# Scientific results at ESO with millisecond and nanosecond time resolution

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**Abstract.** We present recent results obtained in Paranal and La Silla, using infrared arrays and APDs operated at very fast time rates. The results include some of the most precise measurements ever achieved in the fields of high angular resolution and fast variability, such as angular diameters and binary stars at the milliarcsecond level, faint and compact circumstellar shells, and the fine sampling of pulsar light curves. We will illustrate our experience with presently available instruments, and our wishes for future high time resolution detectors.

## 1 Introduction

As far as the development of astronomical detectors is concerned, high time resolution applications have been relatively neglected in the last couple of decades. Emphasis has been mainly on the size and on the noise. While this is perfectly understandable, it is noteworthy that IR detector sizes have increased by a factor ~1,000 in area over the last twenty years, but the time resolution of such large arrays is worse by about the same factor compared to the single-pixel InSb detectors of the seventies.

At present, high time resolution is a rather broad term, which may include anything below one second. The scientific applications range from observations of transient phenomena in stars such as flares and transits (typical duration minutes to seconds), to surface oscillations, to accretion in very close binary systems, to lunar occultations and pulsars (milliseconds). Further, proposed experiments aimed at measuring fundamental physical parameters of photons would require time resolutions in the picosecond range. It can be noted that the range of high time resolution is in fact much larger than the range of standard time resolution observations, which require seconds to hours.

In the recent years, some important innovations have taken place in this area. Firstly, even large format IR arrays can be read routinely at relatively high rates, if one is satisfied with a subwindow only. In fact, specific small format detectors with low noise are now being developed specifically for the mounting needs of adaptive optics. Secondly, avalanche photo-diode detectors (APDs) have provided continuously improving performance in terms of sensitivity and speed, and are now intrinsically able to be used for applications well below the millisecond level.

We present here two examples of both these applications, and show preliminary results from lunar occultations observations of a crowded and very extincted region in the general direction of the Galactic Center, and from observations of a faint pulsar in the southern hemisphere.

## 2 The Lunar Occultation Method

The geometry of a lunar occultation (LO) event is sketched in Figure 1. The lunar limb acts as a straight diffracting edge, moving across the source with an angular speed that is the product of the lunar motion vector $V_M$ and the cosine of the contact angle CA. This produces a scan of the source along an angle which is the algebraic sum of the position angle PA and local limb slope $\psi$. Lunar mountains have a limited effect since limb irregularities are averaged over scales much larger than the geometric size of the star at the Moon. The result is a light curve similar to Figure 1, simulated for a reappearance under typical conditions in the near-IR, without noise. Abscissae are marked in seconds from the time of geometrical occultation, and intensity is arbitrary.

The light curve has characteristic fringes of increasing frequency and decreasing amplitude. These fringes embed information on the brightness distribution of the source along the direction of scan, and with proper analysis information can be retrieved on milliarcsecond (mas) scales. The main advantage of the LO method is that observations are very economical in terms of instrumentation and of telescope time. Essentially, fast photometry on ms scales is required, without needs of calibration observations. Data reduction is also not very intensive, compared to other high angular resolution techniques. The downside is of course that targets cannot be chosen at will: the Moon apparent orbit covers only about 10% of the sky, with a repetition rate of about 18.5 years (Saros cycle). Since LO are fixed time events, bad weather or technical downtimes are especially frustrating.

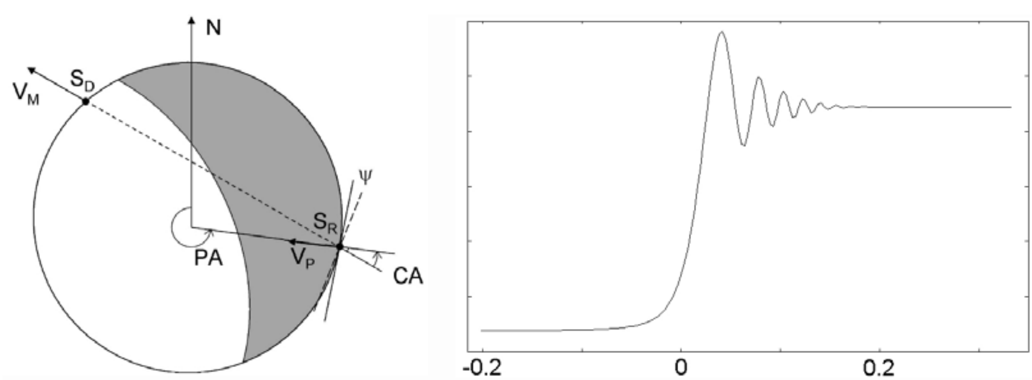


**Fig. 1.** Geometrical elements of an occultation (left), and model of a light curve with relative time in seconds (right). See text for details.

## 3 Lunar Occultation Observations

LO events have been observed routinely since the 1970's with fast photometers, but their use has gradually decreased for a number of reasons. The fact that millisecond time resolution capabilities are not easily found in modern large telescope instruments was certainly a factor. Additionally, IR all-sky surveys had been traditionally limited (and incomplete) to very bright magnitudes, for which LO had already provided almost all possible results. The increasing availability of long-baseline interferometers, operating with similar sensitivity and angular resolution but with more ease of repeatability, also influenced continuing efforts with LO.

A significant breakthrough has been reached in the recent years, thanks on one side to the availability of deep IR-surveys, and on the other side to the ability to use fast read-out modes on subwindows of the IR detectors commonly found on large telescopes. Given that LO are affected by high background values, the possibility to use array detectors has a great potential of increasing the effective sensitivity.

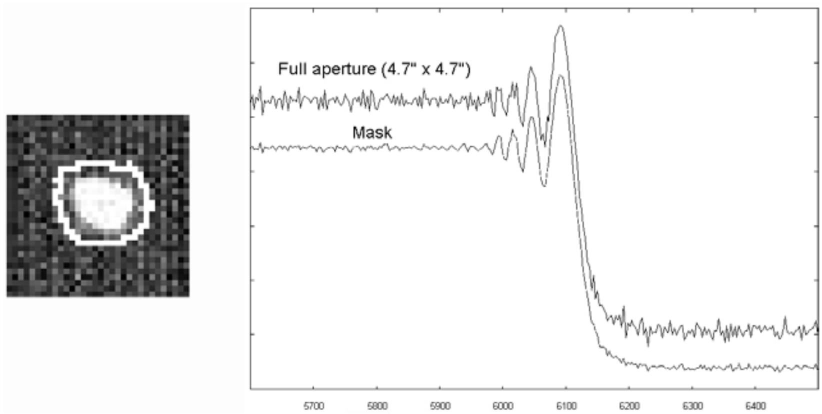


**Fig. 2.** Left: average of 5,000 frames at 3.2ms DIT, of a LO event. Right: light curves extracted from the full aperture, and using the mask defined by the *SExtractor* algorithm in our automated pipeline [1], as shown by the solid contour overimposed on the average of the frames.

Figure 2 shows data taken with the ISAAC instrument at the ESO VLT. Two light curves are shown, obtained from the full window as in a photometer, and by using an extraction mask [1]. To make a comparison, in the 1980's a 4m telescope equipped with a fast IR photometer was sensitive to K≈9 mag, but predictions could be made only for a small number of events per night, generally one or two dozens in the luckiest situations. At present, a 10m class telescope with an array detector is sensitive to K≈12.5 mag, and using the 2MASS Catalogue predictions run in the order of hundreds of events on each night, up to tens of thousands in special cases (see Figure 3). Of course, due to telescope overheads it is not possible to observe all of them, but recent observations by our group have collected up to 100 events in one half night, or an average of one every three minutes including overheads for pointing and data storage.

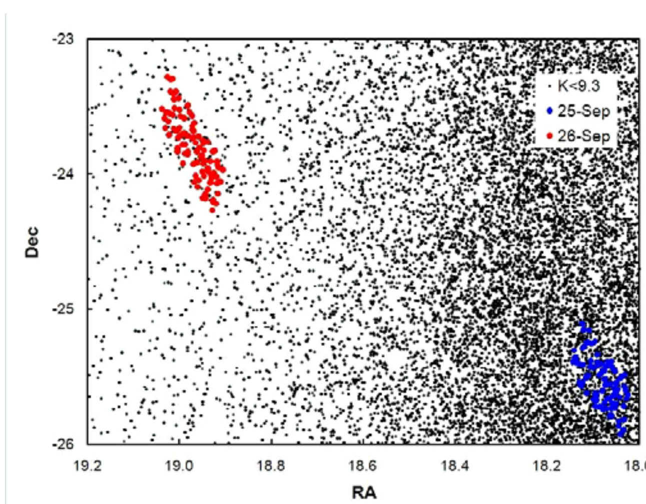


**Fig. 3.** Location of sources occulted by the Moon during two half nights on September 25 and 26. The small dots represent sources in the 2MASS catalog with magnitude K ≤ 9.3. The heavier colored dots are the sources for which we could record a lunar occultation.

An additional advantage of telescopes in the 8-10m class is that scintillation, a major source of noise for bright sources, is drastically reduced with respect to smaller telescopes. This provides excellent SNR, which in turn leads to very precise measurements: our observations in a broad-band K filter with the ISAAC instrument at the VLT reach SNR>200 for bright sources, and have a limiting angular resolution below 1 mas.

Since the start of our observations at the VLT three years ago, a total of about 500 events have been recorded, with magnitudes as faint as K~11. An accurate census of the results for the latest observations, completed in September 2009, is still in progress but we can already anticipate that the total number of binaries detected is ~50, the large majority of which not previously known and in fact without known optical counterparts.

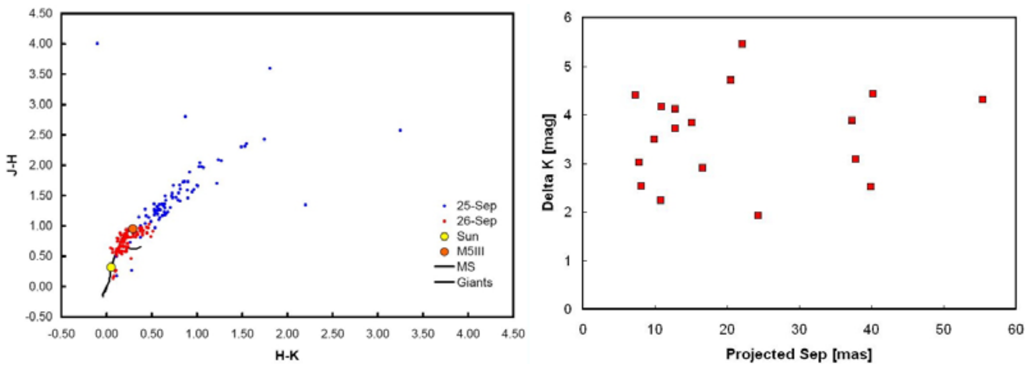


**Fig. 4.** Left: color-color location of the sources described in the text. The extreme reddening can be appreciated (compare with positions of main sequence, giants, and the Sun). Right: parameters of the binaries detected in this sample.

Figure 4 shows the colors of the sources detected during two half-nights in September 2009. The extreme reddening can be appreciated, mainly due to interstellar extinction in the general direction to the Galactic Center. However, cases of extreme local colors can also be seen. Only very few of the sources have known optical counterparts. In this sample of ~180 sources, a preliminary analysis shows that 18 sources have close companions (some of them are actually triple, but we only refer to the brightest two components here). In Figure 4, it can be seen that the magnitude differences are quite high, making the follow up of these sources quite challenging by any other method. In fact, the pairs with projected separations <20 mas (i.e. about 1/3 of the Airy disk of a large telescope at this wavelength) would require long-baseline interferometers, which however in most cases are unable to detect these systems due to their faintness.

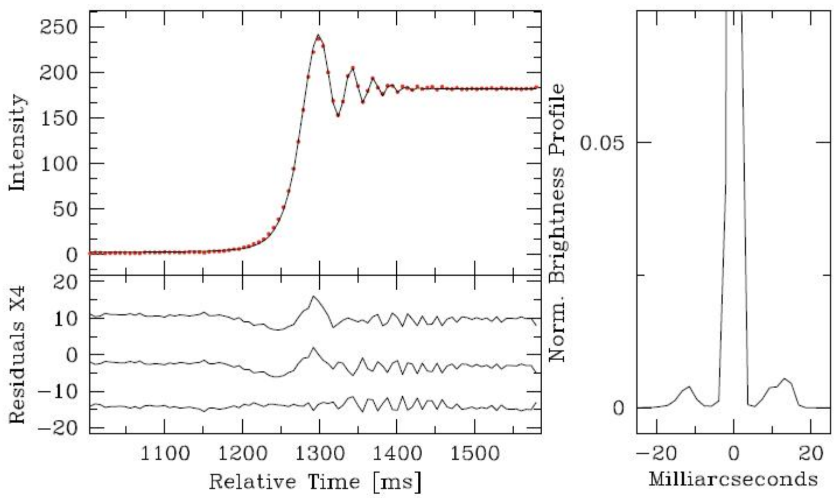


**Fig. 5.** Left: upper panel, data and best fit for 2MASS 17453224-2833429, a SiO maser with no optical counterpart. The lower panel shows on an enlarged scale the residuals of three different fits, see [2] for details. Right: brightness profile reconstructed by a model-independent method, with the typical signature of a circumstellar shell.

In addition to binary stars, LO are also ideal to study features and structures with low contrast, well inside the Airy disk of the telescope. An example is given in Figure 5, which shows the detection of an IR circumstellar shell associated with a radio maser. Details about the size and the distance are given in [2]. Here we mention that this and other measurements have proven the capability of the LO technique at a large telescope to achieve a dynamic range of 7-8 magnitudes in broad K band, on angular scales which are a fraction of the Airy disk.

## 4 Pulsar Observations with Iqueye

LO events require milliarsecond resolution as we have seen, but other applications are much more demanding and push the technological requirements significantly further. One example is the measurement of the properties of astronomical light sources close to the quantum limit. If one could measure the time of arrival of a photon with a resolution close to the inverse of its frequency, and measure at the same time its energy with sufficient accuracy, then the outcome would be subject to Heisenberg's principle and one would enter a regime where classical physics might not apply. As shown in Figure 6, for visual light this requires time resolution of below 1 nanosecond. An experiment designed to investigate light in this regime would need a sufficiently large flux of photons even on such short integration times. In fact, to be efficient an extremely large telescope would be required. A group led by one of us (CB) has proposed such an instrument called Quanteye for the E-ELT. While the plans for both the telescope and its instrumentation are being shaped, two prototypes have been built, Aqueye and Iqueye. The former has been installed at the Asiago Observatory in Italy, while the latter is a subsequent evolution which has been used for a brief run at the ESO NTT telescope in January 2009 (see Figure 7), and that will be deployed there again in December 2009.

Iqueye [3] is designed to achieve a time resolution at the nanosecond level. It uses a pupil splitter, which forms 4 identical beams for the purpose of minimizing spurious events and reducing the correlation time. The detectors are four SPADs (single-photon APDs). Events are time-tagged thanks to a board developed for nuclear physics by CERN. Absolute time is obtained from an improved GPS antenna coupled to a rubidium clock, and is accurate to 0.5ns/hr. Relative timing is a few times more accurate than this. Currently the main limitation in Iqueye is the response of the SPADs, which have a very fast rise but produce a shower which extends over about 70ns. Therefore the arrival of subsequent photons within this time range cannot be detected. However, the control electronics as well as the SPADs themselves are rapidly improving, and it is anticipated that this limitation will be significantly reduced in future versions.

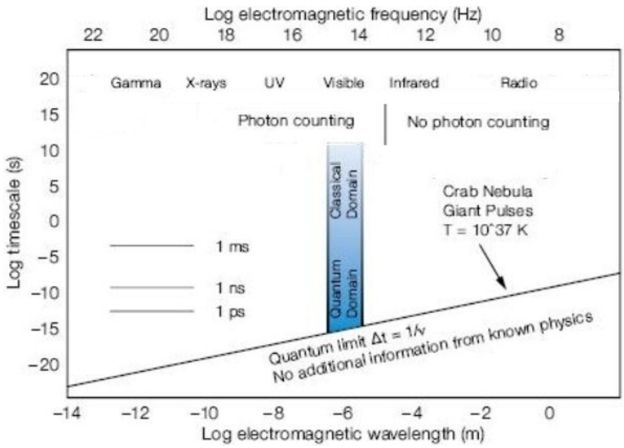

**Figure 6.** Diagram illustrating the quantum regime for astronomical light sources.


**Figure 7.** Iqueye installed at the NTT telescope in January 2009. The instrument is the black box attached to the Nasmyth focus, while the control electronics and rubidium clock are in the cabinet in the foreground.

Iqueye has been used to observe several sources during its inauguration run in January 2009. Here we show only the observation of the pulsar B0540-69 (Figure 8). This object is quite faint (V=23 mag, or 6 magnitudes fainter than the Crab pulsar), and due also to its southern declination it could be observed before only with the 4m telescope at Cerro Tololo (1985) and with the HST (1995). The new observations with Iqueye prove the potential of this instrument: the photometric period could be retrieved with two short measurements, and is quite consistent over two independent nights. The baseline of about 25 years between the first observations and those of Iqueye has allowed Gradari et al. [4] not only to provide a precise determination of the period (50.6ms, with 8ns error), but also to measure the braking index.

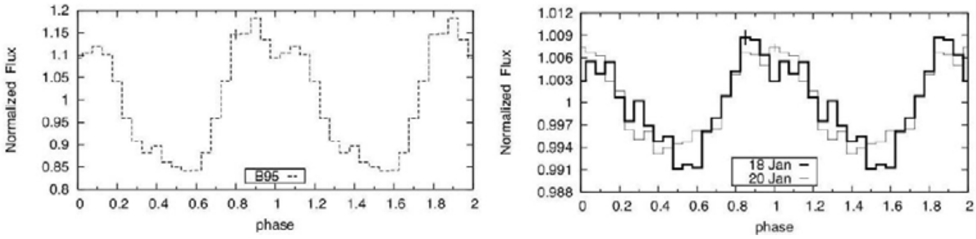


**Figure 8.** *Left* : photometric period of the pulsar B0540-69 obtained with the HST in 1994. *Right* : the same, with two osbervations with Iqueye at the NTT in subsequent nights in January 2009.

## 5 Conclusions

The combination of large telescopes on one side and of faster and more accurate detectors on the other, promises to open the gates to a new exciting era of high time resolution in astronomy. We have given here just two examples, but many more exist.

Lunar occultations have limitations in the choice of the objects that can be investigated and in being fixed-time events. However they are a very economical technique which offers an unparalleled combined performance in terms of sensitivity and angular resolution. Significant improvements could be brought about if the current time resolution to read out a subwindow could be decreased from about 3 to 1 ms or less.

SPAD-based instruments such as Iqueye have shown the capability to investigate very fast phenomena such a pulsars with unprecedented efficiency. Improvements in the SPAD dead times and the use of extremely large telescopes will allow to tackle ultimately the quantum limits of light.

## References

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