Collimating system for the Space Optics Calibration Chamber (SPOCC) of the Optical Payload Systems (OPSys)facility

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Report nr. 140 date: 19/10/2010

DOCUMENT CHANGE RECORD

Sheet: 1 of 1

DATE	DESCRIPTION OF CHANGE	BY	APPROVED BY
19/10/2010	1st Draft	G. CRESCENZIO	S.FINESCHI

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Introduction

Last year's solar and astronomical research is increasingly faced to the space with the lunch of several scientific satellites. That's because the atmosphere of our planet filter most of the electromagnetic radiation coming from the celestial bodies including in the UV and the IR bands that carries a lot of scientific information. Furthermore the atmosphere introduce into optical systems a "seeing effect" that blurs images and indeed reduces the optical performances of the telescopes, this effect is not present in space.

Because the space is characterized also by the absence of atmosphere, before to lunch space telescopes it is necessary to test their reliability in vacuum condition. SPOCC is the test chamber into the OPSys new facility located in Altec Laboratory (Turin) its task is to test spatial optical system in artificial vacuum condition. In particular the firsts payloads that will be tested into SPOCC will be two space coronagraphs: SCORE and METIS. To test optical performances a sun simulator coherent with the specifications of the 2 space mission is needed.

Figure 1 Images of SPOCC parts: on the left the pump section, on the right the test section, the optical movable table is visible under the cover lifted.

Sun Simulator

SCORE and METIS are both space coronagraph, their principal difference (from the sun simulator project point of view) is the working distance from the sun: for SCORE 1 AU for METIS 0.5-0.3 AU. That's because METIS is included in the Solar Orbiter mission a mission that has the goal to send this instrument in solar orbit while SCORE works at earth-sun distance. This difference lead to a great field of view difference that comes from the real divergence of the sun at different distances (Tab. 1).

	E.F.L.	F.O.V.	Working distance	Sun Divergence	d_{source} (mm)
SCORE	470 mm	1.5 - 3.2	1 AU	$\Omega_{0,S}$ 0.55°	19.2
METIS	305 mm	1.8 - 5.3	0.3 AU	$\Omega_{0,M}$ 1.77°	63.9

Tab. 1 Description of the two Coronagraph SCORE and METIS

If we want simulate the sun as collimated beam with the sun divergence that lightens uniformly the instrument we need a extent source and a collimator mirror. A mirror is needed instead a lens because we are going to make tests in the visible and in the UV band. This optical system follow 2 principal rules:

1. The divergence of the beam coming from the source must be equal to the divergence of the sun Ω_0 This means that the center of the collimator must see the source disk into an angle $\Omega_{0,S}$ or $\Omega_{0,M}$ (S for SCORE M for METIS). From this first concerning it is clear that 2 different sources are needed (or

at least a source and 2 different diaphragms) of diameter:

$$d_{source} = f \cdot \tan \Omega_0 \qquad \text{eq.1}$$

where $f = 2000\ mm$ is the focal length of the collimator (tab1.).

2. Every point of the front aperture (FA) must see the sun disk with the sun divergence Ω_0 . This means that the FA must be uniformly illuminated, now, because the divergence Ω_0 and the FA diameter d_{FA} are fixed one can work on the distance collimator-FA and/or on the aperture of the collimator:

$$d_{coll} = d_{FA} + l_{beam} \cdot \tan \Omega_0 \qquad \text{eq.2}$$

where d_{coll} is the diameter of the collimator and l_{beam} is the distance collimator-FA.

Collimator diameter

To solve the second point of previous paragraph about the calculation of the collimator's diameter and pipeline length the two case METIS and SCORE need to be discussed separately. Common points are the SPOCC mechanical constrains (figure 1)

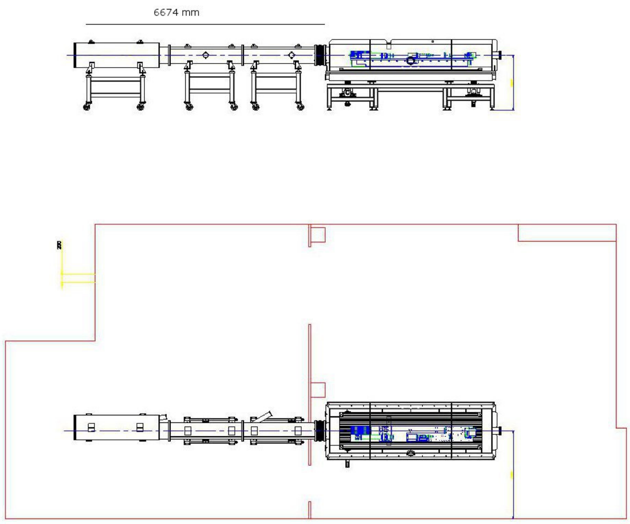

Figure 2 The projections of the final drown of SPOCC, in the lower picture is visible also the contour of the clean room that hosts the vacuum chamber . The name of the facility is OPSys

The pipeline length is l_{beam} = *6674 mm*, its internal diameter 200 mm, for the following discussion those are the quotas we need.

SCORE

From eq.2 , knowing SCORE's d_{FA}= *100.32 mm*, d_{coll}=*162.06 mm* this is the lower limit to get uniform illumination for FA. What is important is also the upper limit for collimator diameter, this limit is given by the ray that connect the edges of the collimator, the external occulter and the entrance pupil (EP) of the coronagraph (Figure 2).

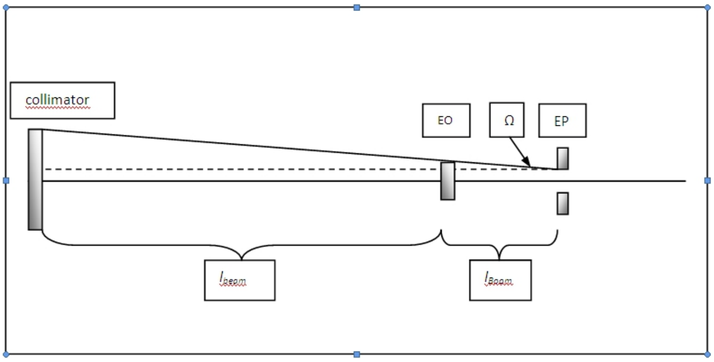

Figure 3 A schematic representation of the collimator coupled with SCORE occulting system.

Indeed a mirror too little could cut part of the FOV otherwise a too big mirror could be seen by the telescope while it is looking out of axis where there should be only corona and this could lowering of the sun/corona contrast from the required 10^9. Starting from the specifications taking the inner FOV limit 1.5 → 0,825°, the EO-EP distance $l_{Boom} = 2317.5\ mm$ and the radius of EP $r_{EP} = 18\ mm$:

$$d_{coll} = 2 \cdot [r_{EP} + (l_{beam} + l_{Boom}) \cdot \tan(FOV/2)] = 165.5\ mm \qquad \text{eq. 3}$$

So a suitable diameter for collimator mirror is 165 mm.

METIS

In METIS case the situation is pretty different because the divergence of the beam is almost 3 times the divergence used for SCORE. Calculations says that whole pipeline length cannot be used the in this case because the beam is going to hit the tube before to reach the instrument. So there are 2 possible solutions:

1. Shorten the pipeline, indeed SPOCC is projected to be shorten of 1836 mm removing one of the modules that composes the pipeline;
2. Find another way to perform instrument illumination.

We have to consider also that for eq. 2 the mirror need to be changed from to 165 mm diameter to 260 mm. With this collimator diameter the diameter of the beam at 6774 mm is 466 mm and at 4838 mm is 410 mm, in every case the beam is too large with respect to the tube diameter that is 400 mm.
Another solution could be to use the same SCORE mirror and calculate the pipeline length to get uniform illumination on the METIS's FA. In this case the pipeline length should be 3713 mm that is shorter than what we can do.
So another way is needed far from the two equations that describe the system. Now the goal is to perform a sun simulator without change mirror and pipeline length. METIS stray light tests need a uniform illumination of the FA of the instrument with a beam that has the divergence of the sun at 0.3 AU but the FA of METIS is a disk of 40 mm diameter[1] so changing the source position it should be possible to conjugate the source with the FA and focus on the edge of the disk an annular source. In this case is important that rays reach the FA with angle equal the sun divergence.

[1] METIS is an inverted coronagraph so the FA is a hole rather than an occulter as in SCORE and as a rule in coronagraph

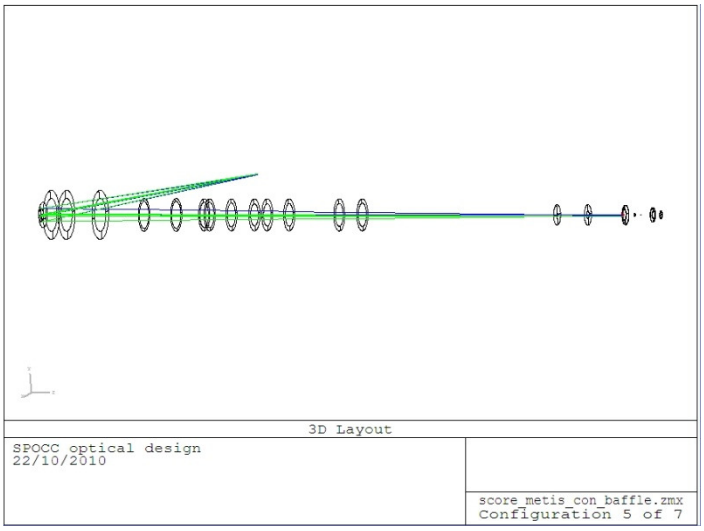

Figure 4 The system in conjugate mode. The rings visible in the picture are the baffling system for the control of the stray light. At the end of the beam METIS, the inverted coronagraph with its annular mirrors.

Calculating conjugate points with usual geometrical optics formula and optimizing with Zemax the result is

Mirror Radii (mm)	S_o (mm)	S_i (mm)	Height on parabola axis (mm)	Annulus diameter (mm)	Divergence on FA (deg)	Spot µm
4000	-2854,92	6674	150,75	17,5	1.764	191,835

Tab. 2 Solutions for the METIS sun simulator

displayed in Tab. 2. Now positioning the source at 898.65 mm from the focus of the collimator the result is that at 6674 mm from the mirror there is a focus. In this focus an annulus of 17,5 mm diameter on the object plane is focused in an annulus (the FA) of 40 mm in the image plane and the marginal rays come on the image plane into a cone of 1.764° that is what we want.

This is a practical and economical solution because now it isn't need to change the mirror or un mount a module from the pipeline and after that to realign all the system. Now it is just needed to move the source on a line and then to change and realign it. Furthermore the dimension of this source is similar to the source for METIS and this is another advantage on the projecting point of view.

Mirror Design

The shape of the collimator it is an off axis parabolic mirror as advanced in Tab. 2 . The parabolic shape is necessary to avoid aberrations coming from a spherical shape. The mirror is a 350 mm off axis of 165 mm diameter from a 4000 mm curvature radius parabola as shown in figure 4,

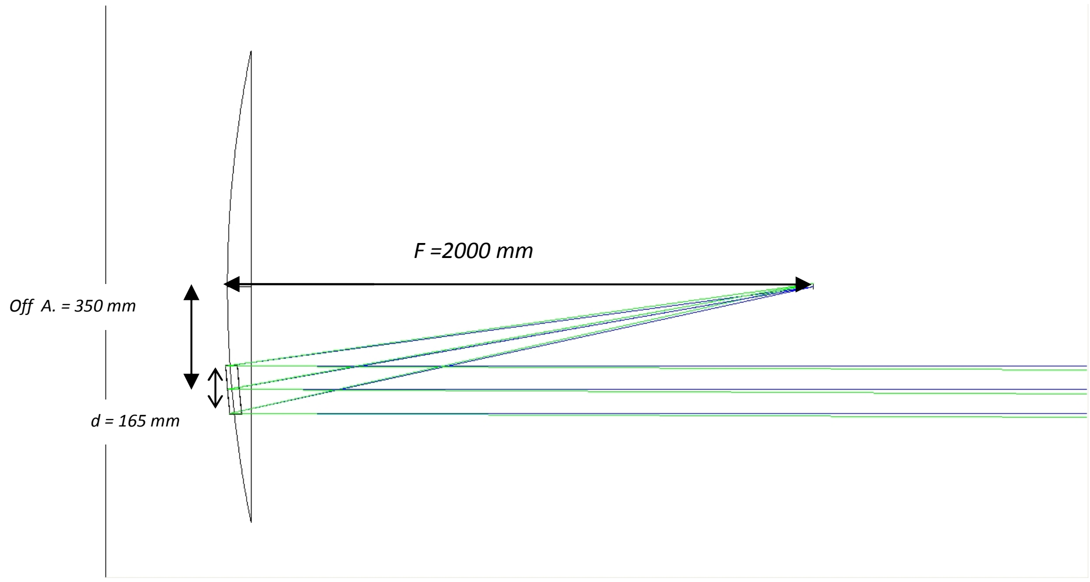

Figure 5 Specification of the mirror, the main parabola and the off axis shape that will be used in SPOCC.

The mechanical interface design of the mirror is in draft (figure 6), it will be provided of a tilting mount that allow movements around x and y axis (as usual z axis is the line of sight).

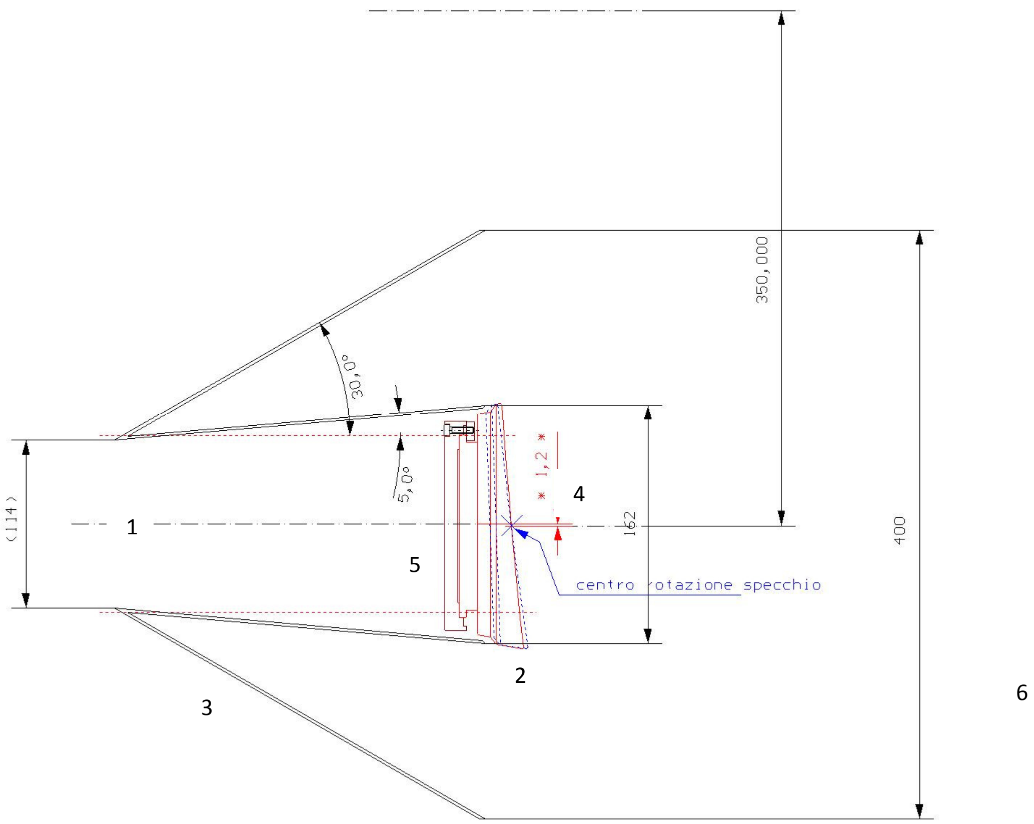

Figure 6 A sketch of the mirror and all its parts: 1. Mechanical Axis, 2. Mirror, 3. Light trap, 4. Mechanical axis mirror tilting mechanism/optical axis off set, 5. Back side of the mirror.

Furthermore the back side of the mirror is surrounded by a light trap Fig. 6(3) needed to minimize the stray light [6]. The mirror Fig. 6(2) is shaped as an off axis parabolic 2000 mm focal length mirror, the back side of the mirror Fig. 6(5) is shaped to fit to the mechanical interface. The mechanical axis of the mirror tiling mechanism Fig. 6(1) does not overlap the optical axis Fig. 6(4) of 1.2 mm.

Mechanical tolerance

Z tilt

Now the goal is to understand the influence of the presence of a tilt around the z mechanical axis on the spot size. Mechanical Axis (MA) is the mirror's axis that will overlap the mechanical axis of the pipeline, otherwise Parabola Axis (PA) is the axis of the "main" parabola so it is parallel to the mechanical axis and contains the focal/source point. This tilt can be introduced by constructor or by a misalignment in the assembly procedure.

To tilt the mirror around the MA means to tilt the main parabola around this axis, so because the mirror is 350 mm off axis with respect to the PA this means that the source point draws a circle of 350 mm radius around the MA in the MA's normal plane. The situation is traced in figure 7 where are visible 4 different sources for 4 angles of rotation of the mirror around MA (0°, 90°, 180° 270°). In this case both mirror and source are rotated of the same angle so the beam is always collimated.

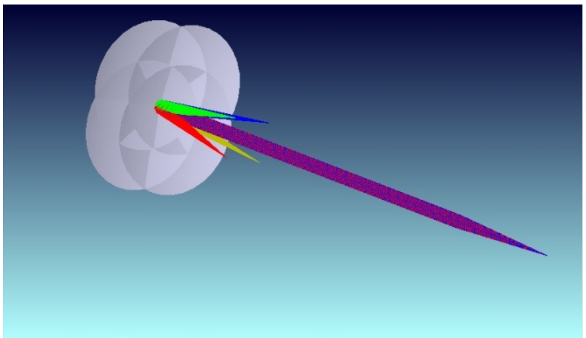

Figure 7 A simulation of the rotation of the source around the mechanical axis of (0°, 90°, 180° 270°).

In the following analysis the choice is to tilt the PA so the source around the mechanical axis on a circle of 350 mm radius leaving the mirror firm. In the FA is placed a paraxial ideal lens of *f=2000 mm* and the spot created by this system is the object of study. Considering the beam from the point source placed in focal point of the mirror we get a spot of *0 µm* that because we have an ideal system: an ideal point source in the focus of an ideal parabola that generates a ideal paraxial beam focused by a paraxial ideal lens! In the real world where nothing is "ideal" the reference can be the Airy disk that in this case has a radius of *8,394 µm* so the worsening of the spot size, tilting around z axis, is roughly calculated as

$$\frac{\sqrt{R_{airy}^2+R_{RMS}^2}}{R_{airy}}$$

eq.4

Where R_{airy} is the ray of the airy disk of the system and R_{RMS} is the degradation of the RMS spot for every considered angle of z tilt.

angle [deg]	RMS Spot	Spot worsening
0	0	1,00000
0,005	0,078	1,00004
0,01	0,153	1,00017
0,05	0,791	1,00443
0,1	1,556	1,01704
0,15	2,346	1,03832
0,2	3,111	1,06647
0,3	4,667	1,14417
0,4	6,222	1,24477
0,5	7,778	1,36331
1	15,556	2,10581
5	77,86	9,32942

Tab. 3 Tolerance of the rotation around z of the off axis shape. The worsening of the Spot size is given in function of the angle of rotation.

When the worsening parameter is 1 it represents the Airy limit best case, when it is 1,5 it means a worsening of 50%, 2 a worsening of 100% etc…

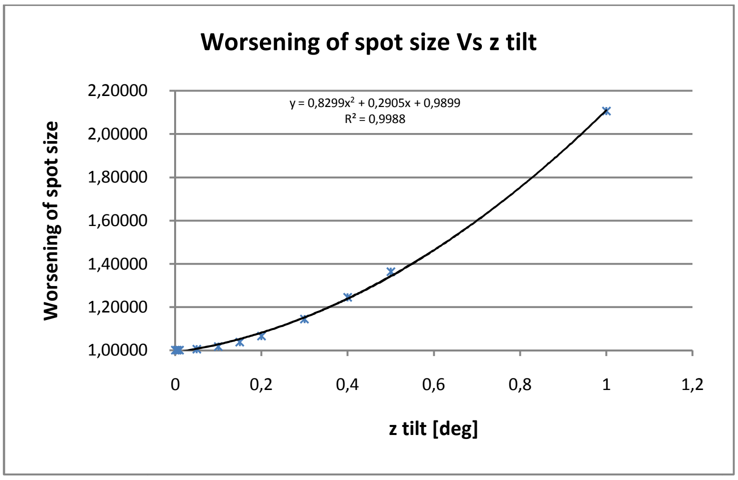

Figure 8 The plot represent the worsening of the spot size in function of the z tilt.

Conclusion

In conclusion, analyzing figure 8 one can say that in order to have an amount of error less than the 5%, the accuracy in the fabrication and in the installation of the mirror in z tilt must be at least 0.05° (3 arcmin), but to have a more clear idea of the needs this error must be introduced in a wider error budget.

Mirror surface accuracy specifications

Surface accuracy is usually specified in terms of the wavelength of light from an HeNe laser (0.0006328 mm). It is determined by an interferometric comparison of the surface with a test plate gage, by counting the number of (Newton's) rings or "fringes" and examining the regularity of the rings. The space between the surface of the work and the test plate changes one-half wavelength for each fringe. The accuracy of the fit between work and gage is described in terms of the number of fringes seen when the gage is placed in contact with the work. Commercially the surface accuracy is indicated as $i{\cdot}\lambda$ where λ is the test wavelength and i is a factor that indicate the quality (i.e. $\lambda/4$ is an excellent surface quality).
In this case we simulate this test thanks to ZEMAX optical design software in order to give to the constructor the theoretical specifications needed.

Ray Trace

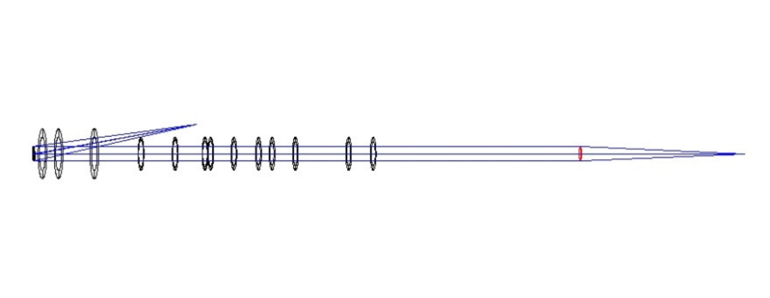

Figure 9: A 3D plot of the CAD file, in red the paraxial ideal lens, along the beam the baffling system.

The ray trace used is the same used for the optical design of SPOCC. A *paraxial* lens of 2000 mm focal length is added at the end of the collimated beam. Te source is a point source on the focus of the parabolic collimator. The spot diagram utility calculates an RMS spot of 6E-14 mm with an airy disk of 8.14E-3 mm.

Now the task is to degrade the surface quality of the collimator and find how the spot size is sensitive to this degradation. To this operation is used the tolerance and sensitivity ZEMAX algorithm. The *sensitivity* mode allow to apply to the optical system the desired imperfection and analyze its impact on the spot size or the wavefront. The tolerance editor allow to set the operands necessary to our task. We need the TFRN operand and TWAV operand. The TWAV operand simply set the working wavelength: 6.328E-4 mm. The TFRN operand is used for large radii surfaces it deforms randomly the surface and the change in the sag of the surface is related to the error in Newton's fringes by

$$\Delta Z = \frac{\lambda}{2} N \qquad \text{eq.5}$$

Where N is the number of fringes, λ is the working wavelength. The free parameter is then N.

Test

The sensitivity algorithm was run with a series of different fringes numbers to check the best candidate for the mirror surface accuracy.

Newton Finge (N)	i*λ	RMS Spot degradation (mm)	Airy spot variation	Δz (mm)
0	0,00	6,46E-14	1,00E+00	0,00E+00
0,5	0,25	3,73E-04	1,00E+00	1,58E-04
1	0,50	7,46E-04	1,00E+00	3,16E-04
2	1,00	1,49E-03	1,02E+00	6,33E-04
3	1,50	2,24E-03	1,04E+00	9,49E-04
4	2,00	2,99E-03	1,07E+00	1,27E-03
5	2,50	3,75E-03	1,10E+00	1,58E-03
6	**3,00**	**4,50E-03**	**1,14E+00**	**1,90E-03**
7	3,50	5,26E-03	1,19E+00	2,21E-03
8	4,00	6,02E-03	1,24E+00	2,53E-03
9	4,50	6,78E-03	1,30E+00	2,85E-03
10	**5,00**	**7,54E-03**	**1,36E+00**	**3,16E-03**
12	6,00	9,06E-03	1,50E+00	3,80E-03
14	7,00	1,06E-02	1,64E+00	4,43E-03
16	8,00	1,22E-02	1,80E+00	5,06E-03
20	10,00	1,53E-02	2,13E+00	6,33E-03
100	50,00	8,46E-02	1,04E+01	3,16E-02
1000	500,00	7,91E+00	9,72E+02	3,16E-01

Tab. 4 The worsening of the spot size in function of the mirror accuracy.

In table 4 are displayed the test data. In the first column the number of Newton's fringe, in the second the error in wavelength, in the third the RMS spot degradation calculated and in the fifth column shows the mean errors in mirror radii. In the fourth column the airy spot variation is calculated as rough indicator of the worsening due to the surface deterioration calculate as in eq. 4

It is clear that in the best case this parameter is equal to 1 because R_{RMS} goes to 0, as shown in figure 2a, and that in example at ≈*9λ* the worsening is the 100%.

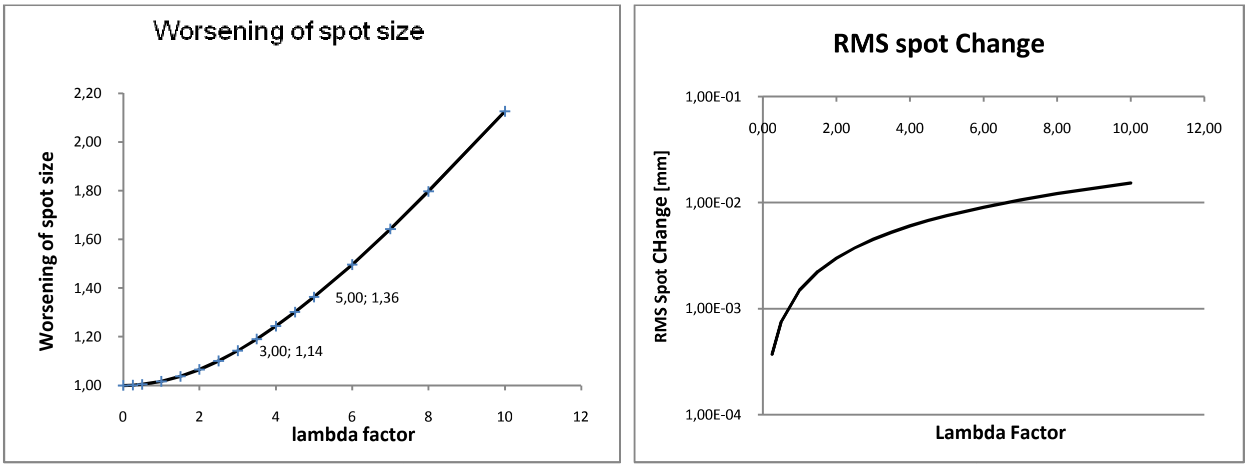

Figure 10: (a) On the left the RMS spot plot in airy unit, the suitable values are highlighted in the graph; (b) on the right the RMS spot change plot in log scale

Conclusion

Looking at Figure 2a. we locate 3 suitable candidates for the required surface accuracy. They are 3λ and 5λ. It is clear that better accuracy would be preferable but better accuracy means more costs so we have to compare performances with our requirement. 3 λ accuracy gives an estimated spot changing of 2.2 µm. If we compare this number with the detector pixel size 15 µm and the airy best case dimension 8.14 µm we see that summing the dimension of the airy spot and the degradation (quadratic sum as above) the dimension of the airy degraded spot follow again into the pixel size even if the degradation is the 14%. For 5λ the degradation is the 36% but again the degraded airy disk is contained into one pixel even if now the tolerance margin for other possible imperfection (parabolic constant, decenter, tilt, thickness etc…) is reduced. So we can set as goal 3λ and acceptable 5λ accuracy.

List of Acronyms

EO: External Occulter
EP: Entrance Pupil
FA: Front Aperture
MA : Mechanical Axis
PA: Parabola Axis
METIS: Multi Element Telescope for Imaging and Spectroscopy
OPSys: Optical Payload System Facility
SCORE: Sounding – Rocket Coronagraph Experiment
SPOCC: Space Optics Calibration Chamber

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