Shaping the PSF to nearly top-hat profile: CHEOPS laboratory results

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ABSTRACT

Spreading the PSF over a quite large amount of pixels is an increasingly used observing technique in order to reach extremely precise photometry, such as in the case of exoplanets searching and characterization via transits observations. A PSF top-hat profile helps to minimize the errors contribution due to the uncertainty on the knowledge of the detector flat field. This work has been carried out during the recent design study in the framework of the ESA small mission CHEOPS. Because of lack of perfect flat-fielding information, in the CHEOPS optics it is required to spread the light of a source into a well defined angular area, in a manner as uniform as possible. Furthermore this should be accomplished still retaining the features of a true focal plane onto the detector. In this way, for instance, the angular displacement on the focal plane is fully retained and in case of several stars in a field these look as separated as their distance is larger than the spreading size. An obvious way is to apply a defocus, while the presence of an intermediate pupil plane in the Back End Optics makes attractive to introduce here an optical device that is able to spread the light in a well defined manner, still retaining the direction of the chief ray hitting it. This can be accomplished through a holographic diffuser or through a lenslet array. Both techniques implement the concept of segmenting the pupil into several sub-zones where light is spread to a well defined angle. We present experimental results on how to deliver such PSF profile by mean of holographic diffuser and lenslet array. Both the devices are located in an intermediate pupil plane of a properly scaled laboratory setup mimicking the CHEOPS optical design configuration.

Keywords: CHEOPS, Exoplanets, Transits, ESA Small Mission, top-hat PSF, holographic diffuser, lenslet array.

1. INTRODUCTION

The CHEOPS (CHaracterizing ExOPlanet Satellite) mission ([1],[2],[3],[4]) is an ESA small mission completely dedicated to transit follow-up measurements of already known exoplanets, hosted in near bright stars (V<12). CHEOPS, thanks to the ultra-high precision photometry, will be able to accurately measure the radii of planets in the super-Earth to Neptune mass range (1<Mplanet/MEarth<20). The knowledge of the radius by transit measurements, combined with the determination of planet mass through radial velocity techniques, will allow the determination of the bulk density for hundreds of planets during the scheduled 3.5 year life mission. The determination of targets for CHEOPS is ongoing and it will be essentially constituted by the exoplanets discovered by present radial velocity surveys (such as HARPS-N [5]) and incoming ground-based and space transits surveys (such as NGTS [6] and TESS [7]). CHEOPS has been recently adopted (February 2014) by the ESA Science Programme Committee and it is currently in the Preliminary Design Review phase. The launch is scheduled to be at the end of 2017.

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The overall noise budget for bright target (m ∼8) is required to be less than 20 ppm in order to assure the ultra-high precision photometry. This error budget represents the combination of several sources of noise: the uncertainty on the knowledge of the detector flat field combined with the satellite jitter and PSF size and shape, the PSF stability, the straylight rejections and modeling are some of them. It is well known that spreading the PSF over a quite large amount of pixels and having a nearly top-hat PSF shape minimize the first of these error sources. During the previous study phase, in case of CHEOPS it has been demonstrated through detailed simulation that by simply applying a certain amount of defocus the noise related to this error source can be maintained within an acceptable budget (< 6 ppm). Never the less, in the meanwhile we have studied the possibility to insert an optical device able to shape the delivered PSF. In this article, we present laboratory results related to the optimization of the PSF shape and, in particular, the performances of two optical devices (holographic diffuser, lenslet array) dimensioned to the deliver a nearly top-hat PSF.

2. CHEOPS OPTICAL CONCEPT

The CHEOPS optical configuration is basically composed by a classical on-axis Ritchey-Chretien telescope and a Back End Optics (BEO). The optical system entrance pupil is located at the primary mirror (diameter 320 mm, central obstruction diameter 68 mm). Due to satellite envelope constraint, the distance between the primary and the secondary mirror has been compressed during the design phases to 300 mm. The BEO is placed after the telescope focal plane and it is composed by two optical elements: a collimator that re-images the pupil and a camera that re-images the focal plane at the right plate scale. The intermediate focal plane and the intermediate pupil are required for straylight suppression by means of dedicated focal plane mask and pupil mask (together with internal baffling system). Both the collimator and the camera are spaced doublets. Again, in order to reduce instrument envelope, in the BEO it has been introduced a fold mirror after the intermediate pupil position.

A scheme of the telescope and BEO is shown in Figure 1 while the optical system parameters are reported in Table 1.

![Figure 1. Scheme of the telescope optical configuration (left) and of the Back End Optics configuration (right).](image)

Table 1 – Parameters of the optical configuration.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range</td>
<td>400 – 1100 nm</td>
</tr>
<tr>
<td>Entrance pupil diameter</td>
<td>320 mm</td>
</tr>
<tr>
<td>Central obstruction diameter</td>
<td>68 mm</td>
</tr>
<tr>
<td>Working F/#</td>
<td>8.38 @ 750 nm</td>
</tr>
<tr>
<td>Field of View (diameter)</td>
<td>0.32 degrees</td>
</tr>
<tr>
<td>Effective focal length</td>
<td>2681 mm @ 750 nm</td>
</tr>
<tr>
<td>Pixel size</td>
<td>13 micron</td>
</tr>
<tr>
<td>Plate scale</td>
<td>1 arcsec/pixel</td>
</tr>
<tr>
<td>Detector format</td>
<td>1024×1024 pixel²</td>
</tr>
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</table>
3. PSF SHAPER DEVICES

Because of lack of perfect flat-fielding information and satellite jitter effect, in the CHEOPS optics it has been studied the possibility to insert a device able to spread the light of a source into a well defined angular area, in a manner as uniform as possible. Furthermore this should be accomplished still retaining the features of a true focal plane onto the detector. In this way, for instance, the angular displacement on the focal plane is fully retained (and it can be used as feedback to the tracking system to improve the resulting jitter) and in case of several stars in a field these look separated, as much as their distance is larger than the spreading size. During the mission, this device also allows to change the area onto the detector where the measurements are achieved, by simply changing the offset in the pointing system.

As this aim in not reached by placing the detector onto the pupil plane, several approaches have been investigated. The obvious one is to apply pure defocus by simply shifting the detector out of the focal plane. On the other hand, the presence of an intermediate pupil plane in the BEO makes attractive to place an optical device that is able to spread the light in a well defined manner, still retaining the direction of the chief ray hitting it. This can be accomplished through several approaches, including the ones we studied: an Axicon, a Schmidt-like corrector plate, a holographic diffuser and a lenslet array.

An Axicon [8] is a rotationally symmetric surface, but does not have a spherical shape. Typically there is a discontinuity of the first and/or second derivative at the intersection point with the optical axis: in the simplest form, the Axicon is formed by a cone. This option has been studied only theoretically with a Zemax model: the slope angle of the Axicon has been locally optimized in order to obtain a homogenous irradiance in the final spot. The optimized Axicon shape is an aspheric surface. The resulting polychromatic PSF is flat as intended, except for the sharp spot in the center (Poisson spot) due to the primary mirror central obstruction. Unfortunately, the performances degrade quickly with optical elements misalignments, imposing tight requirements on the optical system stability. For this reason, this option is no further investigated.

A Schmidt-like corrector plate to be placed at the intermediate pupil has been studied only theoretically with a Zemax model: the idea behind it is to introduce a certain amount of spherical aberration in the wavefront in order to mitigate the effect of the primary mirror central obstruction on the PSF at the focal plane. Results have shown that an acceptable mitigation is reached only for quite large aspheric coefficients values, making the plate difficult to be manufactured. For this device no laboratory test has been carried out.

The other two optical devices we considered are the holographic diffuser and the lenslet array. Both techniques implement the concept of segmenting the intermediate pupil into several sub-zones where light is spread over a well defined angle. In the case of CHEOPS, the PSF angular size at the focal plane has been set to about 30 arcsec. Given the primary mirror diameter of 320 mm and the intermediate pupil diameter of about 10.7 mm, Lagrange invariant establishes in a firm manner which spreading angles are required at the intermediate pupil, i.e. about 0.25 degrees. A scheme of the optical concept is shown in Figure 2.

It is easy to see from diffraction limit consideration that, if the spreading must be of the order of 30 arcsec, the intermediate pupil cannot be segmented into more than a certain number of subapertures, to avoid the diffraction limited ability of a single subaperture exceeds the angular spreading. For both the holographic diffuser and the lenslet array we have accomplished laboratory tests in order to evaluate their ability to re-shape the PSF and mitigate the primary mirror obstruction.

![Figure 2. Scheme of the optical concept related to the introduction of a spreading optical element at the intermediate pupil.](http://proceedings.spiedigitallibrary.org/ on 07/10/2015 Terms of Use: http://spiedl.org/terms)
4. LABORATORY SET-UP AND RESULTS

In this section we present the laboratory test of the two possible considered solutions for the light spreading by mean of placing an optical element at the intermediate pupil of the CHEOPS BEO, which are the holographic diffuser and the lenslet array.

4.1 Holographic diffusing plate

As first device to generate PSF with top-hat shape, we have considered a holographic diffusing plate to be inserted at the intermediate pupil location of the BEO.

An incident collimated beam on the diffusing plate will be spread with a specified divergence angle (depending by the diffuser characteristics) with almost uniform illumination. If the beam is focalized by a camera, the PSF results to be spread over an area which size depends by the divergence angle and its profile results homogenized.

In the case study, the BEO has been designed to produce an intermediate pupil having diameter about 10.7 mm. For the Lagrange invariant, a diffusing plate with a divergence angle of about 0.25 degrees is required to spread the PSF on a circular disk having diameter 30 arcsec that corresponds to about 30 pixels in the case of CHEOPS detector sampling (the plate scale is about 1 arcsec/pixel).

The expected effect of introducing such diffusing plate is:

1. the disappearance of the central obstruction feature on the refocused PSF;
2. the mitigation Poisson spot feature in the refocused PSF;
3. the nearly top-hat shape of the refocused PSF

A laboratory test has been carried out on an off-the-shelf holographic diffuser. We have purchased and tested an Engineered Diffusers™ EDC-0.25-A-1r (diffusing angle 0.25 degrees) produced and distributed by the RPC Photonics (www.rpcphotonics.com). The tested holographic diffuser has circular shape with radius 1 inch and thickness equal to 2 mm. This kind of diffusers is also available with direct etching of the diffusing structure on fused silica, making it suitable also for space application thanks to the radiation resistant properties of such glass. During the manufacturing process, it is adopted a laser writing process that is capable of producing deep analog surface structures with lithographic precision. For best uniformity illuminating beam should be several times larger than diffuser feature size.

The scheme of the laboratory set-up for the holographic diffuser test is shown in Figure 3. We made use of an optical fiber (diameter 5 micron) as source which could be fed with both HeNe laser and white light. The produced beam was initially collimated by a first lens having effective focal length of 200 mm. An iris diaphragm, located after the collimator, allowed setting the pupil diameter to the desired value: 10 mm in the case study. Then, the holographic diffusing plate spread the collimated beam and homogenized the light over an angle of 0.25 degrees. A photographic plate (not shown in the figure) with a black circular dot having 2 mm diameter was place just behind the diaphragm simulating the primary central obstruction. At the end, the obtained beam was focalized by a second lens, having effective focal length of 150 mm, on a CCD camera with pixel size of 4.65 micron.

The system was previously aligned without the diffusing plate. In this way, we were able to obtain diffraction limit PSF with both HeNe laser and with light sources. In particular it has be paid attention to be able to deliver an accurate collimated beam.

The images of the obtained diffused PSFs and its profiles along two orthogonal directions for both HeNe laser and white light are shown in Figure 4. The obtained PSF presents for both HeNe laser and white light sources a larger angle than what it is declared in the datasheet (0.25 degrees). The nominal diffusing angle is represented in the PSF images by the red circle and by the black box in the profiles. In both cases, the central obstruction features disappear, and at least in the central part of the PSF, the profile presents some sort of top-hat shape. Moreover, the Poisson spot feature seems to be mitigated at least at the level of the profile value. On the other hand, the PSF shape presents much more smoothed wings with respect to the expected sharp profile, making the overall PSF profile look much more Gaussian than top-hat. As expected, the PSF obtained with the HeNe laser source presents much more diffraction ripples with respect to the PSF obtained with the white light source.
Figure 3. Scheme (Top) and a picture (Bottom) of laboratory set-up for the test on the holographic diffuser.

Figure 4. Images of the obtained diffused PSFs (Top) and its profiles along two orthogonal directions (Bottom, red and green lines) for both HeNe laser (Left) and white light (Right). Red circles (Top) and black boxes (Bottom) represent the nominal spreading angle (0.25 degrees).
4.2 Lenslet array

As second device to generate PSF with top-hat shape, we have considered a lenslet array to be inserted at the intermediate pupil location of the BEO.

In a geometrical approximation each subaperture of the lenslet array spreads the light into a conveniently shaped beam. As this is performed uniformly over the whole pupil, the central obstruction is basically cancelled out in the final focal plane image. However, the superposition of the lights is not achieved in a geometrical, incoherent manner, but -in contrast- the lenslet acts as a sort of grating and some interference patterns would arise. These can be smoothed out by introducing a further defocus at the focal plane where the image is collected. However, the larger the introduced defocus, the larger the influence of the central obstruction; initially it is close to nil and then it will increase.

A parameter describing how much the non geometrical description is playing a role more and more significant is given by the Fresnel Number (FN) defined as:

\[
FN = \frac{a^2}{\lambda \times efl} \approx \frac{D}{\lambda \times F/\#}
\]

where \(a\) is the semi-diameter of the single lenslet, \(\lambda\) is the wavelength, efl is the effective focal length of the single lenslet, \(D\) is the single lenslet diameter and \(F/\#\) is the single lenslet F-Number.

For small lenslet apertures and a long focal length, i.e. for lenslet beam homogenizers with a Fresnel Number \(FN < 10\), the flat top profile might be distorted by Fresnel diffraction at the lens apertures. In cases where the FN is much larger than unity \((FN > 10)\) with the proper defocusing the resulting PSF can be a rather smooth square pattern. However, in the final configuration of CHEOPS the resulting FN is 2.4 and that implies that a careful choice of the defocus is to be placed in action, with the aim of selecting the more uniform central area at the expenses of smoothed skirts.

The scheme of the experimental setup for the lenslet array is shown in Figure 5. Also in this case, we made use of an optical fiber (diameter 5 micron) as source which could be fed with both HeNe laser and white light.

The light was collimated by a first lens having effective focal length of 100 mm. An iris diaphragm, located after the collimator, allowed setting the pupil diameter (10 mm in the case study). A photographic plate with a black dot having 2 mm diameter was placed just behind the diaphragm simulating the primary central obstruction. Then the lenslet array spread and homogenized the light over an angle of about 0.25 degrees. The beam was then focalized by a second lens, having effective focal length of 75 mm, on a CCD camera with pixel size of 6.45 micron.

As lenslet array we have considered and tested several combination of aperture size and effective focal length of the single lenslet. Here, we show two cases: in the first one we have considered a lenslet array delivering a high FN (17.1) and which parameters are reported in Table 2. This case represents somehow the best results achieved in terms of Poisson spot and primary mirror central obstruction features mitigation and nearly top-hat PSF shape. The second one is rather close within 10% to the final figures for CHEOPS: in this case the lenslet array is the SUSS MicroOptics Microlens Array Nr. 18-00181 (www.suss-microoptics.com) which parameters are reported in Table 3.

<table>
<thead>
<tr>
<th>Aperture (mm)</th>
<th>efl (mm)</th>
<th>F/#</th>
<th>Array size (mm)</th>
<th>angle (rad)</th>
<th>angle (deg)</th>
<th>FN</th>
<th>efl camera (mm)</th>
<th>PSF size (mm)</th>
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<tr>
<td>1.000</td>
<td>29.3</td>
<td>29.30</td>
<td>18</td>
<td>0.034</td>
<td>1.96</td>
<td>17.1</td>
<td>75</td>
<td>2.560</td>
</tr>
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</table>

Table 2 – Parameters of the first lenslet array.

<table>
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<th>efl (mm)</th>
<th>F/#</th>
<th>Array size (mm)</th>
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<th>angle (deg)</th>
<th>FN</th>
<th>efl camera (mm)</th>
<th>PSF size (mm)</th>
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<tbody>
<tr>
<td>1.015</td>
<td>218.3</td>
<td>215.07</td>
<td>10</td>
<td>0.005</td>
<td>0.27</td>
<td>2.4</td>
<td>75</td>
<td>0.349</td>
</tr>
</tbody>
</table>

Table 3 – Parameters of the second lenslet array.
Figure 5. Scheme (Top) and a picture (Bottom) of laboratory set-up for the test on the lenslet array.

Figure 6. Best result obtained with lenslet array having FN = 17. Image (top) and profile (bottom) for the on-focus PSF (left) and defocused PSF (right).
Figure 7 – Result of scaled experiment (within 10%) to CHEOPS figure result obtained with lenslet array having FN = 2.4. Image (top) and profile (bottom) for the on-focus PSF (left) and defocused PSF (right) re-sampled with a pixel size of 12.90 micron.

The PSF image and profile related to the best case (FN=17.1) for both the on-focus PSF and defocused PSF obtained with white light source are shown in Figure 6. The distortion effect in the image is due to lenslet substrate defect. The red box represents the expected theoretical size. In the focused PSF, the diffraction features at the edges are clearly visible. By applying a certain amount of defocus, it is possible to reduce these features and to obtain a nearly top-hat shape. The drawback of the defocusing is the change in the PSF wings from a nearly sharp profile to a much more smooth profile. In both cases, the central obstruction and Poisson spot features disappear as expected.

The PSF image and profile related to 10% CHEOPS scaled experiment (FN=2.4) for both the on-focus PSF and defocused PSF obtained with white light source are shown in Figure 7. In this case the images have been re-sampled to a pixel having size 12.9 micron, very close to the one foreseen for CHEOPS (13 micron). The focused PSF shape is almost completely dominated by the diffraction pattern introduced by the lenslet itself. By introducing a certain amount of defocus, the diffraction pattern almost disappears but the central area and the wings of the PSF deviate by far from a top-hat shape, leading to an illumination pattern that is somehow intermediate between the achieved holographic one and the best lenslet PSF obtained with a large FN.

5. CONCLUSIONS

In the framework of the CHEOPS mission project, it has been studied the possibility to reduce the impact of the PSF shape on the noise budget in order to assure high precision photometry by introducing a dedicated optical device in the intermediate pupil of the Back End Optics. The aim of such device is to mitigate both the primary mirror central obstruction and Poisson spot features and to shape the PSF to a nearly top-hat.

Between the possible solutions, we have considered the following devices: an Axicon, a Schmidt-like corrector plate, a holographic diffuser and a lenslet array. While for the first two, we have only simulated the behavior through theoretical models, for the last two we have tested the performances in the lab. In both tested cases the features of the central obstruction and of the Poisson spot are largely reduced. The considered holographic diffuser delivers PSF that has much more Gaussian shape rather than top-hat shape. Lenslet array, when coupled with detector defocusing, is able to deliver a nearly top-hat PSF with smoothed wings only when the Fresnel Number is much larger than unity. For the CHEOPS scaled experiment, the required Fresnel Number is 2.4 and the lenslet delivers a PSF which illumination pattern is in
between the one delivered by holographic diffuser (Gaussian) and the one delivered by the lenslet array with a large FN (top-hat with smoothed wings).

At the end, for CHEOPS mission, it has been decided to avoid any kind of PSF shaper device, because it has been demonstrated through simulations that the shape of the PSF has much smaller impact with respect to other noise sources. On the contrary, the PSF stability and the straylight background are dominant noise factors and the introduction of an additional optical element in the intermediate pupil could be a source of deterioration for them.

REFERENCES


