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Time-Domain Instrumentation at ESO

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Abstract. Over the years the European Southern Observatory (ESO) has offered a number of time-domain instruments that enable the user to achieve time resolution as small as milliseconds. They have been used for a wide range of applications, from binary studies with Lunar occultations, characterisation of X-ray binaries and exoplanet transits, to quasar variability. Furthermore, ESO provides a target-of-opportunity (ToO) rapid-response-mode (RRM) channel to trigger quick follow-up observations within as little delay as minutes after a transient has been detected. This talk reviewed the available time-domain observing modes and instruments at ESO, giving priority to FORS2, HAWKI and UltraCam. It described the ToO and RRM, and gave examples of the most common science cases that take advantage of those channels and capabilities.

Keywords. Instrumentation: detectors, instrumentation: photometers, instrumentation: spectrographs, white dwarfs, planetary systems

1. Introduction

A general-purpose astronomical facility like the European Southern Observatory (ESO) must cater to a wide variety of community requirements, even though they sometimes conflict with one another. The need for stability implies permanently mounted instruments, while the finite number of telescope foci forces the instrument building consortia to adopt complex multi-mode designs.

In ESO's early years, time-domain astronomy was perceived in the context of daily, weekly or yearly **monitoring** peogrammes. Typical examples were astrometric variable-star and supernovæ programmes. However, the last decade or two have brought forward science cases to study phenomena that occur on time-scales of seconds and milliseconds (e.g., X-ray binaries, lunar occultations, occultations by asteroids and trans-Neptunean objects) and one-time phenomena that span a limited time so measurements cannot be repeated later to boost the signal-to-noise ratio (e.g., measuring transit timing variations of exoplanets). Prerequisites for those types of observations are high time-resolution and high cadences, which in turn require fast detectors and rapid data transfers. Such instruments and programmes are referred to as **fast**. This talk summarised both the organizational and technical infrastructures that facilitate the **monitoring** and the **fast** programmes.

2. Organizational and Technical Infrastructure

There is a number of channels for carrying out time-domain experiments at ESO. Perhaps the 'classical' programmes **target of opportunity, ToO** are the most widely known ones – they are meant for observing when a target's position and/or times for observing are unknown more than a week before the observation could be made. Types of ToO include:

(1) a rapid response mode (RRM) for quick observations up to 4 hrs after an announced event, and (as of P10) is implemented on FORS2, UVES, X-SHOOTER, SPHERE, HAWK-I, SINFONI and MUSE;

(2) 'hard' ToOs, which are triggered manually and need to be executed on a specific night or within 48 hrs after the trigger;

(3) 'soft' ToOs, which are triggered manually when a delay of more than 48 hrs is acceptable, or can be executed within ±1 d from a given night.

A special class of **monitoring** programme that spans 2–4 periods can be used to follow the photometric, spectroscopic or astrometric behaviour of targets whose characteristics are known in advance. Those programmes are carried out in service mode (SM). P2PP (http://www.eso.org/sci/observing/phase2/P2PP3.html), the Phase 2 Proposal Preparation tool, allows for the definition of sophisticated absolute or relative time constraints. An example might be: "observe the first epoch between 13 and 15.01, the second epoch 5±1 nights after the first, the third 17±3 nights after the second, etc.". Compensation for missed epochs, caused for instance by poor weather, is possible upon approval by the User Support Department.

The typical science cases that take advantage of these observing modes involve variable sources, including supernovæ (e.g., Graur *et al.* 2014) and quasars (e.g., Ivanov *et al.* 2016). Recent years have seen some more unusual applications, such as photometric and astrometric observations of the Galactic Centre source G2 (Plewa *et al.* 2017).

3. 'Fast' Instruments

FORS2 (FOcal Reducer and low dispersion Spectrograph; Appenzeller *et al.* 1998) is one of the most commonly used instruments for ToO and monitoring programmes. It also has 'fast' capabilities – the so-called HIT modes. HIT-Imaging allows high time-resolution imaging with simultaneous integration and detector readout (see Fig. 1, left). The actual time resolution depends on the seeing; for 1 arcsec it is between 2.3 and 560 millisec, depending on the readout speed. As one might expect, HIT-Spectroscopic and HIT-MultiSpec enable fast spectroscopic observations, without and with reference stars, respectively. More information about these modes is available on the FORS2 web pages at http://www.eso.org/sci/facilities/paranal/instruments/fors/. However, owing to low demand they have now been decommissioned. Typical FORS2 'fast' science cases have been related to X-ray sources. An example is the work of Hynes *et al.* (2009), who observed the black-hole candidate Swift J1753.5−0127 with FORS2 and RXTE simultaneously during its 2005 outburst, and found strong correlation between what one would have called noise in either light-curve, thus demonstrating the value of such a campaign. The optical flux variations also appeared to lag behind the X-ray ones.

HAWKI (http://www.eso.org/sci/facilities/paranal/instruments/hawki) is a High-Acuity Wide-field K-band Imager (Pirard *et al.* 2004), and works in the near-IR in the wavelength range 1–2.5 μm. It is equipped with 4 HgCdTe 2k×2k arrays (Fig. 1, right). IR detectors are fast by design because they have to cope with the high thermal background from the sky and from the telescope itself. The slow charge transfer approach adopted for the optical detectors is not acceptable here, because the modern IR cameras on 4- to 8-m-class telescopes saturate in 10–30 sec, and spending nearly the same time on reading out would reduce the observing efficiency. Even so, a typical minimal integration time of 1–2 sec is still too slow for many applications.

Fortunately, there are some relatively simple software changes that allow one to shorten the readout overheads of the near-IR detectors. (i) Windowing down, which shortens the minimum integration times and lowers transfer times; (ii) adopting faster readout modes that read only at the start and end of an integration (RdRstRd) instead of reducing readout noise via multiple non-destructive reads, or 'ramp'; (iii) storing the data in a

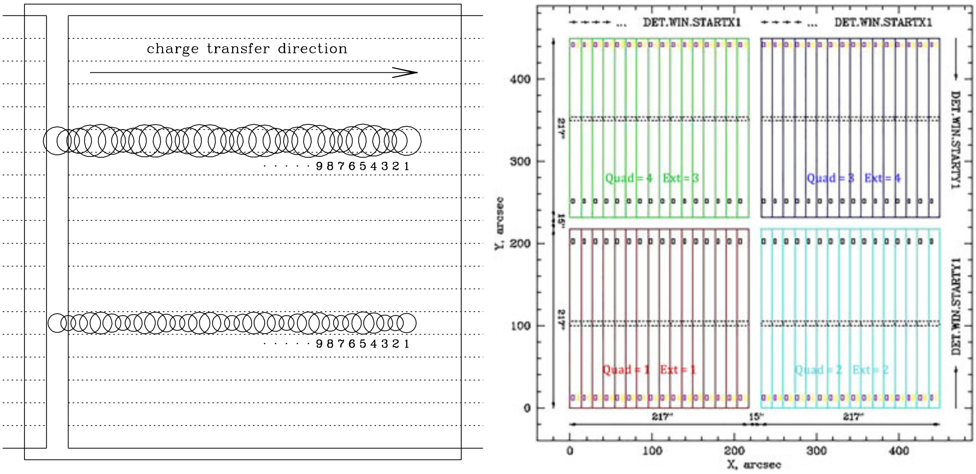

Figure 1. *Left:* FORS2 HIT–Imaging. The movable slits are placed on the left; the target and the reference stars are in the middle of the exposed area. The rest of the detector is shaded and the charge is moved and stored there. *Right:* HAWKI fast photometry, showing the four detectors, the vertical stripes and the sub-windows.

cube in the detector's controller memory and downloaded later. The latter measure does not reduce the transfer losses but clusters the 'dead' time, so short observations like lunar occultations can be scheduled to start at the time when the detector's cadence is at its highest. The application of these measures enables one to reach time-resolutions of 51 millisec for a 128×32 pix window.

HAWKI has an additional advantage: the parallel and independent reading of the 16 detector stripes lets one apply the same window on every stripe, thus increasing 16-fold the useful field of view. This is important when the target is a bright star and a second equally bright star is necessary as a photometric reference; the widest separation between the two is ∼11 arcmin, a number that no other 'fast' instrument can match.

Similar modifications were implemented on other ESO near-IR instruments to provide 'fast' capabilities: ISAAC (Infrared Spectrometer And Array Camera; Moorwood *et al.* 1998a) but now decommissioned, NaCo† Nasmyth Adaptive Optics System and Near-Infrared Imager and Spectrograph; Lenzen *et al.* 2003) on the VLT, and SofI‡ Son of ISAAC; Moorwood *et al.* 1998b) on the NTT.

Exoplanets are an obvious science case for these instruments. Thermal emission from WASP-4b was detected with ISAAC by Cáceres *et al.* (2011). Multiple primary transits were observed by Cáceres *et al.* (2009) and Cáceres *et al.* (2014), among others. The richly populated light curves ($\sim 10^4$ points per hour) allows one to study and parameterise reliably various systematic effects such as intrapixel sensitivity variations.

Other science cases include occultations. Dias-Oliveira *et al.* (2015) used NaCo to observe a stellar occultation of Pluto, measuring its diameter and the extent of its atmosphere with an accuracy comparable to that achieved by space missions. Similarly, Berard *et al.* (2017) measured the properties of Charicoś rings with HAWKI during a stellar occultation. Lunar occultations prove useful in searching for binary stars; Richichi *et al.* (2014) reported the results of a campaign to do that using ISAAC.

UltraCam (www.vikdhillon.staff.shef.ac.uk/ultracam; Dhillon *et al.* 2007) is a simultaneous 3-channel ($u'g'r'$, $u'g'i'$ or $u'g'z'$ filters), 6×6 arcmin camera at the ESO NTT,

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† http://www.eso.org/sci/facilities/paranal/instruments/naco/
‡ http://www.eso.org/sci/facilities/lasilla/instruments/sofi/

capable of recording up to 300 frames $\sec^{-1}$. It was designed to carry out 'fast' observations, unlike the instruments discussed earlier that had been modified for that purpose at a later point during their operational life. Despite being mounted at a smaller telescope, it has completely replaced FORS2 for 'fast' imaging applications because of (i) the simultaneous multi-band observations and (ii) the high cadence – it is capable of carrying out continuous 'fast' observations over extended periods of time, for full nights if necessary.

Maxted *et al.* (2013) used UltraCam to study a pulsating-stripped red giant in a binary; Antoniadis *et al.* (2013) used it to study binary pulsars. Exoplanet projects are common; e.g., Marsh *et al.* (2014) reported dynamical confirmation of the exoplanet in the white-dwarf binary system NN Ser; Hallakoun *et al.* (2017) found that unexpected colours of transits were caused by a disintegrating asteroid around WD 145+017. (This is only a small extract of a long list of publications based on UltraCam). Its successor, the 5-channel HiPERCAM (Dhillon *et al.* 2016), saw first light in early 2018 on the GTC.

4. Summary

(i) ESO offers a number of channels for proposing time-domain programmes, and a suite of competitive state-of-the-art instruments capable of carrying out high-cadence and fast time-resolution observations.

(ii) There is a mutually exclusive interplay between time-resolution and signal-to-noise. Improving one worsens the other, and *vice versa*. Users need to seek a reasonable compromise between the two.

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