A facility to evaluate the focusing performance of mirrors for Cherenkov Telescopes

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Abstract

With the advent of the imaging atmospheric Cherenkov technique in late 1980’s, ground-based observations of Very High-Energy gamma rays came into reality. Since the first source detected at TeV energies in 1989 by Whipple, the number of high energy gamma-ray sources has rapidly grown up to more than 150 thanks to the second generation experiments like MAGIC, H.E.S.S. and VERITAS. The Cherenkov Telescope Array observatory is the next generation of Imaging Atmospheric Cherenkov Telescopes, with at least 10 times higher sensitivity than current instruments. Cherenkov Telescopes have to be equipped with optical dishes of large diameter – in general based on segmented mirrors – with typical angular resolution of a few arc-minutes. To evaluate the mirror’s quality specific metrological systems are required that possibly take into account the environmental conditions in which typically Cherenkov telescopes operate (in open air without dome protection). For this purpose a new facility for the characterization of mirrors has been developed at the labs of the Osservatorio Astronomico di Brera of the Italian National Institute of Astrophysics. The facility allows the precise measurement of the radius of curvature and the distribution of the concentrated light in terms of focused and scattered components and it works in open air. In this paper we describe the facility and report some examples of

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its measuring capabilities from recent tests campaigns carried out performed on mirrors devoted to Cherenkov telescopes.

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1. Introduction

Since the first detection of the Very High-Energy (VHE) $\gamma$ photons from the Crab Nebula in 1989 using the imaging atmospheric Cherenkov technique [1], VHE $\gamma$-ray astronomy is making fast progress. Almost 160 sources have been discovered and the number is increasing year by year. The recent advances in $\gamma$-ray astronomy have shown that the 10 GeV – 100 TeV energy band is crucial to investigate the physics in extreme conditions. Ground-based experiments using Cherenkov photons produced in air represent a cost-effective way to implement observations in this band. In order to achieve a high sensitivity, Imaging Atmospheric Cherenkov Telescopes (IACTs) need huge collecting areas that can be obtained by combing several mirrors to be optically qualified. At present, H.E.S.S. [2], VERITAS [3] and MAGIC [4] are the state of the art of such ground-based experiments. The Cherenkov Telescope Array (CTA) represents the future generation of IACTs [5], with the goal of increasing sensitivity by a factor of 10 with respect to the present best installations and a total mirror area of the array of the order of $10^4 \text{ m}^2$. The CTA observatory is a project designed by a worldwide consortium that will make use of well demonstrated technologies of present generation Cherenkov telescopes as well as new ad hoc developed solutions. CTA will be based on telescopes with different sizes installed over a large area. At its southern site e.g. 70 Small Size Telescopes (4 m primary mirror diameter), 20 Medium Size Telescopes (12 m) and 4 Large Size Telescopes (23 m) are envisaged to be implemented in order to cover a broad spectral energy range from a few tens of GeV up to more than 100 TeV.

The mirrors for Cherenkov telescopes are in general formed by many reflecting segments to be assembled together in order to mimic the full size mirror of
a given telescope. So far, just single reflection telescopes have been used with Davis-Cotton or parabolic layouts. In both cases the segments are in general designed with a spherical geometry and proper radius of curvature.

The mirrors for CTA [6] are characterized by a good reflectivity performance (in the 300−550 nm energy band) but, at the same time, require angular resolution of typically a few arc-minutes, i.e. about two orders of magnitude less if compared to mirrors for optical astronomy. Despite the quite modest requirement, the distribution of the concentrated light of the mirror segments that populate the dish of the telescopes is an important parameter in the performance of such telescopes. In fact, it has a direct impact on the measured energy and flux of gamma rays from the observed sources; and moreover in the determination of the energy threshold of the instrument.

Optical properties, reflecting surfaces and mechanical structure are designed aiming at obtaining the best compromise between costs and performances. Costs of the industrial production have to be sufficiently low but they have to fulfill the requirements for Cherenkov optics. Production and testing of such mirrors need a full characterization thoughgth appropriate facilities with suitable set-up for the testing of the prototypes and to perform the quality control during the production phase in order to cross-calibrate mirrors from different industrial pipelines. CTA observatory is planning to take advantage of some calibration facilities to perform this kind of job. There are already optical calibration facilities available in Tübingen (Germany) [7], Saclay (France) [8] and San Antonio de los Cobres (Argentina) [9].

Another approach which is now widely being used for the CTA mirrors is based on the deflectometry method. It consists in observing the distortions of a defined pattern after the reflection by the examined surface and from them to reconstructing the surface shape. A facility based on this concept has been developed for CTA at Erlangen University [10]. A variant of this method has been implemented at the Osservatorio Astronomico di Brera of the Italian National Institute of Astrophysics (INAF-OAB) to test and characterize the mirrors for the ASTRI SST-2M telescope proposed for the CTA [11]. A similar approach
was previously used also for the characterization of mirrors for ring imaging Cherenkov counters [12].

In this framework, a new optical facility has been implemented by INAF-OAB. It has been designed and developed to test spherical mirrors with curvature radius in the range of 30 - 36 meters. The facility is a system working in open-air, so that accurate evaluation of the main parameters can be achieved under different environmental condition. Moreover this facility is able to accurately investigate the scattering effect by means of an high sensitivity large format CCD camera. Several light sources with different spectral emissions are also available. In this paper we present the facility and discuss its measuring capabilities.

2. Apparatus description

The facility measures the focused light of the mirrors using a simple optical configuration. Since mirrors have a spherical surface profile, a spherical wavefront can be used to generate the focal spot from the radius of curvature. This setup is commonly referred to 2-f method, as sketched in Figure 1. To retrieve the focal length $f$ of the mirror under test the well known formula for the conjugate points can be used:

\[
\frac{1}{f} = \frac{1}{p} + \frac{1}{q}
\]

where $p$ is the distance of the object (e.g. a light source) from the mirror and $q$ is the distance of its image from the mirror. Assuming spherical mirrors (i.e. the typical geometry of the mirror segments used by Cherenkov telescopes), once the light source is positioned at a distance of $p = 2 \cdot f$, then the image can be seen at the same distance $q = p$, as the incoming rays hit the surface of the mirror perpendicularly and are reflected back along the incoming direction – this distance being the radius of curvature $r = 2 \cdot f$ of the mirror under test.

The above mentioned optical setup is the simplest one to check the imaging quality of the mirrors properly, however it requires a long baseline. The only
possibility to provide a setup with a shorter length would be to produce parallel light rays which hit the surface and get focused at a distance $q = f$ from the mirror. The problem with the 1-f setup is that one needs a light source emitting parallel rays which illuminate the whole mirror facet (typically larger than 1 m²), which would be much harder to realize.

The equipment needed to perform the test discussed here is schematically based on a light source, a detector and a dark room which shall be large enough to host the baseline. Our facility is indeed composed of two stages. The stage #1 is a mirror’s support structure mounted on a long travel rail. The mirror’s support and the rail are motorized in order to allow the alignment of the mirror under test. Figure 2 shows a rendering of the design study performed on this part and a photo of it. The stage #2 is located into a control room where a compact bench hosting a light source and a detection unit takes place. This system is motorized, thus enabling the possibility to scan the focusing plane. A control-command unit (i.e a desktop computer), an electrical cabinet and storage space complete the apparatus.

The facility is installed at the Merate (Lecco, Italy) site of INAF-OAB. It is based on a long baseline to fit mirrors with radii of curvature ranging from 30 meters up to 36 meters. This choice was driven by the fact that most of the current and future Cherenkov telescopes (e.g. H.E.S.S., MAGIC and CTA) make use of mirrors with similar characteristics. Moreover, the stage #1 is installed

Figure 1: Schematic representation of the 2-f method measurement setup.
outdoor, thus giving the possibility to study also the mirror performance for different thermal conditions, i.e. mimicking the real operative configuration of the mirrors mounted on a real Cherenkov telescope.

As previously stated, this method is widely used for the characterization of Cherenkov telescopes mirrors. However the facility presented in this paper has a few peculiar characteristics that, combined together, make it unique innovative system very useful to calibrate the mirrors of future IACTs, as e.g. those of CTA. These features are:

- the entire system has been designed to be user-friendly. To this regard, the manipulator hosting the mirror and the support of the detector are fully robotized. They can be easily automated to run long-time acquisitions without the on-site intervention of the operators;

- the stage #1 is installed in open air in order to simulate as much as possible the environmental conditions of a Cherenkov telescope;

- the direct imaging on a large format CCD camera (about 70 mm in diagonal) mounted on a 2-axis motorized stage. This configuration is an high sensitivity setup that allows to catch diffused photons on a large area and perform a correct evaluation of the Encircled Energy function of the mirror. This kind of studies is of great importance for the evaluation of the
large deviations from the ideal focal position due to the scattering from the micro-rough profile of the mirror.

In the following subsections we report a detailed technical description of the two stages.

2.1. The stage #1, outdoor

The outdoor stage has three main subsystems: a rail, a mirror’s support and an electrical cabinet. It has been conceived and designed at the INAF-OAB. The engineering, realization and installation activities were performed by the Officina Opto-Meccanica Insubrica and Automation One companies [13].

![Figure 3: Detailed view of the rails subsystem. It is composed of the two 6 m long linear guides, a carriage and the drive system.](image)

The rails subsystem. It is composed of a couple of 6 m long stainless steel linear guides. The drive system uses one brushless motor from Emerson Industrial Automation. The motor has an IP code 65 and can work in open environment, it is further protected by means of carters to prevent against the accumulation of water or snow. Its rear shaft is equipped with an absolute rotary 16 bit
encoder with EnDat interface. The front side of the motor shaft has a reduction
gearbox linked to the main shaft. This last shaft brings the motion to both the
linear guides and is then distributed to the carriage through toothed belts. This
solution turns to be quite economic. It is able to ensure a positioning of the
carriage well below 1 mm on the full travel range of the rail, because the position
loop is closed through the reading of the encoder. To this regard, the actual
position of the carriage with respect to the indoor stage of the facility is recorded
by an external laser distance meter, it is suitable for outdoor measurements over
large distances. This guarantees a knowledge of the optical baseline within a
few mm over more than 30 m.

The rail subsystem is mounted over an optical bench made of aluminum
profiles. Figure 3 details the rail subsystem.

The mirror support. The mirror support is shown in Figure 4. It is installed over
the carriage and is designed to ease the mounting and dismounting operation
of the mirror under test as well as to facilitate the alignment of the mirror
itself over the optical baseline of the entire facility. It can be divided into
two subsystems: the mechanical jig and the motorized holder. The jig can be
horizontally reclined to execute the loading and unloading of the mirror. This
movement is performed manually by means of a small steering wheel and it is
supported by gas springs. Two stainless steel linear guides with toothed belts
are installed (the same kind used for the rails subsystem). When the support is
standing vertical, it can be blocked to prevent undesired movements.

The holding for mirrors is obtained by means of an adjustable system of
aluminum beam profiles and soft clamps. This holding system can be moved
in such a way the mirror tilts with respect to two axes. The drive system
adopts the same solution of the rails, being based on brushless motors equipped
with absolute encoders, one for each axis. However, in this case the motion is
achieved through linear actuators with re-circulating ball screws. Again, this
solution has been adopted since it represents a good trade-off between cost and
Figure 4: Detailed view of the mirror’s support subsystem. Panel (a) shows the support itself, the box in mounting/dismounting configuration; panel (b) shows the holder with a mirror’s template; panel (c) shows the reference axes for the three motorized motions of the outdoor stage of the facility.

performance. It guarantees a wide angular range for alignment purposes of 5° along the x axis and 10° along y, with a resolution better than 12 arcsec. This resolution corresponds to a translation of about 1.9 mm at the indoor position with the carriage at 33 m (half of the rails traveling length). The mirror’s support can be loaded with mirrors up to 45 kg having different tile’s shapes (e.g. squares, hexagons, rounds) up to 1.5 meters in diameter.

The outdoor electrical cabinet. The electrical cabinet is made of a stainless steel water tight box for external applications. It is equipped with a thermoregulation system composed by heaters, coolers and dryers controlled by a hydro-thermostat to keep the electronics within its working conditions. This solution ensures the functionality of the facility within a wide range of environmental conditions.

In addition to the thermoregulation system, the cabinet hosts the drivers to pilot the three motors of the motion system, an ethernet switch and a gateway to handle the input/output digital signals, working under the Modbus TCP/IP communication protocol. The cabinet receives the power from the main grid of the Observatory through a dedicated line carrying 400V. The power is handled by the system to provide 220V and 24V lines that are distributed to all the devices of the outdoor stage whether they are resident in the cabinet or not. A safety stop red push button is available for emergency handling. The cabinet is
equipped with a proper interface to connect a keypad to send motion commands to the system. Figure 5 shows a photograph of the cabinet.

Figure 5: Electrical cabinet on-board the outdoor stage. The drives, the ethernet switch, the I/O modules of the gateway and the thermostat are visible.

2.2. The stage #2, indoor

The indoor stage is based on three main subsystems: a light source, a photon detection unit and an electrical cabinet.

The light source. The light source is a compact device able to generate an appropriate wavefront of light for the measurements. Five ultra-bright LED sources are disposed in a pattern: an RGB LED is surrounded by a red (626 nm), a green (525 nm), a blu (470 nm) and a warm white LEDs. Any combination of LEDs can be switched on and off, as needed for the measurement. The choice of LEDs has been made as a compromise for their cheapness and safety of use versus the quality of the wavefront generated, with respect to laser generated one, in terms of light intensity, spatial distribution and emission angle. In fact, we
would like to point out again that the facility operates in open-air environment, where the access can not be easily restricted only to authorized personnel. The typical emission diagram of the LEDs used is shown in Figure 6(a), the cone angle is about 10°, with an intensity of about 12000 mcd. A filter wheel with logarithmic neutral filters permits to dim the light intensity and illuminate the mirror with a suitable light flux (see Figure 6(b)). The source is equipped also with a very low power laser beam for alignment purposes.

The detection unit. This unit is composed of a CCD camera and a long-range laser distance meter for outdoor applications. The laser meter gives the absolute measurement of the distance between the detector plane and the mirror. The device is a DISTO$^TM$ D8 model from Leica producer [14], with a declared precision better than ±5 mm up to 36 m. It is mounted on a tip-tilt stage to adjust its alignment toward the mirror’s support.

The CCD camera is used to detect the light reflected back from the mirror under test. It is a commercially available camera for astronomical applications from the Finger Lakes Instrumentation producer [15]. The model is PL4301E from the ProLine series characterized by low noise, high sensitivity and reso-
olution and deep cooling. The sensor mounted is a CCD Truesense KAF-4301 from ON Semiconductor Inc. producer [16]. It is a large format CCD with 2048 × 2048 pixels 24 μm side for a total diagonal of 70.7 mm. The camera is equipped with a 90 mm shutter to avoid any vignetting of the detector. A filter wheel can be mounted on top either to dim the incoming light or to select a particular wavelength, in case of need. The PL4301E has a thermoelectric cooling system capable to cool down the detector temperature to 50° below the ambient one (see Figure 7(d)).

The CCD camera has undergone a careful characterization in terms of gain (named also conversion factor $e^-/count$) and Read-Out Noise (RON), linearity, dark current and Charge Transfer Efficiency (CTE). The gain has been evaluated acquiring a series of images with increasing exposure times followed by another series with decreasing ones. For each image the variance is computed and plotted against the median counts of the image itself. The gain hence corresponds to the angular coefficient of the best fit line, while the RON is obtained by multiplying the gain and the mean value of the bias frame. Each image used is given by the mean of two subsequent acquisitions A and B, both corrected for dark and bias signals. This procedure guarantees to check both shot- and long-term variations of the camera.

Linearity and dark current are evaluated by varying the exposure time for a number of bright and dark acquisitions, respectively, and then taking the median value [17].

The CTE has been derived by the cosmic rays impacts detected after a 1800 seconds dark exposure. Cosmic rays impact the detector as stochastic events with casual angles and energy but they can be used to diagnose the CTE of the detector as suggested by A. Riess et al. [18].

All these parameters depend on the frame readout frequency that we call download speed. We report in Figure 7 the results for the 1 MHz high gain setup that is typically used. In table 1 the full set of calibration results are reported.

The detection unit is completed by a 2-axis stage to move around the CCD camera along the detection plane. The scan covers an area of 280 × 290 mm².
Figure 7: Plots derived from the CCD camera calibration activity: (a) gain and RON estimation, (b) linearity (c) dark currents for the 1 MHz high gain download speed setup and (d) evolution of the cooling during time.

Table 1: Analytical results of the CCD calibration for different download speeds.

| Download speed | Gain  | RON  | Dark currents | CTE    |
|----------------|-------|------|---------------|--------|
| 1 MHz high gain| 1.95699 | 10.8632 | < 0.03 | 99.999878 |
| 1 MHz high range | 12.6399 | 37.4377 | < 0.2 | 99.999731 |
| 1.7 Mpps high gain | 1.73786 | 13.0477 | < 0.3 | 99.999769 |

The motion is obtained by means of two belt-teethed linear guides equipped with hybrid bipolar high-torque stepper motors. The resulting resolution of the motion is 0.1 mm. The communication interface is through the CANopen protocol.

Figure 8 shows the system assembled and a close view of the CCD camera alone.
The indoor electrical cabinet. This cabinet is placed into the control room and routes all the I/O commands and communication signals between the computer and the outdoor stage. In fact, it manages a LAN type network with assigned static IPs to each device of the facility (e.g. the drives, the I/O units, the computer, etc.). Its main components are the ethernet switch and the gateway.

It has an independent 220V power line with respect to the outdoor cabinet. The main power is handled by the system to provide proper voltages to all its internal devices. A safety red push stop button is available for emergency handling.

Also this cabinet has the interface to connect a keypad to send motion commands to the system.

2.3. The software interface

To run the complete facility four independent programs are available: one for the outdoor stage, two for the detection unit and one for the light source. However, not all these computer programs are mandatory to acquire measurements, since the choice depends on the kind of measure the user is interested in.
Concerning the detection unit, one application is devoted to the motion of the axes. It can be programmed to allow the linear guides to follow a specific path. The CCD detector has its own software that permits a variety of acquisitions and settings (e.g. the dark and flat field frames, binning mode, gain etc.), it commands also the filter wheel. Both are commercially available software programs that come with the hardware.

The light source can be commanded to switch on the different LEDs with which it is equipped.

The outdoor stage control program. The control software establishes a real-time communication (scheduled every 5 ms) with the entire network of I/O signals (e.g. the drives and the encoders) and disseminates any system alarms. The main window contains a display panel devoted to update the user on the system status. The same applies to the whole set of system functional parameters (e.g. temperature, humidity, etc.).

Command and setting instructions can be transmitted using this application. It shows three panels, one for each axes of the motion. The user can set the maximum speed of the motion and the position to be reached, either in an absolute or relative way with respect to a user-defined origin position. The user can also set the motion in manual mode, this configuration being particularly useful during the alignment phase.

Each axis can be independently set with respect to the other ones; more axes can be moved at the same time.

Additional windows are accessible for advanced settings and diagnostic purposes. In particular, the advanced settings concern the parametrization of the mechanical components of the facility and the dynamic properties of the drive system. The diagnostic returns the status of the devices, the network and statistics on the use of the facility.
3. Measurements and calibration with the facility

In this section we discuss some typical measurements and calibration that can be pursued with the facility and the results that it is possible to obtain. All the results are based on the photometric analysis of the data retrieved and on the information of the distance read by the laser distance meter.

3.1. Evaluation of $r_{80}$ and best focus position

In analogy with an optical telescope, the angular resolution quality of a mirror for Cherenkov telescope is evaluated from its Point Spread Function (PSF). However, the parameter in general used for the Cherenkov case is the $r_{80}$, i.e. the radius that contains the 80% of the focused light. This parameter is typically preferred with respect to the more commonly used (in optical astronomy) Full Width Half Maximum (FWHM). Indeed the PSF of the mirrors for Cherenkov telescopes can hardly be reducible to a Gaussian distribution since the shape's errors introduced from the low cost manufacturing processes adopted are dominant with respect to the intrinsic aberration of the theoretical design. The micro-roughness can also play an important role. Moreover, since Cherenkov observations often deal with very faint signals, the $r_{80}$ turns to be a better estimator to qualify the mirrors and hence the amount of concentrated light.

A standard measurement carried out with the facility is the acquisition of a number of images at various distances from the mirror. After the mounting of the mirror on its support and the alignment of its optical axis with respect to the light source and detector units (z axis in Figure 4), the procedure foresees the rough localization of the best focus position. All the measurements are then taken with discrete steps around this position referred as the local origin. The value of the origin in terms of distance from the mirror is retrieved by averaging a number of reads with the laser distance meter. The discrete steps are measured by means of the encoder mounted on the shaft of the z axis motor. Particular care is taken in settling of the reference point, for the local origin measurement, in order to avoid systematic errors.
Each image is then treated as an astronomical image and analyzed following standard aperture photometry procedures (i.e. use of dark and bias frames, evaluation of the background, etc.) and using standard software routines (e.g. Daophot photometry library [19], SAOImage DS9 [20], etc.).

An example of the results is shown in Figure 9 and Figure 10 respectively: the serie of PSF images taken at the various distances from the origin and the re-

Figure 9: PSFs generated by the mirror along its optical axis for the full measuring length.
Results of the images analysis are shown. In particular, from the plot in Figure 10 it is possible to estimate two geometrical parameters of the mirror under test: the best focus position (being also the radius of the best fitting sphere) and the focal depth. The first parameter is evaluated from the vertex of the parabola that best fits the experimental data, while the latter is due to the sensitivity in estimating the $r_80$ and its relative uncertainty from the experimental PSFs data. The errors associated to the $r_80$ and the relative distance are evaluated in two different ways. For the $r_80$ we use the Poissonian noise associated both with the PSF photometry and the background evaluation. The two values are quadratically summed, even if typically the second one is the dominant contribution. For the relative distance the sensitivity of the DISTOM D8 is taken. In the example shown in Figure 10 we obtained the best focus position at $+73$ mm from the local origin with a focal depth of 100 mm (over a radius of curvature of $32084 \pm 5$ mm). For the $r_80$ values we have computed an error of $\pm 0.1$ mm.

![EVALUATION OF THE BEST FOCUS PROPERTIES](image)

Figure 10: Evaluation of the best focus and depth of focus values for a mirror by means of the $r_80$ property. With this facility it is possible to define the best focus position within few per thousand.
3.2. Evaluation of the astigmatism

More detailed investigation on the errors of the mirrors can be undertaken using the FWHM. By evaluating the contributions over the two orthogonal axes lying on the focus plane (x and y axes in Figure [I]) it is possible to disentangle the astigmatism aberration of the mirror.

The procedure to acquire the measures is the same as that described in Section 3.1, the analysis is also based on standard aperture photometry, but FWHM is taken as reference instead of r80.

In Figure [I] we present, from bottom to top, the plots of the total FWHM, the FWHM along the x axis and the FWHM along the y axis as functions of the focal distance (the radius of curvature). Experimental data and best fit parabolas are shown. It is possible to appreciate a difference in the best focus positions independently achieved on the x and y axes of 60 mm, over a radius of curvature of 35910 ± 5 mm.

Figure 11: Evaluation of the astigmatism aberration, as function of the radius of curvature, on a mirror by measures of the FWHMs along two orthogonal axis. Total FWHM is also shown.
3.3. Scattering evaluation

The diffuse scattering is, in general, due to irregularities of the surface of the mirror at microscopic level that induce coherent large angular deviations from the specular one, thus generating a broad diffused light component surrounding the core of the PSF. If those irregularities have a specific spatial pattern, the scattering can generate structured tails in the PSF. The more pronounced the irregularities are, the more diffused the light is, thus covering a wide area on the focus plane and reducing the amount of light falling into a telescope camera detector. The method to detect the scattering is very important to understand the behavior of the mirror in terms of angular resolution.

To cover a wider area around the PSF we therefore raster scan the focal plane. For each position an image is acquired that is later stitched together with the others to generate a wide single image of the focus plane.

Different approaches have been suggested to evaluate the integral value of the specular plus scattered components \[21\] that require an ad hoc setup. The one proposed here makes use of the same equipment as for \(r_{80}\). Moreover, aperture’s photometry directly on the CCD is profitably exploited to avoid using any objective or imaging screen that would imply a transfer function.

As an example of the application, we show the images of the PSF acquired by a single frame at the center of the focal plane (Figure 12 left panel) and the same PSF acquired with a raster scan (Figure 12 right panel). In the second case, the contrast has been intentionally stretched in order to saturate the bulk of the PSF (in this way the tails due to surface imperfections are clearly visible). While these tails do not influence by a reasonable amount the estimation of the best focus position, they have some effects on the total amount of concentrated light. To give the reader a quantitative value, we compared the \(r_{80}\) obtained from the two images. From the single frame we obtained \(r_{80, \text{frame}} = 9.1 \pm 0.1\) mm while from the raster scan we got \(r_{80, \text{frames}} = 12.5 \pm 0.01\) mm. The plot of the encircled energy is shown in Figure 13.
Figure 12: (a) PSF acquired by a single frame of the CCD located at the center of the detector plane and (b) PSF acquired by means of a composition of 9 frames of the CCD obtained with a raster scan of the detector plane. The image’s contrast is intentionally exaggerated to highlight the scattering component.

Figure 13: Evaluation of the $r_{80}$ value from a 1-frame PSF image and a 9-frame PSF image of the same mirror.
4. Future developments

In-focus total reflectivity is among the most important parameters for understanding the performance of a mirror for Cherenkov telescopes, indeed one of the most difficult to assess. While the local surface reflectivity is commonly measured sampling the mirror’s surface with spectrophotometer devices, their detector’s acceptance angle is in general wide enough to collect also an important fraction of the scattered component, mixing it to the specular reflection one. The mirror’s surface shape quality is obtained through the use of facilities based on the 2-f method, as described in this paper. The capability to combine together the afore-mentioned information by means of a single measurement (now wavelength dependent) will allow us to get a more reliable evaluation of the expected PSF of the entire Cherenkov telescope and to estimate the background component due to the optical surface errors. Such a measurement is possible thanks to the facility presented in this paper as soon as the scattering evaluation method presented in Section 3.3 is coupled with a reliable way to measure the light flux of the source in use. This can be done for instance by using a calibrated photodiode and a semi-reflective folding mirror. A detailed study is ongoing and some preliminary tests have been already carried out.

Activities to improve the software programs integration are also ongoing. This will give an easier and faster measuring experience.

5. Conclusions

An open-air user-friendly facility for the characterization of mirrors for Cherenkov telescopes with long radius of curvature is presented. It is devoted to the precise determination of the radius of curvature and the measurement of the on-focus light distribution generated by the mirror under test. The latter in terms of focused and scattered components, normalized to the total incoming light at the detector. The facility has a flexible light source able to provide wavefronts at different
wavelengths. This capability combined to the large field of view of the camera and the possibility to perform raster scans, makes the facility ideal to pursue calibrations of Cherenkov mirrors with direct CCD imaging, with a correct evaluation of the Encircled Energy function.

A detailed technical description covering its electro-mechanical, electrical, optical and software components has been presented. Some typical measurements made possible through the facility have been discussed together with the forthcoming possibility to implement the on-focus total reflectivity evaluation.

The radius of curvature and the on-focus light distribution measurements can be correlated to the ambient and/or mirror temperature opening the possibility to experimentally assess the thermal behavior of the mirror.

The facility is run by the INAF personnel of the Observatories of Brera and Padova but the access is open to the entire scientific community who may feel the need of such type of measurements, in particular in view of the implementation of the telescopes of the CTA observatory, with its 10000 m² of reflecting surface.

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