The AstraLux Sur Lucky Imaging Instrument at the NTT

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Lucky Imaging is an observational technique that aims to achieve nearly-diffraction-limited image quality from the ground on 2–4-metre-class telescopes. While diffraction-limited observations from the ground are usually accomplished with the help of adaptive optics in the near-infrared spectral range at almost all 8–10-metre-class telescopes, Lucky Imaging aims for a similar imaging performance at shorter wavelengths, in particular from 0.7–1.1 microns. AstraLux Sur, a visitor instrument for the NTT, built at the Max-Planck-Institute for Astronomy, is described and some early results are presented.

Matter of luck: optical turbulence statistics

The working principle of Lucky Imaging is fairly simple and passive when compared to conventional adaptive optics systems with actively controlled deformable mirrors. The Lucky Imaging technique exploits the temporal behaviour of atmospheric turbulence. By selecting only the best few percent of several tens of thousands of short exposure images, it is possible to recover the full angular resolution of medium-sized telescopes at visible wavelengths. This can be realised with a fraction of the instrumental effort and cost that is needed for adaptive optics.

In his 1978 paper, David Fried showed that the probability of finding an image with a Strehl ratio ≥ 37 %, i.e. a wavefront variance < 1 rad^2, depends on the exponential of the ratio of the telescope diameter, D, to the square of the Fried parameter r_0. The Strehl ratio is an empirical measure of image quality, defined as the ratio of the peak height in an image to that expected for a diffraction-limited image. The Fried parameter is a direct measure of the length scale of atmospheric turbulence and is related to the seeing. For $D = 2.2$ m and $r_0 = 0.3$ m (this corresponds to a good I-band seeing of 0.55 arcseconds), the probability of obtaining an image with Strehl ratio > 37 % is about 0.0013. For a 3.5-metre telescope under the same conditions, the corresponding probability is about 3.5×10^{-9}. In a series of 20 000 images one would therefore expect 26 and 0 Lucky Images, for a 2.2-metre and a 3.5-metre telescope respectively. It is important to stress that this is the probability of obtaining nearly-diffraction-limited (Strehl ≥ 37 %) images at a wavelength of 800 nm, and with an angular resolution of 90 milliarcseconds (mas; for $D = 2.2$ m) and 47 mas (for $D = 3.5$ m).

In fact, the probability increases if we look for images with Strehl ratios < 37 %. Baldwin et al. (2001) could show that using exposures with the highest 1 % of Strehl ratios can result in a final image with a Strehl ratio of 0.3. All this of course only works if the exposure time is short enough to freeze the atmospheric turbulence, i.e., shorter than the speckle coherence time, τ_e. According to Robert Tubbs, τ_e depends on the ratio of the Fried parameter to the average wind velocity, v. This dependence requires an exposure time of about 30 ms for $r_0 = 0.1$ m and $v = 10$ m/s. Fortunately, CCD detectors with sub-electron read noise that can be operated at frame rates of 30 Hz and above are nowadays available. These electron multiplication CCD detectors are, in this respect, the cornerstone for the Lucky Imaging technique, combining very high quantum efficiency and very low noise at high speed.

The sequence of images in Figure 1 a–e shows how Lucky Imaging works. From a series of 50 000 images taken in z-band (central wavelength: 912 nm) at a speed of almost 40 images per second with the Calar Alto 2.2-metre telescope, five different long-exposure images have been created:

- The first image (Figure 1a) is just the sum of all 50 000 images, which is almost the same as the 21-minute (50 000/40 seconds)-long exposure, seeing-limited image. It looks like a typical star image, but slightly elongated. The full width at half maximum (FWHM) of the seeing disc is around 0.9 arcseconds.
- The second image (Figure 1b) is the sum of all 50 000 single images, but here with the centre of gravity (centroid) of each image shifted to the same reference position. This is the tip-tilt corrected — or image-stabilised — long-exposure image. It already shows more detail — two objects — than the seeing-limited image in Figure 1a.
- The third image (Figure 1c) shows the 25 000 (50 % selection) best images added together, with the brightest pixel in each image used to shift to the same reference position. In this image, the object is resolved into a triple system.
- The fourth image (Figure 1d) shows the 5000 (10 % selection) best images added together, with the brightest pixel in each image again used as the reference position. The surrounding seeing halo is further reduced and an Airy ring around the brightest object becomes clearly visible.
- The last image (Figure 1e) shows the 500 (1% selection) best images added together, with the brightest pixel in each image used for registration. The seeing halo is further reduced from the result in Figure 1d. This image provides the maximum signal-to-noise ratio of the five images.

The difference between the seeing-limited image and the result of selecting the best 1% of the images is quite remarkable: a triple system can be detected. The brightest component, to the west, is a V = 14.9 magnitude M4V star. This component is the Lucky Imaging reference source. The weakest — tertiary — component is an M7–M8 spectral type star. The distance of the system is known to be about 45 parsecs. Airy rings can be seen, which indicate that the diffraction limit of the Calar Alto 2.2-metre telescope, 86 mas, was reached. The signal-

Figure 1. Pictorial representation of the image selection process of Lucky Imaging. The image in Figure 1a is the sum of 50 000 z-band images each of 25 ms duration. Figure 1b shows the result of combining the 50 000 images, but with shifting to align the centroid of each image. Figures 1c through 1e show the results of selecting the best 50, 10 and 1 % of the images according to the Strehl ratio. See text for details.

to-noise ratio of the point sources increases with stronger selection. On the other hand, the seeing halo is more suppressed. The separation between the two brighter objects is around 0.55 arcseconds and between the two fainter objects less than 0.15 arcseconds. At a distance of 45 parsecs this corresponds to 6.75 astronomical units (AUs), around 10^9 km.

Lucky, well not always, but well-earned

In July 2006 we installed the Lucky Imaging instrument ASTRALUX at the 2.2-metre telescope of the German–Spanish Astronomical Center at Calar Alto (Hormuth et al., 2007; 2008). The simplicity, robustness and great success of this instrument — around 10 publications so far[1] — resulted, in autumn 2007, in the idea of building a copy of the instrument for the 3.5-metre New Technology Telescope (NTT) at the La Silla Observatory in Chile.

In May 2008, eight months after the starter's gun fired, we shipped the heaviest piece of the instrument, now christened AstraLux Sur, to Chile. The 225 kg adapter flange was especially designed for the NTT adapter/rotator counterpart. Accompanied by the camera mount, filter wheel, Barlow lens, an electron multiplying, thinned and back-illuminated CCD (model Andor iXon+), four computers and an electronic rack, everything arrived safely at the observatory. The instrument is sensitive in the visible spectrum and deploys the Lucky Imaging technique with nearly-diffraction-limited performance (~ 0.1 arcseconds) in I'-band and z'-band. The instrument provides a field of view of 16 × 16 arcseconds with a pixel scale of 31 mas.

First light of AstraLux Sur took place on the night of 19 July 2008. The first light target was the ~ 0.7 arcsecond binary system γ Lupi. Even though the observing conditions were rather poor and the NTT was closed for most of the night, with the exception of about half an hour, we could perform basic instrument tests. The opto-mechanical interface with the telescope, as well as our computing equipment, worked as expected. After some adjustments, the AstraLux Sur online data pipeline and the communication with the NTT control system via pctcs (a special telescope control system software module) ran smoothly. Pointing and focusing worked nicely. The image orientation, image scale and optical throughput were determined and the first photometric data could be obtained. Apart from one 25-minute window during the first night, no observations were possible in the first three nights due to high wind speeds and snowstorms. On the fourth night, the telescope could be opened during the second half of the night, and on the fifth night observations were able to start about two hours after sunset. Observing conditions were non-photometric for most of the time, and the seeing (DIMM) varied between 1 arcseconds and 2.5 arcseconds. Because of the high wind speed, the observations were also subject to very short coherence times.

In summary, after the first two observing runs in 2008, the performance of AstraLux Sur is as expected, in terms of Strehl ratio, but obviously slightly worse than its sister instrument at the 2.2-metre telescope on Calar Alto on account of the larger telescope diameter. The full diffraction limit was reached in I'-band with a FWHM of ~ 50 mas. In general an angular resolution of around 150 mas was achieved in I'-band and z'-band. This is slightly worse than our result on the 2.2-metre telescope at Calar Alto. To understand this behaviour, one should ask if there is an ideal combination of telescope diameter, seeing and filter bandpass for Lucky Imaging. It has been shown by Hecquet & Coupinot (1985) that the Strehl resolution, R, reaches its maximum at $D/r_0 = 7$ if the best 1 % of short exposures are selected. The Strehl resolution is defined as the product of the Strehl ratio and the ratio of the telescope diameter to the wavelength squared. The Strehl resolution is a measure of the image quality, including both the Strehl ratio and the

Figure 2. The AstraLux Sur commissioning team, from left to right: Stefan Hippler, Wolfgang Brandner and Boyke Rochau in July 2008. The AstraLux Sur instrument is attached to the aluminum adapter flange, which itself is connected to the NTT Nasmyth adapter/rotator.

image resolution, roughly corresponding to terms like contrast and sharpness. Both higher and lower values for D/r_0 than the supposed optimal value of 7 lead to a loss of image quality. If the telescope diameter is increased at a fixed r_0, equivalent to fixed wavelength and seeing conditions, then the probability for a Lucky Image will decrease, leading to a smaller resulting Strehl ratio. If the telescope diameter is decreased, the higher resulting Strehl ratio is achieved at the cost of image resolution.

Figure 3. Since November 2008 — with the second AstraLux Sur observing run — observations with AstraLux Sur have been carried out from the La Silla remote control building, the RITZ. The remote operations include control of the instrument, as well as online data reduction and inspection. Observers Sebastian Daemgen and Carolina Bergfors are shown.

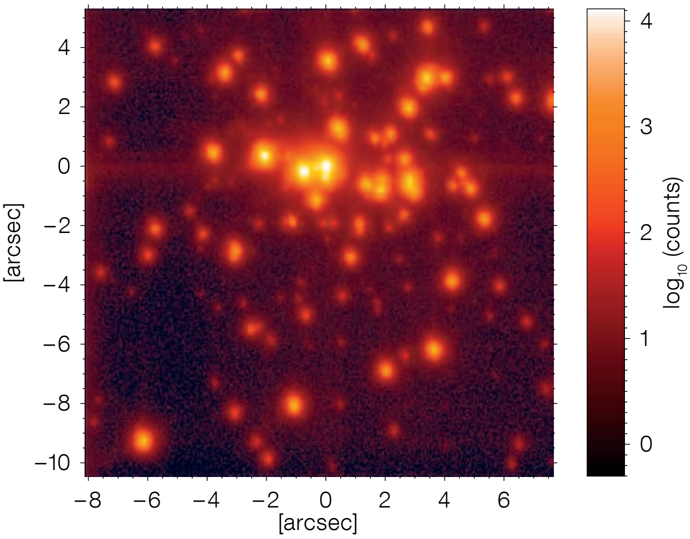


Figure 4. The core of the Galactic starburst cluster in the giant H II region NGC 3603, which serves as one of our astrometric calibration targets, as seen by AstraLux Sur in the SDSS z'-band at the NTT. The 1 % image selection (100 out of 10 000 frames) yields a resolution (FWHM) of 120 mas.

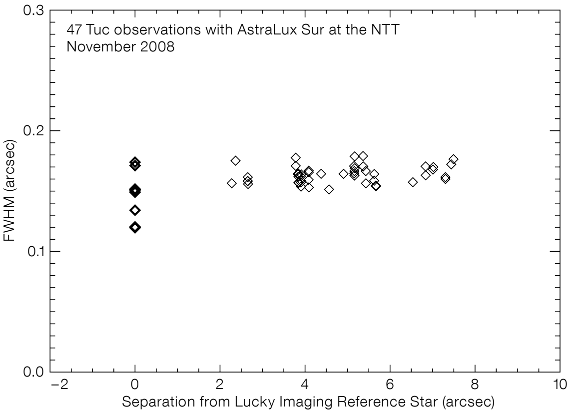


Figure 5. The measured point source full width at half maximum, FWHM, is shown at different separations from the Lucky Imaging reference star in observations of the globular cluster 47 Tuc. We analysed 9 z'-band images with a single frame integration time of 30 ms and used a 10 % selection process (1 000 out of 10 000 frames). The ASM (DIMM) seeing varied between 0.8 and 1.8 arcseconds. Hence, even under worse than median seeing conditions, Lucky Imaging can deliver images with resolutions below 200 mas.

Science programmes: Lucky Imaging survey for binary M dwarfs

With the AstraLux Sur instrument at the NTT visitor focus, we achieved nearly-diffraction-limited imaging performance in the SDSS I'- and z'-band filters, a wavelength range not accessible with other ground-based high-resolution (adaptive optics) instruments.

In Period 81 we initiated three science programmes at the NTT with AstraLux Sur. The first programme is a second epoch follow-up of T Tauri binary and multiple systems, which were originally discovered some 15 to 20 years ago. The second epoch observations obtained with AstraLux Sur test if the individual components of each system have a common proper motion, and hence are gravitationally bound. In addition we will derive first estimates of orbital periods and system masses of a statistically significant sample of T Tauri stars. The final observations for this programme were obtained in March 2009, and the analysis has just been completed and we are preparing the findings for publication. A survey of about 800 young, active M dwarfs in the Solar Neighbourhood aims at improving binary statistics, identifying very low-mass and substellar companions, finding systems suitable for dynamical mass determination, and establishing a sample of M dwarf binaries suitable for future astrometric exoplanet searches with GRAVITY at the VLT Interferometer. The final observing run for this programme is scheduled for Jan/Feb 2010. A third observing programme surveys transiting exoplanet host stars with the aim of identifying close binary companions. If unresolved, such binary companions bias the determination of planetary parameters from the light curve (see, e.g., Daemgen et al., 2009, for first results obtained with the Northern AstraLux camera). A number of previously unrecognised binary companions were indeed discovered with AstraLux Sur, and the data are currently being analysed.

Lucky future!

Two new science projects planned for Period 84 are a study of the binary properties of massive young stars in the Carina Nebula, and the analysis of the light curves of eclipsing binaries located in the centres of starburst clusters. We are also very open to collaborations with other research groups who want to take advantage of the high angular resolution and fast time resolution facilitated by Lucky Imaging at the NTT. The NTT on La Silla is the only readily accessible place in the Southern Hemisphere for applying the Lucky Imaging technique under almost optimal conditions.

With the availability of the so-called burst mode offered by quite a few VLT instruments (e.g., VISIR, NACO and ISAAC, see Richichi, 2008), individual readouts, rather than simply the co-added frames, can now be stored and made available to the astronomer for post-processing. Thus Lucky Imaging-like procedures such as image selection and re-registration of individual frames before co-adding are becoming more and more common and help to further optimise angular resolution and sensitivity of observations. NACO observations in *J*- and *H*-bands benefit most, as the decreasing atmospheric coherence time at shorter wavelengths makes it harder for the adaptive optics system to keep up with the atmospheric variations. Experiments carried out with a Lucky Imaging camera in combination with adaptive optics at the Palomar 5-metre telescope (Law et al., 2009) appear highly promising. A Lucky Imaging camera like AstraLux Sur attached to the visitor port of the VLT NAOS instrument could achieve an angular resolution of 20 mas at a wavelength of 900 nm.

References

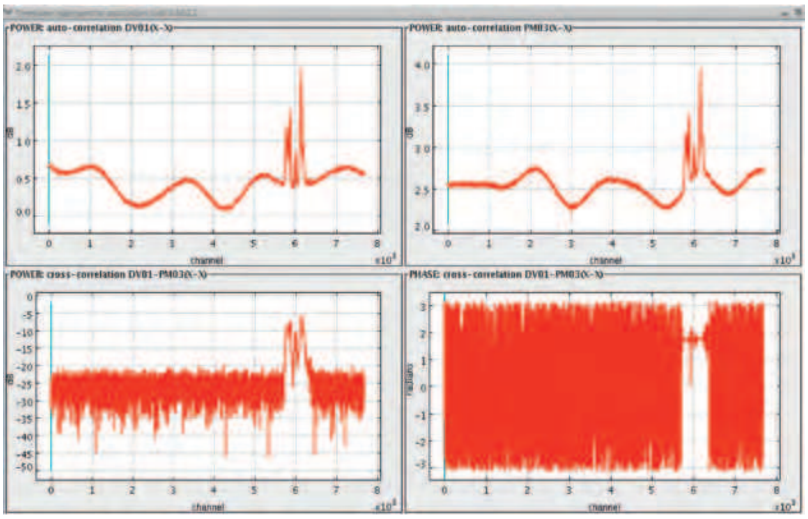
Baldwin, J. E. et al. 2001, A&A, 368, L1
Daemgen, S. et al. 2009, A&A, 498, 567
Fried, D. L. 1978, JOSA, 68, 1651
Hecquet, J. & Coupinot, G. 1985, Journal of Optics, 16, 21
Hormuth, F. et al. 2007, A&A, 463, 707
Hormuth, F. et al. 2008, SPIE, 7014, 48
Law, N. et al. 2009, ApJ, 692, 924
Richichi, A. 2009, The Messenger, 135, 32
Tubbs, R. N. 2003, PhD Thesis, University of Cambridge

Links

[1] http://www.mpia.de/ASTRALUX/Publications.html

Credit: L. Knee/ALMA

Two ALMA antennas at the Operations Support Facility (OSF) pointing to the same source in the sky.



Following the initial success of the first fringes between two ALMA antennas at the OSF (see release ESO 18/09), the system has been undergoing further tests, software upgrades and debugging. In early June 2009, stable fringes under computer control were routinely achieved. An example of the tests on an SiO maser source is shown. The top two panels show the autocorrelation signal from each of the two antennas and the bottom panels show the amplitude and phase of the cross-correlation signal.

Fringes with three telescopes, including closure phase, at the 5000 m high site are expected toward the end of the year. This event will be a major milestone toward the first Early Science observations with sixteen telescopes in 2011.