Burst or Bust: ISAAC at Antu Sets New Standards with Lunar Occultations

Andrea Richichi[1]
Octavi Fors[2,3]
Elena Mason[1]
Jörg Stegmeier[1]

[1] ESO
[2] Departament d'Astronomia i Meteorologia, Universitat de Barcelona, Spain
[3] Observatori Fabra, Barcelona, Spain

Imagine a car as fast as a Ferrari, and as cheap as a Trabi. Sounds crazy? Maybe it is, but when it comes to high angular resolution in astronomy there is something that comes close to the miracle: lunar occultations. As the Moon moves over a background star, the phenomenon of diffraction causes tenuous, quick fringes to appear in the stellar light just before it vanishes. The fringes carry valuable information on the size of the source, on scales much smaller than possible with even a perfect, extremely large telescope. Paranal is now superbly equipped to perform this kind of observation, and for that matter all sorts of high-speed near-IR photometry. And the results are impressive. Find out more about the ISAAC burst mode, which is now officially supported from Period 79.

The power of lunar occultations

Astronomers are always seeking to resolve the smallest possible angular details of their favourite sources, and for this they are prepared to invest huge amounts of money and resources. You are certainly familiar already with the wonderful results afforded by adaptive optics and long-baseline interferometry, but no doubt you will have also been struck by their complications. However, there is a way to obtain very high angular resolution, far exceeding the diffraction limit of any telescope, and still keep the whole business simple for the mind and easy on your observatory budget. Even better, it is possible to achieve this under any seeing and with an optical quality of your mirror which would send any self-respecting optician into a rage. How? Well, let us forget about the telescope in the first place. Instead, let us use an entirely different apparatus, namely the Moon. More precisely, its edge. As the lunar limb occults a distant background source, diffraction fringes are generated. From the analysis of these fringes, it is possible to infer the size of the occulted source, and even to reconstruct a precise scan of its brightness profile. Since the diffraction phenomenon takes place in space, the quality of the atmosphere or the optical quality of the telescope we use to look at does not really matter to a first approximation. The fringes have a characteristic size which is determined by the distance to the Moon and the wavelength, and is typically several metres across at the Earth surface. However, they also move rather fast, almost one kilometre per second on average. Therefore, the trick is to measure them fast: in order to achieve a good measurement, sampling rates of about 1 millisecond are required.

To be sure, there are some critical limitations in this technique: for one, you cannot choose which sources in the sky the Moon is going to occult, and when. Other more subtle limitations are that, lunar occultations being fixed-time events, their observation can easily be wiped out by a single cloud in the wrong place at the wrong time. And it might take a long, long time until the next opportunity: the Moon moves across the sky following a so-called Saros cycle, the same as solar eclipses. For the record, it lasts about 18.5 years! Also, a lunar occultation only gives a one-dimensional scan of the source. In spite of these limitations, lunar occultations have represented the main provider of stellar angular diameters for decades. Their typical angular resolution and sensitivity have been only recently reached, and sometimes surpassed, by a few long-baseline interferometers such as the ESO VLTI.

Lunar occultations at Paranal

So if some interferometers can now offer the performance of lunar occultations, why do we still go around bragging about the Moon? There is one good reason: lunar occultations have just added a few more magnitudes to their sensitivity limit, thanks to a mode recently implemented at Paranal. Because occultations require very fast integration times, they have been traditionally observed by photometers, which in turn are usually found at small telescopes. However, clever read-out electronics also exist to read an array detector at a sufficiently fast rate, pro-

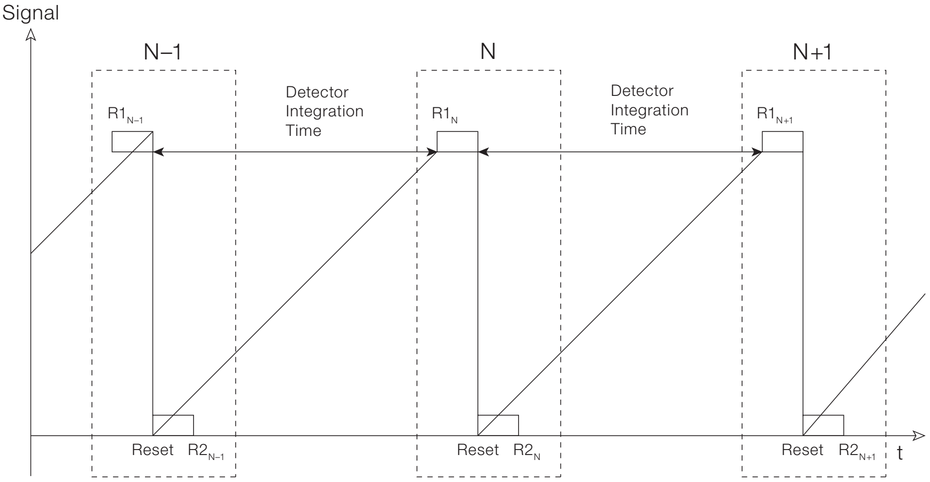

Figure 1: Read-out scheme (Read-Reset-Read). Two lines of the sub-window are read, then reset and read again. This is repeated for the whole sub-window and the result is computed as $R1_N - R2_{N-1}$. This read-out scheme allows a 100 % duty cycle for minimum integration time (= read-out time of the sub-window).

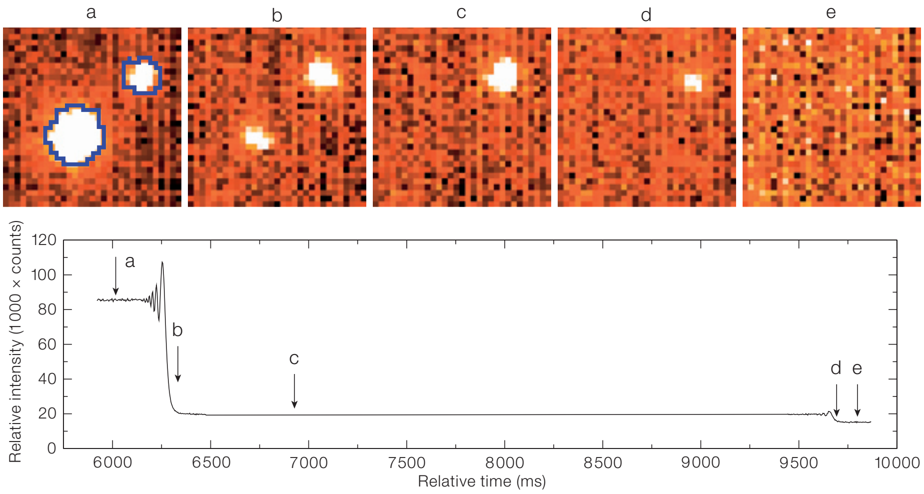

Figure 2: The occultation disappearance of 2MASS17560902-2830501. At the top, five frames are shown at arbitrary positions in the data cube (total 6000 frames), as marked by the letters a–e. The light curve at the bottom has been reconstructed by performing a simple aperture photometry on each frame, using a mask shown in blue in the first frame. Two clearly separated stars are visible, giving rise to distinct diffraction patterns. The projected separation is 1423 ± 4 mas, and the brightness ratio ΔK = 2.96 ± 0.02 mag. This 'binary' is in fact too wide for occultations: not only are the two stars clearly resolved in standard imaging, but the wide separation also implies possibly different slopes of the lunar limb at the contact point.

vided that you are satisfied with a subwindow rather than the whole array, and the ESO IRACE is one of them (see Figure 1). Moreover, for such short integration times, the sensitivity is of course critically dependent on the telescope area.

The combination of Antu, ISAAC and IRACE seemed thus perfect, but we still needed a good justification to try them together in a convincing demonstration, and the opportunity was given by the close approach of the Moon to the Galactic Centre (GC). This is an event which is repeated every 18.5 years (remember, the Saros cycle!), and is observable only a few times from restricted regions on Earth. Due to lunar parallax and the southern location of the Paranal observatory, this time around the Moon would not go exactly over the GC, but still it would traverse a very crowded, very obscured region with literally tens of thousands of largely unknown infrared sources. We obtained time to perform observations of two such passages, one in March and one in August 2006, for some hours each.

Obviously it was not possible to observe all the occultations: even if each event lasts less than a second, significant chunks of time are required just to point the telescope and to read out the data (refer to the ISAAC web pages for some typical numbers). After some practice, we found a good compromise in which each observation would require about two minutes. Thousands of frames for each cube are analysed and photometry is extracted through software masks that maximise the SNR by sampling as much as possible of the stellar signal and as little as possible of the background. An example of a lunar occultation data cube and the corresponding light curve is given in Figure 2. The analysis of hundreds of light curves is a tedious task, and for this we have developed a data pipeline that creates template files for the initial data reduction, aimed at a preliminary estimate for each occultation of parameters such as background and stellar intensity, rate of lunar limb motion, time of the occultations. These parameters are subsequently refined in an interactive analysis.

The passages near the Galactic Centre

The reward for these attempts was certainly satisfactory: we could record 53 events on 22 March, and 71 on 6 August. Thanks to the large collecting power of Antu, the quality of the data is unprecedented and it allowed us to reach new standards of sensitivity and precision. The VLT mirror is so large that scintillation is reduced to a very low level, since differences in wavefront amplitude from one turbulence cell in the atmosphere to the next are averaged out. Figure 3 illustrates this quality, by showing the light curves for both an unresolved and a resolved star.

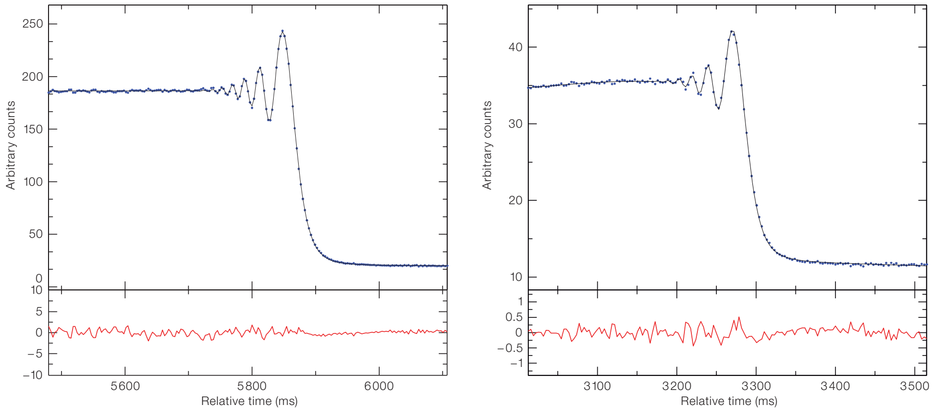

Figure 3: The light curves (top, blue) and best fit models (black) for 2MASS17474895-2835083 and 2MASS17582187-2814522. The bottom panels show the fit residuals (red), enlarged by a factor of four for clarity. The star on the left is unresolved, with an upper limit of the diameter of 0.65 mas. The other one is resolved, with an estimated diameter of 3.67 ± 0.56 mas. The difference between the two cases is in the number and amplitude of the diffraction fringes.

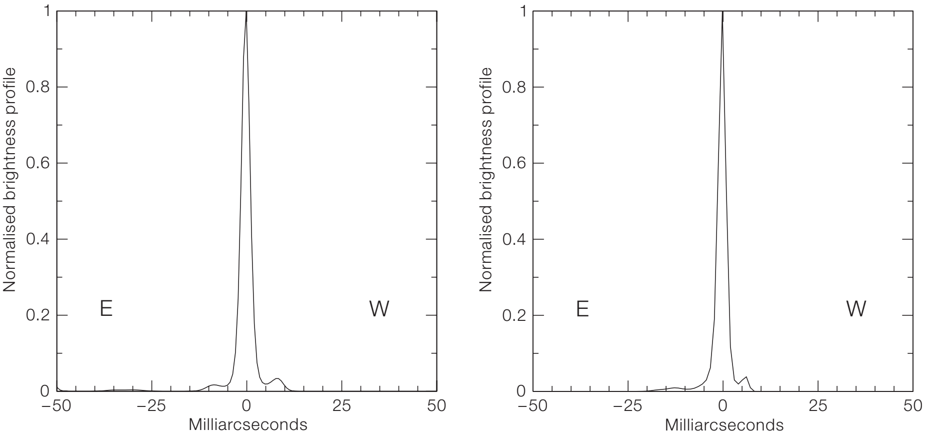

Figure 4: Examples of brightness profiles of stars surrounded by what are presumably compact dust shells. Left, the carbon star C2490 (2MASS17531817-2849492). Right, 2MASS17553507-2841150. In both cases, the inner rims of an optically thin shell are visible, indicating a non-symmetric structure and a characteristic size of about 20 mas.

A detailed analysis of the observations is in preparation, but we can already provide some general results for the August run. We have detected seven binaries, five resolved angular diameters and four stars with extended emission. It should be noted that almost all of our targets have no optical counterpart, and in fact almost no information is known except from that in 2MASS. Colours are very red, as is to be expected from the high interstellar extinction, but extreme cases (*J-K* up to 8 mag) are also present which point to possible strong local reddening. The stars with extended emission are particularly interesting, since this is probably due to the presence of compact circumstellar shells (see Figure 4). We have now submitted a proposal to follow up a selected number of sources by adaptive optics observations with NACO, and for which we hope to derive a fully consistent model of the star and the surrounding dust from the combination of occultation, AO imaging and photometry.

We also mention that about 50 sources were found to be unresolved. This is also a useful result because it helps to establish a database of stars with high-accuracy upper limits that can be in turn adopted as calibrators for long-baseline interferometry at intermediate and faint magnitudes. We have established upper limits for the diameters of our unresolved sources which vary between 0.5 and 1.5 mas. We have also evaluated the sample in terms of SNR against magnitude, and we can reliably extrapolate to predict that the limiting sensitivity of this method at the VLT would be close to $K = 12.5$ mag, a new record for measurements with milliarcsecond resolution. This is fainter than even the theoretical performance of the VLTI in the combination of 2 UTs. Therefore, occultations with ISAAC at UT1 represent at the moment the most sensitive technique available for such measurements anywhere in the world.

The way is now paved to observe lunar occultations in a routine fashion from Paranal. In fact, since occultations require a minimum amount of time and can be observed practically at any moment in which the Moon is above the night horizon, they represent an ideal filler programme for those occasional chunks of time when no other programmes are readily available either because of insufficient atmospheric conditions or because of their duration. In addition, the burst mode has many applications other than occultations by the Moon: phenomena that require rapid photometry for sustained periods of time are relatively frequent, and it is now up to the inventiveness and imagination of astronomers to find the best applications.

Gordon Gillet (ESO) captured this stunning photo of a moonset over Paranal. In addition to the four main unit telescopes (UTs), the VLT Survey Telescope (VST) is visible at the far right and the small, white VLTI auxiliary domes can also be seen.

This image was selected as Astronomical Picture of the Day on 4 November 2006; see *http://antwrp.gsfc.nasa.gov/apod/ap061104.html*