The Beauty of Speed

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The burst mode of ISAAC has been used systematically to record lunar occultations with high time resolution, producing several unique new results that remain unattainable by any other technique. This is not the only possible choice of instrument for high time resolution, and fast time modes of one kind or another have been implemented on several other ESO instruments. We provide a brief overview of the present capabilities and summarise some scientific results. We speculate about the future of high temporal resolution applications, presenting the trail-blazing instrument Iqueye that recently completed its first technical run at La Silla.

The quest for high time resolution

Encoded somewhere in the human genome, there must be a love for speed. Filippo Marinetti, founder of the artistic movement known as Futurism, stated it best in his Manifesto of 1909: "We affirm that the world's magnificence has been enriched by a new beauty: the beauty of speed… Time and Space died yesterday. We already live in the absolute, because we have created eternal, omnipresent speed." Young or old, many people are infatuated with the concept of speed: in technology, in sport, or on the highway. But what about astronomers? It is generally considered that, in spite of some peculiarities, they are people too, and therefore they should not be immune to the fascination with speed. However, almost all the instruments that astronomers design and build are geared to the highest spectral resolution or the utmost sensitivity, and these demand in turn long integrations.

Yet there is a wealth of knowledge to be gained by going to the other extreme, and observing with high time resolution (see Table 1). Pulsars, stellar pulsations and oscillations, flares and bursts, transits and occultations, and more, are phenomena that are best studied by recording data at rates much faster than those usually employed by astronomers. The extragalactic community need not feel left out either: for example, the variability of active galactic nuclei (AGN) holds a crucial key to the size and structure of the central engine, and, if it is studied on timescales of minutes today, it is natural to expect that in the era of Extremely Large Telescopes (ELTs) these timescales could be down to seconds. Last but not least, if we really observe very fast, then we can also beat atmospheric turbulence, to the point that, at least for some applications, we no longer need expensive and complex correction systems.

To be sure, there are many problems in going very fast: we collect far fewer photons; we have to fight harder against detector noise and other unpleasant features; there may not be sufficient time to read the whole area of our large-format detectors for which we have paid so dearly. But first and foremost, what do we mean by "fast"? Examining Table 1, it will be noticed that the wish-list spans a range of six orders of magnitudes or more, from seconds down to microseconds or less. At ESO, most of the instruments currently in operation were originally designed without an explicit requirement for high time resolution. But as the standard modes have become more and more routine, a number of requests for fast observations are starting to be implemented on a best-effort basis. Today, several instruments at the La Silla Paranal Observatory offer high time resolution, as summarised in Table 2. We have not included here subsystems that by necessity have to include fast operation, such as adaptive optics and fringe trackers.

Modern panoramic detectors have quite large formats, and as a consequence typical readout times are, at minimum, of the order of seconds. In order to beat this limit by up to three orders of magnitudes, as required by some applications, it is generally necessary to sacrifice the number of pixels, by reading out only a small sub-window (used for example by the ESO infrared [IR] instruments ISAAC, SOFI and NACO). Other approaches are to shift the charge in CCDs, as in FORS2. Other detectors are intrinsically quite fast by design and have a relatively small format, such as the mid-IR detectors of VISIR and MIDI that have to avoid saturation by the high background signal.

In the following we will focus on recent results in two areas: the near-IR detection of lunar occultations with ISAAC in the millisecond range; and the "blazingly fast" detection enabled by a unique instrument that recently had its first technical run in La Silla.

At Paranal: the Moon in slow motion

Lunar occultations (LO) are a phenomenon in which the lunar limb acts as a straight diffracting edge. As the Moon moves over a distant background source, a fringe pattern is generated that moves over the observer. Typical speeds of this pattern are about 0.5–1 m/ms (or

Phenomenon	Timescale (current)	Timescale (ELT era)
Stellar flares and pulsations	seconds, minutes	10–100 ms
Stellar surface oscillations e.g., white dwarfs, neutron stars	1–1000 µs	1–1000 µs 0.1 µs
Tomography, eclipses, flickering e.g., close binary systems	10–100 ms	1–10 ms
Pulsars	1 µs–100 ms	1 ms–1 ns?
Variability in AGN	minutes	seconds?
Stellar occultations	1 ms	1 ms
Planetary occultations and transits	100 ms–10 s	100 ms–10 s

Table 1. Fast time applications in astronomy (partly based on an E-ELT study by Redfern & Ryan, 2006).

Instrument	Modes	Detector	Time Rate (Window)	Configuration and Mode
VISIR	Burst	DRS	12.5 ms SF	imaging, visitor
SOFI	Burst, FastPhot	Hawaii	4 ms (8 x 8), 15 ms (32 x 32)	imaging, visitor
ISAAC	Burst, FastPhot	Hawaii-1, Aladdin	3 ms (32 x 32), 6 ms (64 x 64)	imaging, visitor, service
ISAAC	Burst	Hawaii-1, Aladdin	9 ms (1024 x16)	spectro, under commisioning
NACO	Cube	Aladdin	7.2 ms (64 x 64), 350 ms (1024 x 1024)	imaging, visitor
HAWK-I	Fast	Hawaii-2RG	6.3 ms (16 x 16)	imaging
FORS2	HIT	CCD (charge shift)	up to 2.3 ms	image/spec, visitor, service
VLTI	Fast	Various	up to 1 ms	image/spec, not foreseen

Table 2. A summary of instruments available at ESO for fast time resolution with their main characteristics.

500–1000 m/s). The fringe spacing is determined by the distance to the Moon and the wavelength of observation: in the near-IR it is a few metres, so that time sampling of about one millisecond is required to measure the fringe pattern. From this measurement, a wealth of information on the background source can be recovered, including the angular diameter of stars, the projected separation and brightness ratio of binaries. It is also possible to reconstruct the brightness profiles of complex sources by a model-independent analysis. A typical concern of those who learn about LO for the first time is the effect of mountains and irregularities of the lunar limb. Luckily, this can generally be safely neglected, since we are dealing with diffraction and not with geometrical optics. A number of peculiarities characterise LO, in particular the fact that the angular resolution achieved is not dependent on the size of the telescope used for the observation. In fact, the Moon itself can be considered as our telescope in this case.

We have already reported in a previous *Messenger* article (Richichi et al., 2006) on the first successful observations of LO at the Very Large Telescope (VLT) with ISAAC at Unit Telescope 1. Using the Aladdin detector, an area of 32 x 32 pixels were read out every 3.2 ms. We announced this ground-breaking performance at the time, and this has now been confirmed by the detailed analysis carried out in two recently published papers (Richichi et al., 2008a; 2008b): an angular resolution as good as 0.5 milliarcseconds (mas), or about 100 times better than the diffraction limit of the telescope and comparable with that of the much larger and complex VLTI; a limiting sensitivity close to K ≈ 12.5, or several magnitudes fainter than the VLTI; and a dynamic range of 8 magnitudes even within one Airy disc from the central star. All this in the blink of an eye, or, to be realistic, in a few minutes, taking into account telescope pointing and data storage: sounds too good to be true? There are indeed some major limitations to LO: they are fixed time events, and we cannot choose the targets at will.

We report a summary of the results obtained in those first two runs in Table 3. Figure 1 provides an illustration: for the AGB star 2MASS 17453224-2833429, a maser source, we could derive a clear detection of the circumstellar shell and an estimate of its angular size and distance. As a result of these first observations, the so-called burst mode of ISAAC has subsequently been offered on a regular basis since Period 80, and is now a routine technique for LO observations at the VLT. Since LO observations require a minimum amount of time, they represent an ideal filler programme: every interval of at least five minutes during which no other service mode programmes are available

Table 3. Statistics of the results obtained from the first burst-mode runs with ISAAC for lunar occultations. R and D events are reappearances and disappearances, respectively.

	March 06	August 06	Total
Total hours	4.2	8.5	12.7
Type of event	R	D	
Attempted events	51	78	129
Successful events	30	72	102
Diameters	3	1	4
Binaries/triples	2/0	6/1	9
Shells/complex	0	2	2
Planetary nebula, central stars	0	1	1
Masers	2	1	3

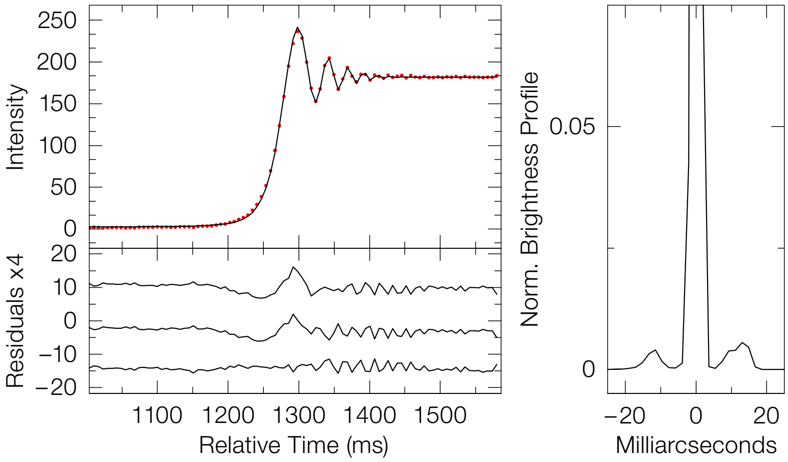
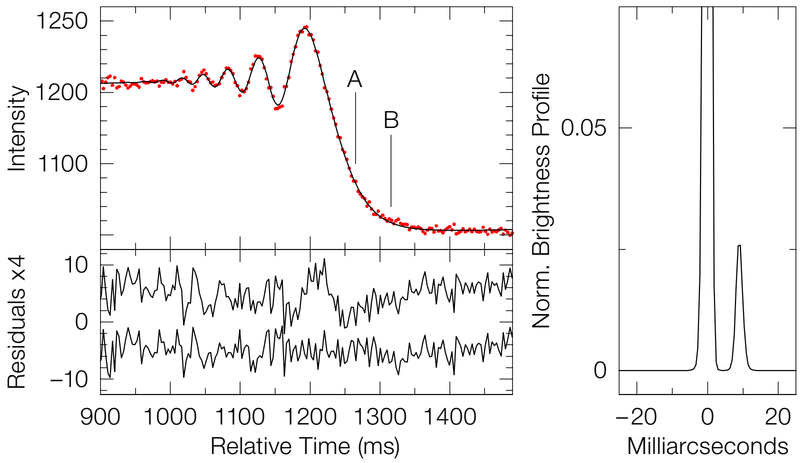


Figure 1. Left: Upper panel, data (dots) and best fit (solid line) for 2MASS 17453224-2833429. The lower panel shows, on a scale enlarged by four and displaced by arbitrary offsets for clarity, the residuals of three different fits. The upper two are for an unresolved and a resolved stellar disc (reduced χ^2 = 6.3), the lower one is with a model-independent analysis (reduced χ^2 = 1.6). **Right:** Brightness profile reconstructed by the model-independent analysis. The inner shell radius is estimated to be about 40 AU.

or for which the atmospheric conditions are not met, an LO observation can be attempted if the Moon is above the horizon. In fact, we note that LO observations are almost insensitive to seeing and other adverse atmospheric conditions. With this strategy in mind, we submitted a filler proposal for Period 80, which unfortunately did not produce many results due to the unavailability of ISAAC during much of the period. However we submitted again for Period 81 and we waited during Period 82 so we could see the first results. These were very encouraging, and the programme was resubmitted for Period 83, and accepted. We provide here a first account of the observations carried out in Period 81.

Figure 2. Same as Figure 1, for a source observed in Period 81 (K = 7.1, no known bibliographical entries). The fit residuals are for a point source (upper) and a binary source with a separation of 9.4 mas and a brightness ratio of 1:11 (lower). The right panel shows the reconstruction by a model-independent method.



For Period 81, we computed LO predictions to a limiting magnitude of K = 9.3 — a compromise between the number of computations and the volume of potential events. This choice resulted in 28 682 events observable within good observational constraints. Note that we discard full and waning Moon phases, the first because of the brightness and the latter because they are more challenging, and not well suited to service mode. We developed a prioritisation rule based on the K magnitude and J–K colour, preferring stars with very red colours indicative of possible circumstellar extinction. We further refined the priorities for sources with known counterparts or that had been studied previously. Then we applied a selection rule such that for every five minute interval only one star would be selected, with the highest priority among the other events close in time. As a result, 1629 Observing Blocks (OBs) were generated — a significant load for the User Support Department and our colleagues at Paranal to handle, whom we thank for their support. Equipped with this reservoir of OBs, our programmes lay dormant until summoned by an ISAAC night astronomer… an exciting wait for us in Garching! By the end of the period, a total of 125 LO events had been attempted in service mode. Of these, 116 resulted in positive detections of well-recorded light curves, a very satisfactory outcome indeed.

In order to cope with such a volume of data, we developed our own data pipeline (Fors et al., 2008), which generates extraction masks for each data cube (*viz.* sky image with time). The masks isolate the signal from the star, which, at these data rates, often has a variable and aberrated image, using twin criteria of contiguity and continuity. The background is then computed from the remaining pixels and subtracted. The pipeline processes the resulting light curve further using a multi-resolution wavelet transform analysis to produce first guesses of parameters such as the time of occultation, the intensity of the star, etc. From these parameters an initial fit is produced, and we are then presented with preliminary results and quality estimates that allow us to carry out an interactive analysis more efficiently and to focus on the interesting cases. First indications are that about six stars observed in Period 81 appear to be binary, with projected separations as small as 5 mas. One of them is illustrated in Figure 2. A few stars also appear to be resolved, although a more detailed analysis is still needed.

Most of these results, as well as those obtained previously, pertain to stars that are absent from the literature or have little information available. For some of them, not even an optical counterpart is known. Clearly, further investigations are needed in order to collect direct imaging by adaptive optics and optical and near-infrared photometry, and to provide spectral classification. We are waiting to prepare a corresponding proposal when a significant number of such stars are available. At the same time, we note that a large number of unresolved sources have been measured with upper limits on their angular diameters of order 1 mas. These limits, and the relatively faint magnitudes, make this a valuable list of calibrators for long-baseline interferometry, starting with the VLTI.

At La Silla: zooming in on pulsars

The observations presented so far may seem fast by the standards of most astronomers, but they pale in comparison with some observations recently carried out in La Silla. In January 2009, a new instrument emerged from its packing cases, and was quickly assembled at the Nasmyth B focus of the New Technology Telescope (NTT) by a team of Italian astronomers and engineers. Iqueye (Figure 3) is the NTT version of Aqueye, a prototype already previously deployed at the Asiago Observatory. The “queye” part of their names indicates the close relationship to QuantumEye, an instrument concept proposed initially for OWL, and now for the E-ELT (Dravins et al., 2005; Barbieri et al., 2008). The driver for this class of instruments is to reach ultimately the regime of time resolution in which photons are subject to quantum limits. From Figure 4, it can be seen that the Heisenberg uncertainty principle plays a dominant role in the visible range when the time resolution approaches a few picoseconds (1 ps = 10^{-12} s). But how is it possible to reach such time resolutions?

The solution selected for Iqueye is to combine astronomy with the state of the art offered by detector and nuclear physics. Iqueye and its siblings are equipped with single photon counting avalanche photodiodes (SPADs) which attain 50 ps time resolution with count rates as high as

Figure 3. Iqueye at the NTT, with some members of the team and of the supporting staff from La Silla. Two of the four SPADs are clearly seen, protruding from above and below the middle of the instrument. The rack includes the control electronics and the rubidium clock.

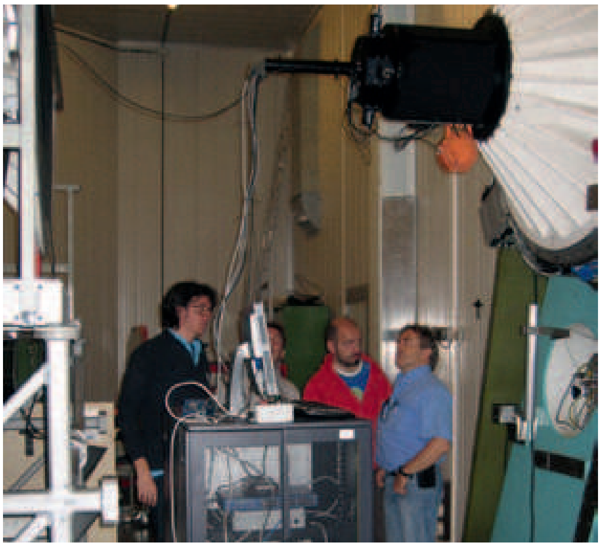
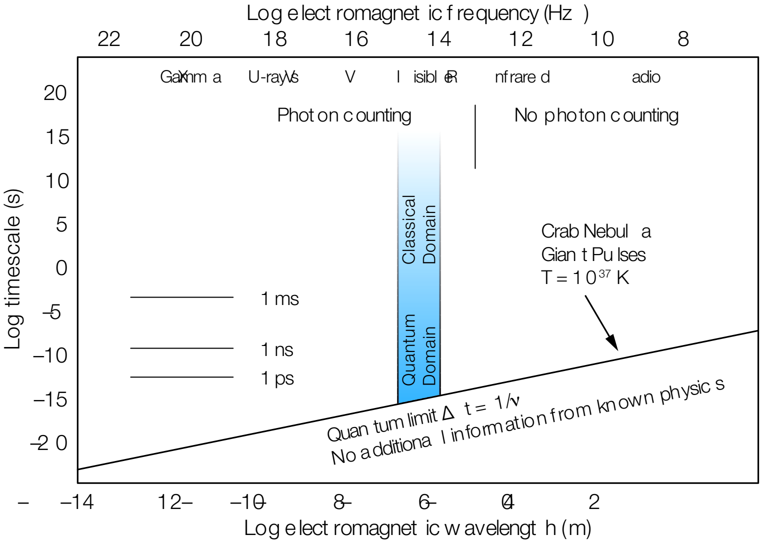


Figure 4. Astronomy in time and frequency. Pushing the time resolution towards the limits imposed by the Heisenberg uncertainty principle might be compared with the opening of a new window.



10 MHz. SPADs are very robust to high light levels, use standard voltages and do not require external cooling; their quantum efficiency reaches 60% in the visible. One shortcoming of these detectors is their deadtime, which at 70 ns limits the count rates to 14 MHz. Such devices are in a constant state of evolution, and improvements are foreseen in the near future. Both to avoid saturation in case of bright sources, and to provide independent detection statistics, Iqueye splits the telescope pupil into four, and each quadrant is observed with one SPAD. However this is only one part of the problem: the other gigantic hurdle is how to tag the arrival time of each photon. This has been achieved with two aids: an event-tagging board originally designed for CERN and a reliable and accurate time base. For this latter task, both a Global Positioning System (GPS) signal and a rubidium clock are employed. This clock has the required resolution, but it is not sufficiently stable, and so it is aligned occasionally with the GPS signal. By combining these two systems, the time-tagging achieved in Iqueye is reliable to about 30 ns over long periods of time, and to much less over shorter periods. The capabilities of Iqueye are impressive, especially if one considers that the whole is achieved in a highly compact and portable instrument, installed and successfully operated at the NTT by a small group of people, most of whom had never visited the site before!

The basic scheme of Iqueye is shown in Figure 5 and a more detailed account will be presented in the near future. For the moment, we show some impressive light curves of pulsars (Figures 6–8). The first was obtained with Aqueye at the Asiago 1.8-metre telescope in October 2008 (average signal over 30 minutes), and is compared with that taken at a much larger telescope. At the NTT, Iqueye was able to detect the Crab pulsar in a single cycle, showing its individual pulses clearly. The quality is unprecedented, and theoreticians will be able to zoom in on small details and refine their models. One can thus study pulse amplitude variations, noise in the arrival times, precession of the rotation axis, correlations with the giant radio pulses and much more. But the Crab pulsar is not the limit: at the NTT, Iqueye has been able to study another pulsar, B0540-69, with a V magnitude of only 23! This pulsar had previously been measured with good quality only by the Hubble Space Telescope (HST), and comparison of the NTT and HST data will provide an accurate deceleration rate for the pulsar. Note that these results are still preliminary, and the quantities in the figures need to be corrected for a number of effects.

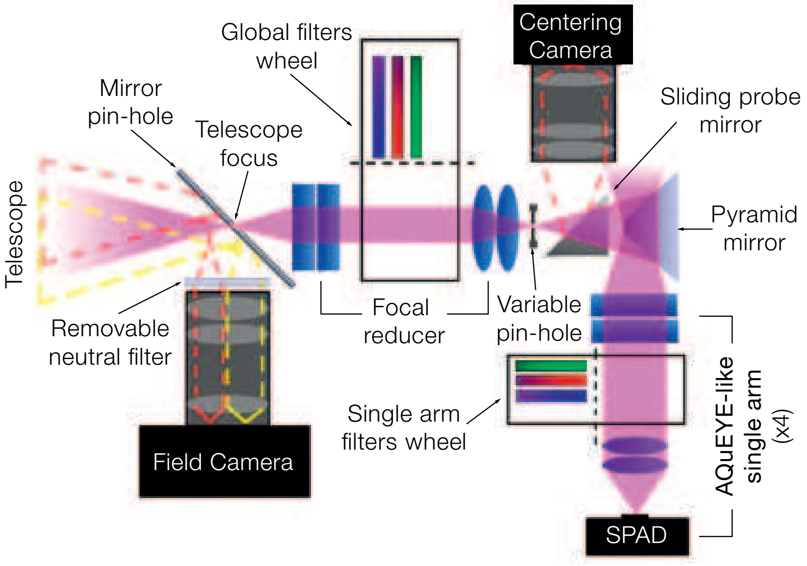


Figure 5. Schematic representation of Iqueye. Both the centering camera and the individual filters in each of the four arms are planned, but could not be included in the version for the first run at La Silla. With these additions the efficiency is increased and can provide the capability for simultaneous multi-colour observations.

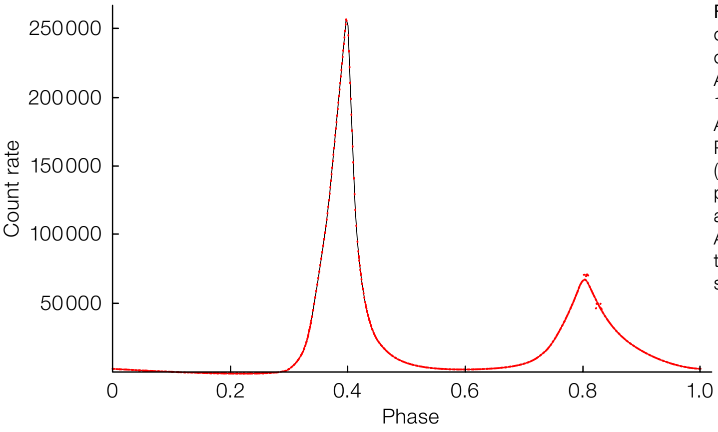
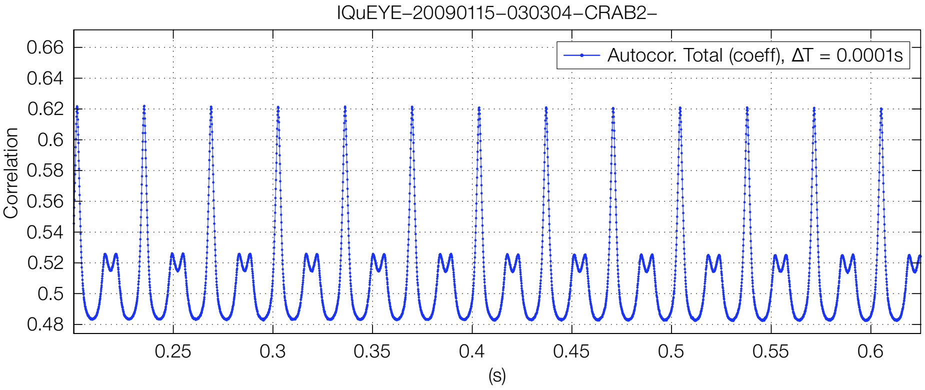


Figure 6. The light curve of the Crab pulsar (period 33 ms) observed with Aqueye in 2008 (blue, 1.8-metre telescope in Asiago) and with the Kitt Peak 4-metre telescope (red). Note the almost perfect reproducibility, and the performance of Aqueye consistent with that of a larger telescope at a better site.

The power of instruments such as Iqueye is only starting to become evident. The ability to measure events at nanosecond timescales with accurate time-tagging has already opened the door to a number of unique applications. It becomes possible not only to measure the individual light curves of fast variables such as pulsars, but also to compare, on a precise timescale, light curves taken at different times and at different locations. For pulsars, this enables the study of phase changes, derivatives, and comparison with radio observations, for example. It also offers a new approach to the technique known as intensity interferometry, originally devised and applied by Hanbury-Brown and colleagues. The method revolutionised interferometry in the 1960s through the study of the second order flux correlations between two telescopes. It was shown that this method allowed the coherence function of the emitting source to be measured, with the advantage that the required tolerances on the wavefronts were centimetres and millimetres, not microns and nanometres as in Michelson interferometers. The disadvantage with intensity interferometry is that it requires very large photon fluxes, and thus has limited sensitivity. This limitation can be significantly overcome by the better detection efficiencies and larger telescopes than were available in the 1960s; many in the community are debating the revival of intensity interferometry. In this context, plans to bring two Iqueyes to the VLT are already being proposed.

In the future, with improved hardware and the immense photon collecting power of the European ELT, it should become possible to truly attain the quantum limit, attempting detections at the picosecond level. This will open an entirely new window on the Universe, and push our knowledge into the regime where even the concept of photon and wavelength come to lose their accustomed meaning: a truly quantum eye will be born. Marinetti would have loved it!



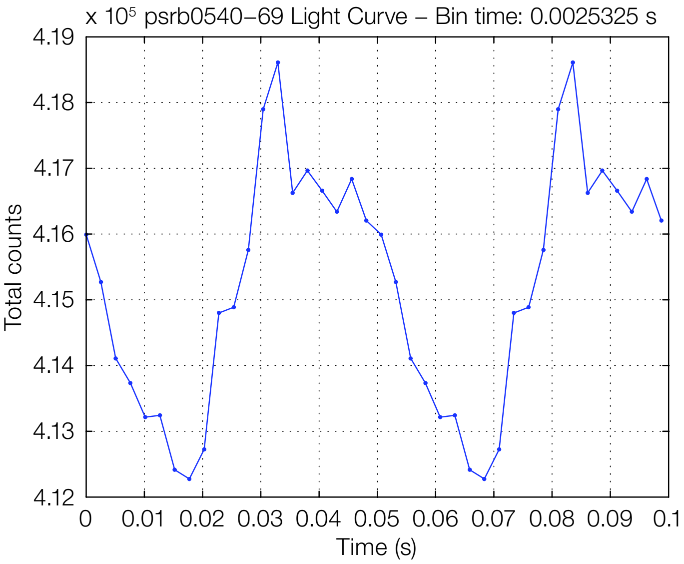


Figure 7. (Top) A zoom of the autocorrelation function of single pulses from the Crab pulsar, obtained by Iqueye at the NTT in January 2009. The structure in the secondary peak is due to the double-pulse shape of the light curve.

Figure 8. (Left) The light curve of the pulsar PSR 0540-69, with magnitude V = 23. The period can be well established from these data (preliminary value 50.7 ms), as well as features in the curve that reproduce well previous observations by HST. The data timing needs to be corrected for Earth's rotation, orbit and other effects.

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