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NOTES TO CONTRIBUTORS

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The Managing Editor of 'THE OBSERVATORY'
16 Swan Close, Grove
Wantage, Oxon., OX12 0QE
Telephone +44 (0) 1235 767509
Email: manager@obsmag.org
URL: www.obsmag.org

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A REVIEW OF ASTRONOMY

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D. J. STICKLAND

R. W. ARGYLE

S. J. FOSSEY

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PISCO2: THE NEW SPECKLE CAMERA FOR THE NICE 76-CM REFRACTOR

By R. Gili, J.-L. Prieur§, J.-P. Rivet*, F. Vakili‡, L. Koechlin§ and D. Bonneau‡*

** Université de Nice Sophia Antopolis*
§ UPS–OMP & CNRS–IRAP, Université de Toulouse
‡ Observatoire de la Côte d'Azur

We present the new speckle camera *PISCO2*, made in 2010–2012 for the 76-cm refractor of Côte d'Azur Observatory. It is a focal-plane instrument dedicated to the observation of visual binary stars using high-angular-resolution speckle-interferometry techniques partly to overcome the degradation caused by atmospheric turbulence. Fitted with an EMCCD detector, *PISCO2* allows the acquisition of short-exposure images that are processed in real time by our specially designed software. Two Risley prisms are used for correcting the atmospheric dispersion. All optical settings are remotely controlled. We have already been able to observe faint, close-binary stars with angular separations as small as 0″·16, and visual magnitudes of about 16. We have also measured some particularly difficult systems with a magnitude difference between the two components of about 4 magnitudes. This level of performance is very promising for the detection and study of large sets of yet unknown (or partly measured) binaries with close separation and/or large magnitude difference.

Introduction

This paper presents the new speckle camera *PISCO2* (*Pupil Interferometry Speckle camera and COronagraph*, 2nd version) made in 2010–12 for the 76-cm refractor telescope (*Grand Equatorial de l'Observatoire de la Côte d'Azur*, hereafter L76, see Plate 1). *PISCO2* is a focal-plane instrument (see Plate 2) the purpose of which is to provide high-angular-resolution images using speckle-interferometry techniques. Those techniques allow us partly to overcome the degradation caused by atmospheric turbulence[1].

PISCO2 is a simplified version of *PISCO* that was developed in 1993 for the 2-metre *Bernard Lyot* telescope (Pic du Midi, France). *PISCO* is a multi-purpose focal instrument with many observing modes: pupil interferometry, pupil-mask aperture synthesis, SCIDAR atmospheric-turbulence measurements, grism spectroscopy, coronagraphy, and Shack–Hartmann wave-front sensing. A detailed presentation can be found in ref. 2. Since 2004 *PISCO* has been operated on a dedicated 1-m telescope in Merate (Brera Observatory, Italy) (see, *e.g.*, refs 3 & 4).

The optical design of *PISCO2* (Plate 2) is similar to that of *PISCO* but the observing modes are reduced, and are mainly limited to speckle observations. Indeed, *PISCO2* was specially designed for the observation of visual binary stars. Associated with an electronic detector, it allows the acquisition of enlarged short-exposure images exhibiting 'speckles'. Those images can then be processed as first suggested by Labeyrie[1], to provide high-angular-resolution information.

PISCO2 was specially designed for the Nice 76-cm refractor belonging to Observatoire de la Côte d'Azur (OCA). Built in 1887, when it was the largest refractor in the world, this famous telescope has a free aperture diameter of 74 cm and a focal length of 17·89 m. It is one of the largest refractors still in operation in the world. It has mainly been devoted to binary observation since its construction. The good quality of its optics makes Airy rings clearly visible when the seeing is good, and that happens very frequently, despite the proximity to the city of Nice.

Paul Couteau[†] is probably the most famous astronomer who has used it. He was the architect of the renovation of the refractor from 1965 to 1969[5], and many binaries from his impressive catalogue[6] were measured with that telescope[7,8]. When he retired in 2000, one of his closest collaborators, R. Gili (hereafter RG), decided to continue the long story of binary observations with the L76. Although he was an experienced binary-star observer with a filar micrometer, RG wanted to use more modern techniques, such as precise binary measurements on short-exposure CCD images that he had already obtained in collaboration with other colleagues[9–12].

For this new operating mode, it soon appeared that the L76 needed a serious revision and that a specially designed speckle camera was needed for improving the efficiency and quality of the observations. The 76-cm lens was then dismounted, thoroughly cleaned, and the two (crown and flint) components were fitted into a new improved mechanical mount. The dome motorization was thoroughly revised, both the electronics and the mechanics.

In 2008, two webcams were fitted to the existing magnifying optics of the hour angle and declination circles to allow their reading from a dedicated control computer. This allowed the observer safely to control the telescope while remaining seated in front of a control computer. Before this modification, for pointing at any object with the telescope, the observer had to move to each

† Died 2014 August 28.

of the two co-ordinate circles and then climb on top of a ladder to view the star in the finder. Obviously, this could be dangerous in the darkness, especially when the observer started getting tired and feeling sleepy! Owing to the great length of the telescope (about 18 m), this was particularly dangerous when the telescope was pointing to low-elevation targets. A few months later, a new ANDOR DV885 camera was acquired for speckle observations, and replaced the ANDOR LUCA camera that was formerly used for that task. That ANDOR LUCA camera was installed on the Zeiss 25-cm finder, and was thus able to transmit field images to the control computer. This happened to be a decisive improvement to the pointing procedure, and since then both the L76 telescope and its focal instrumentation have been operated from this computer by a single observer.

Focussing the telescope was another hazardous operation, especially for observations made by a single observer (by far the most frequent case). For CCD or EMCCD observations, the observer had to climb on the top of a large step-ladder to actuate the big focussing hand-wheel, then go down to check the quality of the CCD image on the computer screen. This had to be done a few times until satisfactory focussing was achieved. Furthermore, this operation had to be done in total darkness, which was necessary to avoid saturating the camera.

The few thousands of measurements published by Gili & Agati[13] and Gili & Prieur[14] were obtained in those difficult conditions. Indeed, the original focussing system was part of the L76 mechanics and could not be motorized easily without a thorough modification of that historical instrument. Consequently, an important specification for the design of *PISCO2* was to include a remote-control focussing capability.

Introduction to PISCO2

The decision to build a new speckle camera for the L76 was taken in 2009. The main idea was to ease and speed up the observations while extending the observable domain to lower-elevation targets. The basic constraints were simplicity, lightness, small overall dimensions, and low cost. The last constraint was rather severe since most of the expenditure had to be covered by personal funds. For this design, we profited by our experience in binary-star observations with the L76 and with *PISCO* on other telescopes.

PISCO2 was made entirely at OCA between 2010 and 2012. Most of the mechanical parts were machined in the OCA workshops. When possible, complete manufactured units were integrated into *PISCO2* to reduce the development time and the cost. For example, that was the case for the remote-control units dedicated to the motorized focussing or the angular control of the Risley prisms.

Optical design

The optical layout (see Plate 2) is similar to that of *PISCO*[1]. An achromatic lens L1 of focal length F_1 is placed at a distance F_1 from the primary focal plane of the telescope. This lens thus creates a collimated beam which is used for placing the Risley prisms and the filters. A second achromatic lens L2 focusses this parallel beam onto the image plane of the detector. A retractable mirror and a set of two lenses (L3 and eyepiece) enable a visual inspection of the images. The Risley prisms are located very close to the pupil plane. Unlike *PISCO*, there is no field lens in the focal plane of the telescope. This improves the overall transmission, but imposes a longer distance for the collimated beam.

PISCO2 can use different detectors, which may have different pixel sizes. The adaptation can be done by changing the lens L1, and choosing its focal length accordingly. For instance, two L1 lenses of 50- and 100-mm focal length have been used for the ANDOR DV897 and DV885 detectors, respectively.

The available filters are the IRC (IR-cut), which is a low-pass filter rejecting all wavelengths above 700 nm, the Schott BG39, which has a band-pass between 350 and 600 nm, and the AF (anti-fringe or *V*-block), which has a band-pass 450–650 nm; the AF filter considerably reduces the secondary spectrum of the 76-cm refractor, with no significant loss of energy in the *V* band. When combined with the transmission of the lenses and the quantum-efficiency response of the detector, the resulting transmission curve of those filters is close to a standard *V* filter with a maximum around 570 nm.

Most optical settings of *PISCO2* can be remotely controlled with a computer including focussing, filter selection, and Risley-prism correction. Motorized focussing and filter-wheel selection are controlled by ASCOM interface programs provided by the corresponding manufacturers. Focussing is driven by a stepping motor whose step corresponds to a translation of 4 μm, with a full range of 40 mm. Risley prisms can be set by the THORLABS program which works with a USB interface.

Description of the detectors

The *PISCO2* instrument was successively fitted with two EMCCD detectors from ANDOR Technology: an iXON DV885 and an iXON DV897 (see ref. 15). We first used the DV885 belonging to RG, which is equipped with a front-illuminated EMCCD chip. We then used the DV897 belonging to FV, which is more recent and has a better performance. It has a back-illuminated EMCCD with a higher quantum efficiency and is fitted with a more elaborate cooling system. Another advantage of the DV897 is its higher reading frequency.

The main characteristics of the two detectors are given in Table I. For each one, we indicate its full format in pixels (Col. 2), the pixel size in μm (Col. 3), the digitization depth in Col. 4, *i.e.*, the number of bits per pixel used for encoding the output values, the maximum frequency rate (Col. 5) used for reading out the pixel data, the theoretical quantum efficiency of the detector (Col. 6), and the cooling temperature that was used during our observations (Col. 7).

The quantum efficiency values in Col. 6 of Table I are those given by the EMCCD chip constructor for wavelengths in the range 550–720 nm. The overall effective efficiency is unfortunately much smaller. With *PISCO* in Merate (Italy), we have made some comparative tests in 2011 with the iXON DV885 and the *PISCO* ICCD cameras[4]. For speckle observations, the DV885 was roughly equivalent to the ICCD. Note that the ICCD camera is fitted with an *R*-photo-cathode amplifier whose quantum efficiency is only 7%!

TABLE I

Main characteristics of the ANDOR iXON EMCCD cameras

Name	*Format (pixels)*	*Pixel size (μm)*	*Digitization (bits)*	*Read freq. (MHz)*	*Quantum Eff. (%)*	*Max. cooling T. (°C)*
DV885	1004 × 1002	8 × 8	14	27	60–65	−70
DV897	512 × 512	16 × 16	14	10	80–92	−90

PLATE I

PISCO2 on the Nice 76-cm refractor (L76)

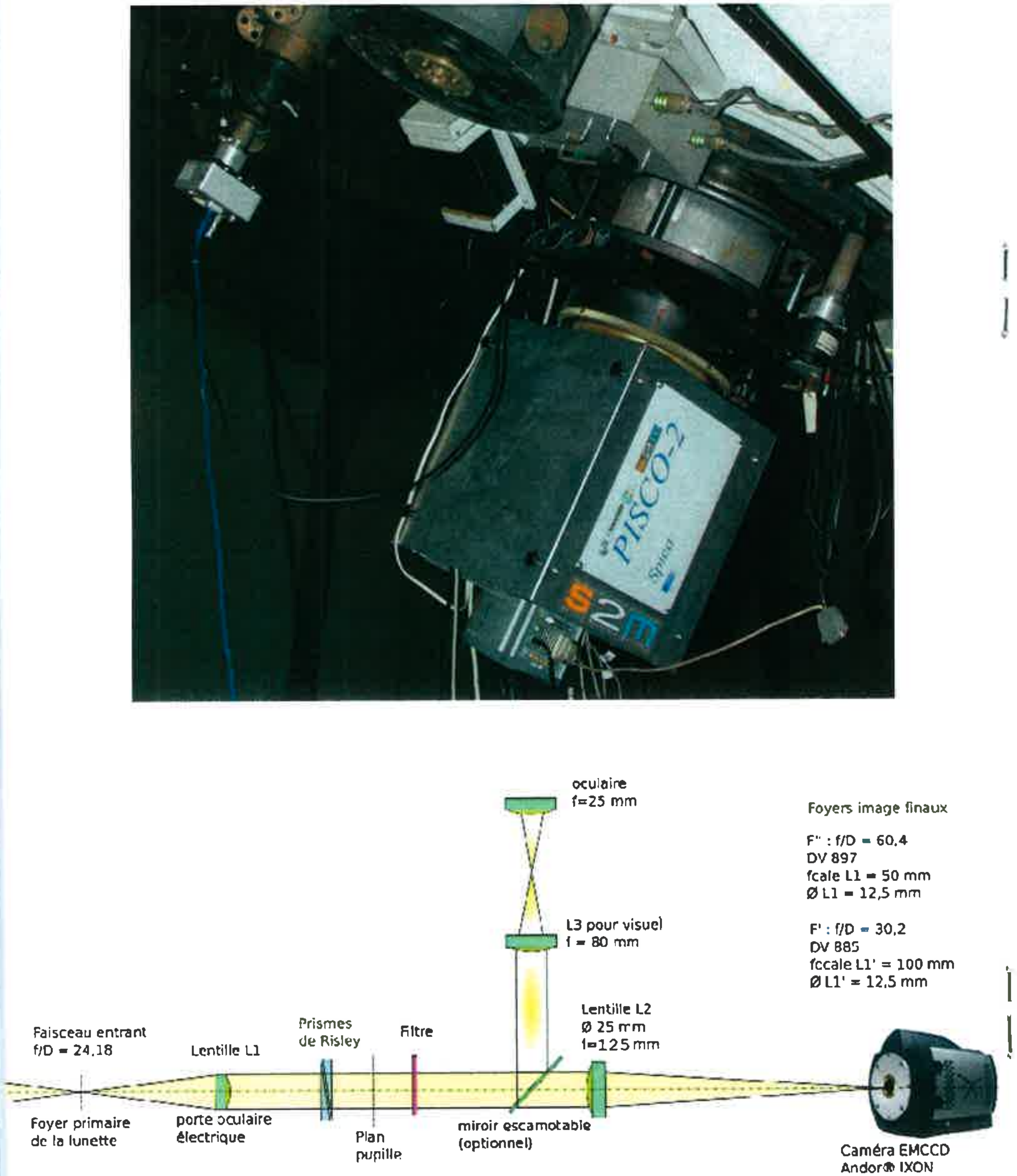

PLATE 2

PISCO2 with the ANDOR DV897 detector (top) and optical layout (bottom)

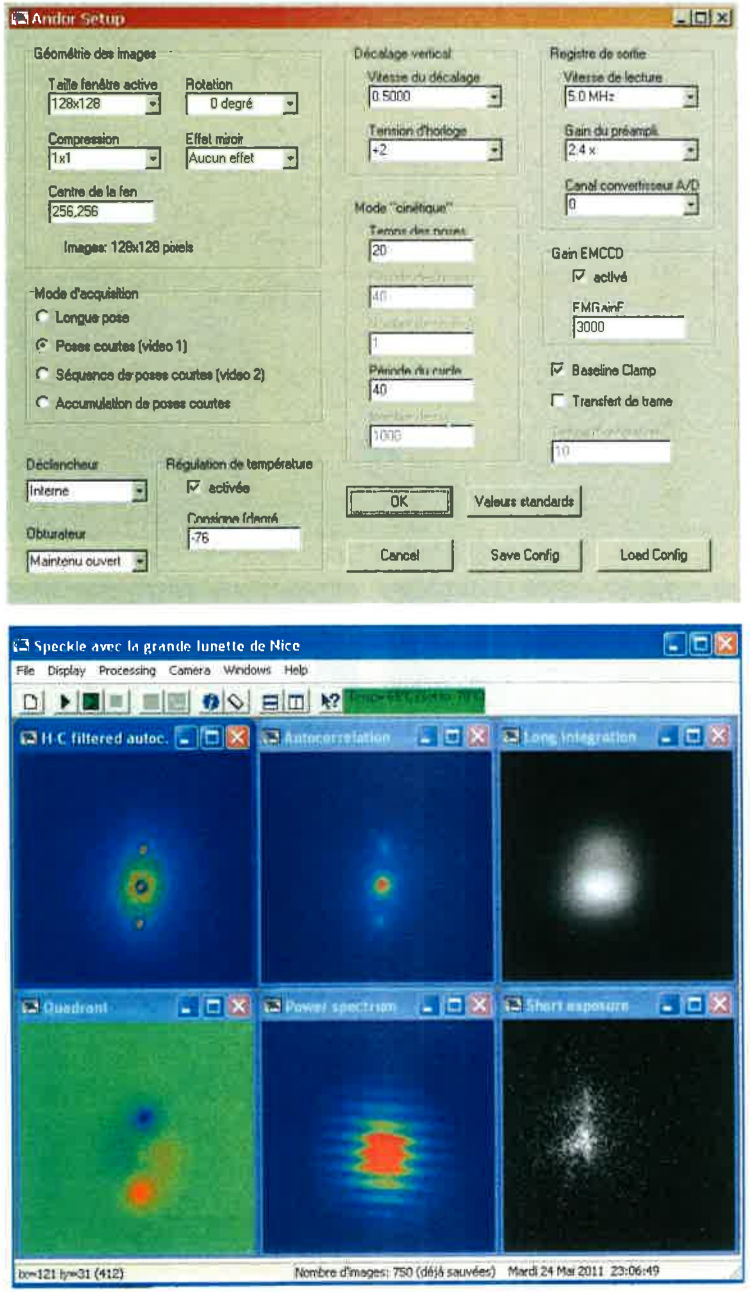

PLATE 3

Program BUILDSPECK1 used for the data acquisition with ANDOR cameras and real-time processing. Top: camera setup. Bottom: example of image processing of the binary star BU1273 ($\rho = 1''\!\cdot\!3$, $V = 9^{m}\!\cdot\!6$, $\Delta V = 1^{m}\!\cdot\!3$).

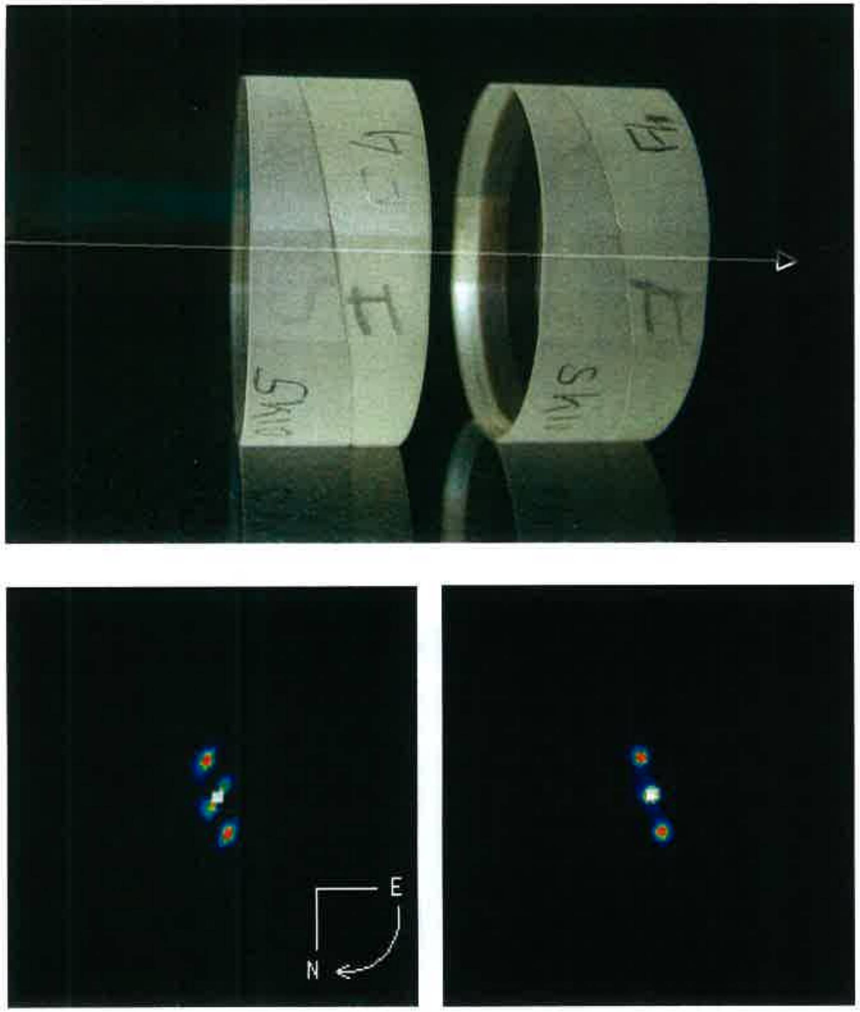

PLATE 4

Set of the Risley prisms used for correcting the atmospheric dispersion (top). Bottom left: uncorrected autocorrelation of the binary star A2724 ($\rho = 0''\cdot8$, zenith distance: 42°). Bottom right: autocorrelation obtained with the good orientation of the Risley prisms (instrumental setup: L76, *PISCO2*, and the ANDOR DV897 camera).

For both detectors, the image transfer is performed through a dedicated link between the detector and a CCI-22 frame-grabber board installed on a PCI slot of the acquisition computer, which allows a reading frequency as high as 27 MHz. This would correspond to an acquisition rate of 27 full-size images per second. In practice, we used a lower readout frequency (5·13 MHz) to reduce the noise in the images. Those detectors can be used in EM mode, which reduces the read-out noise of the output register to less than one electron.

We wrote a specially designed program (BUILDSPECK1, see Plate 3) for handling the data acquisition of those two detectors. This program controls the electronic settings and the basic functions of the EMCCD detectors. It also performs real-time processing of speckle-interferometry observations.

Exposure times of elementary frames are set in the range 20–30 ms for speckle observations. The standard format of the acquisition window is 128 × 128 pixels which corresponds to a field of view of $9''\cdot5 \times 9''\cdot5$ for the DV897 camera. For faint objects or wide pairs, a wider field of 256 × 256 pixels on the detector can be used with a binning factor of 2 × 2 which thus amounts to 128 × 128 pixels for the elementary frames. The EM gain is generally set to values of about 170–200 and 3000 for the DV885 and the DV897, respectively. To avoid saturation on bright objects, the EM gain can be reduced or even put to 'off', which corresponds to observing in conventional CCD mode.

Correction of the atmospheric dispersion with Risley prisms

For ground-based observations of astronomical objects, the atmosphere behaves like a dispersive prism[16]. Polychromatic images are spread into a small vertical spectrum. This effect can be neglected for observations close to the zenith, but is very strong at low elevations, and can severely degrade the angular resolution. For instance in the visible, for a $\Delta\lambda$ = 250-nm band-pass centred at λ = 500 nm, the typical atmospheric dispersion is $\Delta\theta = 1''$ for an elevation $h = 60°$ and $\Delta\theta = 2''$ for $h = 30°$.

PISCO2 contains an atmospheric-dispersion corrector to circumvent this problem. This corrector is similar to that of *PISCO*[2] and is based on Risley prisms[17,18]. They consist of two identical sets of prisms (see Plate 4) that can be rotated to produce a chromatic dispersion tuneable both in amplitude and direction. Each set is made of two prisms that have different indices and roof angles, and that are glued together in an upside-down position.

As with *PISCO*, we have used the same combination of Schott glasses (F4, SK10) that was used at Kitt Peak in the combinations proposed by Wallner & Wetherel[18], and which are close to the atmospheric dispersion curve. The F4 + SK10 combination has the advantage of low cost and was efficient enough for our purpose.

The Risley prisms of *PISCO2* have been designed to have a null mean deviation, and a dispersion allowing atmospheric correction from the zenith down to an elevation of 30°, when using the DV897 detector. The F4 and SK10 prisms have a roof angle of 10°·0 and 9°·92, respectively. The tolerance on the roof angle is 6 arcmin, and the surface accuracy is $\lambda/4$ (for λ = 550 nm). Those specifications lead to a reduction of the residual dispersion down to a level smaller than $0''\cdot01$ for any object located at an elevation larger than 30°, with the AF filter (450–650-nm band-pass). That is much smaller than the diffraction limit of $0''\cdot16$ of the 76-cm refractor.

During the observations, a specially designed program (PISCO2_RISLEY.CPP) computes the elevation of the star and the atmospheric dispersion inferred from models[19]. The Risley prisms are then rotated with the THORLABS remote-control program, so that their total dispersion has the same magnitude as the atmospheric dispersion and an opposite direction. The observations have shown that the correction is very good (see Plate 4), even for objects whose declination is as low as $-7°$, which is the lower pointing limit for the present instrumentation setup, imposed by the camera cable length.

Scale calibration with a grating mask

The on-sky pixel scale of the whole instrument (telescope and *PISCO2*) can be calibrated in an absolute manner with a grating mask placed in front of the refractor objective lens. This is the method used for calibrating *PISCO* in Merate, as described in detail by Scardia *et al.*[3]. We present here the procedure we followed in 2012 September for calibrating the scale of the DV897 detector.

A grating mask was mounted on the entrance baffle of the telescope. This mask was originally designed for the calibration of the OCA 50-cm refractor. It has a diameter of 50 cm and a period of $p = 22{\cdot}43 \pm 0{\cdot}10$ mm. To obtain measurements with high precision, we used a narrow-band filter, centred on $\lambda = 570$ nm, with a bandwidth of 10 nm. The corresponding period of the diffraction pattern was then $\lambda/p = 5''{\cdot}241$. For this calibration, we observed the single star ε Leo. The measurements were made on the mean of a series of a few 1000-image data cubes. The equivalent focal length with *PISCO2* and the DV897 detector was found to be $44{\cdot}66 \pm 0{\cdot}2$ m and the scale $0''{\cdot}0739$ per pixel.

The 76-cm refractor has actually a free aperture of 74 cm. The corresponding diffraction limit λ/D is $0''{\cdot}16$ with $\lambda = 570$ nm. The sampling of the detector mounted on *PISCO2* is thus less than half this diffraction limit for $\lambda = 570$ nm and so is compatible with the Nyquist–Shannon criterion, and therefore allows measurements down to the diffraction limit.

The calibration of the origin of the position angles was done by recording star trails caused by the diurnal motion. We used the largest available field for this purpose, which was $53'' \times 40''$ with the DV897.

Conclusion

The first observations have shown that *PISCO2*'s performance has reached the initial goal. Fitted with remote-control components such as a filter wheel, a motorized focussing system, and an atmospheric-dispersion corrector, this instrument is very easy to operate.

PISCO2 is dedicated to the observation of visual binary stars. In the last few years, it has already permitted us to obtain numerous measurements, with an average rate of about 2100 objects/yr. With the DV897 detector, we have been able to observe faint, close-binary stars with angular separations as small as $0''{\cdot}16$ and visual magnitudes of about 16. We also have measured some particularly difficult systems with a magnitude difference between the two components of about 4 magnitudes.

In future, we intend to use *PISCO2* for observing large sets of yet-unknown (or partly measured) binaries with close separations and/or large magnitude differences, many of which could not be measured by space missions. *PISCO2* may thus provide a significant contribution to stellar physics.

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STELLAR MULTIPLICTY IN THE σ ORIONIS CLUSTER: A REVIEW

By José A. Caballero
Centro de Astrobiología (CSIC–INTA), Madrid, Spain

The nearby, young, extinction-free σ Orionis cluster is acknowledged as a cornerstone for studying stellar and sub-stellar formation and evolution, especially at very low masses. However, the relatively limited knowledge of multiplicity in the cluster is dispersed among numerous papers and proceedings with very different aims and, therefore, is difficult to apprehend even for researchers in the subject. Here, I review comprehensively the sexdecuple system σ Ori in the central arcminute, and all close ($\rho = 0{\cdot}4$–4 arcsec) and wide ($\rho > 4$ arcsec) binaries, triples, hierarchical multiples, and spectroscopic binaries in the cluster that had been reported in the literature up until 2014. I conclude with a brief enumeration of the steps that should be taken in the near future for gaining a clear picture of the multiplicity in the σ Orionis cluster.