Analysis of the relative movement between mirrors and detectors the for next generation X-rays telescopes

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ABSTRACT

Focusing X-ray telescopes with imaging capabilities, like SIMBOL-X, HEXISAT and IXO, are characterized by very long focal lengths, greater than 10m. The constraints posed by the launchers on the maximum dimensions of a payload, make necessary using alternatives to monolithic telescopes. One possibility is that the mirror and the detectors are carried by two separate spacecrafts that fly in formation. Another is placing the detector module on a bench that will be extended once in final orbit. In both the case the system will be subjected to deformation due the relative movement of the mirrors with respect to detectors. In one case the deformation will be due to the correction on the position and attitude of the detector spacecraft to maintain the formation with the mirror spacecraft, while in the other to oscillations of the detectors on the top of the bench. The aim of this work is to compare the behavior of the system in the two different configurations and to evaluate the performances of the on board metrology systems needed not to degrade the telescope angular resolution.

Keywords: X-rays telescopes, Image reconstruction, Dynamic system, Effective area, HEW degradation.

1. INTRODUCTION

Next generation focusing X-ray telescopes with imaging capabilities, like SIMBOL-X[1], HEXISAT[2] or IXO[3], will be characterized by very long focal length, greater than 10m. Due to the constraints posed by the launchers dimensions, alternative to monolithic telescopes need to be evaluated. One possibility is that the mirror and the detectors are carried by two separate spacecrafts that fly in formation as it was foreseen for Simbol-X. Otherwise the detector module can be placed on a extendible bench that will be extended once in final orbit.

In both the case the system will be subjected to deformation due the relative movement of the mirrors with respect to detectors. In one case the deformation will be due to the correction on the position and attitude of the detector spacecraft to maintain the formation with the mirror spacecraft, while in the other to the oscillations of the detectors on the top of the boost. Depending on the dynamical model of the system the performances of the system will be of course different.

The Simbol-X formation flight configuration causes a degradation[4] of about 3'' of the mirror optics HEW: the reconstructed image degradation is a combination of different effects and follow as consequence one the design of the mission is given. In formation flight case, the reconstruction is based on the Line Of Sight concept. In practice, the only correction needed is the one relative to the lateral displacement of the detector with respect to the mirror: in this case in fact the correction for the tilts of the mirrors with respect to the target do not need to be applied, as the image on the focal plane of the source will not follow these tilts.

On the other hand, the HEXISAT and IXO missions, based on the concept of an extendible bench, will need a different approach for image reconstruction. When the mirror and the detector are connected, the tilt of the mirror results into a displacement of the focal spot on the detector. As this displacement depends from the tilt and from the focal length, the knowledge of the value of the mirror tilt is necessary for the reconstruction. Of course the dynamic of the system will depend on the forces acting on it. While for HEXISAT a low orbit (1.5 hour) it is foreseen, the IXO observatory will be placed in L2, a very quite environment. As the perturbations on the systems, as for example the radiation pressure, have a big impact on which will be the dynamic of the systems, a detailed analysis of the performances of a telescope need a dynamic model of the system in its ambient.

We present here the first results obtained with a simulation tool that we have developed in order to evaluate the effects of a dynamic behavior of the system. With this tool we can simulate a system in formation flight configuration or on a bench. In this work, we want to compare which are the correction needed for image reconstruction in the two cases and

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which are the dynamic effects that we have to take in to account. In paragraph 2 we describe our model. In paragraph 3 we describe the effect of mirror tilts. In paragraph 4 we analyze the detector tilts and displacement effects. In paragraph 5 we calculate the performances of the system with respect to the accuracies of the measure system for the mirror attitude and the displacement between mirror and detector.

2. SIMULATOR DESCRIPTION

The system is assumed as composed by a mirror module and a detector. Their dynamics is described in a fixed reference system, by means of translation and rotation matrix. Both the mirror and the detector can rotate around a certain point/axis and displaced one with respect the other. For simplicity, we can assume that the mirror is tilting with respect its optical centre, that is the centre of the intersection plane. On the other hand, fixed the position of the mirror, we will consider displacement of the detector with respect to this centre.

Photons are injected near the mirror aperture as they were arrive from a desired direction. Their direction is recalculated in the mirror reference system. In this reference system are described the reflections on the mirrors shells. Concerning the mirror performances, it can be assumed a perfect mirror profile or a profile with residues calculated via FFT^-1 from the PSD. The On-Axis HEW is around 15’’ for HEXISAT optical design and around 4.5’’ for IXO optical design.

Once the ray-tracing routine has calculated if the photon has been geometrically reflected and eventually also by the multilayer (depending by its energy and incidence angle on the mirror surfaces), their position and directions are converted into the detector reference system. Of course the detector can be assumed in formation flight configuration or linked to the mirror. In the first case the position and the direction are calculated in the fixed reference and therefore changed into to the detector reference system. In the second case if the mirror and the detector are assumed to be rigidly linked, this passage in the fixed reference system is skipped. Once the photon are described in the detector reference system, it is calculated the point in which they will intercept the focal plane. At the moment the model for the detector is just a simply grid of point.
Depending on the configuration of the mission, the image reconstruction will be different:

- In formation flight missions[4], the mirror tilts have absolutely negligible effects on the position of the image of the source on the focal plane. This means that the image do not need to be corrected for the mirror tilts. This can be an advantage as the performance of the star tracker have no impact on the reconstruction.
- In a telescopic system instead, there is a link between the mirror and the detectors: this means that when the mirror is tilting, for whatever reason, the image on the focal plane moves. The amplitude of the displacement depends of course on the focal length and on the amplitude of the tilt. The image on the detector moves accordingly and the Star Tracker (STR) performances will have an impact on the telescope performances.

The results presented in this work are of course dependent from the optical design of the system. The results for HEXISAT are derived for one of the four optical modules. The optical configuration is the one presented in (V.Cotroneo, et al. 2009) assuming 60 shell. All the shells are assumed coated with the same multilayer coating (Graded Pt/C). The results presented for IXO are derived from an optical configuration with diameter between 0.5 m and 2.7 m in Wolter I configuration. The main characteristics of the optical designs are reported in Table 1.

	HEXISAT	IXO
Number of shells	60	603
Height of the shells	60 cm	40 cm
Thickness	0.13 – 0.3 mm	0.15 mm
Coating	Pt/C +Overcoating	Pt/C
Min-Max Radius	154.4 - 346.8 mm	253-1344 mm
Min-Max Angle	0.002 -0.004 rad	0.003 - 0.016 rad

Table 1: Main characteristic of the optical design assumed for IXO and one optical module of HEXISAT missions.

3. MIRROR TILTS

The effects of the mirror tilts can be analyzed with respect to the effective area modification and to the defocusing. In the following paragraph we analyze the effects derived from the multilayer coating properties and from the geometry of the mirror optical module.

3.1 Vignetting function determination

As the reflectivity of the coating depends on the incidence angle of the incoming photons, the effective area will change with respect to the arrival direction of the photons. Let's assume that the mirror optical axis are, for whatever reason, mis-oriented with respect to the direction of the source: the photons will hit the surface of the mirrors as they were arriving from an off-axis source in the opposite direction and therefore the effective area of the system will change. In order to study the variation of the effective area, we evaluate the effective area of the mirror at different off-angles in a tolerances range typical of the pointing error for a X-telescope. Here we present the results obtained for one optical module of the HEXISAT mission. In the next figure is reported the vignetting function obtained with ray-tracing code on a mirror with a perfect profile. As it is possible to see the reduction of the effective area at 30 keV remain less of 10% for angles less than 20''. Instead, the vignetting factor is not so relevant for photons at 1 and 10 keV as it remain less than 3%. Of course these differences come from the multilayer reflectivity and depend on the coating design.

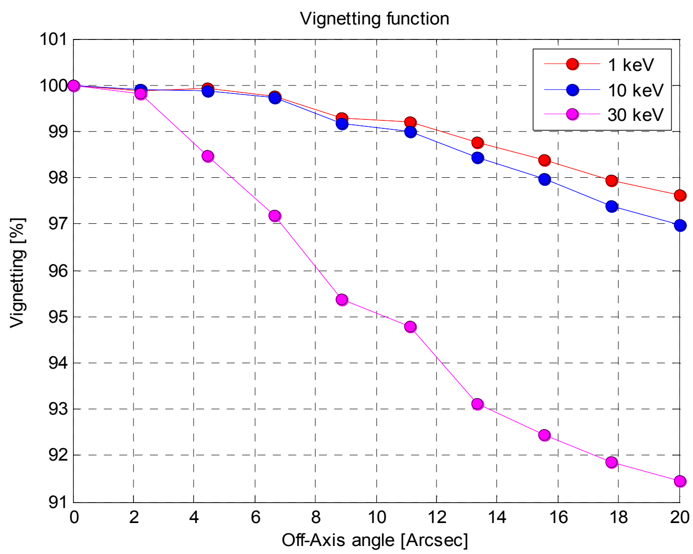

Figure 1: HEXISAT optical module vignetting function at 1 keV, 10keV and 30keV.

3.2 Signal modulation

As we have shown in the previous paragraph, the tilt of the mirror induces a variation of the effective area of the mirror itself. Now, we want to verify if a periodic variation in the attitude of the mirror with respect to a given target direction induces a modulation in the output signal: in practice if the number of photons transmitted by the system is linked to the frequency of the mirror attitude variation.

Let's assume that the mirror is sinusoidal oscillating around X axis with certain periodicities. The amplitude of the oscillations is fixed to 20''. At each simulation temporal step, we calculate the tilt of the mirror with respect to the target direction: due to the tilt the effective area of the mirror will be different and therefore the expected number of photons transmitted. The idea is to simulate a fixed number N of photons (of a certain energy) per temporal step near the mirror entry pupil, to calculate by means of ray tracing how many of these photons will be transmitted by the mirror at each temporal step. Let's indicate the number of transmitted photons at each time t with $N_{TR}(t)$. In order to search for periodicity of these numbers, we calculate the Fourier components with the FFT algorithm and then the power spectrum distribution. In parallel we calculate the same power spectrum but assuming a fixed configuration. Subtracting this power spectrum to the previous one, we can easily see if there are some peaks and at which frequencies. As the temporal resolution of our simulation is fixed to 0.1 sec, the minimum period we can consider is 0.2 sec.

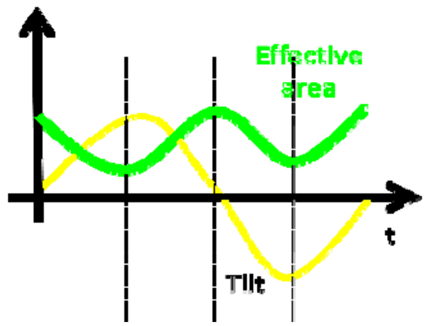

Figure 2: The yellow curve represents Mirror tilt evolution while the Effective area is in green.

The left side of Figure 3 reports the residual power spectrum for 1sec period mirror tilt. The crosses indicate the results obtained using geometric reflected photons, while the points indicate the multilayer reflected photons. Both the two show peaks at 0.5 and 0.25 sec. The period of the residues is half of the period of the tilt as it changes accordingly to effective area variation, that is the same for positive and negative tilt. On the right side of Figure 3 are reported the results obtained for the multilayer reflected photons for several value of the mirror tilt period. All the peaks are visible, apart the 1000 sec one, that needs a longer simulation period. The presence of the peaks in the number of collected photons means that we need to carefully analyze the data as spurious periodicity can be induced by the movement of the mirror itself when the surfaces of the mirror are coated with multilayer with significant variation of effective area with the incidence angle.

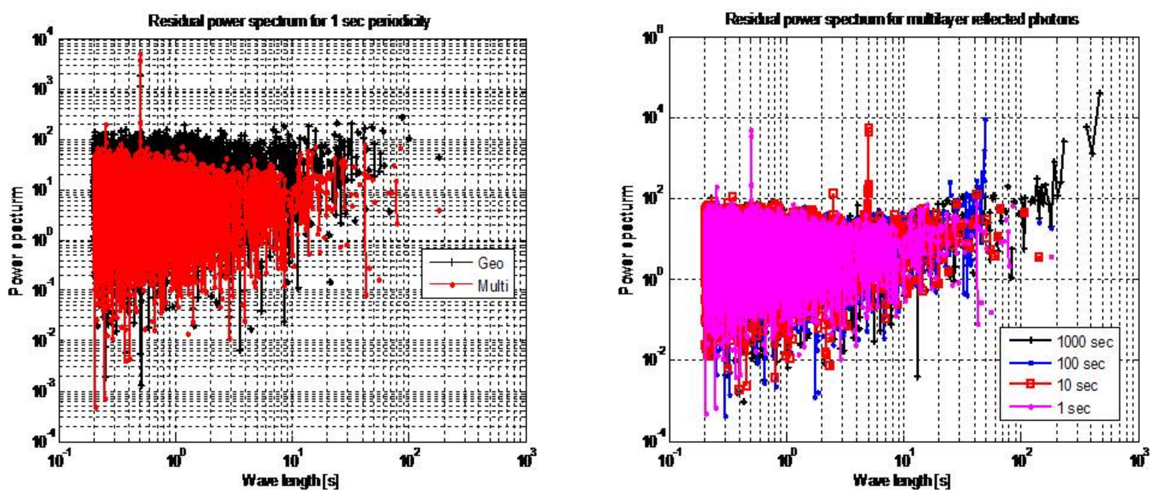

Figure 3: Residual power spectrum for the transmitted number of photons. Crosses refer to the photons geometrically reflected and the points to the photons actually reflected from the multilayer at 30keV. On the right, the residual power spectrum calculated for mirror tilt oscillations with period of 1000 sec, 100 sec, 10 sec and 1s.

3.3 Field curvature effect

When the mirror is tilting, both in the case of formation flight configuration and in case of a fixed link between mirror and detectors, the image will results as acquired in Off-Axis configuration. In the first case the image barycenter remains approximately fixed while in the second case it displaces. In both the case the HEW of the focal spot increases due to the field curvature. For long focal length this effect is negligible as shown in Figure 4 for both the HEXISAT and the IXO designs.

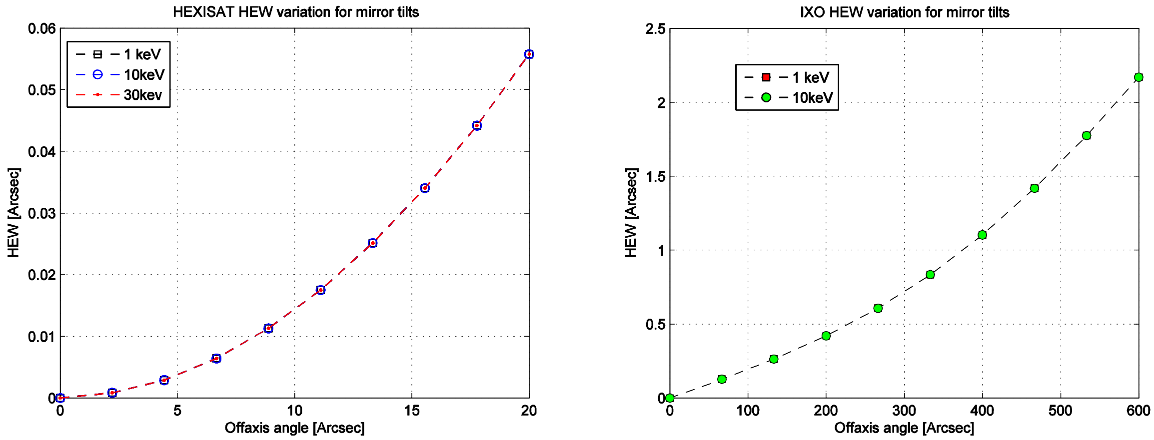

Figure 4: Left, the field curvature for one HEXISAT module. Right the field curvature of the IXO optical module

3.4 Not corrected blurring

When the detector is assumed rigidly linked to the mirror, the oscillation of the telescope, around axis orthogonal to the mirror optical axis, will produce a path on the focal plane that is visible depending on the mirror HEW, on the focal length and on the size of the pixel. Knowing the value of the tilt of the mirror, it is possible to recover the good arrival position. Instead, if the orientation of the mirror with respect to the target direction is not known, it is not possible to reconstruct the image and the mirror tilt will result in blurring the image. We have quantified this effect in the case of HEXISAT.

In Figure 5 are presented the results obtained for one of the HEXISAT mirror modules. On X axis there is the absolute value of the maximum tilt around X and Y directions (Z is the optical axis). The range is divided into 20 steps and the evaluation of the arrival photon positions is done by means of ray-tracing code. On Y axis is reported the resulting HEW of all the acquired photons. Until the tilt is under 1'' this effect is negligible. Instead, for greater tilt amplitudes, the blurring effect becomes significant in terms of HEW variation and in terms of imaging performances, as the resulting image starts to be visible asymmetric (on a detector with pixel size of 100 µm). The effect of the image deformation needs to be evaluated taking into account the final value of the pixel size of the detector.

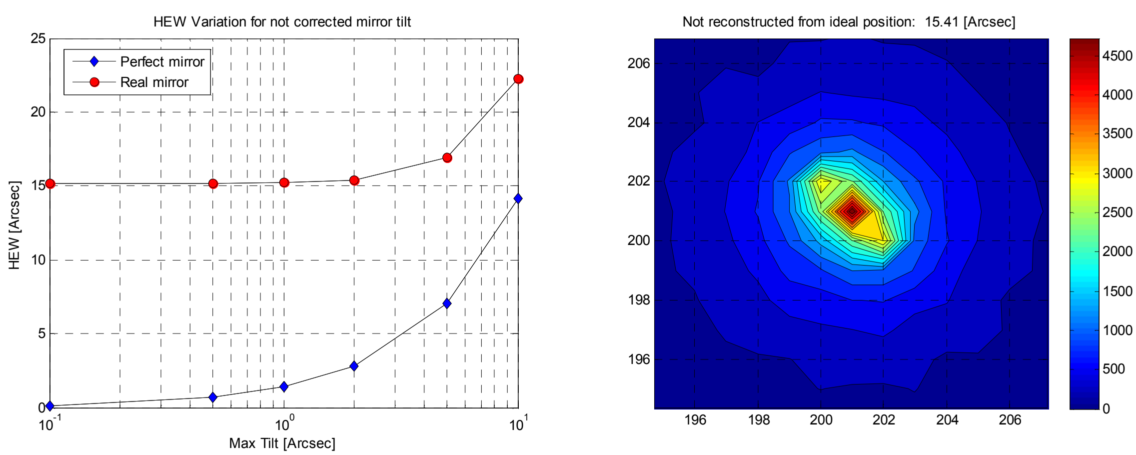

Figure 5: On the left, the HEW variation for not corrected mirror tilt. On the right the acquired image without correction for a mirror tilt in the range [-2,2]'' on a detector grid of 100 µm.

4. FOCAL PLANE TILTS AND DISPLACEMENT

In principle, in a dynamic configuration, the relative distance/orientation between the mirrors and the focal plane is not constant. Due to the formation flight or to structure torsion, the focal plane could be tilted with respect to the optical axis of the mirrors. For the same reasons, the focal plane can be displaced in longitudinal and lateral direction with respect to the mirror focus. In the following paragraphs we analyze the effects that these movements have on the system performances.

4.1 Focal plane tilts

As we said, the focal plane can be tilted with respect to the optical axis of the system. As long as the tilt angle are limited, the HEW degradation is completely negligible. In Figure 6Figure 6 is presented the HEW degradation for an HEXISAT optical module: the HEW is calculated by means of ray-tracing code assuming for each point a fixed value of the detector tilt.

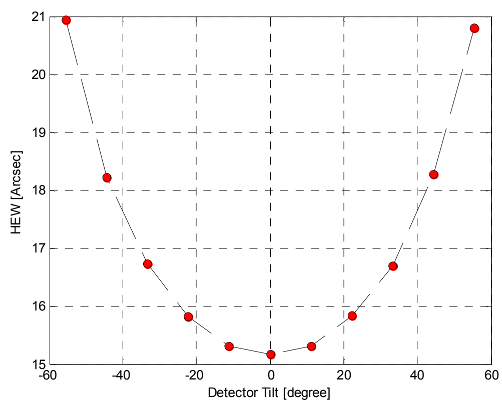

Figure 6: HEW variation with focal plane tilts. HEW is in Arcsec while the detectors tilt is in Degree.

4.2 Longitudinal displacement

When the focal plane moves with respect to the focus of the mirror along the optical axis, the HEW is expected to increase as these are intra-focal and extra-focal condition. In case of a perfect mirror, an annulus, with increasing size as long as we go far away from the focus, will be observed. Instead, in the case of a real mirror, the focal spot just increases its size as long as the focal plane moves from the focus position. The HEW of the focal spot is a good estimator of the effect.

If the focal plane displaces along the optical axis during an observation, the resulting focal spot will be a mix of photons will be intercepted by the focal plane at different distances: the global effect will be an increase of the HEW. As it is not possible knowing which part of the mirror reflected the photons, this defocusing effect is not corrigible. This means of course that when dealing with 'deformable' telescope it is necessary to evaluate which is the impact of the possible displacement with respect to the HEW.

When calculated for a perfect mirror, the defocus curve has a very sharp minimum at the focal length of the mirror. Instead the errors of a real mirror induce a flattening of the curve. For this reason a good estimation of the HEW degradation needs to be calculated for a realistic mirror, while not taking into account this effect means overestimate the degradation.

Figure 7 reports the variation of the HEW along the optical axis for one HEXISAT mirror module. The result is calculated with ray-tracing code calculating the HEW of the distribution of photons when they intercept the focal plane at different distances. The results are given for both a optics with perfect profiles or adding surface errors. As it is possible to see, the defocusing effect is different depending on the off-axis angle of the sources. In order to keep the effect limited to 2 arcsec on the whole field of view, the displacement box should be limited at the range [-3,1.5] cm.

Figure 8 shows the defocus effect for the IXO optical module for both ideal mirrors and realistic ones. Since the requirements on the mirror performances are in this case more tight, the displacement of the focal plane needs to be limited. With a displacement of 5 mm the HEW increase above 6''.

The resulting HEW degradation effect will depend of course on the relative time that the focal plane spends in different positions: the effect should be carefully analyzed considering the dynamics of the system. In any case, a telescopic bench appears the favorite solution as the possible displacements are limited.

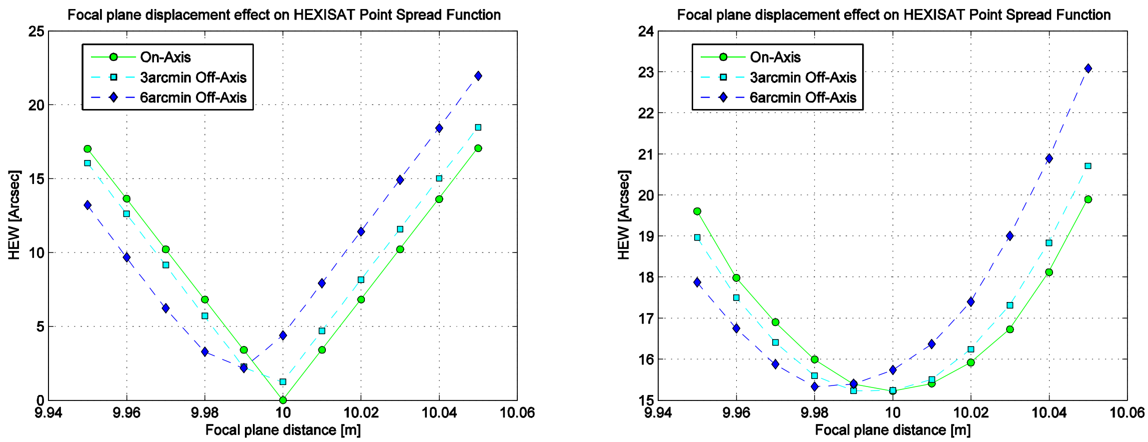

Figure 7: Effect of the focal plane displacement along the optical axis for a HEXISAT mirror module. On the left the HEW is evaluated for perfect optics, while on the right it is presented the results in case the mirrors presents profile errors. The three curves corresponds respectively to On-Axis sources, 3' and 6' Off-Axis sources.

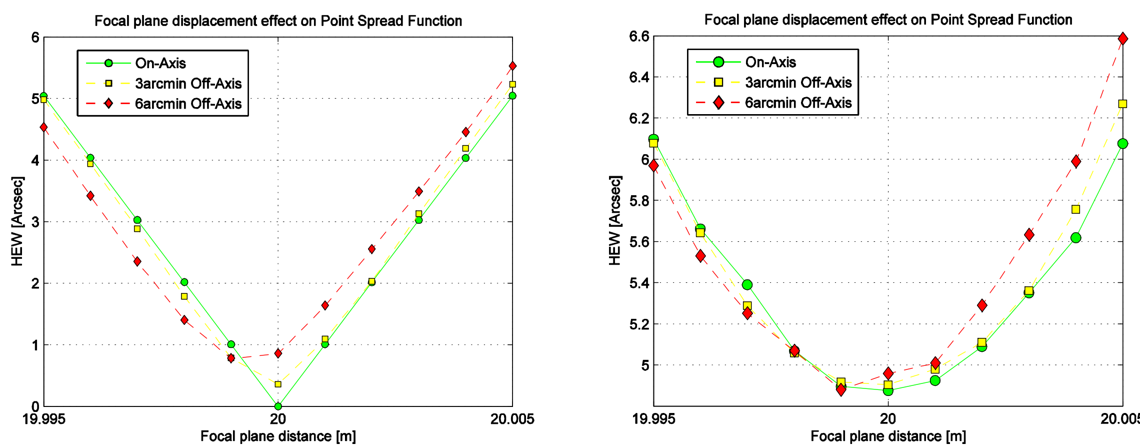

Figure 8: Effect of the focal plane displacement along the optical axis for IXO mirror module. On the left the HEW is evaluated for perfect optics, while on the right it is presented the results in case the mirrors presents profile errors. The three curves corresponds respectively to On-Axis sources, 3' and 6' Off-Axis sources.

4.3 Not corrected Lateral displacement

When the focal plane is displacing with respect to the mirror in lateral direction, photons will arrive on the focal plane in different positions. If the value of displacement is known, it is possible to correct this effect and to reconstruct the correct arrival position of the photons. Of course the results will depend on the accuracy of the metrology system used and in the next paragraph we present the possible results. Now we want to quantify the HEW degradation in case no correction is foreseen, in order to establish the need of a metrology system: depending on the entity of the dynamic displacement assumed for the structure it is also possible that the blurring effect is negligible.

Assuming a displacement inside a certain range, a rough estimation of the effect can be done calculating the HEW in correspondence of a resulting focal spot of a system in which the focal plane has displaced at a certain number of steps in between the range. Of course in this way all the displacement are equally weighted, leading to overestimate the effect. A more detailed dynamical model of the system guarantee a more reliable results.

Figure 9 presents the results obtained for one of the HEXISAT mirror modules. On X axis is reported the absolute value of the maximum displacement along detector X and Y axis. The total range is divided into 20 steps and the evaluation of the arrival photon positions is done with ray-tracing code. On Y axis of the figure is reported the resulting HEW of all the acquired photons. Until the displacement is under 100µm its effect is negligible in the HEXISAT case. For greater values, it becomes significant in terms of HEW variation and in terms of imaging performances, as the resulting image starts to be visibly asymmetric (on a detector with pixel size of 100 µm). As usual, the effect of the image deformation needs to be evaluated taking into account the final value of the pixel size of the detector.

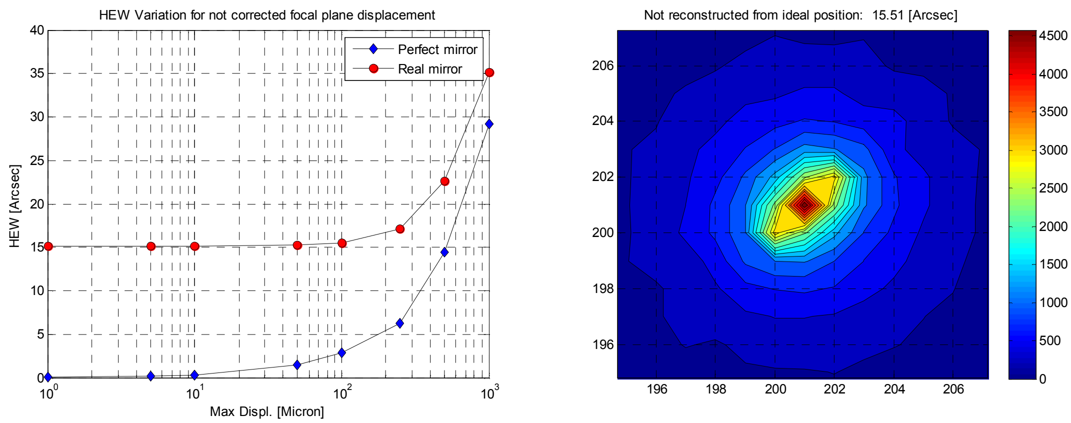

Figure 9: On the left the HEW variation in case the focal plane displacement is not corrected. On the right the not reconstructed image in case the Max Amplitude of the displacement is of 100 µm.

5. RECONSTRUCTION ALGORITHM

The reconstruction algorithm is different in case the telescope is in formation flight configuration or mounted on a telescopic bench. In the first case, the image reconstruction is performed from the knowledge of the Line Of Sight (LOS) of the system. In this case the LOS is defined as the vector joining the mirror and the detector optical centers. The information of the relative lateral displacement is the only needed as the correction for the mirror tilt is not necessary for reconstructing the image at the focal plane. The relative lateral displacement can be thought as measured by a metrology system with a certain error. These errors will have an impact on the telescope performances.

On the other hand, when the detector rotate following rigidly the mirror, the correction for the mirror dither becomes not negligible for increasing dither maximum angles values as we have shown in the previous paragraph. Moreover it is possible that the spacecraft has a built-in dither on its pointing position to average across calibration uncertainties (like in Chandra). This dither keeps one bad pixel from ruining an entire observation and smoothes over chip gaps, prevents too many photons entering a single micro channel and smoothes out small effects of QE variations. In Chandra case the line-of-sight is commanded through a Lissajous pattern ($x = a \sin(nt + c)$, $y = b \sin(t)$).

In order to evaluate the impact of the measurement errors (attitude and distance), we should know if there is a dither pattern and in general the amplitude/frequencies at which the tilt is. A rough estimation based on fixed configuration superposition is given in the next paragraphs.

5.1 Mirror tilt correction

Let us consider an On-Axis source and assume that the attitude measurements is affected by different values of the standard deviation. We want to calculate which is the impact of a less precise knowledge of the mirror tilt on the telescope performances.

In Figure 10 are presented the results obtained for one of the HEXISAT mirror modules. On X axis the Standard deviation of the mirror tilt measurement for example given from the Star Tracker. The mirror is assumed tilting in [-20,20]'' range. This range is divided into 20 step and the evaluation of the arrival photon positions is done with a 10000 photon ray-tracing at each step. The On Y axis is reported the resulting HEW of all the acquired photons after correction. Until the std is below 1'' the effect on the HEW is negligible. For greater values of standard deviation, instead, it becomes significant in terms of HEW variation and in terms of imaging performances, as the resulting image starts to be visibly asymmetric (on a detector with pixel size of 100 µm). As usual, the effect of the image deformation needs to be evaluated taking into account the final value of the pixel size of the detector.

If instead of using a large number of photons at few angular step and therefore few values of measurement errors, we divide the tilting range in 10000 step, each one with 10 photons, we arrive to the same results in terms of HEW variation. Instead in this case the image reconstructed will remain much more symmetric even for greater values of standard deviation.

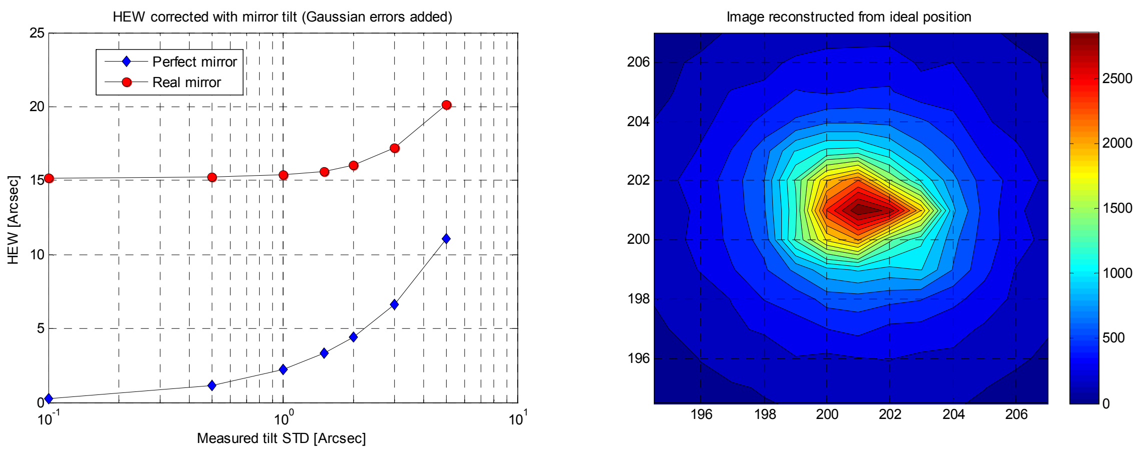

Figure 10: Left: HEW variation in case the mirror tilt is corrected from a measurement affected by different values of Gaussian noise. Right: the reconstructed image in case the rms of the measurement is 2''.

5.2 Detector displacement correction

Let's consider the correction for detector displacement. As before we consider an On-Axis source and assume that the lateral displacement measurements is affected by different standard deviation values. We want to calculate which is the impact of a less precise knowledge of the detector displacement on the telescope performances.

In Figure 11 are presented the results obtained for one of the HEXISAT mirror modules. Standard deviation of the detector displacement measurement are reported on X axis, as they were derived from a given metrology system. The detector is assumed displacing in [-2,2]mm range into 100 step and the evaluation of the arrival photon positions is done with a 5000 photons ray-tracing. On Y axis, is reported the resulting HEW of all the acquired photons after correction. Until the std is below 100 µm the effect on the HEW degradation is negligible. For greater values, instead, it becomes significant in terms of HEW variation. Concerning the imaging performances, depending on the distribution of the errors, the resulting image starts to be visible asymmetric (on a detector with pixel size of 100 µm). Of course the effect of the image deformation need to be evaluated taking into account the final value of the pixel size dimension of the detector.

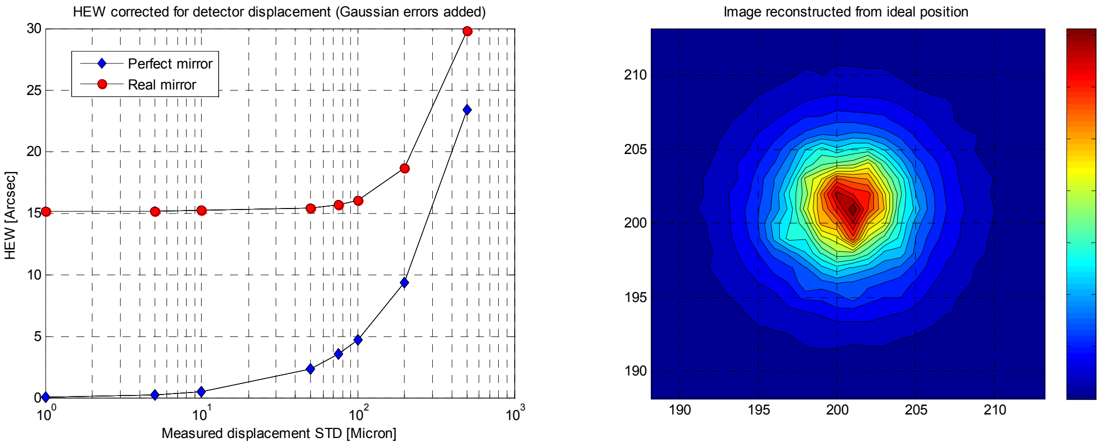

Figure 11: Left: HEW variation in case the focal plane displacement corrected from a measurement affected by Gaussian noise. Right: the reconstructed image in case the rms of the measurement is 200 µm.

6. DETECTOR PIXEL SIZE SELECTION

Taking into account a FOV of 12’, adding some space for eventual dithering and for possible displacement, the detector size of HEXISAT can be roughly fixed at 4cm. Depending on the value of the mirror HEW the dimensions of the pixel should be 312.5 µm (for HEW ~ 20’’) and 156.25 µm (for HEW ~ 15’’). What we intend to show here are some artifacts of the image reconstruction and the way in which they can be avoided. Figure 12 shows the image as reconstructed from data acquired by detectors with different Pixel-Size: on the left the Pixel-Size was of 312.5 µm while on the right the pixel size was 156.25 µm. The reduction of the size of the pixels reduces the post-facto artifacts and should be carefully analyzed in terms of cost/benefits.

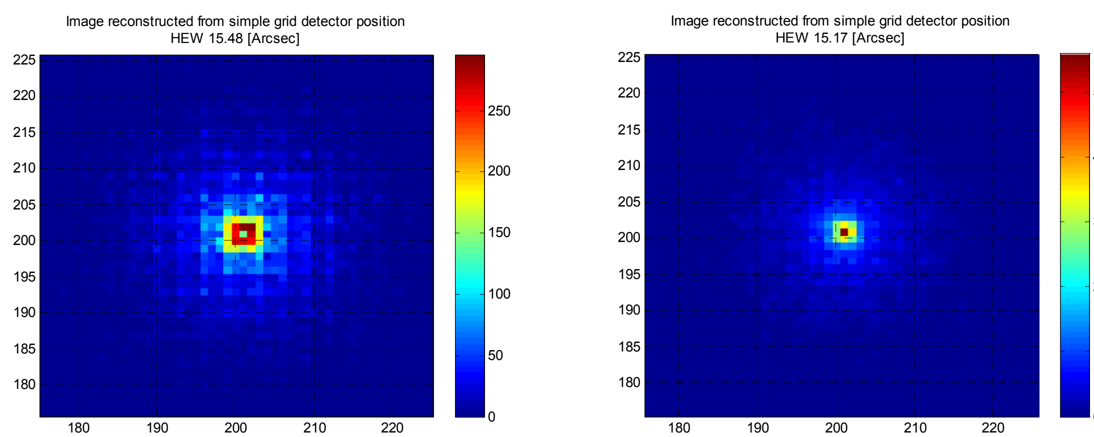

Figure 12: Left, image reconstructed for the tilt from a detector with Pixel-Size equal to 315 µm. Right, image reconstructed for the tilts from a detector with Pixel-Size equal to 156 µm.

In fact, on the other hand, Figure 13 shows that it is possible to avoid the post-facto reconstruction artefacts simply randomizing the arrival position with respect to the centre of the pixel. This solution should be deeply investigated in its conseguences as it is can have an impact on the telescope performances.

In any case, once the size of the pixel has been selected, all the previous consideration need to be applied to the mirror-detector system for estabilishin the real impact of the metrology systems on the telescope performances.

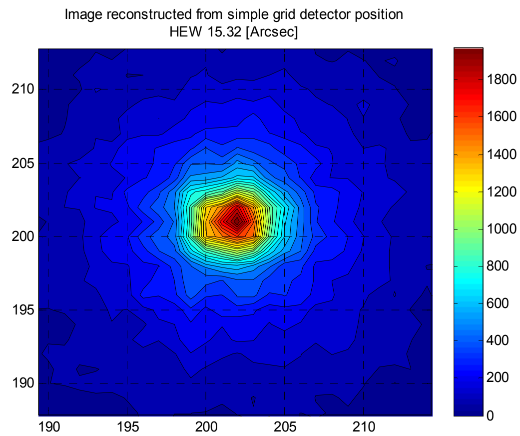

Figure 13: Image reconstructed from data acquired by a detector with Pixel-Size equal to 315 µm one the positions on the pixel have been randomized.

7. CONCLUSIONS

A tool for dynamic simulation has been developed taking into account the optical mirror module and the detector. When applied to HEXISAT design, it shows the necessity of a metrology system for controlling the lateral displacement. An improvement of the simulator would be to fix the detectors parameters: in this way a reliable analysis can be performed. A reliable dynamic model of the system is necessary to fully understand and quantify the effects. We are in contact with ATK in order to have a thermo-structural model for the MAST foreseen for HEXISAT and use it in the next future.

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