complete DENIS system normalized response curves (atmosphere, optics, filters, detectors)

the sky level, in mag arcsec^{-2}, and the median and minimal values of the sky image noise in electrons, calculated from more than 2000 images taken during the last year of observations (April 1998 to April 1999), and adopting zero-points of 23.5, 21.3, and 19.2 in i, J, and K_s, respectively (see Section 4 and Table 5). The large values of sky and sky noise in K_s come from the thermal background of the instrument, which does not include cool stop optics. The "best" value of the sky level in J is suspect.

Note that some care must be taken in applying the conversion factors and zero-points to the whole DENIS survey: first, J and K_s conversion factors seem to be slightly variable (11.4 to 15.3 in J, 51.6 to 57.0 in K_s), and second, changes in the instrument have altered these values: the pre-amplifier boards of J and K_s cameras were changed in June 1996, and a spare J camera has been in use from April 3, 1998 to May 9, 1999. Old conversion factors valid until June 1996 were 12.47 in J and 39.3 in K_s (Chevallier, 1996). Zero-point variations will be analyzed in a future paper.

4. Absolute calibration

The next interesting characteristics to establish for absolute photometric work is the flux of a zero magnitude star in the three DENIS bands. Many infrared systems and several ways to calibrate them exist. We have decided to use the calibration scheme described

Table 1. Conversion factors (expected and measured, in e$^-$/ADU) in the three bands

Gain	i	J	K_s
Expected	3.08	18.4	58.6
Measured	3.04	11.4	56.2
Std dev	0.01	0.1	0.1

Table 2. Read-out noise, sky level, and sky image noise in the three bands

Band	RON	SKY		SKY noise	
		median	best	median	min
	e$^-$	mag arcsec^{-2}	mag arcsec^{-2}	e$^-$	e$^-$
i	7.3	19.2	20.2	15	11
J	21	16.6	18.1?	37	27
K_s	40	11.2	12.0	311	222

by Cohen et al. (1992): they start from a model of Vega from Kurucz (1991), taking into account its lower than solar metallicity, and normalize it to $F_{5556} = 3.44\ 10^{-8}$ W m$^{-2}\mu$m^{-1} from Hayes (1985). Additionally, we adopt V = 0.03 mag, V-I = 0, so I = 0.03 mag, but JHKLM = 0.00 mag for this star. For a more detailed discussion of Vega magnitudes and colours, see Bessell et al. (1998).

Now, we have to determine the isophotal wavelength of each filter, taking into account the filter response curve, the atmospheric transmission, the detector radiance response and the Vega spectrum. Isophotal wavelengths are preferred over effective wavelengths, because the latter vary with input source spectrum much more than do the former (see Golay, 1974, for details and definitions). Results are given in Table 3.

Using the isophotal wavelengths of our bands, and the Vega spectrum, we can compute the flux densities for a zero magnitude star. Table 4 gives the results in wavelength and frequency units.

From these flux densities, we can estimate how many ADUs would be measured if the atmosphere, telescope and instrument totally transmitted the photons from this zero magnitude star. Comparing to the actually observed zero-point will give the overall transmission of the system. We first integrate the product of the Vega spectrum (shifted by 0.03 mag in i) by the transmission of the full system (fad), over the wavelength

Table 3. Mean filter wavelengths (pure filter, and filter + atmosphere + detector, hereafter "fad"), effective and isophotal wavelengths for Vega

Wavelength (μm)	i	J	K_s
$\lambda_{\rm fil}$	0.802	1.248	2.152
$\lambda_{\rm fad}$	0.795	1.235	2.160
$\lambda_{\rm eff}$	0.788	1.221	2.144
$\lambda_{\rm iso}$	0.791	1.228	2.145

Table 4. Flux densities of a zero magnitude star for the three DENIS bands

Band	$\lambda_{\rm iso}$	F_λ	F_ν
	μm	W/m^2/μm	Jy
i	0.791	$1.20\,10^{-8}$	2499
J	1.228	$3.17\,10^{-9}$	1595
K_s	2.145	$4.34\,10^{-10}$	665

domain of our filters (λ_0 and λ_1 correspond to the first and last wavelengths where filter transmission reaches 0), to obtain the measured flux of a zero magnitude star:

$$F_{\rm t} = \int_{\lambda_0}^{\lambda_1} S(\lambda)\ \frac{F_\lambda(\rm Vega)}{h\nu}\ d\lambda. \tag{1}$$

The theoretical zero-point is given by:

$$ZP_{\rm th} = 2.5\ \log\left(F_{\rm t} \times A\,t/G\right), \tag{2}$$

where A is the unobscured telescope collecting area (0.68 m^2), t is the effective integration time (8.998 sec in i, 8.809 sec in J and K_s), and G is the conversion factor. Table 5 gives the results.

Zero-points are measured during calibration nights, where only photometric standards are observed, and routinely during survey nights, to follow possible instrumental variations and make a rough estimate of the extinction coefficients. They are measured from aperture magnitudes inside a 7 arcsec diameter circle around the standard star. To make a valid comparison with the theoretical zero-points, a first correction is necessary to include flux falling outside this aperture. This has been estimated to amount to 0.1 mag in all three bands from a comparison of observations through a 15 arcsec diameter aperture.

Table 5. Theoretical and observed zero-points. Derived overall transmission and its components (τ, ρ and QE correspond to transmission, reflection and quantum efficiency, respectively)

Parameter	i	J	K_s
Theoretical zero-point	25.10	23.29	20.43
Observed zero-point (7")	23.4	21.1	19.1
Corrected zero-point	23.5	21.3	19.2
Measured overall transmission	0.24	0.16	0.32
$\tau_{\text{atmosphere}}$	0.955	0.912	0.912
τ_{mirrors}	0.868^2	0.964^3	0.978^3
$\tau_{\text{blade, field lens}}$	0.938^2	0.939^2	0.940^2
$\tau_{\text{dichroics}}$		0.784	0.810×0.870
$\rho_{\text{dichroics}}$	0.993	0.970	
$\tau_{\text{coated mirrors}}$	0.993^2	0.970	0.97^2
$\tau_{\text{objective}}$	$0.979^3 \times 0.982^2$	$0.979^3 \times 0.985^2$	0.70×0.982
$\tau_{\text{cryostat window}}$	0.94	0.985	0.982
τ_{filter}	0.909	0.846	0.926
$\text{QE}_{\text{detector}}$	0.65	0.8	0.8
Resulting overall transmission	0.31	0.32	0.25

A linear fit of the observed magnitudes vs. airmass (assuming that Bouguer's (1729) law is valid) gives the extinction coefficient as the slope and the zero-point as the intercept. However, it is well known that extrapolation to zero airmass leads to a systematic error in the near-infrared (the Forbes (1842) effect), which has been quantified for the J and K bands by Manduca & Bell (1979). For the La Silla typical water vapour contents (1 to 10 mm of precipitable water), the error is about 0.10 mag in J and 0.02 mag in K, and should be similar in K_s. Therefore, we also add this J correction to the observed zero-point, while we neglect the K correction, given the uncertainty in measured zero-points. The corrected zero-points (for infinite aperture and non-linear variation with airmass) are given in Table 5, and the derived overall transmissions follow.

To interpret the measured overall transmission, we have tried to estimate the contribution of each component of the system, namely atmosphere, aluminium reflections (telescope mirrors, and microscanning mirror for J and K_s), thin blade protecting the field lens, field lens itself, dichroics, coated mirrors, objectives, cryostat entrance windows, filters, and detector quantum efficiency (converted to radiance response). For details about each value, see Galliano (1999). Table 5 gives all these estimates, and their final product. The agreement with the measured overall transmission is satisfying, and shows a good performance of the instrument, with overall throughput of 20 to 30% in all three bands.

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