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Integration of the Athena mirror modules: development status of the indirect and direct X-ray methods

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ABSTRACT

Within the ATHENA optics technology plan, activities are on-going for demonstrating the feasibility of the mirror module integration. Each mirror module has to be accurately attached to the mirror structure support by means of three isostatic mounts ensuring minimal distortion under environmental loads. This work reports on the status of one of the two parallel activities initiated by ESA to address this demanding task. In this study awarded to the industrial consortium, the integration relies on optical metrology and direct X-ray alignment. For the first or “indirect” method the X-ray alignment results are accurately referenced, by means of a laser tracking system, to optical fiducial targets mounted on the mirror modules and finally linked to the mirror structure coordinate system. With the second or “direct” method the alignment is monitored in the X-ray domain, providing figures of merit directly comparable to the final performance.

The paper updates on the laser tracking characterization results of 2 mirror modules, performed at PTB’s X-ray Parallel Beam Facility (XPBF 2.0) at BESSY II. The same 2 mirror modules have then been co-aligned and integrated in a technology demonstrator, with performance verified in full illumination at Panter. The paper provides an overview of the results obtained from the technology development activities.

Keywords: ATHENA, X-ray optics, X-ray mirror integration, Silicon Pore Optics

1. THE CONTEXT OF THE STUDY

ATHENA is a technologically innovative mission [1-2], demanding a novel high performance telescope optics technology. The required large effective area, several times larger than that of its predecessor XMM-Newton, combined with an improved angular resolution, less than half that of XMM-Newton, while effectively maintaining the mass, would not be achievable with the established X-ray optics technologies. Replicated nickel shells or polished Zerodur have typically been used for X-ray focusing in space missions. Although these are able to achieve very good angular resolution, they are too heavy for many applications. ATHENA requires the provision of high energy optics that can still provide low mass, high resolution and high energy response across a broad spectrum. A new optics technology, the Silicon Pore Optics (SPO) is being developed in the last decades [3-6] under the lead of ESA, and this technology is the baseline for the adoption of ATHENA.

Due to the small effective area of each single X-ray reflecting surface, a large aperture telescope is required, and ATHENA envisages a diameter close to 3 meters. To create the aperture of such a large X-ray telescope, a modular approach is envisaged to form the mirror. The aperture area is filled with smaller modules, which are easier to handle during production, alignment and characterization. The optic modules for ATHENA are required to have an in-orbit half-energy-width (HEW) resolution better than 5 arcsec over an energy range of 0.1 to 6 keV. This demanding requirement places tough constraints on the performance of individual modules and their integration. Each mirror module (MM) is formed from Silicon Pore Optics (SPOs), approximating the parabolic input (SPO-P) and hyperbolic output (SPO-H) surfaces of a Wolter I configuration, aligned and fixed into a pair of brackets [7-8]. The brackets include three points

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from which the MM can be mounted into the larger X-ray aperture. A modular approach using several hundreds of mirror modules is foreseen for the ATHENA X-ray observatory. These mirror modules need to be integrated and co-aligned in a mirror support structure. The support structure, the mirror module and the interface have to be compliant with environmental conditions during launch and in orbit operation. Furthermore, a process is needed to integrate about two mirror modules per day in a flight production environment. An accurate co-alignment of the mirror modules is required which needs to be verified during populating the mirror support structure.

This paper reports on the status of one of the two parallel activities initiated by ESA to address the mirror modules integration aspects. In the study here presented, the integration relies on opto-mechanical metrology and direct X-ray alignment. The paper reports on the laser tracking characterization results, performed at PTB's X-ray Parallel Beam Facility (XPBF 2.0) at BESSY II and on the results from the campaign performed at PANTER during and after the integration of the technology demonstrator.

2. TECHNOLOGY DEMONSTRATOR

A demonstrator has been produced, having the goal of experimentally verifying the alignment tolerance of the indirect and direct X-ray methods. The optical part of this demonstrator consists of 2 mirror modules representative of the flight design (in terms of materials and processes).

The 2 mirror modules (MMs) are taken from the same radius of the ATHENA design:

- MM mid radius = 709.184 mm
- Focal Length = 12'000 mm
- Width of the MM stacks = 65.678 mm
- Plate thickness = 3 mm

The Mirror Structure Element of the demonstrator, is designed to accommodate the two identical mirror modules as described above. It features titanium plates which are bolted together, such that the geometry of the two cells is representative of the full mirror structure design (see Figure 2 left). The spacing between the MMs has been chosen in order to maximize the effective area of a given row, but keeping sufficient clearances for integration and alignment of the MMs. This spacing is defined by the angle between two consecutive MMs of the same row.

The mirror structure element has been designed also taking into account the following considerations:

- the design is representative of the material and local geometry of the mirror structure;
- the design implements the interfaces for two neighboring MMs;
- the design provides interfaces and references for the MMs integration, co-alignment and metrology;
- the design provides interfaces suitable for environmental testing;

The MM mounting concept is based on stainless steel dowel pins bolted at the base of the mirror structure. The 3 interface points are defined so to lie on a radial line w.r.t. the mirror structure. This is a purely bolted interface, and the exchange of a MM can be easily performed if needed. A shim with a defined nominal thickness is foreseen for adjustment along Z (direction of the optical axis). For the demonstrator, no adjustment for the MMs focal length was performed. However, a shim is integrated in order to keep representative interfaces. In-plane adjustments are not performed at this interface but at the upper interface, where the MMs are integrated via a bonding line making use of the MM bracket features.

The X-ray Optical Units (XOUs) of the MMs are held in position by two Invar brackets, one on each side of the MM. The two brackets are not identical in the number of interface points towards the mirror structure element: one bracket has one lug and the other bracket has two lugs.

In the frame of this study, the brackets design, inherited from previous ESA/SRON studies, has been slightly adapted in order to: i) have sufficient area on the lugs for the bonding; ii) create interfaces for the optical elements needed by the indirect method; iii) adapt the interfaces for the handling of the MMs during alignment and integration.

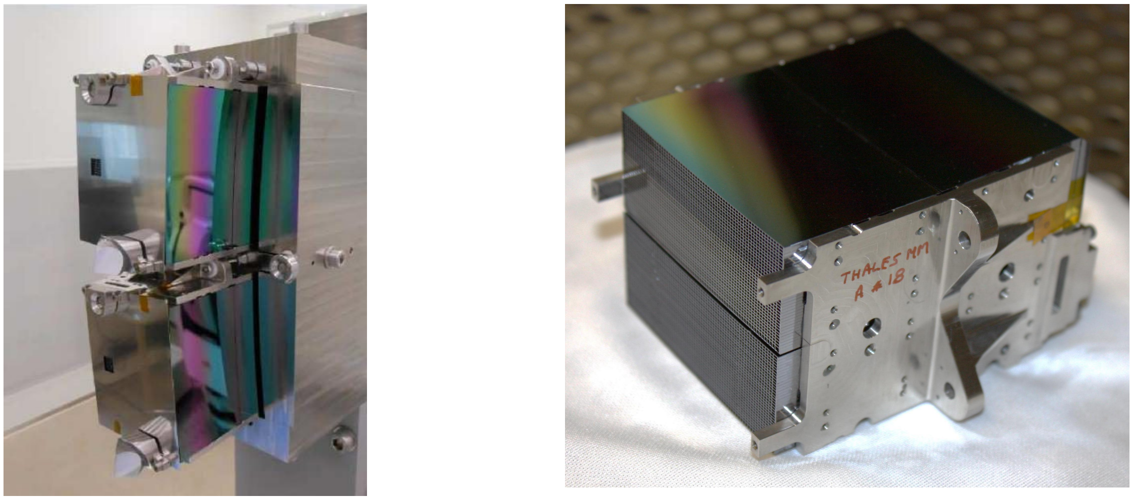


Figure 1. Technology Demonstrator (left) and of one Mirror Module with the modified brackets (right)

3. MIRROR MODULES MANUFACTURING AND CHARACTERIZATION

The Mirror Modules (MMs) of the demonstrator were assembled by cosine at the X-ray Parallel Beam Facility (XPBF 2.0) in the laboratory of the Physikalisch-Technische Bundesanstalt (PTB) at the electron storage ring BESSY II [9].

As the illumination of the Mirror Module's aperture is limited by the pencil beam size of XRPB 2.0, a mosaic scan is carried out in order to cover the full aperture of the MMs. The global Point Spread Function (PSF) is then recombined using the sub-aperture-images of the scan. The Half Energy Width (HEW) of MM1 and MM2 provided by cosine are:

- MM1 = 23”
- MM2 = 28.5”

Being these numbers significantly above the assumed 4.3” HEW, it has been decided to mask the apertures with a smaller aperture of 7 mm x 7 mm. The goal of this masking is to achieve higher resolution on the MMs peak separation at the later integration demonstration stage. The reduced aperture has been centered arbitrarily on the center of the MM aperture (see Figure 2 right). As an example for MM1, the effect of the mask on the PSF shape is shown in Figure 2 left. The white circles on the top and the bottom of the image are real references on the detector, this shows that the scale is the same for both PSFs.

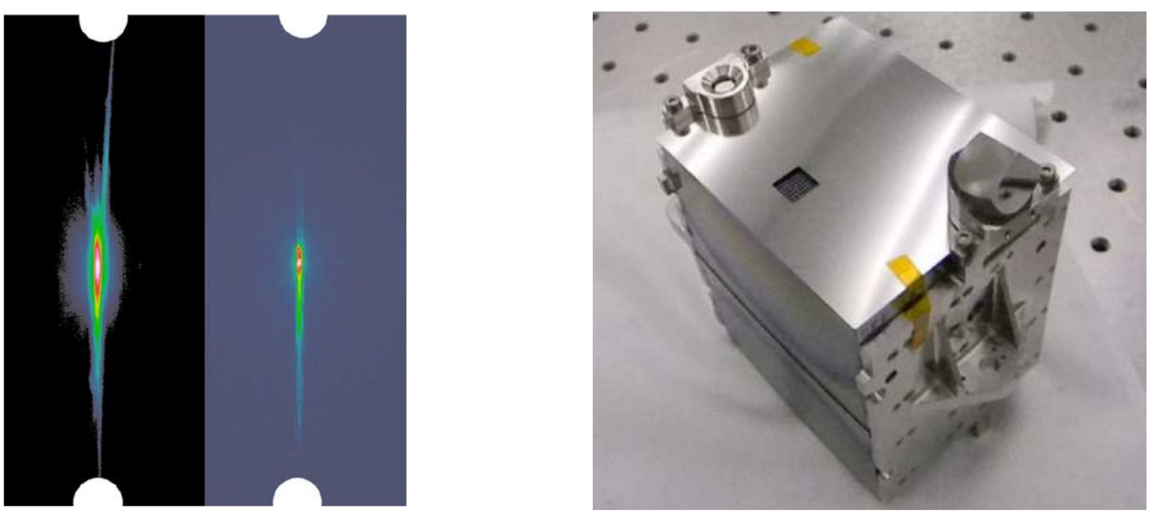
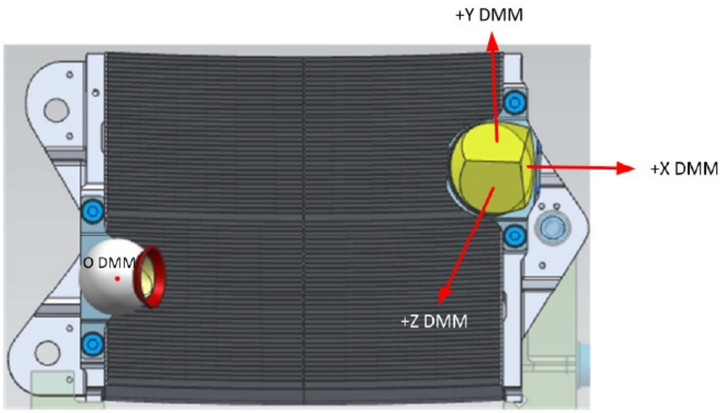


Figure 2. MM1 PSF without (very left) and without the 7 mm x 7 mm mask (left); picture of the masked MM1 (right)



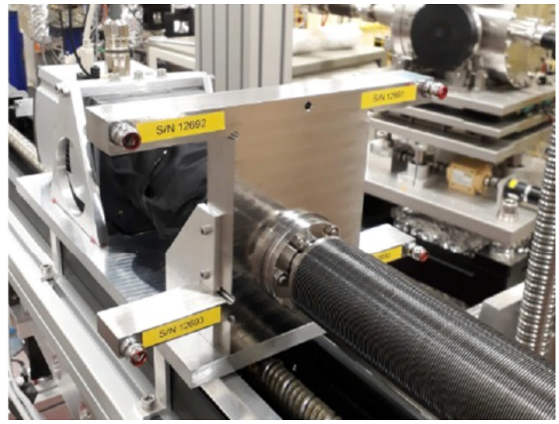


Figure 3. Optical fiducials positioned on the MM (left) and XPBF 2.0 detector stage (right)

Right after the MMs manufacturing, the characterization with the laser tracking system was performed. The aim of the characterization is to reference the position of the Focal Point and the direction of the Optical Axis of each MM in a reference frame defined by optical references (One corner cube and one Laser Tracker Target) attached to the MM (see Figure 3 left). With this information, it was later possible to align the MMs by only relying on the optical fiducials position/angular measurements.

The mirror cube defines 3 axes for the reference frame directions and the Laser Tracker Target (LTT) defines the origin of the reference frame. The output of this characterization is the Optical Axis direction and the Focal Position coordinates in the reference frame of the mirror module. Two steps are required to complete this characterization under X-ray illumination:

1. MM X-ray illumination and Focal Point position measurement to optical references
    - Once the MM is installed and aligned on the beam-line, the centroid position of the PSF is defined by measuring the LTTs positioned on the detector stage (see Figure 3 right). The position of the centroid on the CCD of the camera is determined. The pixel positions of the camera with respect to the LTT were characterized mechanically and optically beforehand
    - The measurements on the optical references mounted on the MM inside the vacuum chamber are done at ambient conditions with the lateral door open and the top window removed. A characterization of the vacuum chamber during vacuum-to-air transition showed no significant displacement of the MM with regard to an external reference.
2. Optical Axis direction measurement
    - The optical axis direction of the MM is, by definition, the beam-line axis direction during focus characterization. This direction is defined by illuminating a pinhole (diameter 200 µm) with direct beam and referencing the image of this pinhole on the detector.
    - The sequence was performed right after the Focal Point characterization for stability reason. The Optical Axis is defined by the direction between the pinhole center inside the vacuum chamber and the centroid of its image on the detector (ca 12 m away).

To compare the results from the characterization of the 2 MMs, a reference frame attached to the beamline built as follows was used:

- Y loc: Gravity direction
- Z loc: Optical Axis direction normal to gravity
- X loc: normal to Y and Z

The distance between the 2 MMs Focal Points in this reference (given in Table 1) were used to define the relative alignment between the MMS, to be considered in the integration of the Technology Demonstrator.

Table 1. Relative positions of the MMs Focal Points in the beamline Coordinate System

Beamline LTT Coordinate Axis	MM1 (m)	MM2 (m)	Delta (m)
X loc	0.031817	0.030895	-0.000922
Y loc	0.712146	0.711156	-0.000990
Z loc	11.834330	11.834388	0.000058

With reference to the relative positions summarized in Table 1:

- The Y deviation can be assimilated to the difference of radius between MM1 and MM2, this deviation of ca 1 mm was compensated during integration. MM1 has a larger radius than MM2.
- The deviation in X-direction has been later compensated during integration by translating along X and rotating around the optical axis.
- The deviation in Z-direction indicates a deviation in focal length between the 2 MMs of 58 µm. This is considered acceptable as it can be compensated by adhesive thickness adaptation.

The characterization campaign showed that, due to manufacturing discrepancies between MM1 and MM2, the alignment margin was reduced w.r.t. the original design margin. This reduced alignment margin complicated the integration activities, nevertheless it didn't prevent to align the two MMs (ref § 4).

4. DEMONSTRATOR INTEGRATION

After the characterization campaign, the two MMs were integrated into the Technology Demonstrator at the Panter X-ray facility of Max Plank Institute (MPE) [10]. A dedicated setup was designed to align and integrate the MMs in position within the alignment budget. The setup was designed in a way that both indirect and direct X-ray method could be tested. The optical references were kept visible as well as a portion of the MM aperture, so to allow X-ray measurement even during alignment.

For the indirect metrology, the alignment was performed using the focus characterization data measured at XPBF 2.0. For this alignment, two Laser Trackers (LTs) were used in order to cover the 6 degrees of freedom.. For the Technology Demonstrator configuration, the two LTs were positioned on each side of the test item as they have to be in autocollimation with the mirror cube faces as shown in Figure 4.

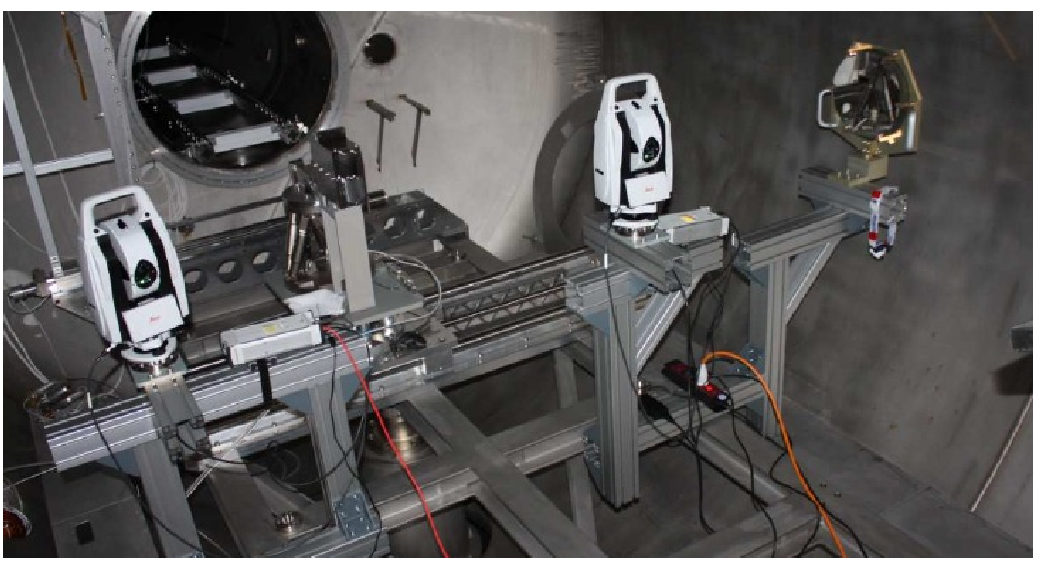


Figure 4. Integration set-up in the vacuum chamber of Panter X-ray facility

Each LT can measure one mirror cube face and the common transfer mirror on the right hand side which is used to define a common coordinate system. An external reference LTT (which is not visible on Figure 4) is also used to monitor the stability of the LTs. It is also used as the origin of the Coordinate System (CS) which is independent from the test items. The absolute CS (X;Y;Z) is defined as following, with origin in the center of the external LTT:

- Z: Gravity direction
- X: Normal to common mirror direction projected perpendicular to gravity
- Y: Normal to X and Z (right hand CS)

By using the external reference, the LTs were moved from one measurement position (MM1) to the other (MM2) without losing the reference.

During the integration phase and during testing phase two main sets of X-ray measurements were performed:

- After alignment under indirect metrology (MM1 bonded, and MM2 kept in position with the hexapod)
- After final integration (MM1 bonded and MM2 bonded)

Test 1 is the performance measurement of the indirect alignment and Test 2 is the performance measurement of the demonstrator alignment and integration. In between Test 1 and Test2, additional X-ray measurements were taken for MM2 alignment under X-ray monitoring. The tests were led by Panter operators and consisted in the following steps:

1. Demonstrator pre-alignment with laser to pre-align the different parameters (pitch, yaw, lateral position, small chamber alignment, detector pre-positioning), this is done before closing the chamber.
2. Demonstrator first illumination, pitch and yaw scan to define maximum effective aperture
3. Focal search around pre-aligned position to determine the best focus distance
4. Centroids determination at best focus position and separation measurement on detector

The steps 2 to 4 are always split into 3 parts: i) MM1+MM2 illumination; ii) MM1 illumination; iii) MM2 illumination. This is considered as one illumination triplet and is necessary to derive the performance. The main performance parameter is the separation between MM1 and MM2 centroids (in X- and Y-direction) on the sensor of the camera.

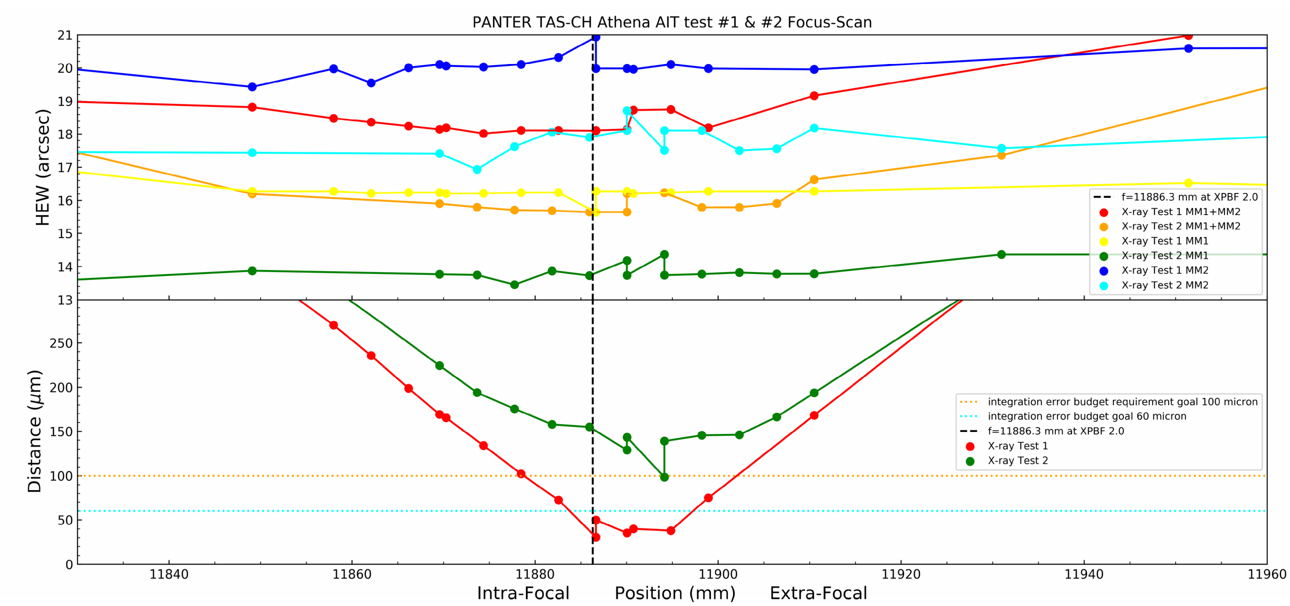


Figure 5. Demonstrator X-ray measurement results

The results of the X-ray performance measurements are shown in Figure 5. The main output of the measurements is the indirect alignment performance (test 1) achieved in terms of centroids separation (red curve in bottom plot) which is in the order of 60 µm. It has to be noted that the measurement repeatability is in the order of 30 µm, so the alignment performance of the laser tracker technology is considered as very satisfying when considering the optical performance of the optics and the other limitations such as the post processing influence on the centroid determination.

Another evidence of the successful alignment is the HEW performance computed for the single MMs and for both MM combined (see top plot in Figure 5). The combined HEW lies in between the HEWs measured for the single MMs. In the ideal case the combined HEW is the average of the single MM HEW.

The test 2 results show a degradation of the centroids separation compared to test 1 (green curve in bottom plot). The separation is between 100 µm and 150 µm which is in the end the performance of the X-ray alignment and integration. The centroid separation is almost exclusively along the Y axis of the camera sensor which corresponds to the longitudinal axis of the PSFs which is very sensitive to the centroid determination.

As the focus characterization was performed with the centroid parameter, the separation is always given in terms of distance between the two centroids.

The results of the measurements done during the MM2 alignment under direct X-ray metrology are shown in Figure 6:

- the centroid positions (upper plot)
- Gauss peak positions (middle plot)
- the evolution of the peak separation during the alignment steps (bottom plot).

As explained before the starting point (1st measurement) is the result of the indirect alignment with LTs, the separation is only along Y axis of the camera sensor. MM2 was shifted so the centroid of MM2 is superimposed with MM1 centroid. Due to measurement instabilities and non-expected cross coupled movements of the centroid, the alignment was considered as successful after 3 steps. Indeed the separation measured was considered within the measurement accuracy. The achieved performance of the direct X-ray alignment is in the same order of magnitude than the indirect method. The separation between the Gaussian peaks is also reported for information in Figure 6.

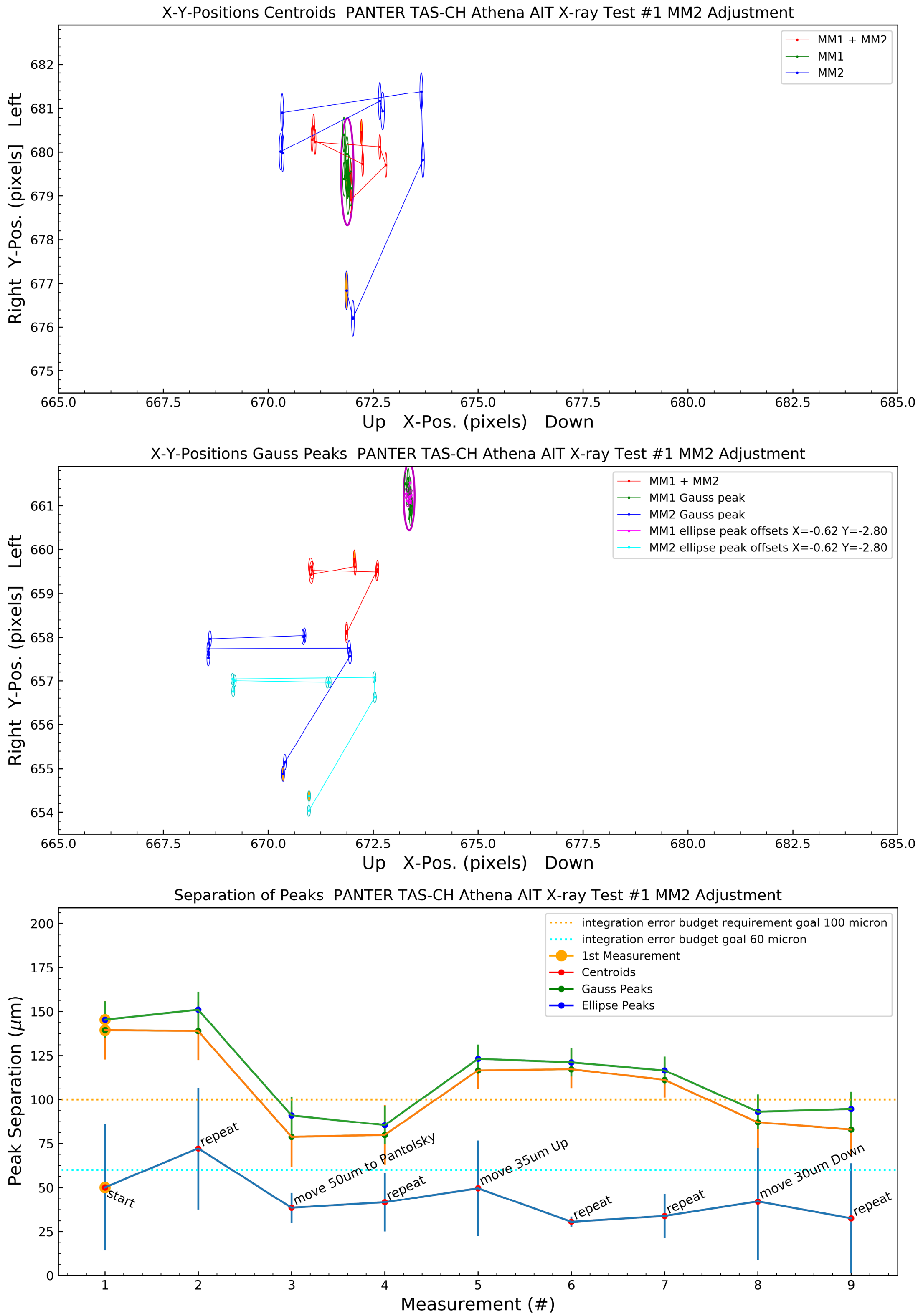


Figure 6. MM2 alignment under X-ray

Table 2. Demonstrator X-ray measurement results summary

Test	Centroids separation (µm)	Goal (µm)	Requirement (µm)
Indirect alignment (Test 1)	50 ± 20 [0.7'' HEW]	60 [0.9'' HEW]	100 [1.5'' HEW]
Direct alignment	40 ± 20 [0.6'' HEW]		
Final test (Test 2)	150 ± 20 [2.2'' HEW]		

According to the results detailed in Table 2, the final performance is measured slightly out of the specification. Thanks to the intermediate results available and reported, the alignment methods are not the root cause of this degraded performance. The discrepancy between the alignment phase (Test 1) and the final result (Test 2) was investigated and possible root causes for this are listed below:

1. The evolution of the alignment over bonding process (including adhesive injection, curing, MGSE releasing and transition air to vacuum) is not monitored except with the LT metrology system. Assuming that the stability degrades the LT measurement performance, these data cannot be relied with accuracy requested. This is anyway a process issue and some improvement on the process could be envisaged
2. MM2 was re-aligned after the alignment under X-ray, even if the alignment was performed only on the out of plane rotations, which have a priori no influence on the HEW performance, the PSF centroid position might have been affected by a side effects. The glue injection system or a contact between the iso-static mount and the MM bracket may create cross coupling between the planned movement of the hexapod and the effective movement.

5. CONCLUSIONS

The following conclusions are drawn:

- The indirect method has been proven compliant to the alignment requirements of ATHENA. The direct X-ray didn't allow significant improvement of the alignment
- About discrepancy between the indirect alignment phase (Test 1) and the final result (Test 2), possible root causes (such as adhesive injection, curing, MGSE releasing) are identified for investigation.
- With the indirect method, the integration requirement of 2 years for 1064 MMs is met with margin (3 MMs per day, meaning in total 1.5 years). Significant time is left for intermediate checks at the X-ray facility and for schedule contingency.
- With the indirect method, the integration can be performed with the mirror structure in horizontal configuration in an ISO5 cleanroom

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