Photometry with Infrared Arrays

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Abstract

Infrared arrays have been in use at a number of observatories for several years. They are more complicated in their construction than optical ones and more problems arise in obtaining good photometry from them. The types of arrays currently available are described together with the observational techniques and the problems encountered in obtaining accurate photometric results.

1. The available arrays

Most infrared arrays used in astronomy are 'hybrids', *i.e.* they are made like a sandwich whose bottom layer is a silicon read-out multiplexer chip and whose upper layer is an array of infrared detectors. The layers are contacted together, pixel by pixel, by microscopic pillars of indium which form cold welds under pressure. Unlike optical arrays, the infrared ones are not usually read out by CCDs, but the charge is accumulated in the self-capacitance of each photodiode and read out by a network of switches in the silicon.

There are three types of detector material in use in astronomical arrays at present. The most popular is HgCdTe, whose proportions can be tailored to make band gaps corresponding to a large range in cut-off wavelength. The well-known NICMOS arrays, developed for an infrared camera to be carried by the Hubble Space Telescope, have a cutoff at about 2.5μm, while the 64 × 64 pixel Philips' arrays used by ESO and SAAO cut off at 4.1μm so that they can cover the JHKL$'$ bands (1.25 to 3.8μm effective wavelength).

Somewhat less tractable as a detector material is InSb. Arrays of 58×62 elements, manufactured by SBRC, were until recently the most popular sensors in infrared cameras but have been overtaken by the NICMOS chips. InSb has a fixed cut-off wavelength at about 5.5μm. Sensitivity at L$'$ (3.8μm) and M (4.8μm) is highly desirable for locating objects with cool shells by means of their high K-L$'$ or L$'$-M colours, especially in galactic plane fields which are crowded at K.

PtSi is a technology which is much more reliable than either of the two compounds already mentioned. Most chips manufactured to date are monolithic, *i.e.* the PtSi is formed by implanting Pt on a Si chip and the whole process is thus much simpler. However, a 256 × 256 sandwich-type PtSi chip has been used with considerable success at KPNO and CTIO (Fowler *et al.*, 1989). Unfortunately, the quantum efficiency of PtSi detectors is at most a few percent, tailing off at a little beyond 5μm. This problem is to some extent offset by the very large formats in which they can be constructed — detectors of 512 × 512 have been used in Japan and others of 1024 × 1024 are being developed.

Table 1 Some currently available infrared arrays suitable for astronomy:

Manufacturer	Rockwell	SBRC	Mitsubishi	Hughes
Material	HgCdTe	InSb	PtSi	PtSi
Format (pixels)	256 × 256	256 × 256	512 × 512	256 × 256
Pixel size (μm)	40 × 40	30 × 30	20 × 26	30 × 30
Eff. fill factor	100%	~100%	71%	~100%
Operating temp.	60-77K	40K	57-60K	40-60K
Dark current	$< 5e^-/s$	$< 10e^-/s$	$< 1e^-/s$	$< 10e^-/s$
Read noise	$< 60e^{-*}$	$< 60e^-$	$< 30e^-$	$< 60e^-$
Well capacity	$2.5 \times 10^5 e^-$	$6 \times 10^5 e^-$	$2 \times 10^6 e^-$	$6 \times 10^5 e^-$?
Quant. efficiency	>50%	>80%	3% to 6%	3% to 6%
Defective pixels	<2%	<1%	<0.01%	<0.5%
"Entry" price	$90,000	$180,000	Y10M (in camera)	$30,000

* $27e^-$ using multiple non-destructive read-outs (Hodapp *et al.*, 1992)

2. Problems in the arrays themselves

Bad pixels

As can be seen from the tables, it is not unusual to find that about 1% of the pixels in an array are faulty — they may be of low sensitivity, noisy, dead or have high dark current. This problem may be overcome by multiple exposures with the array displaced by one pixel at a time and subsequent re-alignment before median averaging during image processing (see Fig. 1). At the very least, three exposures are necessary. Davidge (1992) reports using nine exposures per field in an attempt to obtain high accuracy observations of the globular cluster NGC 4147.

Quantum efficiency variations

Most array detectors need some form of flat fielding to reduce the pixel-to-pixel variations in sensitivity. For example, Hodapp *et al.* (1992) report that a 256 sq NICMOS3 array in use at the University of Hawaii has average q.e. of 32% at J, 41% at H and 45% at K with a factor of 1.6 variation from the worst to the best area of the array. The quantum efficiency and its variations are found to be highly temperature sensitive, necessitating careful thermostating.

Read noise

The read noise of the hybrid arrays (see table) is usually quite high compared with optical CCDs (the latter have typically 3-10e^-), although it is small compared to the fluctuations in the background photons from the sky in broadband exposures. However, for low-background work such as spectroscopy, read noise is often excessive and it is usual to resort to multiple non-destructive read-outs. Several authors have found that read noise can be reduced by up to a factor of ~4 in this way (Persson *et al.* (1992), Hodapp *et al.* (1992).

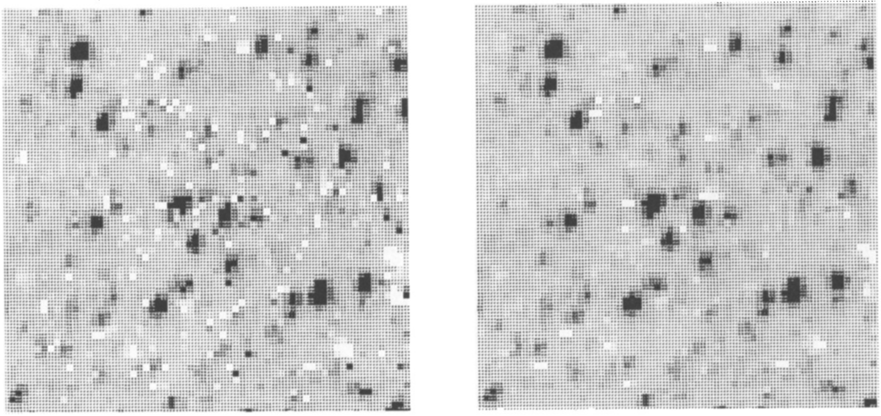

Figure 1 Eliminating bad pixels by median averaging: the left frame is one of three (the other two of which were exposed with offsets of one and two pixels respectively) median averaged to make the right frame, after image processing to remove the offsets. The isolated bad pixels have been removed but extended areas of bad pixels remain in part. This exposure is a K image of the field of the X-ray source 1E 1740.7 -2942 and it covers about 64 × 64 arcsec. Each of the three images is formed from four on-source exposures and four sky exposures of one minute.

Non-linearity

Non-linearity in direct read-out arrays arises from the use of the photodiodes as integrating capacitors. Unfortunately, the capacitance of a solid-state diode changes with voltage so that, as charge accumulates, the developed voltage (the measured quantity) is not strictly proportional to photon flux. A deviation of 4% has been reported for the SBRC 58 × 62 InSb array by Guarnieri *et al.* (1991) and about 1% at 2/3 full well for a NICMOS3 array by Hodapp *et al.* (1992). Persson *et al.* (1992) mention a non-linearity of 5% for a NICMOS2 (128 × 128) array. Such non-linearities must be corrected before any other processing of the array data can be undertaken.

Thresholds and charge-transfer problems

Threshold problems, *i.e.* a reluctance to transfer charges properly, particularly at low light levels, were a common defect in early optical CCDs and had to be overcome by such techniques as pre-flashing. Although this is not usually a problem with direct read-out arrays, it seriously affects the operation of the HgCdTe Philips' arrays at J,H & K. These arrays are unusual in that they have a CCD readout layer. By ensuring that exposures are always sufficiently long that the background level acts as a 'pre-flash', these effects can be overcome partially. However, difficulties remain with flat-fielding in the neighbourhood of 'hot' pixels (*i.e.* those with very high dark current) due to their 'tails' which tend to be background-dependent. The duration of a single exposure is limited by the fact that more pixels become saturated by dark current as the exposure time increases.

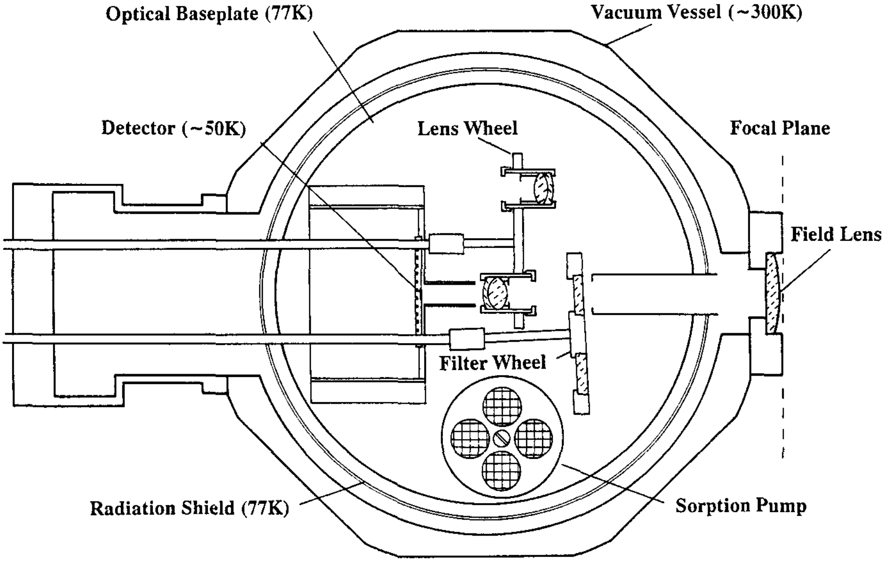

Figure 2 Layout of the cold part of the SAAO infrared camera. The entrance of the baffle forms a cold field stop and the pupil stop is a cold aperture close to the relay lens. The detector is a Philips' 64 ×64 HgCdTe array with a cut-off wavelength of 4.1μm.

Well capacity

Especially when observing at wavelengths beyond 2.5μm, the background from grey- or black-body radiation from the telescope becomes overwhelming except for a cooled instrument in space. The limited well capacity of arrays restricts exposure times in most situations to a small fraction of a second. In order to obtain long effective exposure times, an array must be read out many times and the frames co-added. Even the Philips' array at SAAO, although it has an exceptionally high well capacity of 10^7e^-, can integrate for only about 1s if used at L' (3.8μm) and 1 arcsec^2 per pixel. Other arrays are much more limited. An extreme example is the 10μm camera described by Gezari *et al.* (1992), based on a 58 x 62 SBRC Ga:Si hybrid chip with 0.25 arcsec square pixels, which requires to be read out 30 times per second and the frames co-added. This requires high-speed electronics and data processing. Larger format arrays for long wavelengths rapidly become impractical.

Residual Excess Dark Current

Hodapp *et al.* (1992) report an excess dark current which follows the detected pattern of a previous strong exposure. Although its effects are negligible after a few complete reads of the device for normal background-limited exposures, it can remain a nuisance for up to an hour for exposures with low backgrounds.

3. External Problems

Extraneous Background

Needless to say, every effort must be made to reduce the extraneous radiation falling on the detector. This is done by cooling the detectors and their surroundings as well as the filters (to reduce their emission out-of-band) and by the use of cold field and pupil stops. Fig. 2 shows the design of the camera used at SAAO.

Undersampling of stellar images

The small size of arrays tempts the observer to use a scale which maximizes the sky coverage but which leads to undersampling. This is particularly serious when there is dead space between pixels or uneven sensitivity within pixels such as in the Philips' and many single-layer arrays. The problem can be reduced by multiple exposures with shifted images and by fitting the stellar profiles with models tailored to the characteristics of the array in question. Uneven response within individual pixels has been found in a NICMOS2 array (Allen, private communication).

Flat fielding methods

Ideally, a flat field should be an object in space with colour similar to the objects being measured. In practice, the methods used are to compare the sky with the interior of the dome, to observe a white sheet illuminated by incandescent light, to observe a card similarly illuminated at the top of the Cassegrain baffle and to use the median average of long sky exposures. At L′, a sky exposure can be subtracted from the interior of the dome! Although some of the more stable infrared arrays can be used in almost the same manner as optical CCDs, *i.e.* without frequent observation of background frames, the more usual procedure seems to be to 'chop', *i.e.* to observe blank areas of sky. Because of the threshold problem of the Philips' chip, at SAAO we observe at K by making one exposure on the object followed by two on the sky, two more on the object and so on as necessary in ABBA pattern. The duration of the individual exposures is kept constant at 30s. At L′, we take typically 40 0.6s exposures for each of the As and Bs and co-add the data before recording.

Standard Stars

Most infrared standard star lists contain objects far too bright for array exposures of reasonable length, *i.e.* comparable to those used for observation of programme objects. Some observers report de-focussing the telescope to reduce the flux per pixel. To solve this problem, Brian Carter of SAAO has been observing about 64 stars of around 8th mag at JHK in collaboration with the IRIS group at AAO and others at Mt Stromlo. The programme comprises 64 stars scattered widely around the southern sky. So far, 54 have been observed to the necessary accuracy (~.03 mag). Each programme star is referred to a nearby star from Carter (1990).

Sky background and special filters

Sky backgrounds of J=15.9, H=14.0 and K=11.8 mag/arcsec^2 have been reported by Persson *et al.* (1992). The H-band flux (mainly due to airglow) varies by almost a factor of two from night to night. In order to achieve higher sensitivities at K, Wainscoat & Cowie(1992) advocate the use of a K′ filter which has shorter cut-on and cut-off wavelengths than the standard K band, by about 0.1μm. This reduces the contribution from the thermal radiation of the telescope and atmosphere, at the expense of introducing a new broad-band colour. However, the ability to make measurements on a standard system should not be abandoned lightly, as experience with differing J filters has shown in single-detector photometry.

Photometric Performance

With great care, including proper attention to the quality of the standard stars and the transformations between photometric systems, it appears that photometry of stars bright enough to be well above the background is possible at about the 1% error level (Guarnieri *et al.*,1991; Hodapp *et al.*,1992; Persson *et al.*,1992). Difficulty in obtaining perfect flat fielding, rather than the intrinsic sensitivity of the arrays, seems to be the limiting factor for faint mags.

Acknowledgement

I would like to thank D.A. Allen, J. Elias and A. Moneti for sending me information on various arrays in use at their institutions.

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Discussion

S. C. Russell: *What objection is there to stepping by several pixels in order to eliminate clumps of bad pixels?*

Glass: You could, but clumps of bad pixels occur on several scales, so to do a thorough job you might need to make, say, nine exposures.