The ASTRI contribution to the Cherenkov Telescope Array: mirror production for the SST-2M ASTRI and the MST telescopes

N. La Palombara, G. Sironi, E. Giro, S. Scuderi, R. Canestrari, et al.

N. La Palombara, G. Sironi, E. Giro, S. Scuderi, R. Canestrari, M. Garczarczyk, M. Krause, R. Millul, N. Missaglia, M. Redaelli, G. Valsecchi, F. Zocchi, A. Zannoni, G. Pareschi, "The ASTRI contribution to the Cherenkov Telescope Array: mirror production for the SST-2M ASTRI and the MST telescopes," Proc. SPIE 11119, Optics for EUV, X-Ray, and Gamma-Ray Astronomy IX, 111191U (9 September 2019); doi: 10.1117/12.2531157

Event: SPIE Optical Engineering + Applications, 2019, San Diego, California, United States

The ASTRI contribution to the Cherenkov Telescope Array: mirror production for the SST-2M ASTRI and the MST telescopes

N. La Palombara[⊕*,1], G. Sironi[2], E. Giro[2], S. Scuderi[1], R. Canestrari[3], M. Garczarczyk[4], M. Krause[4], R. Millul[2], N. Missaglia[5], M. Redaelli[5], G. Valsecchi[5], F. Zocchi[5], A. Zanoni[6], and G. Pareschi[2]
for the CTA ASTRI Project[7,8]
[1]INAF - IASF Milano, Via A. Corti 12, I-20133 Milano (Italy)
[2]INAF - Osservatorio Astronomico di Brera, Via Bianchi 46, I-23807 Merate (Italy)
[3]INAF - IASF Palermo, Via U. La Malfa 153, I-90146 Palermo (Italy)
[4]Deutsches Elektronen-Synchrotron (DESY), Platanenallee 6, D-15738 Zeuthen (Germany)
[5]Media Lario s.r.l., Via al Pascolo, I-23842 Bosisio Parini (I)
[6]ZAOT s.r.l., Via E. Restelli 20, I-20010 Vittuone (I)
[7]https://www.cta-observatory.org/
[8]http://www.brera.inaf.it/astri/

ABSTRACT

The Cherenkov Telescope Array (CTA) will be the next generation ground-based observatory for gamma-ray astronomy at very-high energies. It will consist of over a hundred telescopes of different sizes (small, medium, and large) located in the northern and southern hemispheres. The Italian National Institute of Astrophysics (INAF) contributes to CTA through the ASTRI project (*Astrofisica con Specchi a Tecnologia Replicante Italiana*), whose main aim is to provide a series of dual-mirror small-sized telescopes (SST-2M ASTRI) and the mirrors for the single-mirror design of the medium-sized telescopes (MST). Both the primary mirror of the SST-2M ASTRI and the mirror of the MST are segmented, and such segments are realized with cold-slumping technology already used for the mirror facets of MAGIC, a system of two Cherenkov telescopes operating on the Canary Island of La Palma. On the other hand, the secondary mirror of the SST-2M ASTRI is monolithic and is realized with hot-slumping technology. Currently, we have completed the mirror production for nine SST-2M ASTRI telescopes, which will form the so-called ASTRI Mini-Array. Moreover, we have almost completed also the production of mirrors for two MSTs. In this paper, we present the mirror designs and describe the qualification activities that were performed to assess and consolidate the production process. Moreover, we report on the quality assurance approach we adopted to monitor and verify the production reliability. Finally, we present the performance of the produced mirrors and discuss their compliance with the CTA requirements.

Keywords: CTA, ASTRI, dual mirror, cold-slumping technology, hot-slumping technology, coating, quality assurance

1. INTRODUCTION

The Cherenkov Telescope Array (CTA) represents the next generation of Imaging Atmospheric Cherenkov Telescopes (IACTs), designed to observe gamma-ray sources at very-high energies (in the TeV energy range) from the ground. It will be located in two different sites, one in the northern and one in the southern hemisphere, and will be made up of more than one hundred telescopes of three different sizes[1]:

- the Large Size Telescopes (LSTs), with a 23 m mirror diameter, will cover the low-energy range between 20 GeV and 3 TeV;
- the Medium Size Telescopes (MSTs), with a 12 m mirror diameter, will observe the core energy range between 50 GeV and 50 TeV;
- finally, the Small Size Telescopes (SSTs), with a 4 m primary mirror diameter, will be devoted to the high-energy range from ~ 1 TeV up to more than 300 TeV.

⊕* e-mail: nicola.lapalombara@inaf.it

Optics for EUV, X-Ray, and Gamma-Ray Astronomy IX, edited by Stephen L. O'Dell, Giovanni Pareschi, Proc. of SPIE Vol. 11119, 111191U · © 2019 SPIE · CCC code: 0277-786X/19/$21 · doi: 10.1117/12.2531157

Compared with the current generation of IACTs, CTA will provide a tenfold improvement in sensitivity. Therefore, it will allow us to increase significantly the number of known gamma-ray celestial objects and to address some of the most mysterious and intriguing questions in astrophysics[2].

The Italian National Institute of Astrophysics (INAF) contributes to CTA through the ASTRI project. ASTRI aims to provide to CTA a series of dual-mirror small-sized telescopes (SST-2M ASTRI) that will be characterized by innovative technological solutions, such as the Schwarzschild-Couder optical configuration, a modular, light and compact focal-plane camera based on silicon photomultipliers, and a front-end electronics based on an ASIC (Application-Specific Integrated Circuit). The viability of this innovative design has been successfully demonstrated with the ASTRI-Horn prototype. This telescope, installed in 2014 at the Serra La Nave site on Mount Etna (Sicily), is the first Schwarzschild-Couder telescope to be built and tested[3]: it saw its first light in May 2017[4] and detected the Crab nebula in December 2018[5]. Currently the ASTRI Collaboration is developing a Mini-Array composed of 9 telescopes, in the context of the preparatory effort for participating in the CTA observatory.

In addition, ASTRI is also responsible for the procurement of two sets of mirrors for the prototypes of the MSTs, which are single-mirror telescopes with a Davies-Cotton optical design[6] and, in this respect, is cooperating with the Deutsches Elektronen-Synchrotron (DESY, Germany), responsible for the MST structures. In this effort, also industries like Media Lario (Bosisio Parini, LC, Italy) and ZAOT (Vittuone, Mi, Italy) are involved, being in charge for the production of the substrates and of the reflective coating deposition respectively.

2. OPTICAL DESIGN

2.1 The optical design of SST-2M ASTRI

The ASTRI dual-mirror SST is based on the polynomial Schwarzschild-Couder optical design[7], an aplanatic and double-reflection layout that is characterized by a wide field of view. This result is obtained with the combination of two mirrors.

The primary mirror (ASTRI M1) has a radial symmetry and its optical profile is described by an aspherical polynomial function. It has a diameter of 4.3 m and is segmented into 18 hexagonal-shaped panels; the face-to-face dimension of each panel is 85 cm. They are distributed in three concentric coronae (COR1, COR2, and COR3) of six identical panels each, where each corona has a different radial distance from the telescope vertex. Since the radius of the spherical component increases from the inner to the outer corona, the optical design is different for the three coronae. In fact, the best-fit radius of curvature of the segments is 8.6, 9.8, and 11.7 m, respectively for the inner, medium, and outer corona[8].

The secondary mirror (ASTRI M2) is a monolithic element and has a diameter of 1.8 m. It has a spherical shape, with a radius of curvature (RoC) of 1.075 m, and is installed at a distance of 3 m from ASTRI M1. This implies an equivalent focal length of 2.15 m[9].

2.2 The optical design of the single-mirror MST

One design for the medium-sized telescope has a single-mirror configuration with a modified Davies-Cotton optical design[6]. In this case the mirror is spherical, with a radius of 19.2 m, and is segmented into 90 hexagonally-shaped panels, for a diameter of 12 m. Each panel has a spherical profile, with a RoC = 32.14 m, and its face-to-face size is 1.2 m. The telescope focal length is 16 m and the mirror segments are aligned to reflect rays parallel to the optical axis into the focal point.

3. MIRROR DESIGN AND PRODUCTION

All the mirrors provided by the ASTRI project for the SST-2M and MST are realized by replicating a master shape from a reference mould. However, both the technology and the design are different for the ASTRI M1 and MST panels, on one hand, and the ASTRI M2 mirrors, on the other hand.

Both the ASTRI M1 segments and the MST segments are realized using an improved version of glass cold-slumping technology: it was developed in synergy between the Osservatorio Astronomico di Brera-INAF and Media Lario s.r.l. and it was already successfully used for the MAGIC-II telescope[10]. The cold slumping is used to bent a thin glass foil onto a mould with the right profile. Then, a honeycomb layer of Aluminum is glued onto the glass foil and, afterwards, a second glass foil is glued onto the honeycomb layer. In this way two glass foils are assembled in a light but stiff sandwich structure with an Al honeycomb core. Finally, a highly reflective coating is applied to the outer surface of the first glass foil. In the case of the ASTRI M1 segments the thickness of the glass foils is 1.6 mm, while that of the honeycomb layer is 20 mm; for the MST segments the corresponding values are 2.1 mm and 30 mm, respectively. The reflective surface is a multilayer coating composed of $Al+SiO_2+ZrO_2+SiO_2$. The advantage of this technology is that it is based on a cost-saving replica process, which is suitable for CTA due to the multiplicity of the telescope mirrors. Moreover, the panels obtained are lightweight and with shape errors within few microns.

The ASTRI M2 mirror, on the other hand, is based on a monolithic glass substrate with a thickness of 19 mm. This solution allows us to simplify the telescope design but requires a thick glass substrate, which cannot be curved to the required RoC with the cold-slumping technology used for the primary segments. Therefore, the ASTRI M2 mirror is bent to the correct shape using the hot-slumping technology. The reflective surface is obtained with the application of the same multilayer coating used for the ASTRI M1 and MST segments.

4. CTA REQUIREMENTS AND ASTRI SPECIFICATIONS

The mirrors and mirror segments provided by ASTRI will be compliant with the CTA requirements, which regard not only the optical performance of each item but also its reliability, taking into account the environmental conditions of the CTA observing sites.

From the performance point of view, the initial average reflectivity of all facets, in the wavelength range 300-550 nm, must be > 85%. Moreover, there is a requirement on the size of the telescope Point Spread Function (PSF). To this aim, the reference parameter is θ_{80}, which is the diameter of the circle that includes the 80% of the focalized photons. For SST and MST telescopes, the CTA requirement is $\theta_{80} < 0.25°$ and $\theta_{80} < 0.18°$, respectively. Regarding the environmental requirements, the main ones are reported in Table 1; moreover, there are also requirements on the resistance to aggressive atmosphere, dust and sand blasting, and lightning. Finally, the provided mirrors and segments must have a lifetime > 15 yr.

Table 1: applicable CTA environmental requirements

CTA REQUIREMENT	TITLE	VALUE
A-ENV-0210	Observation temperature	-15° C < T < +25° C
A-ENV-0220	Survival temperature	-20° C < T < +40° C
A-ENV-0230	Temperature gradient	< 7.5° C/h
A-ENV-0240	Temperature shocks	± 30° C
A-ENV-0250	Survival temperature gradients	< 0.72° C/h for 25 minutes
A-ENV-0310	Observation humidity	2-90 %
A-ENV-0320	Survival humidity	2-100 %
A-ENV-0410	Rain in 24 hours	200 mm
A-ENV-0420	Rain in 1 hour	70 mm
A-ENV-0430	Rain wind speed	< 90 km/h
A-ENV-0460	Rain during transition	< 0.5 mm/m
A-ENV-0520	Survival snow load	< 50 cm
A-ENV-0530	Hailstone damage	< 20 mm
A-ENV-0620	Survival ice load	< 20 mm
A-ENV-0710	Observation wind speed	< 36 km/h
A-ENV-0720	Transition wind speed	< 50 km/h
A-ENV-0730	Survival wind speed	< 120 km/h

In view of the mirror production, these CTA requirements were converted into specifications for Media Lario s.r.l (ML), the industrial supplier of MST and M1 segments. Initially, from the reflectivity point of view, besides an average value > 85%, we also asked in the contract for a non-uniformity < 8% over the entire mirror surface. Moreover, to be fully compliant with the CTA requirement, during the development of the activities, it was requested a reflectivity R >85% in the range 300-550 nm. Regarding the PSF, for both MST and M1 segments we asked Media Lario for a micro-roughness < 2 nm RMS. For the MST segments we required a RoC = 32.14 ± 0.04 m and $\theta_{80} < 0.12°$ at the nominal focal length; for a focal length of 16 m, this corresponds to 33.66 mm. However, we considered only the value of θ_{80} at the nominal focal length as applicable acceptance criteria. It should be noted that also the additional specification that $\theta_{80} < 12$ mm at 16.07 m (i.e. at one half of the radius of the mirror, which translates to $\theta_{80} < 0.04°$) was considered and verified (this is the final requirement for single mirrors on-axis assumed for CTA).

For the ASTRI M1 segments there is no requirement on the RoC, since they are aspheric. In this case, for the first segments which were produced (40 COR3 and 16 COR2) there was only a requirement on the residual shape error (< 15 μm RMS). However, it was so strict that no segment was compliant with it, although we verified directly with a ray-tracing analysis of the shape data that the shape was correct. Therefore, afterwards we introduced a requirement on the radius of the spherical component (between 8198 and 8298 mm) and relaxed that on the residual shape error (< 20 μm RMS for corona 1 and < 25 μm RMS for coronae 2 and 3). Finally, for both the MST and ASTRI M1 segments the tolerance on the size is ± 2 mm. Regarding the environmental requirements, we kept the original CTA requirements, but we reinforced the survival temperature range (-20° C < T < +70° C) and introduced the requirement that the mirror must survive to wind gusts up to 200 km/h. Moreover, the mirror segments shall be water-tight and the reflective coating must survive to a tape adhesion test with a pulling force < 16 N. From the reliability point of view, the lifetime of the segment substrate must be > 15 yr, while that of the reflective coating must be > 6 yr.

5. QUALIFICATION OF THE PRODUCTION PROCESS

Before starting with the mass production of the mirror segments, it was necessary to validate the production process and to perform qualification tests on a set of preliminary segments. To this end, the industrial activity started in February 2017 with the development phase. During this phase, the moulds used to produce the different types of segments were qualified and the parameters of the glass cold-shaping process were fine-tuned, in order to satisfy the performance requirements of the mirrors. Several segment prototypes were then produced and tested along this period, in order to ascertain that the production process was stable and repeatable. Afterwards, one qualification segment of each type went through a complete set of performance measurements and environmental and reliability tests. For each segment substrate, the measurement of its micro-roughness and shape was performed, and the first measurement was also repeated after the execution of different thermal cycles and the dry-heat and damp-heat tests. Moreover, the immersion in a water tank was executed, in order to verify the water tightness. Regarding the reflection coating, the reflectivity curve on the wavelength range 0.19-1.70 micron was measured on 13 points uniformly distributed along three diagonals. The adhesion of the mirror coating was verified through a tape removal test. Both the reflectivity measurements and the tape test were repeated after the execution of thermal cycles, dry- and damp-heat tests, and solar radiation tests. All these measurements and tests demonstrated that the performance of the segments produced are compliant with the applicable specifications and that the segments do not degrade due to the environmental conditions.

6. QUALITY ASSURANCE APPROACH

Once the production process was qualified, in February 2018 it was possible to start with the mirror mass production, which is now almost completed. For each mirror segment a series of acceptance tests and measures are performed by ML. First of all, a visual inspection is executed, to ascertain the mirror integrity and evaluate the cosmetic defects (such as scratches, spots, and halos) of the reflective surface. Then, a tape removal test is performed, in order to verify the coating adhesion. The reflectivity curves (in the wavelength range 200-550 nm) are measured in five different points uniformly distributed along one diagonal; moreover, the average reflectivity and the reflective non-uniformity are measured. In the case of the focusing MST segments, the measure of the RoC and of the PSF size (at both the best and the nominal focal length) is performed. In the case of the aspheric ASTRI M1 segments, instead, the best-fit value of the spherical component and the residual shape error are measured.

Apart from the acceptance tests performed on each segment, additional sample tests are performed by Media Lario on individual segments; they regard the micro-roughness and the water tightness, and are necessary in order to keep under control the production process. Moreover, sample tests are performed by INAF in its laboratories on ~ 10% of the produced mirrors. They concern the RoC and PSF measurement for the MST segments and the shape measurement for the ASTRI M1 segments. For the MST mirrors, other tests concerning PSF, Radius of Curvature and focused reflectivity are performed under the DESY coordination at a facility operated by the University of Tübingen. In this way we can obtain an independent check of the segment properties, monitor the reliability of the production process and provide a feedback to the industrial supplier.

The contract assigned to ML requires that each mirror segment is associated with an "Identity Card" (IC), which reports the results of all the acceptance tests and measurements. The IC is the reference document to control the mirror quality. Along to the production phase, the QA team employs it to monitor the production process and decide which segments require a direct inspection, in order to evaluate if they can be accepted or rejected. In case a segment shows a major anomaly, which however does not affect its performance or reliability (such as a deep scratch or a wide halo), it can be accepted if a comprehensive description of the anomaly is reported in a Non-Conformance Report (NCR). If, on the other hand, the detected anomaly compromises the segment performance or reliability (such as a large spalling of the mirror edge), the segment is rejected. After its delivery, each segment must be followed by a report with its IC (and the relevant NCRs, if any) for all its life. In this way, at any time it will be possible to retrieve the mirror properties and evaluate if it is suitable for the installation on the telescope.

7. RESULTS

Currently (July 2019) three batches of mirror segments have been delivered. They include 168 MST segments and 161 ASTRI M1 segments (30 COR1, 65 COR2, and 66 COR3). Moreover, 10 M2 mirrors have been produced.

7.1 Results for M1 segments

In Fig. 1 we report the main parameters of the MST segments; in each panel, the applicable required values are represented with a horizontal dashed line.

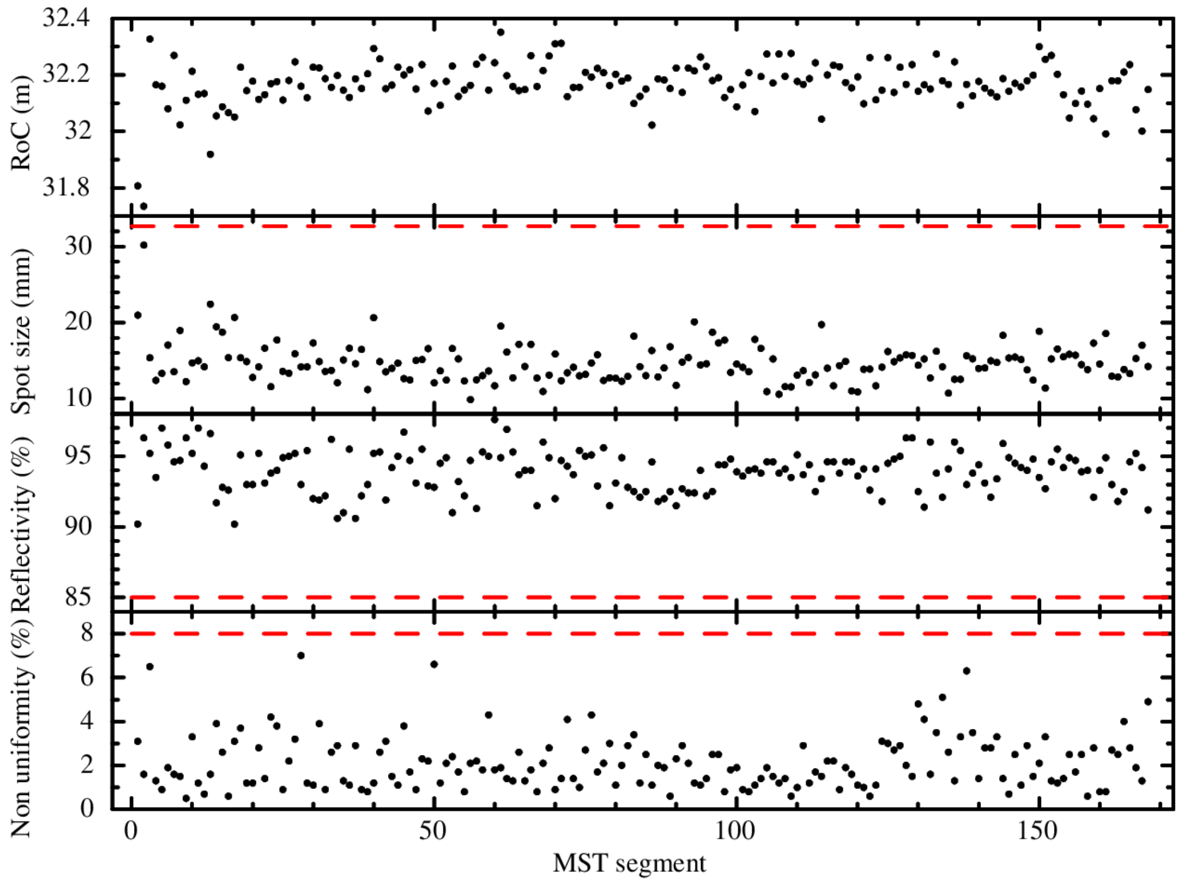

Figure 1. Main parameters of the produced MST segments: radius of curvature (*upper panel*), θ_{80} at twice the nominal focal length (*second panel*), average reflectivity (*third panel*), and reflectivity non-uniformity (*bottom panel*). For each panel the dashed red line represents the applicable reference value.

The upper panel reports the measured value of the RoC. For almost all the segments, this value is close to the nominal value of 32.14 m, although not always within the range 32.10-32.18 m, and shows no tendency to increase or decrease. The only exceptions regard the first two panels, which have a significantly smaller radius. This means that, after these first two segments, the production process has remained stable. On the other hand, it should be noted that the requirement on the RoC is not considered an applicable acceptance criteria, since what matters is only the value of θ_{80} at the nominal focal length. Therefore, although for not all of them the measured RoC is within the range 32.10-32.18 m, all the 168 MST segments delivered up to now are considered compliant with the initial specs given to Media Lario. On the other hand, for all but one of the segments produced so far, the θ_{80} value at 2f (second panel) is not only well below the initial required value of 33.66 mm but, apart from one single case, also below the updated more restrictive specification added-on during the development of the contract of θ_{80} < 24mm. This result also reflects the fact that the mirrors are considered compliant with the CTA requirement at 1f of θ_{80} < 12mm, apart from one single case. Moreover, even considering this isolated worst case, afterwards the measured data show no long-term increasing or decreasing trend in the production. The average reflectivity (third panel) is well above 85% for all the panels, and the average reflectivity non-uniformity of the mirrors (bottom panel) is always below the requirement of 8%. In near future we will verify the compliance of these results by means of focused reflectivity measurements at each wavelength.

7.2 Results for the ASTRI M1 segments

Regarding the ASTRI M1 segments, in Fig. 2 we report the results obtained for the COR1 segments. In the first and second panels we show, respectively, the values of spherical component and the residual shape errors. The first parameter is always within the required range between 8198 and 8298 mm, while for all segments the second parameter is < 20 μm RMS. This means that the segment shape is correct. Regarding the reflectivity, in the third and fourth panel we report, respectively, its average value and its non-uniformity for each segment. As for the MST segments, also for the COR1 segments these parameters are compliant with the lower limit of 85% and the upper limit of 8%, respectively. The same holds also for the COR2 and COR3 segments; for those segments (16 COR2 and 40 COR3) produced before the introduction of the requirements on the RoC and residual shape error, the correct shape was verified with a ray-tracing analysis of the shape data.

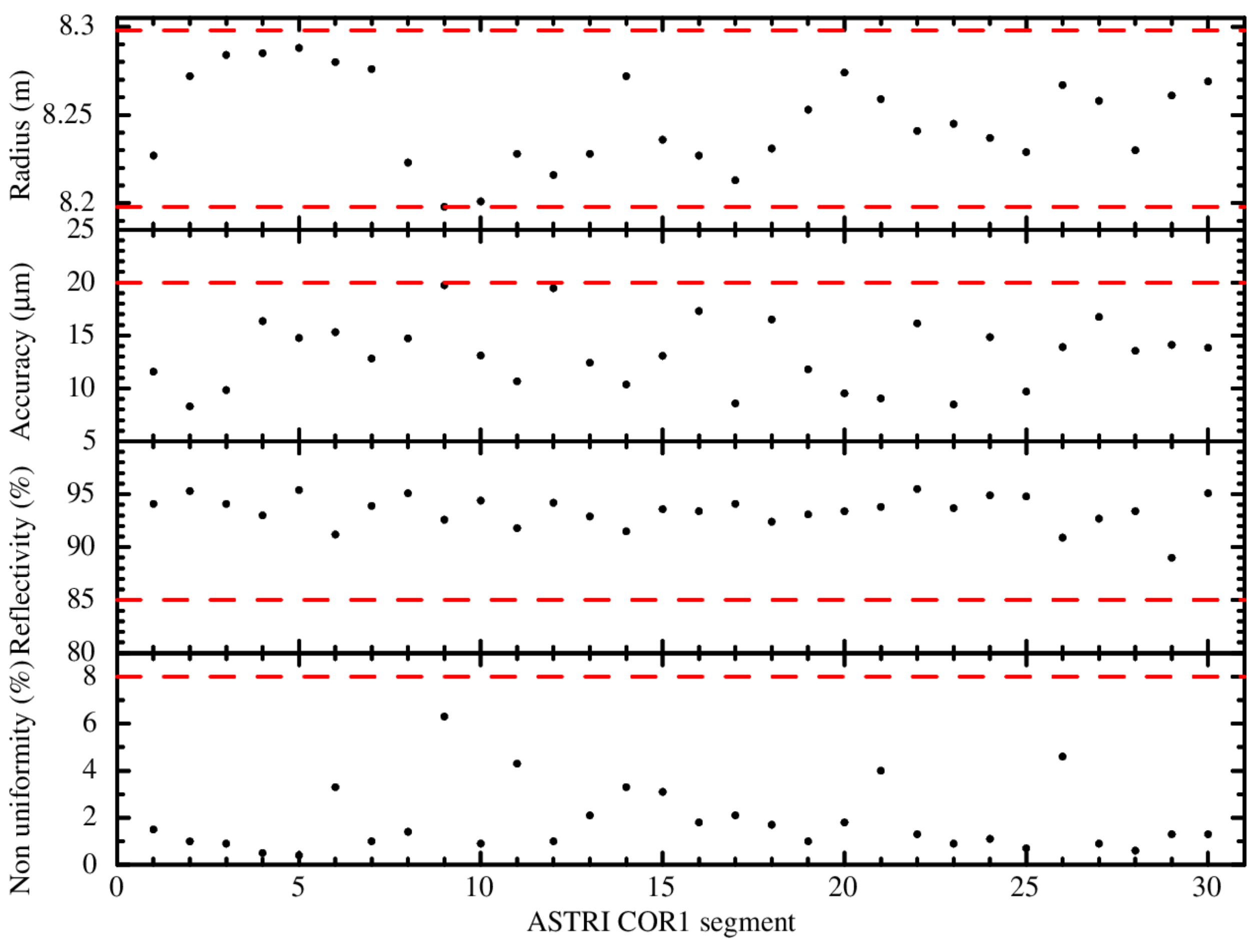

Figure 2. Main parameters of the produced COR1 segments of the primary mirror of the ASTRI dual-mirror telescopes: radius of the spherical component (*upper panel*), residual shape error (*second panel*), average reflectivity (*third panel*), and reflectivity non-uniformity (*bottom panel*). For each panel the dashed red lines represent the applicable reference values.

In Fig. 3 we show one example of the five reflectivity curves measured for each segment at five different positions along a diagonal. Although these curves differ from each other, all of them are always above the required value of 85% between 300 and 550 nm, which is the reference wavelength range, while they decrease at shorter wavelengths. Moreover, they have a maximum at about 360 nm, while they show a gradual decrease at longer wavelengths. It should be noted that in the case of ASTRI, the concept of focused reflectivity is not applicable "tout-court", since we are talking of a dual mirror systems with the panels of the primary not having a real focus. Finally, in Fig. 4 we report an example of the residual map obtained by comparing the theoretical and the real shapes of ASTRI M1 segment. It is used to measure the surface accuracies reported in the second panel of Fig. 2.

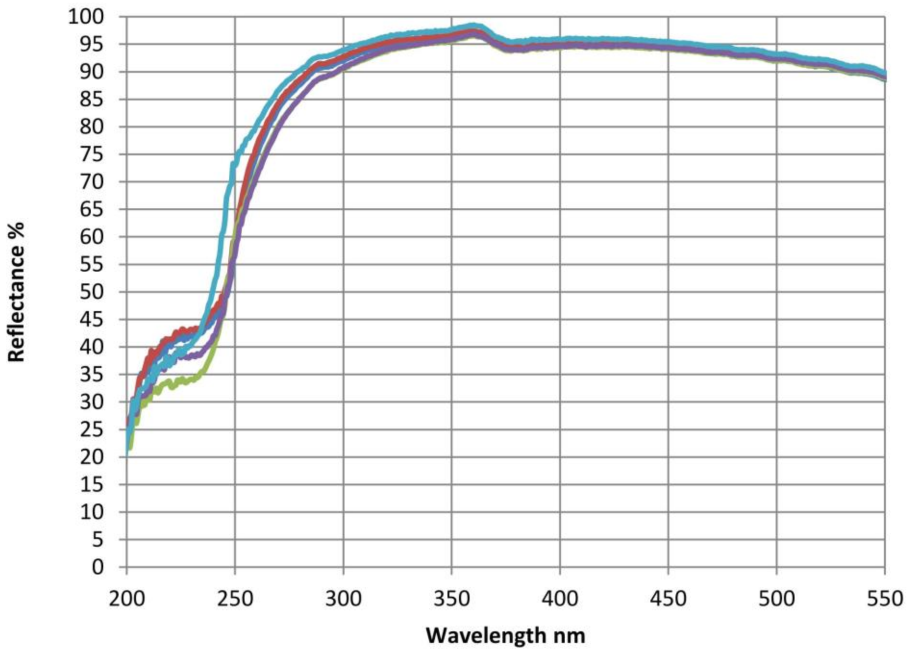

Figure 3. Example of the reflectivity curves of one mirror segment measured at five different positions along a diagonal.

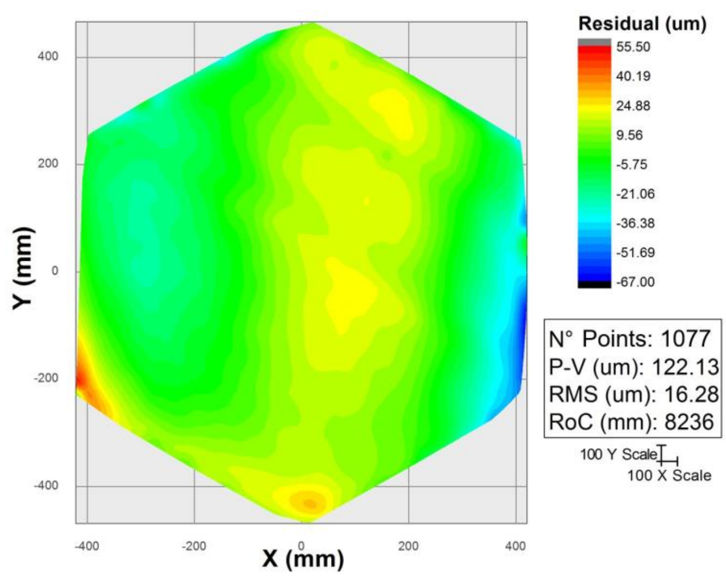

Figure 4. Example of the residual map of one ASTRI M1 segment.

8. OPEN ISSUES

The production process of the MST and ASTRI M1 segments was fully qualified by ML before the beginning of the serial production. On the other hand, the qualification of the coating of the ASTRI M2 mirror is currently on-going that needs the implementation of a qualification plan, a task that will be addressed in the near future. It should be noted that the coating of the M2 mirrors (which has a diameter of almost 2 m) is more difficult to be applied than for the M1 segments and, for a such big size, the process is not yet completely qualified and a special coating set-up is being used.

Measurements of focused reflectivity at each single wavelengths of the MST segments, which is the reflectivity of the overall segment measured at the focal plane, have also been done. This parameter is different from the average reflectivity reported in the IC of each segment, since the latter is the average of the surface reflectivity measured at five different positions along one diagonal and it truly represents the CTA requirement. These measurements have been performed so far just on a reduced number of mirrors and the results seems in agreement with the characterizations performed by Media Lario and INAF, but more verifications are needed. We plan to pursue this calibration approach to a large sample of mirrors, also using the “open-air” facility developed by INAF at its premises in Merate, in addition to the facility already operated by Univ. of Tübingen.

Finally, among the environmental tests to be performed for the coating qualification of MST and ASTRI M1 segments, the two regarding the aggressive atmosphere and the sand and dust blasting are still to be executed. In fact, in their case the assessment of the relevant requirement is not yet completed.

9. SUMMARY AND CONCLUSIONS

Before starting the mass production, the manufacturing process of the mirror segments based on the cold replication process set-up by INAF and Media Lario has been fully qualified for MST and ASTRI (M1 mirrors) in the context of the CTA development phase. It has been verified that the developed manufacturing process ensures the realization of mirror segments that are fully compliant with the CTA requirements from the environmental, reliability, and performance points of view. Moreover, we have implemented an effective Quality Assurance approach that allows us to monitor the stability and reliability of the manufacturing process along the mass production. The mirror production is well defined and, as of July 2019, it has ensured the delivery of 168 MST segments and 161 M1 segments, each of them is fully compliant with the CTA requirements. We plan to complete the mirror production by fall 2019. Since a set of 10 M2 mirrors is already available, the mirror production is perfectly on schedule for the incoming realization of the ASTRI Mini-Array.

ACKNOWLEDGEMENTS

This work is supported by the Italian Ministry of Education, University, and Research (MIUR) with funds specifically assigned to the Italian National Institute of Astrophysics (INAF) for the Cherenkov Telescope Array (CTA), and by the Italian Ministry of Economic Development (MISE) within the “Astronomia Industriale” program. We acknowledge support from the Brazilian Funding Agency FAPESP (Grant 2013/10559-5) and from the South African Department of Science and Technology through Funding Agreement 0227/2014 for the South African Gamma-Ray Astronomy Programme. We gratefully acknowledge financial support from the agencies and organizations listed here: http://www.cta-observatory.org/consortium_acknowledgments.

REFERENCES

[1] CTA Consortium: Acharya B. S. et al., “Introducing the CTA concept”, Astroparticle Physics (43), 3-18 (2013)
[2] CTA Consortium: Acharya B. S. et al., [Science with the Cherenkov Telescope Array], World Scientific Publishing Co. Pte. Ltd., Singapore (2019)
[3] Giro E. et al., “First optical validation of a Schwarzschild Couder telescope: the ASTRI SST-2M Cherenkov telescope”, Astronomy & Astrophysics (608), A86 (2017)
[4] CTA Press Release: “CTA Prototype Telescope, ASTRI, Achieves First Light”, 14 June 2017, https://www.cta-observatory.org/cta-prototype-telescope-astri-achieves-first-light/ (14 June 2017)
[5] CTA Press Release: “ASTRI-Horn is the first Cherenkov telescope in dual-mirror configuration to detect the Crab Nebula at TeV energies”, 7 May 2019, https://www.cta-observatory.org/astri-detects-crab-at-tev-energies/ (7 May 2019)
[6] Garczarczyk M., “Medium size telescopes for the Cherenkov Telescope Array”, Proc. SPIE 10700, 1070023 1-7 (2018)

[7] Vassiliev V., Fegan S., Brousseau P., “Wide field aplanatic two-mirror telescopes for ground-based γ-ray astronomy”, Astroparticle Physics (28), 10-27 (2007)
[8] Canestrari R. et al., “The ASTRI SST-2M prototype for the next generation of Cherenkov telescopes: structure and mirrors”, Proc. SPIE 8861, 886102 1-13 (2013)
[9] Pareschi G. et al., “The dual-mirror Small Size Telescope for the Cherenkov Telescope Array”, Proc. ICRC 33 (2013)
[10] Canestrari R. et al., “Cold-shaping of thin glass foils as a method for mirror processing: from basic concepts to mass production of mirrors”, Optical Engineering (52), 051204 1-12 (2013)
[11] Garczarczyk M., “Interim report from the MST MLT mirror production”, MST-VVRP/18109, 2019
[12] Canestrari R. et al., “A facility to evaluate the focusing performance of mirrors for Cherenkov Telescopes”, Nuclear Inst. and Methods in Physics Research, A, Volume 806, p. 61-69 (2016)