AHEAD Workpackage 8

JRA X-ray Optics

Deliverable D8.8 - D42

Measurements vs theory report of the different X-ray optics units

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Acronym list

HPO High Performance Optics
MM Mirror Module
SPO Silicon Pores Optics
f focal distance
FWHM Full Width Half Maximum
HEW Half Energy Width
HDS Half Death Star
IP Intersection Plane
ML Media Lario
PANTER PAntolsky Neuried TEstanlage Röntgen
PIXI Princeton Instruments X-ray Imager
TAS-CH Thales Alenia Space Swizzerland
TRoPIC Third Roentgen Photon Imaging Camera
xFWHM transversal Full Width Half Maximum
ZPC Zone Plate Collimator

Contents

Abstract

In the last years the PANTER X-ray facility has characterized several optics related to the AHEAD projects. In this document we summarize the measurement test campaigns, the used setups and the main results, i.e. Half Energy Width (HEW), transversal Full Width Half Maximum (xFWHM) and focal distance (f). In some cases the Silicon Pores Optics (SPO) have been used for other test campaign in combination with other optical component (e.g.gratings) and are just mentioned for completeness.

1 Introduction

In this report we describe the last improvements implemented at the PANTER X-ray facility and we summarize the results of the measurements of Mirror Modules (MMs)
Several maintenance cycle has been performed to:

- reduce the size of the source spot of the X-ray source;
- make the source as circular as possible;
- analyze the background;
- implement aperture masks to stop background coming from the interaction of the X-ray radiation with the first part of the vacuum tube (i.e. close to the X-ray source);
- implement aperture masks to reduce the beam section to illuminate a small area that include the optic reducing the interaction with other mechanical components.

At present, the PANTER X-ray facility provides a divergent beam with an angular resolution better than 1 arcsec. In table 2 we list all the test campaigns performed at the PANTER X-ray facility in which are involved the measurement of MMs based on SPO technology.

Table 2: The table lists project and date of the relatives test campaigns.

	Test campaign with date and linked paragraph.				
Mirror Code	**HDS**	**ASPHEA**	**KP-Baez**	**ARCUS**	**TAS-CH**
XOU-0060C HPO-primary-1043 HPO-secondary-1060	2018/09				
XOU-0062B HPO-primary-1043 HPO-secondary-1058	2018/09				
MM-1 MM-2					2018/04
MM-0024 XOU-0038b XOU-0040		2018/03		2017/05 CAT 2017/06 2017/07 OPG 2017/12	
3 slot Petal MM-0025 MM-0027		2018/01 2018/02		2018/03 GWAT	
MM-0025		2017/11			
MM-0027		2017/11			

2 The PANTER X-ray facility, last improvements

In this section we describe the last improvements implemented at the PANTER X-ray facility. In particular a description of the X-ray source spot and of the implementation of aperture masks for background noise reduction will be given. An illustration of the laser alignment procedure is also reported.
A description of facility, off-axis measurement, thin lens equation application has been already reported [1] [2]. Optics are characterized using three main setups [3]:

Setup 1 The optics and the detector are mounted in the big chamber. In this configuration only optics with a focal length smaller than 9 meters can be measured.

Setup 1 + Zone Plate Collimator (ZPC) As like the setup 1 but with the introduction of a ZPC. In this case, the focal length of the measurable optics, can increase up to 12 meters. The setup is under implementation.

Setup 2 The optics is mounted in the big chamber and the focused image is reflected in the tank-e (chamber extension). This setup has been designed to test optics with a focal length of about 20 meters, that is equivalent to an image at 24 meters without ZPC. A modified version of the setup 2 has been used also to measure shorter focal length down to 12 meters (image at 13.3 meters). In this setup the Third Roentgen Photon Imaging Camera (TRoPIC) detector cannot be used for mechanical constraint. For this reason is better to use the setup 3 if the optics fit in it.

Setup 3 The optics is mounted inside of the one meter tube diameter and at from two meters from the end of the tube itself. The image is focused inside of the chamber. The setup has been used for 12 meter focal length optics.

2.1 X-ray source characterization and improvement

In this section we report data on the dimension of the X-ray source and describe the method used to tune the size of the section of the X-ray beam, in order to reduce noise due to the scattering from the X-ray tube components.

2.1.1 X-ray source dimension

The PANTER X-ray source dimension has been reduced to the minimum dimension achievable with our instrumentation. At present, the PANTER X-ray facility can provide a source with a Gaussian shape of about 0.3 mm roughly elliptical with about 20% difference between the 2 axes (See figure 1).

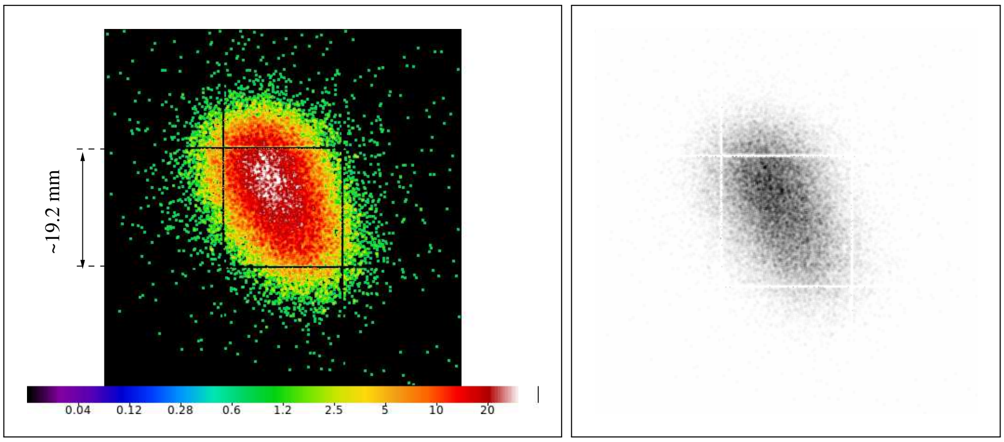


Figure 1: X-ray source spot using the 1.5 Al-k line and a pinhole of 100 micron. Pinhole and detector are respectively 1.65 m and 230 m from the source. On the left: color logarithmic scale. On the right: gray linear scale.

Preliminary analysis based on quadratic correction shows that the X-ray spot has a Full Width Half Maximum (FWHM) of 95 micron. The 50% of the photons are emitted from a spot diameter of 70 micron. The 97% of the flux is emitted from a spot with a dimension of 220 micron. Further characterization are planned in order to have more information on the spatial distribution of the source and also to make the spot round and symmetric.

2.1.2 Tunable X-ray beam section

A new mask with has been mounted at 1.65 meters from the X-ray source. On the mask support can be mounted a pinhole to reduce the size of the beam in order to avoid any illumination of the vacuum tube reducing the scattering noise. At present time we have a set of pinholes with different diameter in the range from 0.5 up to 20 mm with a step of 0.5 mm plus 2 small pinhole of 0.1 and 0.15 mm.
Figure 2 reports the beam section diameter as a function of the pinhole and the position in the chamber. The beam section is calculated for a point source like.
For a finite dimension source the beam section is a little bit larger and it is not homogeneous at the border. For a collimating system with only one pinhole we can identify 3 areas on the beam section:

Pinhole mask size (mm)	at Cham. Entr. (mm)	at Kugel (mm)	at Detector (mm)	Pinhole mask size (mm)	at Cham. Entr. (mm)	at Kugel (mm)	at Detector (mm)
0.10	7.41	7.50	8.06	6.5	482	488	524
0.15	11.1	11.3	12.1	7.0	519	525	564
0.5	37.1	37.5	40.3	7.5	556	563	604
1.0	74.1	75.0	80.6	8.0	593	600	645
1.5	111	113	121	8.5	630	638	685
2.0	148	150	161	9.0	667	675	725
2.5	185	188	201	9.5	704	713	766
3.0	222	225	242	10.0	741	750	806
3.5	260	263	282	10.5	779	788	846
4.0	297	300	322	11.0	816	825	887
4.5	334	338	363	11.5	853	863	927
5.0	371	375	403	12.0	890	901	967
5.5	408	413	443	12.5	927	938	1007
6.0	445	450	484	13.0	964	976	1048

Figure 2: Indicative beam section diameter in three different point: at the entrance of the chamber (Chm.Entr), on the pivot point of the optical bench (Kugel) and at the Detector position. The diameter of the beam are calculated considering a point like source.

1. The area of maximum intensity. It is the area illuminated from the biggest area of the source. It is also called plateau because it is quite uniform in space.
2. The border: it represents the area that receives the contribution of only a part of the source. The intensity decreases from the center to the side.
3. The region of maximum beam size. It represents the full area illuminated by the source with a given pinhole size. It is given by the sum of areas described in the previous points.

Beam section: plateau and full area diameter based on geometrical calculation.

INPUT DATA					OUTPUT DATA					
Source diameter	pinhole diameter	Source-pinhole distance	position of the target		pinhole-detector distance	diameter of all illuminated area	plateau diameter	virtual focus (plateau)	virtual focus for all illuminated area	(max area-plateau)/2
fig 3, 22, 23	*fig 3, 22, 23*	*fig 3, 22, 23*	*planes p, p2 and r*			*p in fig. 23*	*r in fig 22*	*V in figure 22 and 23*	*V in figure 3*	
mm	mm	mm	mm		mm	mm	mm	mm	mm	mm
bs	**bt**	**w**	**w+q**		**q**	**r**	**p**	**hs: fig 3 and 23**	**hs: fig22**	**(r-p)/2**
0	2.5	1650	133822	**Results =>**	132172	202.761	202.761	-1650.000	0.000	0.00
0.1	2.5	1650	133822	**Results =>**	132172	210.771	194.750	-1718.750	63.462	8.01
0.15	2.5	1650	133822	**Results =>**	132172	214.776	190.745	-1755.319	93.396	12.02
0.2	2.5	1650	133822	**Results =>**	132172	218.781	186.740	-1793.478	122.222	16.02
0.25	2.5	1650	133822	**Results =>**	132172	222.787	182.735	-1833.333	150.000	20.03
0.3	2.5	1650	133822	**Results =>**	132172	226.792	178.729	-1875.000	176.786	24.03
0.15	12	1650	133822	**Results =>**	132172	985.267	961.235	-1670.886	20.370	12.02
0.15	13	1650	119722	**Results =>**	118072	953.998	932.530	-1669.261	18.821	10.73
0.15	12	1650	119722	**Results =>**	118072	881.439	859.972	-1670.886	20.370	10.73
0.15	0.16	1650	119722	**Results =>**	118072	22.343	0.876	-26400.000	798.387	10.73
0.15	0.15	1650	119722	**Results =>**	118072	21.618	0.150	#DIV/0!	825.000	10.73
0.15	0.14	1650	119722	**Results =>**	118072	20.892	0.576	23100.000	853.448	10.16
0.15	0.1	1650	119722	**Results =>**	118072	17.990	3.478	3300.000	990.000	7.26
0.15	0.05	1650	119722	**Results =>**	118072	14.362	7.106	825.000	1237.500	3.63
0.15	0.02	1650	119722	**Results =>**	118072	12.185	9.283	253.846	1455.882	1.45
0.3	0.01	1650	119722	**Results =>**	118072	22.193	20.742	56.897	1596.774	0.73

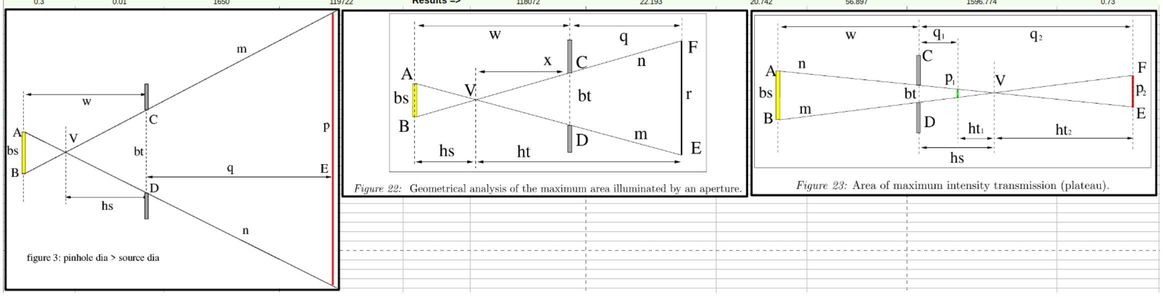


Figure 3: Geometric relationship between source, pinhole diameter at the PANTER facility. This results are based on geometrical calculations in a plane. 3-dimensional model, scattering, and wave propagation (e.g. diffraction) are not taken in account.

2.2 Laser alignment

In this section we describe the general procedure used at the PANTER X-ray facility to pre-align optics and detectors. The image in visible light of the reflected beam cannot be used to determine focal distance, HEW neither xFWHM because the interaction of the light front with the optics creates a very large diffraction pattern. A low divergent laser beam, with a section of about 1 cm2 is aligned with the optcal axis of the PANTER X-ray facility. The laser is used to align the detector on the beam reflected from the optics.
The standard procedure is the following:

1. Alignment of the optics with the laser beam. This position is defined as “direct beam laser alignment” and it is usually the reference point for all the test campaign. We can apply different methods depending on the mirror assembly:
   (a) X-ray mirror with small specular reference mirror: the optics is aligned with the autocollimation method, reflecting the laser beam back to the laser source.
   (b) X-ray mirror without reference mirror:
      i. use of the surface of the mirror itself as a reference rotated of 90 degree. This procedure can be applied only if it is possible to rotate the mirror of 90 degree around the pitch axis.
      ii. if none of the previous point can be applied, we align the optics maximizing the flux intesity passing trough the pores of the optics itself. Double internal reflection can compromise the alignment that is quite subjective and is related to the operator experience.
2. Alignment of the detector with the optics. In this case we can use both double and single reflection to get a better alignment:
   (a) As a first step we detect the position of the beam reflected (focused) from the optics. The focusing point, generated from a double reflection (Wolter telescope) is fixed in space also if the optics is rotated or tilted. We verify that the reflected point falls in the expected theoretical position.
   (b) In order to optimize the yaw alignment, we usually check the shape of the point reflected from the secondary mirror. The shape has to be symmetric respect to the axis of the optic itself.

In those cases in which the optics is mounted outside of that axis, the laser has to be tilted or enlarged. However, the beam-line has one big gate to keep in vacuum more than 100 meters of tube[1]. The laser can pass only trough 3 glass windows of about 70 cm^2 (Figure 4) Figure 5 shows the enlarged beam section passing trough the 3 windows mounted on the one meter gate valve. If the optics are outside of the projection of those windows, the optics cannot be illuminate by the laser itself. In figure 4, the optics MM-1 can be illuminate by the X-ray beam, but the laser cannot be used to align it. On the contrary, the MM-2 can be illuminate both from laser and X-ray.

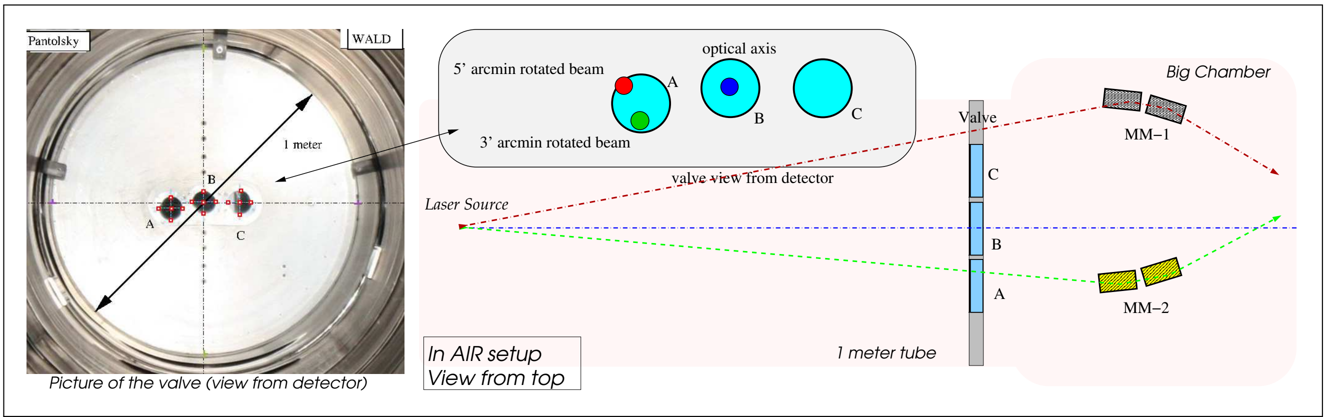


Figure 4: On the left: the one meter valve with the 3 windows. On the right: a side view of the set-up with optics. MM-1 and MM-2 can be both illuminated by the X-ray beam but only the MM-2 can be aligned using the laser beam.

3 Measurements

In this section we summarize measurement results reporting information about: xFWHM, HEW, focal distance, best focus position and azimuthal scan (See table 3). In the caption of each figure are reported other information as like for example the distance from the Intersection Plane (IP) to the detector ($d1$). The focal lens of the optic is calculated using the $d1$ value, the nominal radius of the optic itself and applying the thin lens equation corrected by the off-axis configuration [1].

[1]This is mandatory in order to preserve the tube from humidity, specially during cold days

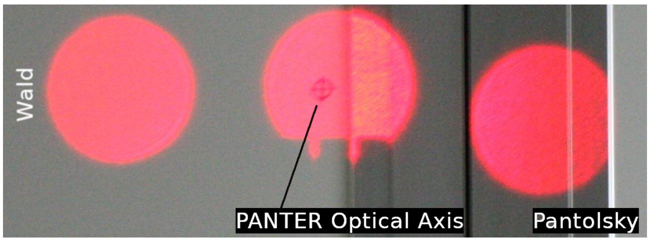


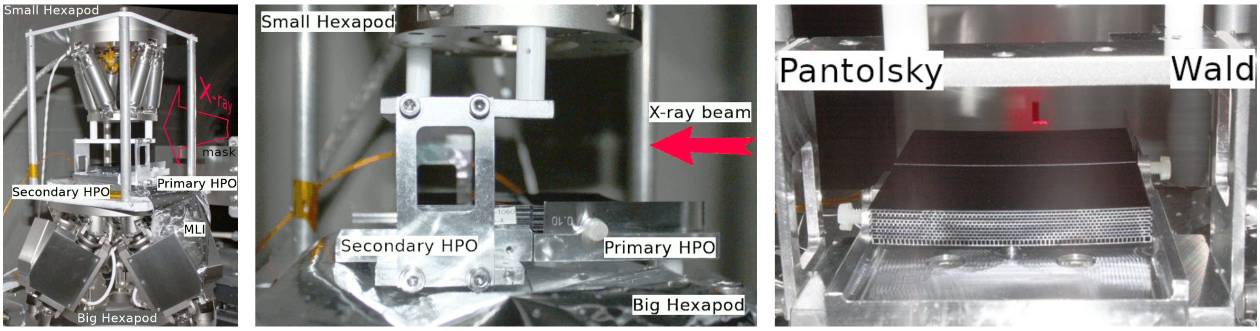
Figure 5: A small telescope system has been used to enlarge the laser beam. The picture show the laser beam section passing trough the 3 windows mounted on the one meter gate valve. The valve is positioned 100 meters from the source.

Table 3: Summary of the main results of the mirrors measured at the PANTER X-ray facility.

	PANTER				**Comments**	
Mirror code	**source-optics distance [mm]**	**xFWHM** [$''$]	**HEW** [$''$]	**f** [mm]		**reference link**
XOU-0060C	119755	2	10	11909		Sec.3.1.1, Fig.8
XOU-0062B	119755	2	13.5	11970		Sec.3.1.2, Fig.9
TAS-CH 1st	123822	1.8	18	11880	2 aligned MMs	Sec.3.2, Fig.13(a)
TAS-CH 2nd	123822	1.7	15	11886	2 aligned MMs	Sec.3.2, Fig.13(b)
MM-0025					A description is available [1]	
MM-0027					A description is available [1]	
ASPHEA 1st	123822	2.3	18.4	11941		Sec.3.3.3, Tab.7
ASPHEA 2nd	123822	2.0	18.1	11963		Sec.3.3.3, Tab.8

3.1 HDS test campaign: HPOs alignment at the PANTER X-ray facility

In this section we report the results of the alignment of two High Performance Optics (HPO)s.
The goal of the HPOs PANTER alignment test campaign is to tune two HPOs under full X-ray illumination and compare the performances with the results obtained at Bessy Synchrotron.
The setup number 3 has been used for the test campaign. The optics has been mounted in the tube, meanwhile the detector was positioned at the end of the chamber. Each HPO was mounted on a dedicated hexapod (Figure 6). The hexapod of the secondary mirror was mounted on the hexapod of the primary mirror. This configuration permits to tilt the two HPOs together but also the secondary can be tilted respect to the primary one.



(a) HDS. (b) Detail of the HPOs. (c) Front view of the mirror.

Figure 6: HDS mounted inside of the tube.

The mirror were aligned with the following procedure:

1. In air laser alignment: the mirrors have been moved alternatively on the laser beam and tilted and rotated until the reflected beam and the one passing trough the pores were coincident.

2. In vacuum X-ray alignment:

   (a) move the secondary mirror away and use the mask in order to illuminate only the primary one.

   (b) Pitch and yaw best alignment: this procedure makes the primary mirror parallel to the X-ray beam, i.e. maximize the flux tilting and rotating the mirror.

   (c) remove the primary mirror from the beam and move the secondary mirror on the beam.

   (d) repeat pitch and yaw best alignment for the secondary mirror.

   (e) from the previous points the mirrors are parallel to the X-ray beam.

   (f) HPOs were moved vertically and horizontally to superimpose the pores each other (e.g. fig. 7). Image of the pores and flux optimization were used to optimize the alignment.

At the end of the previous sequence, the mirror were individually parallel to the X-ray beam and aligned also each other.

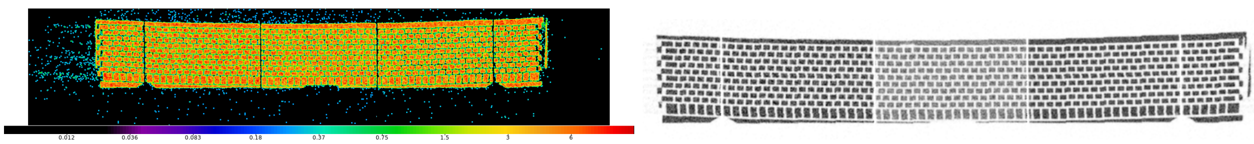


Figure 7: On th left XOU-0060C, on the right XOU-0062B. The images are an X-ray composite images acquired with TRoPIC detector.

3.1.1 XOU 0060C

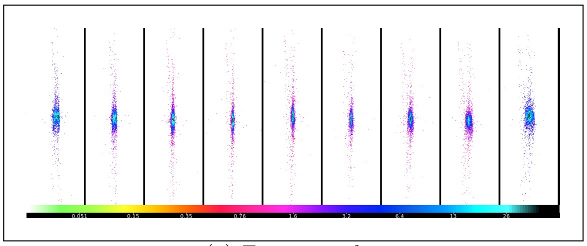
The Wolter configuration has been setup as required from the manufacturer:

kink angle = 1.7544 deg. It represents the tilt angle of the secondary mirror with respect to the axis.

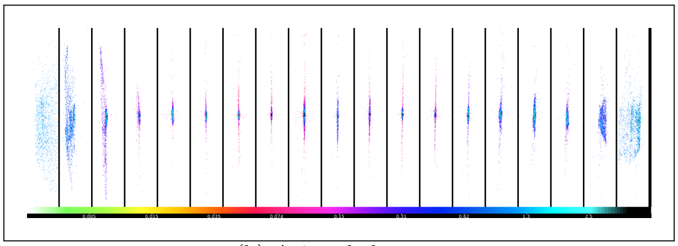
Incidence angle = 0.8772. It represents the angle between the axis and the primary mirror.

Table 4: XOU-0060C: Summary of the main mirror parameters measured in PANTER. PANTER f is calculated with the thin lens equation. The distance *d1* has been taken with the laser meter.

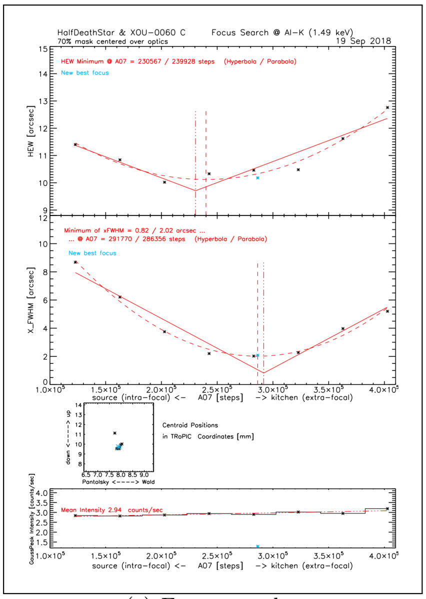
Mirror code	source distance	nominal f	xFWHM ($''$)	HEW ($''$)	d1	PANTER f	reference
XOU-0060C	119755	11950	2	10	13219 ± 2	11909	Fig.8



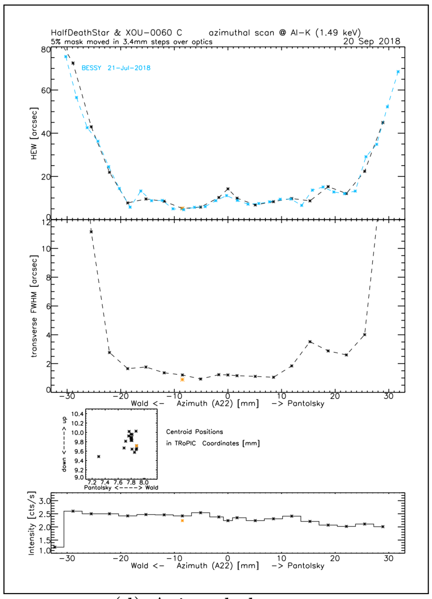
(a) Focus search.



(b) Azimuthal scan.



(c) Focus search.



(d) Azimuthal scan.

Figure 8: XOU-0060C. The curves are obtained using the Al-k X-ray tube fluorescence line.

3.1.2 XOU 0062B

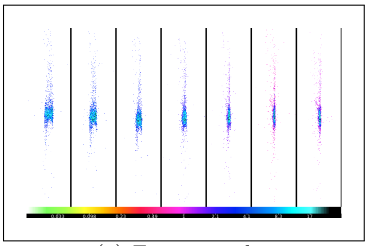
We tilted every HPO of the angle set up from the manufacturer:

kink angle = 1.7544 deg. It represents the tilt angle of the secondary mirror with respect to the axis.

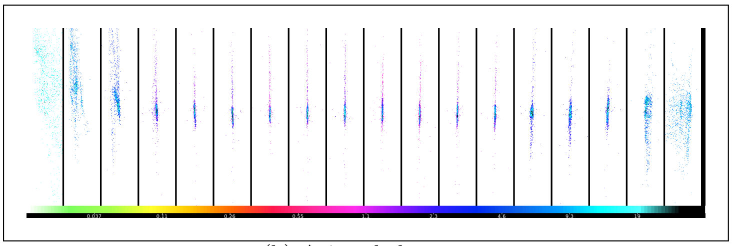
Incidence angle = 0.8772. It represents the angle between the axis and the primary mirror.

Table 5: XOU-0062B: Summary of the main mirror parameters measured in PANTER. PANTER f is calculated with the thin lens equation. The distance *d1* has been taken with the laser meter.

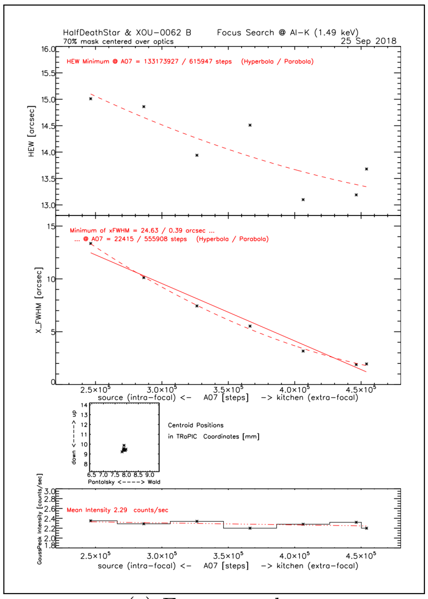
Mirror code	source distance	nominal f	xFWHM (″)	HEW (″)	d1	PANTER f	reference
XOU-0062B	119755	11950	2	13.5 ± 0.5	13294 ± 2	11970	Fig.9



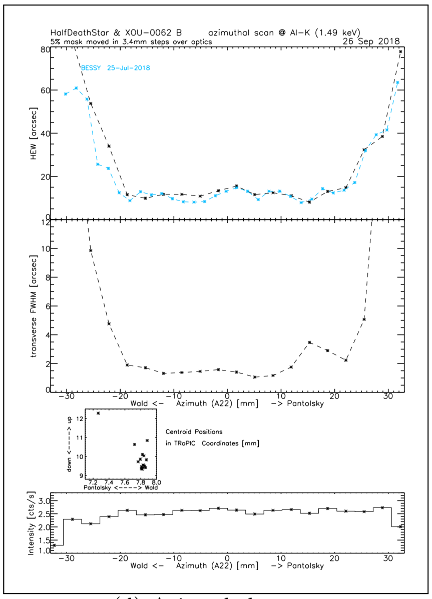
(a) Focus search.



(b) Azimuthal scan.



(c) Focus search.



(d) Azimuthal scan.

Figure 9: XOU-0062B focus search and azimuth scan. The best focus position was just found to be at the end of range.

3.2 TAS-CH Petal alignment

In this section we report the result of the alignment of two MMs performed by the Thales Alenia Space Swizzerland (TAS-CH) team at the PANTER X-ray facility. The test campaign was related to procedure selection for the alignment and integration of the optical system of the ATHENA telescope. The goal of TAS-CH test campaign was to validate the alignment procedure of two mirror modules in a petal configuration. In this test campaign, HEW and xFWHM were of secondary importance.

Table 6: Optics parameters. Nominal radius (r), nominal focal length (f) and focal length measured at Bessy II (f_B)

MM	**XOU**	**r (mm)**	**f (mm)**	f_B **(mm)**	Comments
MM-0026	XOU-0044	737	12000	11830	Alias MM1 in Petal configuration, TOP position at Panter.
MM-0028	XOU-0051	737	12000	11832	Alias MM2 in Petal configuration, BOTTOM position at Panter.

3.2.1 Setup

The optics are mounted using the setup 2, i.e. optics in the big chamber and detector in the extension chamber (Tank-e). In the extension chamber is it possible to use only the Princeton Instruments X-ray Imager (PIXI) detector. The optics were mounted on the Telescope optical bench. To find the pitch and yaw for maximum flux, the entire telescope bench was used as tilting/rotating system.
The optics were positioned 160 mm (*d*5 in figure 10) toward Pantolsky with respect the PANTER optical axis to reflect the X-ray beam in the chamber extension. During the laser alignment the laser beam has been moved in order to illuminate the optics (Figure 10). In this case the optics axis doesn't overlap the PANTER optical axis anymore.

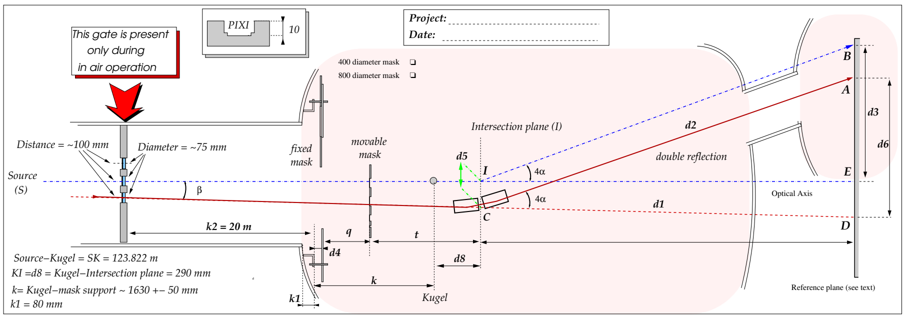


Figure 10: Sketch of the top view of the TAS-CH setup. d8 = 290 mm, d5 = 160 mm, f-nominal = 12000 mm, source-Kugel distance = 123822 mm.

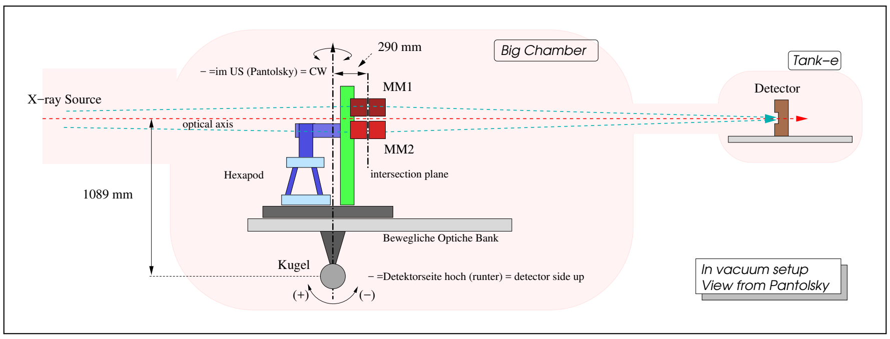


Figure 11: Sketch of the setup view from Pantolsky. Detail of the telescope optical bench.

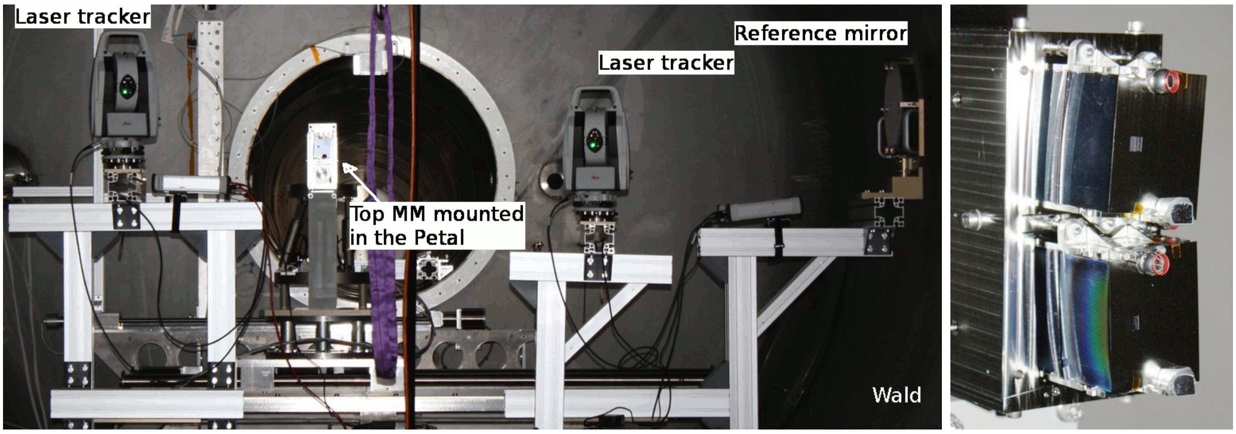
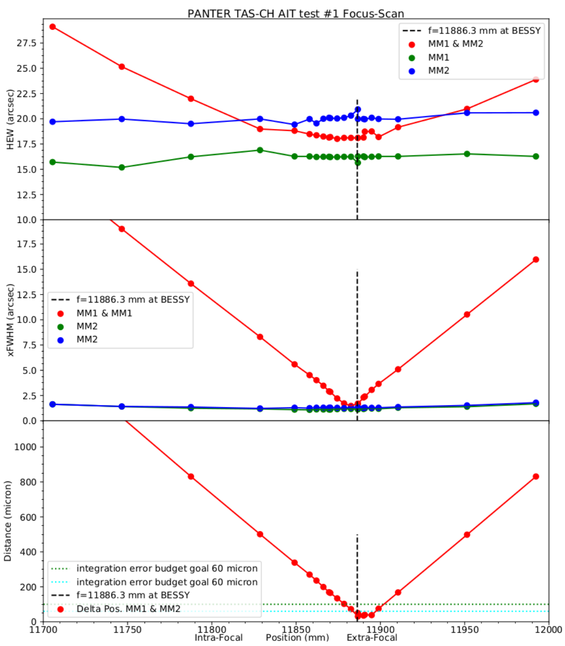


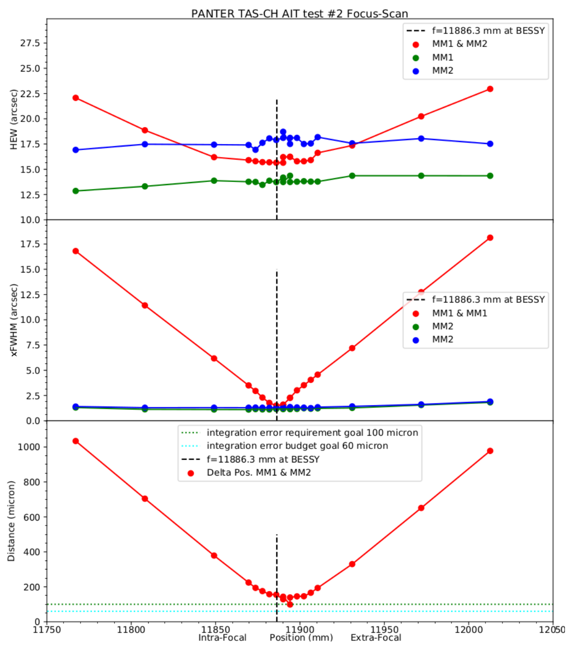
Figure 12: On the left:Laser tracker setup view from the detector side. Top MM mounted. On the right: Petal with both MMs mounted. A mask with a $7 \times 7\ mm^2$ aperture is mounted to select have better optics performance.

3.2.2 Results of measurement test campaign

In this paragraph the HEW and the xFWHM for the petal configuration are reported in figure 13. The measured focal length is compatible with the measurement at the Bessy Synchrotron radiation. The best focus position was found in 11880 mm and 11886 for the first and the second test campaign. However, this parameter was of secondary importance because the alignment was missing the requirement.



(a) Results of the first test campaign.



(b) Results of the second test camapign.

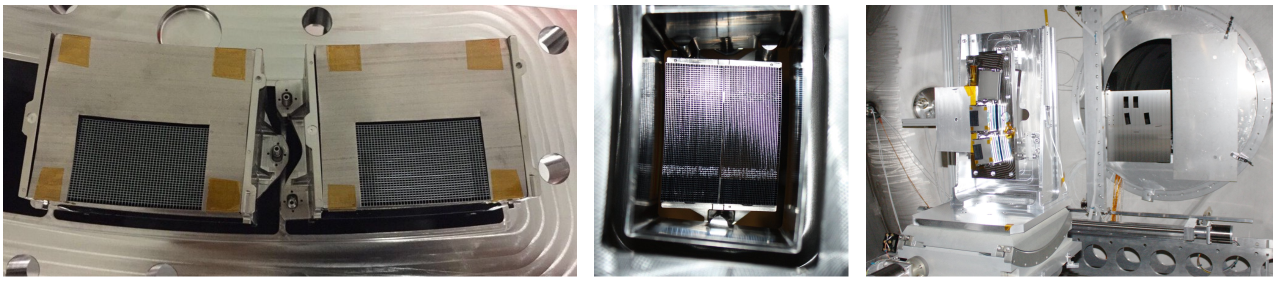
Figure 13: Best focus search for MM1, MM2 and the complete Petal MM1+MM2. The images at the bottom represent the best focus position as a function of the distance of the centroid of the focused image of the two MMs. The best focus position was found in 11880 mm and 11886 mm for the first and the second test campaign respectively.

3.3 ASPHEA Petal mirror alignment

In this section we report the result of the alignment of two MMs performed by the Media Lario (ML) team at the PANTER X-ray facility [4] [5] [6]. The test campaigns were related to procedure selection for the alignment and integration of the optical system of the ATHENA telescope. ML has been then selected for alignment and integration of the ATHEANA X-ray space telescope by the European Space Agency for further development.
Two test campaigns have been performed to verify the repeatability of the procedure of mounting. The mirror module have been mounted and glued a first time (first test campaign). Then one of the two MMs has been unmounted and realigned again (second test campaign).
The results (section 3.3.3) show that there is a small improvement in both HEWs and xFWHMs after the second alignment.

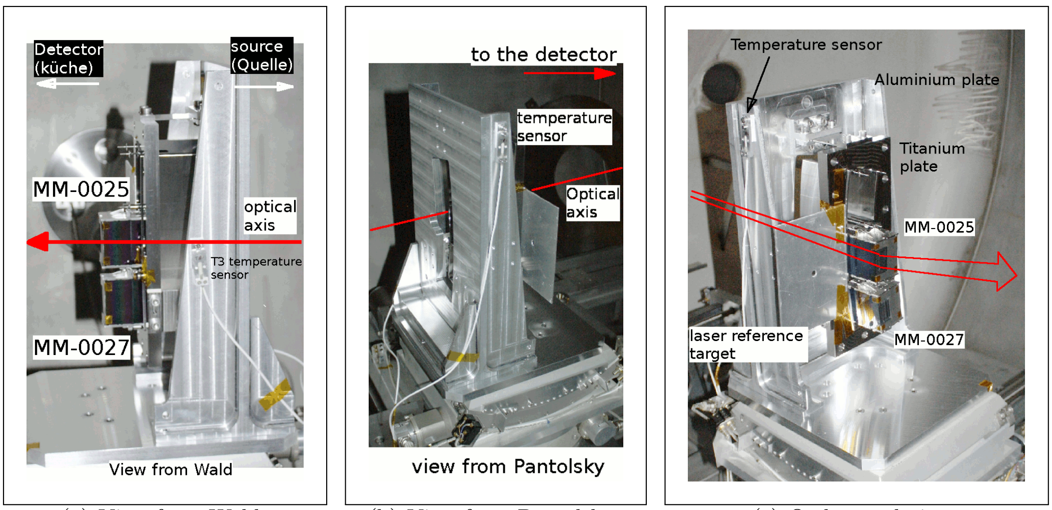
3.3.1 Optics description

Two Mirror Modules, MM-0025 and MM-0027 are aligned on a structure called hereafter Petal. Each MM is made of two X-ray Optical Units (XOU), manufactured with the silicon pore optics technology (SPO). Because the two XOU mounted in the same MM have the same radius, only the outer XOU will be measured. For this reason ML covered completely one of the two XOUs with a titanium foil (Figure 15(c)). Also the side part (12 mm) of the remaining XOU have been obscured in order to use the best part of the optics itself.



(a) Petal view from detector. (b) Petal view from source. (c) Setup overview.

Figure 14: Left image: MM-0025 and MM-0027 mounted in the Petal. The exit window of each single module is covered with a titanium U shaped mask in order to use the best part of the optics. Central image: Petal view from the source side. Right image: a setup overview of mask with six apertures and optics mounted on the petal.



(a) View from Wald (b) View from Pantolsky (c) Orthogonal view

Figure 15: ASPHEA petal. Two temperature sensors are mounted on the aluminum holder. Different view of the Petal.

3.3.2 Setup

The laser was rotated at 186 mm from the Kügel. Then the optics has been translated toward Pantolsky side until the center of the laser illuminated the MM-0025.

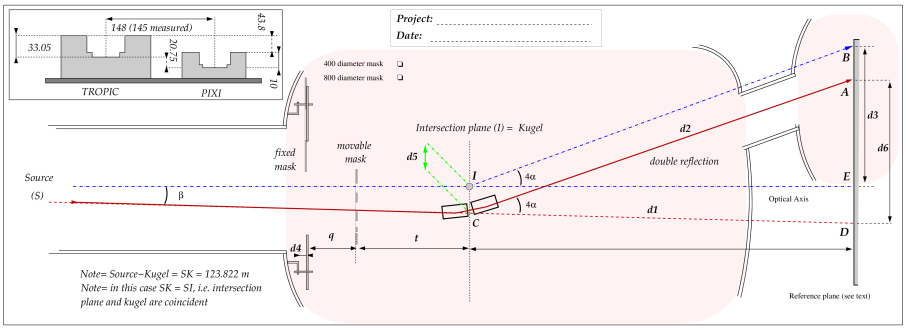


Figure 16: Sketch of the ASPHEA setup.Top View.

3.3.3 Results of the test campaigns 1 and 2

In this section we report the graphs of focus search that gives the focal distance at the best HEW and xFWHM.

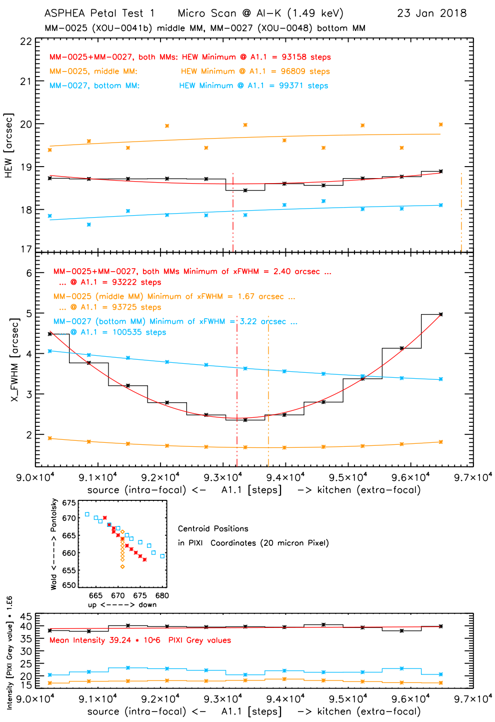


Figure 17: Test Campaign n.1: 5 mm step focus search

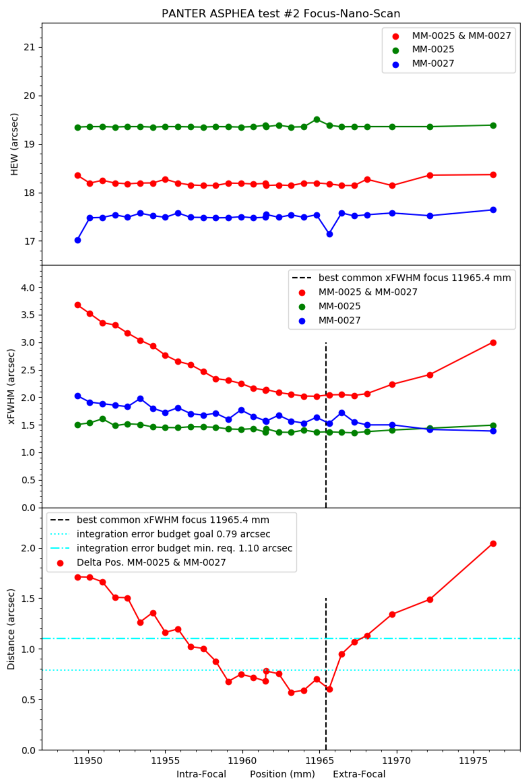


Figure 18: Test Campaign n.2: 1 mm step focus search

Table 7: HEW and xFWHM at best focal distance of 11941 mm measured at the PANTER X-Ray facility during the 1st test campaign

HEW (arcsec) MM#0025	HEW (arcsec) MM#0027	HEW (arcsec) Combined	xFWHM (arcsec) MM#0025	xFWHM (arcsec) MM#0027	xFWHM (arcsec) Combined
19.4	17.1	18.4	1.5	2.2	2.3

Table 8: HEW and xFWHM at the best focal distance of 11963 mm measured during the 2nd test campaign at the PANTER X-Ray facility.

HEW (arcsec) MM#0025	HEW (arcsec) MM#0027	HEW (arcsec) Combined	xFWHM (arcsec) MM#0025	xFWHM (arcsec) MM#0027	xFWHM (arcsec) Combined
19.3	17.5	18.1	1.4	1.6	2.0

4 Conclusions

In the last years the PANTER X-ray facility has measured successfully many SPO MMs acquired experience in co-aligning two MMs (TAS-CH and ML projects). In addition we have gained experience in co-aligning individual SPO stacks (HPOs) into a functional XOU using our double hexapod alignment system (HDS) recently designed and implemented.
In order to respond to the improvement in resolution of the ATHENA MMs, the PANTER facility has been equipped with new instrumentation and the source has been optimized to have an angular resolution at least ten times better than that of the MMs.
In the next months new metrology system (laser tracker) will became operative increasing the accuracy of the focal length measurement.
The results of the measurements obtained at PANTER and presented in this report are in good agreement with the performance prediction provided by the company Cosine that produced the optics.

References

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[6] F. Marioni, "ASPHEA Technical Note n.11," Tech. Rep. Technical Note 11 - ASPHEA - Integration Results - issue 1, Mar. 2018.