The Science Impact of HAWK-I

Ralf Siebenmorgen[1]
Giovanni Carraro[1]
Elena Valenti[1]
Monika Petr-Gotzens[1]
Gabriel Brammer[1]
Enrique Garcia[1]
Mark Casali[1]

[1] ESO

HAWK-I is ESO's most efficient near-infrared camera, and after two and a half years of operations we review its science return and give some future directions in the context of the Adaptive Optics Facility. The instrument underwent major technical challenges in the early phase of its operations: there was a problem with the entrance window, which was replaced, and radioactive events occur in the material of two of the four detectors. A number of high quality science papers based on HAWK-I data have been published, indicating a good performance and scientific return. HAWK-I is well-suited for a variety of attractive science cases and a project is in development to provide a faster readout, which would improve the capabilities for Galactic observations. When combined with the laser-assisted ground layer adaptive optics system, HAWK-I will become an excellent facility for challenging follow-up observations of exoplanetary transits.

Instrument overview and performance

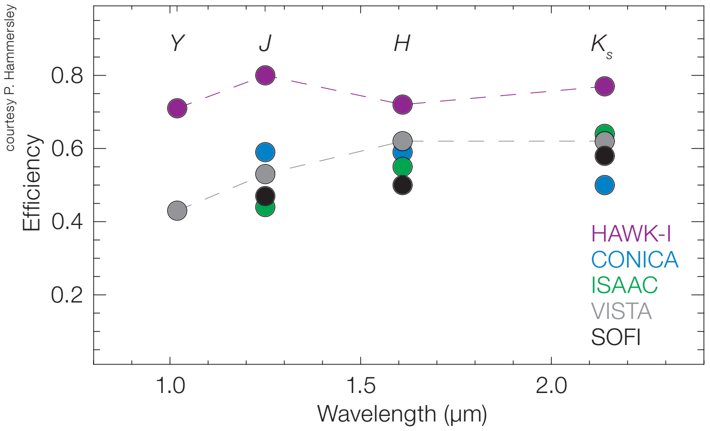
HAWK-I is a cryogenic wide-field camera installed at the Nasmyth A focus of the VLT Unit Telescope 4 (UT4). The field of view is 7.5 by 7.5 arcminutes, with a cross-shaped gap of 15 arcseconds between the four 2RG 2048 × 2048 detectors. The pixel scale is 0.106 arcseconds. The instrument is offered with ten filters in two filter wheels: four broadband filters (Y, J, H and K_s), which are identical to the filters used in VIRCAM/VISTA, and six narrowband filters (Brγ, CH_4, H_2, 1.061 µm, 1.187 µm, and 2.090 µm). The image quality is seeing-limited down to at least 0.4 arcseconds. Typical limiting magnitudes (Vega) to reach a signal-to-noise ratio (S/N) of five on a point source in one-hour on-source integration are: 23.9 in J, 22.5 in H and 22.3 in K_s.

The efficiency, defined as the proportion of photons converted into electrons passing the telescope, instrument optics and detector, is computed for various near-infrared (NIR) instruments and is shown in Figure 1 for the NIR cameras SOFI, VISTA, ISAAC, CONICA and HAWK-I. The efficiency of the HAWK-I instrument is 70–80 % and so it is the most efficient NIR camera in ESO's instrumentation suite. The stability of the zero point is important for absolute photometry. For HAWK-I, there is a small periodic scatter in the zero point of $\Delta J \sim 0.1$ mag over a period of a year, significantly lower than that of either CONICA or ISAAC.

Along with the distortion caused by the instrument optics, atmospheric refraction produces a geometrical shrinkage of the field of view with increasing zenith distance. The differential achromatic refraction is ~ 0.6 arcseconds, as measured over the full 7.5 by 7.5 arcminute field size of HAWK-I and for a zenith distance between 0° and 60°.

During science operations three technical challenges were identified: the entrance window, radioactive events in the detector material and the instrumental distortion correction. The instrument was first installed in July 2007. At the beginning of the observing period P81 in 2008 the instrument suffered from a damaged coating of the entrance window. This defect was fixed by a replacement window installed during an intervention in the summer of 2008. The instrument also suffered from radioactive events which contaminated two of the four chips of the detector mosaic (Finger, 2008). The contamination can be seen in the dark exposures. One of the four detectors shows on average a well-localised decay every 75 s. The event affects an area of 7 × 7 pixels and is eliminated by a cleaning algorithm in the pipeline. Another detector is similarly affected, and, although the events are much less frequent, they generate charge which is not localised to within a few pixels, but spreads in a diffuse charge cloud with an unpredictable location, resulting in glitches that cannot be cleaned during data analysis. However, the sensitivity limit of the individual detectors shows that there is no major degradation of the detection limit caused by these radioactive events.

The HAWK-I instrument team has recently undertaken observations to assess the relative sensitivities of the four HAWK-I detector chips, using observations of the high Galactic latitude field around the $z = 2.7$ quasar B0002-422 (α 00^h 04^m 45^s, δ -41° 56′ 41″) taken during technical time. The observations consisted of four sets of 11 × 300 s sequences in the NB1060 filter; details of such an observational set-up are discussed in the HAWK-I User Manual. The four sequences are rotated by 90° in order that a given position on the sky is observed by each of the four chips of the HAWK-I detector. The jitter sequences are reduced following the standard two-pass background subtraction work flow described in the HAWK-I pipeline manual. Objects



courtesy P. Hammersley

Figure 1. Comparison of the efficiency of the NIR instruments SOFI, VISTA, ISAAC, CONICA and HAWK-I is shown.

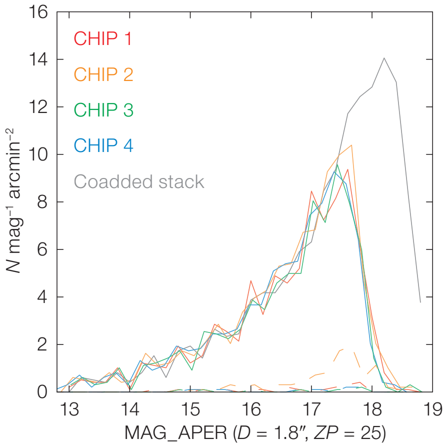


Figure 2. Number counts as a function of aperture magnitude of the four HAWK-I detectors: chip1 (red line), chip2 (orange), chip3 (green), chip4 (blue line) and the co-addition of all four chips (black line). Dashed lines give the number of spurious detections. Radioactive events are most common for chip 2, which nevertheless has a similar detection probability as the other chips, but an enhanced number of spurious detections at faint flux (> 17 mag) levels (shown as dashed orange).

are detected using the SExtractor software. The resulting number counts as a function of aperture magnitude observed by each detector are shown in Figure 2. The limiting magnitudes, here taken to be the magnitude where the number counts in Figure 2 decrease sharply, provide a proxy for the individual detector sensitivities. The sensitivities agree to within 10 % between the individual chips. We also show in Figure 2 the number counts for a deep co-added stacked image of the four rotated and aligned jitter sequences which are a factor of two deeper than the individual sequences. We used the co-added stack to assess the number of spurious sources detected on each individual detector: objects matched from the single chip image to the deeper image are considered to be real, while objects that only appear on the single chip images are considered spurious. The image artefacts on detector 2, which are caused by radioactive events, do result in an elevated number of spurious detections at faint magnitudes, reaching 20 % at the limiting magnitude.

AOF and GRAAL

The Adaptive Optics Facility (AOF; see Lelourn et al., 2010; Paufique et al., 2010 and Arsenault et al., 2010) will provide a correction of the ground layer turbulence, improving the image quality of HAWK-I. The resulting point spread function (PSF) diameter that collects 50 % encircled energy is reduced by 21 % in the K_s-band, and by 11 % in the Y-band, under median seeing conditions at Paranal of 0.0.87 arcseconds at 500 nm. Hence, the AOF will provide better seeing statistics. When installing the AOF on UT4, the secondary mirror of the telescope will be replaced by a deformable secondary mirror (DSM) with more than 1000 actuators. In addition, four laser guide stars will be installed on the telescope structure, and a wavefront sensor system, GRAAL (ground layer adaptive optics assisted by lasers), will be used to measure the turbulence from artificial guide stars. GRAAL will be installed between HAWK-I and the Nasmyth flange. HAWK-I's field of view is not affected by GRAAL. It is planned to begin installing the AOF in 2013, with a total telescope downtime of a few months (subject to the exact distribution of technical time) due to the installation of the new secondary mirror, the lasers and GRAAL. The schedule anticipates that the AOF will be operational from 2015.

Normal adaptive optics systems aim at correcting atmospheric turbulence down to the diffraction limit of the telescope. The price to be paid is a limit in corrected field of view (less than 1 arcminute) and a limit in sky coverage (less than 50 %) since a bright guide star is required even when using laser guide stars. The AOF ground layer adaptive optics mode (GLAO) does not provide diffraction-limited image quality, but it does correct the full 7.5 by 7.5 arcminute field of view and the sky coverage is practically 100 %.

HAWK-I science return

When HAWK-I was conceived, the selected science cases, according to the document, Science Case for 0.9–2.5 μm infrared imaging with the VLT (ESO/STC-323), were:

1. Galaxy evolution from deep multicolour surveys;
2. Multi-wavelength observations of normal and active galaxies;
3. Structure and evolution of nearby galaxies;
4. Galactic star and planetary formation;
5. Outer Solar System bodies.

HAWK-I started to operate regularly in April 2008. A significant number of observations executed during P81 were affected by the damaged entrance window coating, and were re-executed by ESO. In the period from mid-2008 until end of 2010, 26 refereed papers were published containing HAWK-I results. They have 350 citations to date and an h-index of 10. Of these 26 papers, two were published in *Nature*, seven in *ApJ*, four in *ApJ Letters*, one in *AJ*, four in *MNRAS*, and 12 in *A&A*. The two *Nature* papers, Tanvir et al. (2009) and Hayes et al. (2010), resulted in ESO press releases. To evaluate the science impact of HAWK-I, we have compared the number of papers based on data obtained at the other NIR VLT instruments during their first 2.5 years of science operations. The rate of publication turns out to be fairly similar among all the VLT instruments considered (NACO, ISAAC, SINFONI and CRIRES). The science output of HAWK-I up to the end of 2010 can be summarised as follows:

1) In most cases, publications which are based on HAWK-I present results on extragalactic, high redshift astrophysics. The most relevant papers being the characterisation of the galaxy populations around $z \sim 2$ (Galametz et al., 2010; Hayes et al., 2010; and Lidman et al., 2008) and beyond redshift $z \sim 6$ (Vanzella et al., 2010; Fontana et al., 2010; Castellano et al., 2010a,b; and Bouwens et al., 2010). Such a burst of results for extremely high redshift targets was not expected at the time when defining the HAWK-I science cases, while the results at intermediate redshifts were expected from science case #1.
2) The other fields explored so far are Milky Way stellar populations (Brasseur et al., 2010), trans-Neptunian objects (Snodgrass et al., 2010), gamma-ray bursts (D'Avanzo et al., 2010) and quasars (Letawe & Magain, 2010). Stellar

population studies have been hampered by HAWK-I's large minimum detector integration time (DIT), which causes saturation on bright sources and almost completely prevents observations in the Galactic disc.

3) No papers were published in the field of star formation and structure of nearby galaxies (science cases #3 and #4) in the period up to and including 2010, in spite of the fact that several programmes have been queued and successfully executed.
4) Contrary to expectations, HAWK-I was intensively used to study exoplanets, via transit or occultation techniques (Gibson et al., 2010; Anderson et al., 2010; and Gillon et al., 2009), and to conduct supernova search campaigns (Goobar et al., 2009) for spectroscopic follow-up. Transit observations, in particular, are expected to be increasingly important in the nearby future as a windowed readout of the detectors has been implemented.
5) The majority of the observations published require or benefit from the large field of the instrument.

In Figure 3 we give two examples of JHK_s colour-composite maps highlighting the superb image quality of the HAWK-I camera.

ESO/M. Gieles, Acknowledgement: Mischa Schirmer

Figure 3. Three colour (J [1.25 μm], H [1.65 μm] and K_s [2.15 μm]) composite maps obtained with HAWK-I. The upper image shows the nearby galaxy Messier 83, total exposure time was 8.5 hours and field of view 13 arcminutes squared. On the bottom, an image of 6 by 5.2 arcminutes of two stellar clusters in the Carina Nebula is shown, obtained during HAWK-I science verification.

Future directions: HAWK-I + GRAAL

It is anticipated that HAWK-I will be equipped with GRAAL and routinely operate in GLAO mode from 2015 onwards, which will open up new paths for competitive science cases in the coming years. The image quality delivered by HAWK-I + GRAAL is expected to be 20% better in comparison with today. For seeing in the K_s-band of 0.6 arcseconds, the GRAAL-supported instrument is expected to deliver a resolution of 0.5 arcseconds on a regular basis. Given HAWK-I's pixel scale of 0.106 arcseconds, the PSF delivered by HAWK-I + GRAAL will still be Nyquist-sampled, which is particularly important for precise PSF-photometry, astrometry and the analysis of morphological structures on sub-arcsecond spatial scales. Currently, half of the HAWK-I K_s-band images show an image quality (full width at half maximum, FWHM) on point sources larger than 0.6 arcseconds. This arises from the fact that 70% of the HAWK-I observations were executed during DIMM (differential image motion monitor) seeing worse than 0.83 arcseconds. Half of the HAWK-I observations were performed at a median DIMM seeing of almost 1 arcsecond. The poorer than average seeing conditions prevalent during most HAWK-I observations is a result of the demand for good seeing conditions for NACO and SINFONI. Observing with HAWK-I together GRAAL will result in a much better image quality performance. The question arises: what kind of scientific projects will be feasible with HAWK-I + GRAAL that are currently not feasible with HAWK-I, or only under very rare conditions, when the seeing is exceptionally good. We outline three selected science cases of HAWK-I + GRAAL.

1. Cosmological surveys

A deep, wide-field NIR imaging survey complementing the HST/CANDELS cosmological survey is required. CANDELS[1] is the largest single project in the history of the Hubble Space Telescope, with 902 assigned orbits of observing time and obtains images at *J*- and *H*-band over a total field of view of 30 × 30 arcminutes. The survey will be completed in 2014. As the scientific exploitation also relies on multi-colour imaging, HAWK-I + GRAAL is an ideal instrument to complement the survey with very deep K_s- and *Y*-band imaging, as well as with narrowband imaging aimed at searching for very high redshift galaxies. Morphological studies of galaxies at intermediate and high *z* are a particular goal of the project that can be pursued only with a spatial resolution of < 0.5 arcseconds over a wide area. A wide field of view is essential in such a study, since structural properties are analysed on sufficiently large statistical samples. HAWK-I observations in the *Y*-band, complementing the first two CANDELS fields, have already been scheduled.

VISTA does offer the requested wide-field capability, but delivers neither the spatial resolution nor the required sensitivity. In order to reach the same limiting magnitude, VISTA requires an integration time 16 times longer than HAWK-I + GRAAL. However, the NIRCAM[2] instrument onboard JWST will have a field of view almost six times smaller than HAWK-I, but will offer at least a factor 15 in improved sensitivity. JWST is expected to become operational in ~2016.

2. Nearby wide-field imaging

Stellar population studies, both in nearby galaxies and in Galactic fields, currently suffer most from crowding and will benefit from an improved K_s image quality provided by HAWK-I + GRAAL. High spatial resolution coupled with a wide field of view is an important requirement for stellar population studies. A problem of current HAWK-I observations, when targeting crowded stellar populations, is that the relatively large minimum DIT of 1.7 s causes saturation on the brightest sources, which are numerous when observing towards the Galactic disc. The HAWK-I instrument operation team is at present testing a new windowed detector readout scheme that allows very short exposure times on the brightest pixels and, in parallel, long exposures for the remaining field. Such a new detector readout mode in combination with HAWK-I + GRAAL's improved seeing capabilities should lead to an increase of HAWK-I observations in this research field.

3. Exoplanets and transits

HAWK-I has recently proved to be an excellent instrument with which to perform challenging observations of exoplanetary transits. In order to obtain an overall picture of an exoplanet's atmospheric properties, occultation data in many photometric bands are required. With a continuously growing number of newly discovered planets and planetary candidates, there is a high demand for comprehensive follow-up observations by NIR imaging. Crucial requirements for such observations are a wide field of view, allowing for a large number of reference sources for precise relative photometry, and an instrument sensitive enough to collect a sufficient number of photons, typically for a S/N > 1000, in a short time. From space the CoRoT satellite (Moutou et al., 2008) is a mission particularly designed to discover transiting exoplanets. CoRoT has already found several hundred systems with candidate transiting planets. The mission will continue beyond 2015 and will possibly be followed up by PLATO (Roxburgh & Catala, 2006), an ESA project study due to be launched in 2018. Similarly, from the ground, there are robotic search projects ongoing on small telescopes. Instrumentation includes wide-field imaging capabilities covering several degrees in optical bands. The goal is to discover a large sample of candidate planetary transits which will be followed up on larger telescopes by radial velocity studies or NIR imaging. Examples are: WASP (Cameron et al., 2009) which has already detected 16 systems and will continue for several years; or HAT-South, which is the first global network dedicated to search for transiting planets.

The increase in sensitivity of HAWK-I + GRAAL will allow exoplanetary transits to be followed up around stars significantly fainter than those observed at the moment (K_s of 8–11 mag). Therefore a larger volume of planet–host star systems can be probed, so that potential exoplanets detected by CoRoT come within reach of the VLT and hence provide important NIR constraints on the physical nature of the planets. Observations with VISTA will not have the required sensitivity to perform such investigations. Since the large field of view is important for precision photometry, there is no strong advantage in using JWST/NIRCam instead.

References

Anderson, D. R. et al. 2010, A&A, 513, 3
Arsenault, R. et al. 2010, The Messenger, 142, 12
Bakos, G. A. et al. 2011, AAS Meeting 217, 253.02
Bouwens, R. J. et al. 2010, ApJ 725, 1587
Brasseur, C. A. et al. 2010, AJ, 140, 1672
Cameron, A. C. et al. 2009, IAU Symposium, Volume 253, 29
Castellano, M. et al. 2010a, A&A, 511, 20
Castellano, M. et al. 2010b, A&A, 524, 28
Coppin, K. E. K. et al. 2010, MNRAS, 407, L103
D'Avanzo, P. et al. 2010, A&A, 422, 20
Decarli, R. et al. 2009, ApJ, 703, L76
Finger, G. Reports on HAWK-I detectors available at: http://www.eso.org/~gfinger/marseille_08/AS08-AS12-9_H2RG_mosaic_gfi_final.pdf http://www.eso.org/~gfinger/hawaii_1Kx1K/crosstalk_rock/crosstalk.pdf
Fontana, A. et al. 2010, ApJL, i725, 205
Galametz, A. et al. 2010, A&A, 522, 58
Gibson, N. P. et al. 2010, MNRAS, 404, L104
Gillon, M. et al. 2009, A&A, 506, 359
Gogus, E. et al. 2010, ApJ, 718, 331
Goobar, A. et al. 2009, A&A, 507, 71
Greiner, J. et al. 2009, ApJ, 693, 1610
Hayes, M. et al. 2010, Nature, 464, 562
Hayes, M. et al. 2010, A&A, 509, L5
Hickey, S. et al. 2010, MNRAS, 404, 212
Le Louarn, M. et al. 2010, SPIE, 7736, 111
Letawe, G. & Magain, P. 2010, A&A, 515, 84
Lidman, C. et al. 2008, A&A, 489, 981
Mattila, S. et al. 2008, ApJ, 688, L91
McLure, R. J. et al. 2010, MNRAS, 403, 960
Moutou, C. et al. 2008, A&A, 488, L47
Paufique, J. et al. 2010, SPIE, 7736, 57
Roxburgh, I. W. & Catala C. 2006, IAUJD, 17, 32
Snodgrass, C. et al. 2010, A&A, 511, 72
Stanishev, V. et al. 2009, A&A, 507, 61
Tanvir, N. R. et al. 2009, Nature, 461, 1254
Vanzella, L. et al. 2010, ApJL, 730, 35

Links

[1] CANDELS: www.candels.ucolick.org

[2] JWST NIRCam: www.ircamera.as.arizona.edu/nircam