Nature :

Titre / Title :

PRELIMINARY TOLERANCE BUDGET for the Spherical Aberration Corrector (SAC)

Résumé / Summary :	**Classification**
This document presents the manufacturing error budget for the Spherical Aberration Corrector of the SALT. The error budget is given at mirror assemblies level and at integration level .	**Non classifié**
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Sommaire

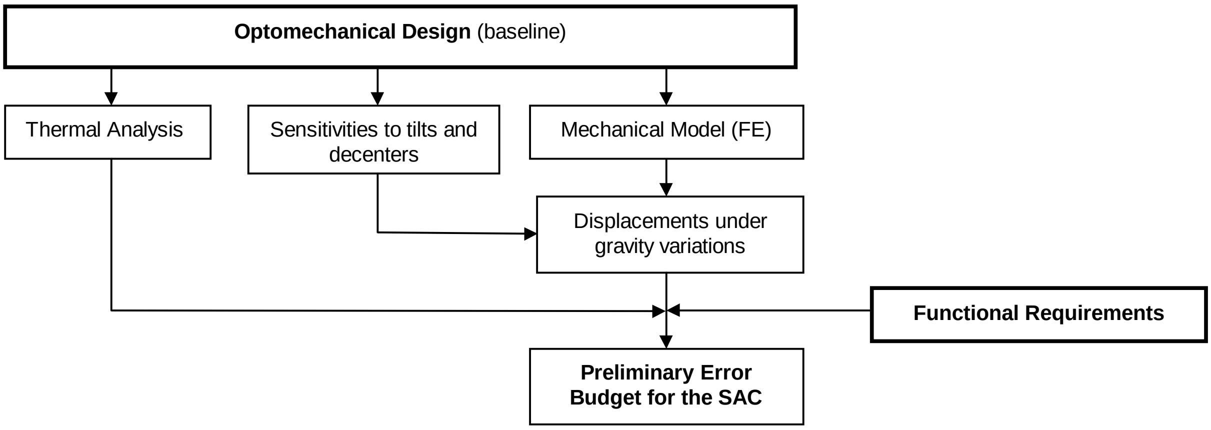
1. INTRODUCTION

SALT, the South Africa Large Telescope, is based on a large, spherical primary mirror. This concept considerably facilitates the fabrication of the mirror segments, that are all spherical and identical, and allows for an innovative pointing approach.

These features are partially compensated by the fact that a spherical mirror is not stigmatic for an object at infinity. Indeed the SALT primary focus suffers from a considerable amount of aberrations. It is the scope of the Spherical Aberration Corrector (SAC) to compensate these aberrations, and to provide images of suitable quality to the SALT focal plane.

This document is based of the design described in document [RD2] “Optical Specification For The Spherical Aberration Corrector”, version 3.1, Chapter 2 : “The 11.0m Entrance Pupil Design”.

Following graph describes the SAGEM approach for deriving the SAC specifications tree :



The functional requirements are expressed in term of image quality in [RD1] : parameters are the diameter of 50% and 80% of Encircled Energy. However, as far as Manufacturing and Integration aspects are concerned, the quality of a mirror, or of an optical instrument, is best described in term of WaveFront Errors (WFE) :

- as for manufacturing aspects, there is an obvious relation between the measured WFE and the job in progress.
- as for the integration phase, the WFE provides, via a decomposition into Zernike polynomials, a set of linear terms highly favorable to the convergence of the alignments.

Therefore, a reliable correlation of Encircled Energy and WFE is needed, adapted to the case of the SAC.

It can be shown that there are no general relations between Encircled Energy and WaveFront Errors (WFE). For example, depending on the type of aberration considered, a given wavefront perturbation (expressed in wavelenth-nm, or nm-rms) will affect the energy concentration EE50 and EE80 in totally different manners. This is particularly true for systems with severe central obscuration, as it is the case for the SAC.

The structure of this document reflects the approach defined in previous graph :

1 – identify the most probable types of wavefront perturbations that will be met during the SAC development. It is assumed that polishing errors consist mostly in terms of high spatial frequencies (simply because any contribution to any ZERNIKE polynomial under term 36, for example, is readily corrected at the optical shop level.) By contrast, the misalignments affect only the low order polynomials, namely Coma (Z8) and Spherical Aberrations (Z9 and Z16),

2 – for each “type” of perturbation, compute the influence of a given WFE on the Encircled Energies,

3 – evaluate of the influence of the operating environment : thermal and gravity. It is anticipated that the SAC will be tested in vertical position, at a temperature of 20°C. It will operate at an inclination of 28.5 to 45.5° and in the temperature range of 0..20°C.

It will be shown that the contributions of the thermal and gravity effects add quadratically, since they address Zernike polynomials of different orders. They will be subtracted from the Functional Requirement Budget.

What is left will be the budget for the complete SAC, as tested in vertical position at 20°C. The determination of the corresponding WFE is the scope of this document.

2. APPLICABLE AND REFERENCE DOCUMENTS

[RD1] : SAC SPECIFICATION, ref. 1523AS0001, Issue 2, as signed during contract negotiation.

[RD2] : Optical Specifications for The SALT Spherical Aberration Corrector, ref 1523AS0002, version 3.1, dated August 15, 2001.

3. LIST OF ACRONISMS

EE : Encircled Energy
EE50 : Diameter for 50% of Encircled Energy
EE80 : Diameter for 80% of Encircled Energy

<EE50> : Diameter for 50% of Encircled Energy, averaged for the angular field 0, 2', 4', with the weighing factors 2, 1 and 1.

<EE80> : Diameter for 80% of Encircled Energy, averaged for the angular field 0, 2', 4', with the weighing factors 2, 1 and 1.

SAC : Spherical Aberration Corrector
WFE : Wavefront Error
FoV : Field of View

4. THE SAC OPTICAL DESIGN

4.1 OPTICAL PRESCRIPTION

The optical prescription has been taken from [RD2]. The corresponding CODEV listing is given hereunder.

The M3 is described by a generalized asphere that includes a term in h^2. This can be confusing (for example when computing the paraxial parameters of the SAC : the contribution of the $A2=2.4236^{e-4}$ term is about 21.8mm @ h=300mm.) The sag of M3, computed from the radius of 2098.823 is about 20.9mm, when the actual sag is 34.66mm. Nevertheless, this can be dealt with CODEV (option SPS ODD in the Lens Data Manager).

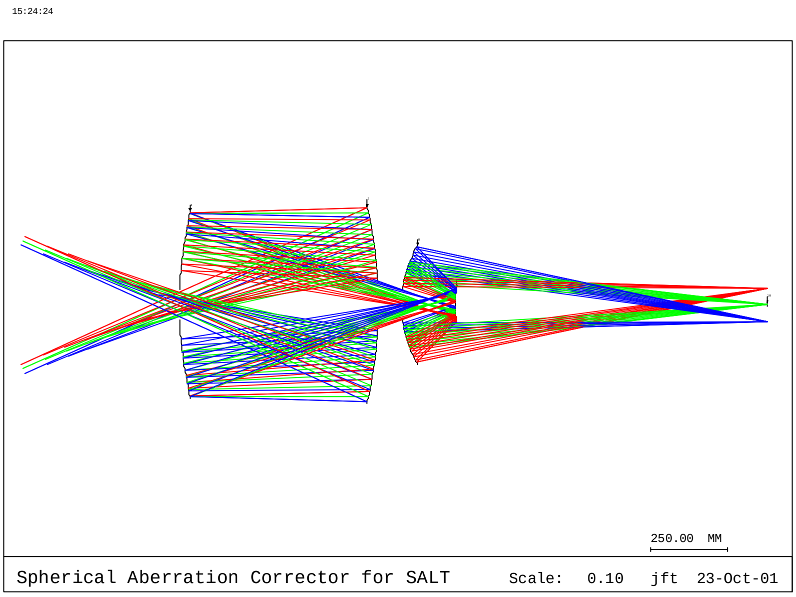
```
RDY             THI       RMD          GLA
  OBJ:        INFINITY        INFINITY
  STO:     26165.00000    12829.670000    REFL
    2:        INFINITY      641.787000
    3:     -1432.34300     -641.787000    REFL
      SLB: "*** M2 ***"
      CON:
      K  :    0.929735

    4:      2098.82300      641.787000    REFL
      SLB: "*** M3 ***"
      SPS ODD:
      IC :     YES
      SCO
           AR2:  2.4256E-04        AR4: -9.1127E-10        AR6: -8.7170E-16
           AR8:  2.6460E-21

    5:        INFINITY       75.000000
    6:        INFINITY      171.597000
    7:       242.86800     -171.597000    REFL
      SLB: "*** M4 ***"
      CON:
      K  :   -2.859464

    8:       375.75000      171.597000    REFL
      SLB: "*** M5 ***"
      CON:
      K  :   -0.198452

    9:        INFINITY     1007.463000
> IMG:        INFINITY       -0.227103
```

4.2 DESCRIPTION OF THE SAC LAY-OUT :

The lay out is given hereunder, for the fields 0 and +/-4’. The M3 is located where the section of the M1 caustic is minimum, a position that minimizes the central obscuration.

The pupil is re-imaged on M3 via M2 so it is up to M3 to compensate for the huge spherical aberration of the primary, that is constant over the complete field of view for obvious symmetry reasons. This account for the very high aspherization of M3.

There is a real, accessible stop at mid distance between M5 and the focal plane.



4.3 APERTURES :

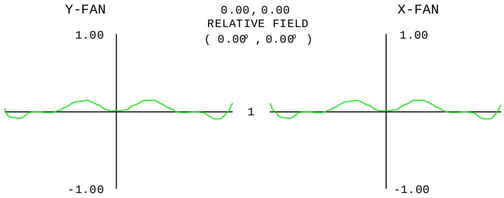
The determination of the apertures is a complex matter, as underlined in [RD2]. Some assumptions are to be made :

- if one wants to favor the on-axis throughput , one may want to minimize some apertures, for example the central hole of the M2. The consequence is a severe vignetting in the FoV,
- correspondingly, improving the illumination uniformity in the FoV is at the cost of on-axis throughput, because increasing some apertures is needed.

Therefore, some kind of trade-off is needed. This discussion is carried-out extensively in [RD2], and will not be recalled here. In this document, we strictly adhere to the aperture defined is [RD2].

4.4 OPTICAL PERFORMANCES :

The optical quality on axis is virtually perfect (about 0.052λ-rms in the best focal plan on-axis). See hereunder for the WFE curves, that shows the contribution of residuals of high order aberrations.



The nominal Energy Concentrations are the following :

```
***************************************************************************
*  YAN (min) *          EE(50)  IN THE FOV (XAN = -4′, -2′ .. 4′)          *
***************************************************************************
*    -4      *    0.2472  *    0.1366  *    0.1094  *    0.1366  *    0.2472  *
*    -2      *    0.1381  *    0.0545  *    0.0321  *    0.0545  *    0.1381  *
*     0      *    0.1089  *    0.0323  *    0.0314  *    0.0323  *    0.1089  *
*     2      *    0.1381  *    0.0545  *    0.0321  *    0.0545  *    0.1381  *
*     4      *    0.2472  *    0.1366  *    0.1094  *    0.1366  *    0.2472  *
***************************************************************************
```

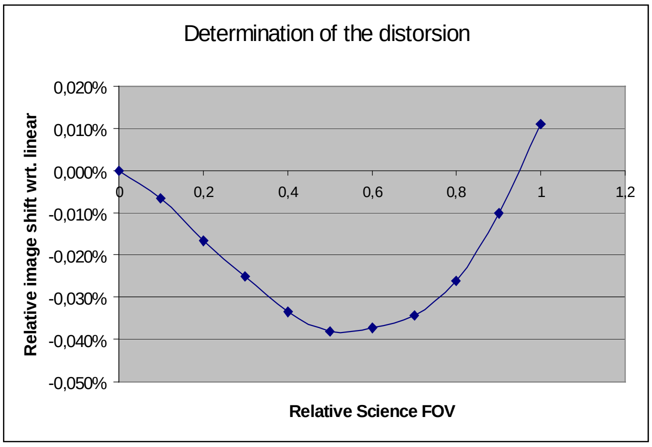
```
***************************************************************************
*  YAN (min) *           EE(80)   IN THE FOV (XAN = -4′, -2′ .. 4′)        *
***************************************************************************
*    -4      *    0.3444  *    0.2084  *    0.1775  *    0.2084  *    0.3444  *
*    -2      *    0.2081  *    0.1071  *    0.0782  *    0.1071  *    0.2081  *
*     0      *    0.1758  *    0.0753  *    0.0648  *    0.0753  *    0.1758  *
*     2      *    0.2081  *    0.1071  *    0.0782  *    0.1071  *    0.2081  *
*     4      *    0.3444  *    0.2084  *    0.1775  *    0.2084  *    0.3444  *
***************************************************************************
```

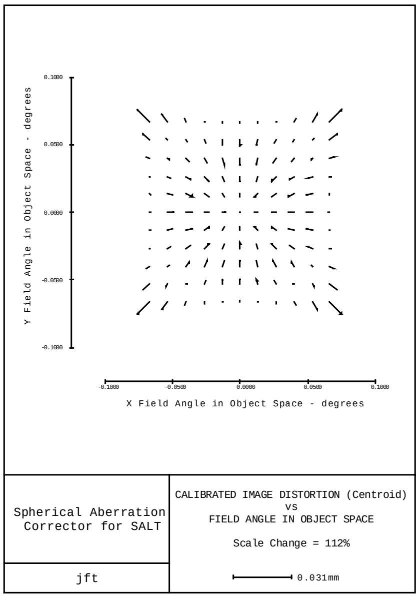
The specifications on EE(50) and EE(80) are 0.240” and 0.420” in the Science FoV of radius 4’. Above tables confirm that the nominal quality is excellent in about the central half of the FoV, but decreases rapidly at the FoV limits (in above tables, the “corners” do not belong to the Science FoV). Therefore, when deriving the SAC tolerances, special attention shall be paid to the behavior of the performances within the FoV.

4.5 DISTORSION :

The paraxial EFL has no meaning in this case (we have EFL ≈ 5520mm for a pupil diameter of 11000…). The Effective Focal Length and the Distortion shall be derived from the computation of the image format within the Science Field of View (FoV). A linear regression on points equally spaced in the Science FoV leads a Focal Length of 46242mm, that matches the 46200mm mentioned at §1.2.3 in [RD2] with a relative precision better than 10^{-3}.

The distortion, expressed as the relative image displacements wrt. to a linear format correspond to +/-0.020%, i.e. about +/-0.01mm ;

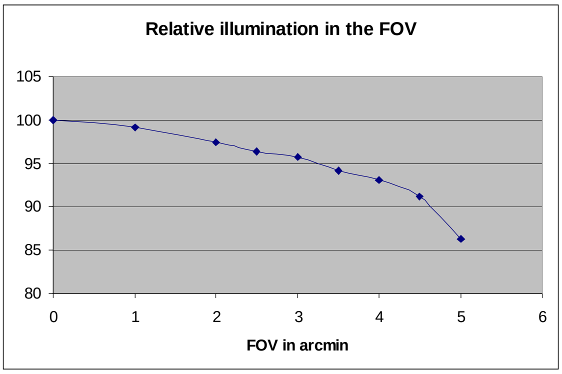




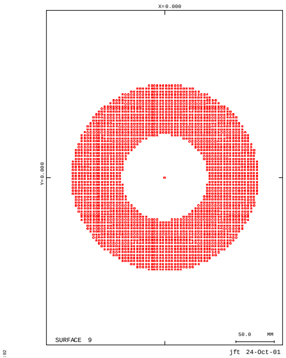
4.6 ILLUMINATION UNIFORMITY IN THE SCIENCE AND IN THE GUIDE STAR FOV :

The following figures illustrate the beam cross-section in the plane of the M4 mirror, on axis and at 5’ of FoV. As a consequence of the mirrors occultations, the illumination is not uniform in the FOV. Computed in absolute terms, the vignetting is 21% on axis , and 26% at the edge of the science FoV. Requirement are 20 and 30%, respectively.

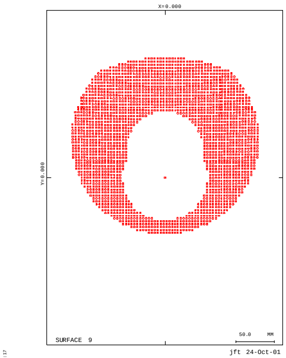
The variation of the relative illumination is shown hereunder :



Footprints on axis and in the FOV are shown hereunder :



Footprint on axis



Footprint at 5 arc-min

5. PERFORMANCES SENSITIVITIES TO PERTURBATIONS

5.1 SCOPE

The performances of the SAC are defined in term of energy concentration ($E_{80\%}$ and $E_{50\%}$) in the image plane. These parameters are adequate for defining the performances in term of image quality, but they are not well suited to the establishment of an error budget.

In effect, there are no clear relations between the energy concentrations, the optical aberrations, and the mirrors figuring quality. A different approach, based on the Zernike polynomials, has been adopted as far as practical. Its allows an accurate evaluation of combined perturbations, since the Zernike terms add algebraically, and a straightforward determination of the compensators (for the same reasons).

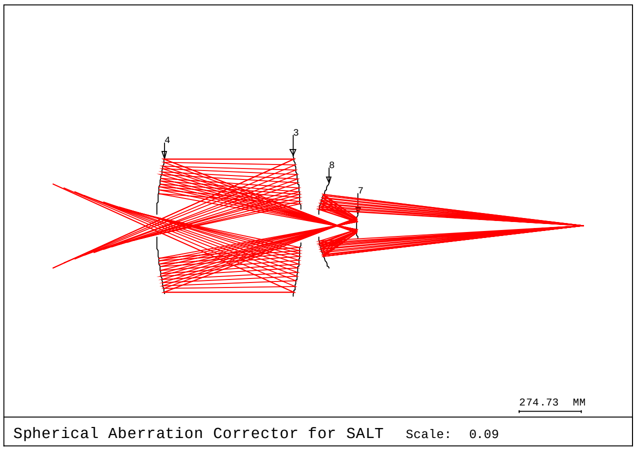
Besides a better understanding of the aberrations of the system, this approach is justified by the fact that we *need* to express the figuring tolerances in term of wavefront error, since it is this parameter that will be checked throughout the manufacturing and alignment process.

Indeed, the Energy Concentration will never been checked, and the conformity of the SAC will be indirectly assessed via interferometric measurements.

The aim of this chapter is to establish a simple model between the wavefront error, defined in term of Zernike polynomials, and the image quality defined in term of energy concentration.

5.2 SENSITIVITIES TO TILTS AND DECENTERS :

We have computed the performances of the SAC, expressed in terms of Zernike coefficients, when affected by the tilts and decenters of the 4 mirrors behaving as rigid bodies. Following CODE V conventions, decenters are noted « YDE », and tilts are noted « ADE ». Results are given in following tables, from 6.2.a. to 6.2.d.



We see that the only aberration induced by the tilts and decenters of the mirrors is the third order Coma, the variation of which being linear with the perturbations. The sensitivities are summarized in the following table :

Contributor	Tilt (in $°^{-1}$) at …			Decenter (in mm^{-1}) at …		
	0’	2’	4’	0’	2’	4’
M2 (s3)	2334.8	2333.7	2331.8	-98.41	-98.31	-98.27
M3 (s4)	-90.37	-90.56	-89.16	104.63	104.53	104.52
M4 (s7)	80.01	79.51	78.43	21.69	21.38	20.56
M5 (s8)	-117.56	-116.18	-112.77	-22.97	-22.66	-21.87

So, in the general case of combined perturbations, the following expression would give the corresponding aberration, on axis (above table shows that the sensitivities are slightly different in the Field of View) :

Z8 = 2334.8*(tilt M2) - 98.41*(decenter M2) – 90.37*(tilt M3) + ….

For example, if M2 is decentered of 0.100mm, and tilted of 0.023°, respectively, its contribution is to 3rd order coma would be –2.8366 (and –2.8316 at 4’ of FoV).

A consequence of these linear sensitivities is the possibility to compensate the contribution of one mirror by an other. This open the possibility, during the Assembly, Integration and Tests phase (AIT), to align the complete SAC by adjusting only the M3, for example.

		Nominal			ADE S3 0.005			ADE S3 -0.005			YDE S3 0.1			YDE S3 -0.1		
		0’	2’	4’	0’	2’	4’	0’	2’	4’	0’	2’	4’	0’	2’	4’
Focus	Z4	-0,0508	0,1755	0,5913	-1,7268	-1,4564	-0,9935	1,6719	1,8533	2,2220	1,4380	1,5748	1,9196	-1,4937	-1,1813	-0,6917
Astig3	Z5	0,0000	0,1546	0,8544	-0,0063	0,0881	0,7261	-0,0063	0,2081	0,9689	-0,0042	0,2274	1,0062	-0,0042	0,0729	0,6931
”	*Z6*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*
Coma3	*Z7*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*
”	**Z8**	**0,0000**	**-0,1670**	**-0,1648**	**11,6747**	**11,5011**	**11,4936**	**-11,6741**	**-11,8361**	**-11,8248**	**-9,8409**	**-9,9981**	**-9,9919**	**9,8413**	**9,6638**	**9,6612**
SA3	Z9	-0,0498	-0,2139	-0,5084	-0,0523	-0,2067	-0,4969	-0,0490	-0,2220	-0,5209	-0,0488	-0,2141	-0,5258	-0,0517	-0,2110	-0,4914
Trefoil	*Z10*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*
”	Z11	0,0000	0,0262	0,2138	-0,0002	0,0255	0,2105	0,0002	0,0276	0,2186	-0,0001	0,0272	0,2174	0,0001	0,0258	0,2113
Astig5	Z12	0,0000	-0,2399	-0,8703	0,0007	-0,2263	-0,8444	0,0007	-0,2523	-0,8944	0,0004	-0,2392	-0,8713	0,0004	-0,2401	-0,8683
”	*Z13*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*
Coma5	*Z14*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*
”	Z15	0,0000	0,0635	0,0266	0,1365	0,1973	0,1591	-0,1364	-0,0707	-0,1068	-0,2841	-0,2253	-0,2607	0,2842	0,3515	0,3131
SA5	Z16	0,1676	0,1801	0,1476	0,1677	0,1767	0,1441	0,1682	0,1830	0,1506	0,1682	0,1715	0,1395	0,1677	0,1865	0,1554

Table 6.2.a : Sensitivities to M2 tilts and decenters

		Nominal			ADE S4 0.05			ADE S4 -0.05			YDE S4 0.1			YDE S4 -0.1		
		0’	2’	4’	0’	2’	4’	0’	2’	4’	0’	2’	4’	0’	2’	4’
Focus	Z4	-0,0508	0,1755	0,5913	0,8414	0,9340	1,1119	-0,7468	-0,4495	0,1855	-1,6887	-1,3236	-0,7872	1,5344	1,6218	1,9163
Astig3	Z5	0,0000	0,1546	0,8544	-0,1564	-1,5139	-2,2496	-0,1564	1,5147	3,6662	-0,0068	-0,1117	0,3397	-0,0068	0,4072	1,3556
”	*Z6*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*
Coma3	*Z7*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*
”	**Z8**	**0,0000**	**-0,1670**	**-0,1648**	**-4,5178**	**-4,6952**	**-4,6102**	**4,5194**	**4,3611**	**4,3053**	**10,4634**	**10,2856**	**10,2860**	**-10,4635**	**-10,6213**	**-10,6185**
SA3	Z9	-0,0498	-0,2139	-0,5084	-0,0827	-0,2961	-0,5610	-0,0842	-0,1307	-0,4450	-0,0516	-0,2166	-0,4984	-0,0484	-0,2114	-0,5183
Trefoil	*Z10*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*
”	Z11	0,0000	0,0262	0,2138	0,0026	0,0446	0,2816	-0,0026	0,0124	0,1575	0,0002	0,0281	0,2205	-0,0002	0,0249	0,2082
Astig5	Z12	0,0000	-0,2399	-0,8703	-0,0079	-0,3992	-1,1393	-0,0079	-0,0938	-0,6001	0,0004	-0,2468	-0,8812	0,0004	-0,2324	-0,8586
”	*Z13*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*
Coma5	*Z14*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*
”	Z15	0,0000	0,0635	0,0266	0,3961	0,4883	0,4325	-0,3960	-0,3578	-0,3967	0,2813	0,3494	0,3110	-0,2812	-0,2229	-0,2595
SA5	Z16	0,1676	0,1801	0,1476	0,1876	0,2447	0,2185	0,1874	0,1128	0,0698	0,1672	0,1870	0,1543	0,1677	0,1730	0,1402

Table 6.2.b : Sensitivities to M3 tilts and decenters

		Nominal			ADE S7 -0.05			ADE S7 0.05			YDE S7 -0.2			YDE S7 0.2		
		0’	2’	4’	0’	2’	4’	0’	2’	4’	0’	2’	4’	0’	2’	4’
Focus	Z4	-0,0508	0,1755	0,5913	2,4495	0,8134	-0,6081	-2,5023	-0,4168	1,8326	2,9345	0,8567	-0,9654	-2,976	-0,448	2,205
Astig3	Z5	0,0000	0,1546	0,8544	0,0251	0,8510	2,1811	0,0251	-0,4912	-0,4229	0,0244	1,3831	3,2094	0,024	-1,025	-1,458
”	*Z6*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,000*	*0,000*	*0,000*
Coma3	*Z7*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,000*	*0,000*	*0,000*
”	**Z8**	**0,0000**	**-0,1670**	**-0,1648**	**-4,0031**	**-4,1434**	**-4,0821**	**3,9977**	**3,8080**	**3,7610**	**-4,3430**	**-4,4413**	**-4,2672**	**4,334**	**4,110**	**3,957**
SA3	Z9	-0,0498	-0,2139	-0,5084	-0,0454	-0,1969	-0,4774	-0,0503	-0,2243	-0,5303	-0,0437	-0,1570	-0,4010	-0,050	-0,262	-0,605
Trefoil	*Z10*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,000*	*0,000*	*0,000*
”	Z11	0,0000	0,0262	0,2138	-0,0003	0,0190	0,1863	0,0003	0,0331	0,2398	-0,0003	0,0131	0,1656	0,000	0,037	0,257
Astig5	Z12	0,0000	-0,2399	-0,8703	-0,0012	-0,2538	-0,8938	-0,0012	-0,2289	-0,8461	-0,0024	-0,2847	-0,9511	-0,002	-0,200	-0,790
”	*Z13*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,000*	*0,000*	*0,000*
Coma5	*Z14*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,000*	*0,000*	*0,000*
”	Z15	0,0000	0,0635	0,0266	0,0088	0,0704	0,0239	-0,0087	0,0567	0,0207	0,0481	0,1092	0,0604	-0,048	0,018	-0,016
SA5	Z16	0,1676	0,1801	0,1476	0,1676	0,1779	0,1445	0,1669	0,1791	0,1496	0,1675	0,1774	0,1430	0,167	0,180	0,150

Table 6.2.c : Sensitivities to M4 tilts and decenters

		Nominal			ADE S8 -0.05			ADE S8 0.05			YDE S8 -0.2			YDE S8 0.2		
		0’	2’	4’	0’	2’	4’	0’	2’	4’	0’	2’	4’	0’	2’	4’
Focus	Z4	-0,0508	0,1755	0,5913	-3,9126	-0,6751	2,6690	3,9132	1,1228	-1,4023	-3,1178	-0,4993	2,2432	3,0901	0,9169	-0,9989
Astig3	Z5	0,0000	0,1546	0,8544	0,0188	-1,4744	-2,3251	0,0188	1,8228	4,0705	0,0016	-1,4126	-2,1959	0,0017	1,7266	3,9086
”	*Z6*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*
Coma3	*Z7*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*
”	**Z8**	**0,0000**	**-0,1670**	**-0,1648**	**5,8701**	**5,6405**	**5,4848**	**-5,8861**	**-5,9775**	**-5,7921**	**4,5895**	**4,3647**	**4,2142**	**-4,5999**	**-4,7012**	**-4,5326**
SA3	Z9	-0,0498	-0,2139	-0,5084	-0,0497	-0,2688	-0,6103	-0,0420	-0,1486	-0,3871	-0,0518	-0,2652	-0,6097	-0,0457	-0,1554	-0,3973
Trefoil	*Z10*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*
”	Z11	0,0000	0,0262	0,2138	0,0002	0,0413	0,2737	-0,0002	0,0086	0,1480	0,0002	0,0398	0,2667	-0,0002	0,0108	0,1559
Astig5	Z12	0,0000	-0,2399	-0,8703	-0,0035	-0,1997	-0,7861	-0,0035	-0,2876	-0,9546	-0,0022	-0,2010	-0,7914	-0,0022	-0,2833	-0,9486
”	*Z13*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*
Coma5	*Z14*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*	*0,0000*
”	Z15	0,0000	0,0635	0,0266	-0,0611	0,0052	-0,0327	0,0616	0,1218	0,0711	-0,0562	0,0099	-0,0245	0,0565	0,1179	0,0682
SA5	Z16	0,1676	0,1801	0,1476	0,1666	0,1799	0,1473	0,1677	0,1771	0,1428	0,1677	0,1794	0,1513	0,1686	0,1775	0,1431

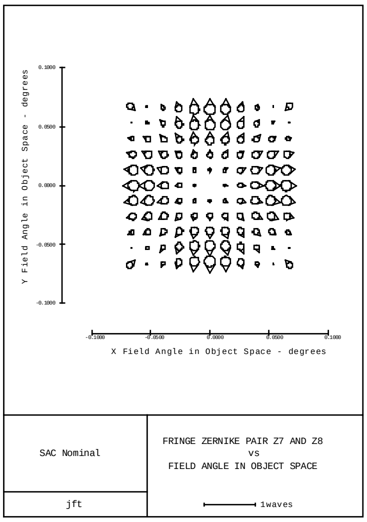
Table 6.2.d : Sensitivities to M5 tilts and decenters

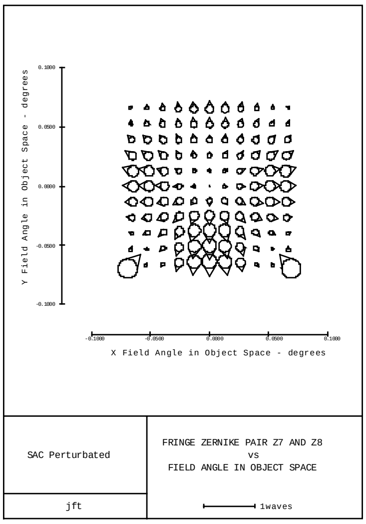
However, this scenario has a limitation : we can see that the sensitivities are not *exactly* identical on axis and in the FOV. This means that a mix of tilts and decenters that perfectly corrects the coma on axis may not be suitable in the totality of the Field of View, in particular in the case of severe decentrations. An additional problem in that case are the residuals of the other aberrations

Let us consider a system will strong decenters, so defined as their contribution cancels out on axis :

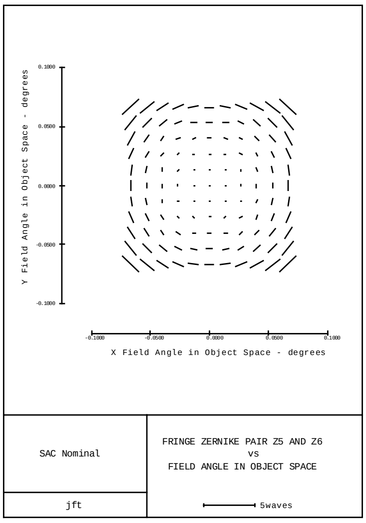
Perturbation		Contribution to 3rd order Coma (on axis)
M2 Decenter	0.15 mm	-14.7615
M3 Tilt	-0.10°	9.0370
M4 Tilt	0.15°	12.0015
M5 Decenter	0.2733 mm	-6.2777
	TOTAL :	**0.0000**

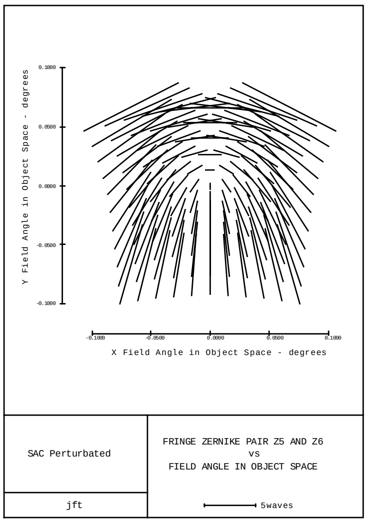
Following sketches show the distribution of coma over the FOV, for the centered and the perturbed cases. For both, coma is 0 on axis, as one could expect. The variations of coma in the FOV are virtually identical (the scale factor appears at lower right corners, and corresponds to 1 fringe in both cases). Note a slight loss of symmetry for the perturbed case, and the strong divergence that occurs in the lower « corners » (x=+/-4' and y=- 4') , which is not relevant here since lying beyond the FoV radius of 4' :



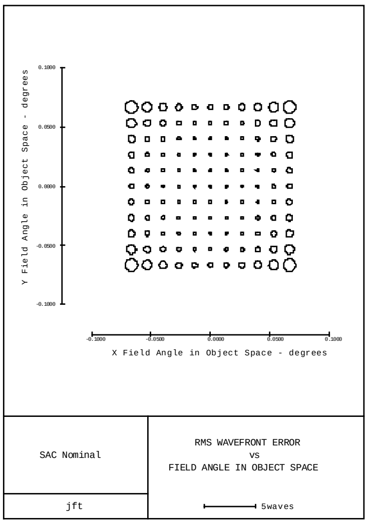


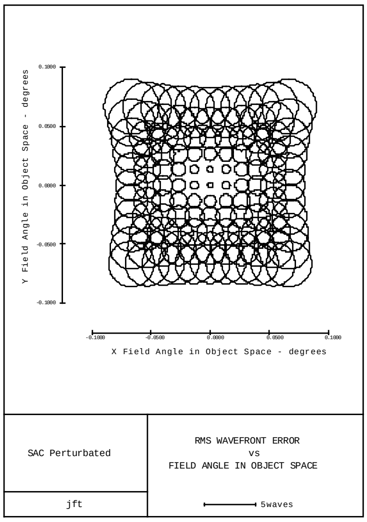
If we consider now the astigmatism, the situation is quite different : the Z5+Z6 map of the perturbed system is totally different from the map of the centered systems (but note that the astigmatism is still OK on axis ; this is because the same set of decenters that compensates the Coma shall compensate all the linearly dependent aberrations, such as the on-axis astigmatism) :





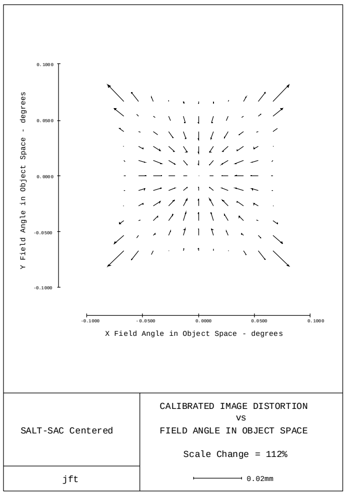
And globally, considering the WFE map in the FoV (all aberrations included) we see that even with a good on-axis correction, the WFE degrades much more rapidly in the FOV than in the case of the centered system (even if virtually OK on axis) :

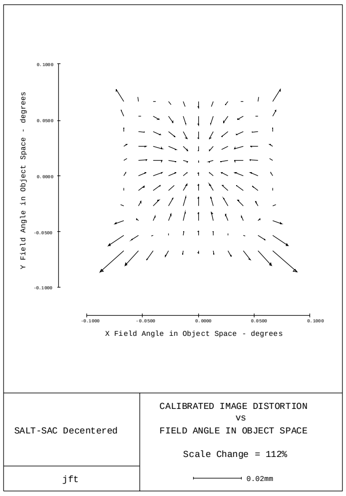




Therefore, relying on the M3 alone for compensating the contributions of the 3 others mirrors, by performing interferometric measurements only <u>on axis</u> may not be suitable in case of severe initial decenters.

As for distortion, decenters have little effects, and the symmetry of the perturbed system is slightly affected :





5.3 SENSITIVITIES TO AIR-SPACE ERRORS

We have evaluated how the performances of the SAC are affected by a displacement of M3 w.r.t. M2 and of M4 w.r.t. M5. The central “group” M2-M5 has been taken as an axial reference. In all cases, the refocusing has been carried out at the SAC level, and the criterion for the determination of the best refocus has been the optimization of <EE50> at λ=633nm averaged in the science FOV (0’, 2’ and 4’).

5.3.1 Sensitivity to the displacements of M3 w.r.t. M2 :

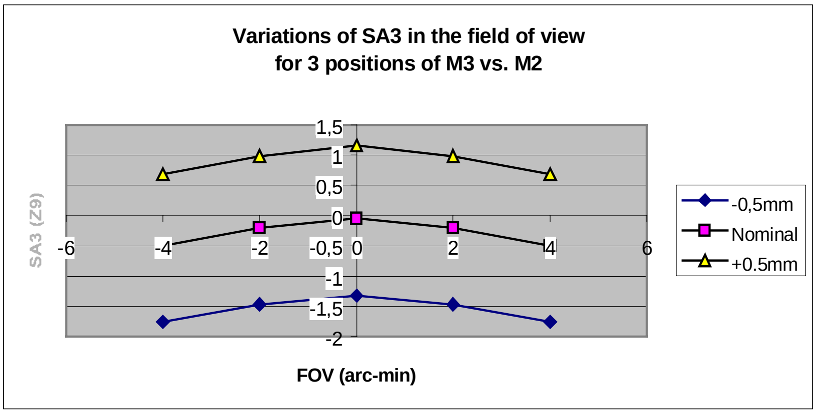
In following table, we have computed the Zernike terms up to the 5th order (Z16) for the 3 fields. At the last line is given the corresponding distance between the M2 and the first (virtual) surface of the SAC :

	Nominal system			δ(M2-M3) = +0,5mm			δ(M2-M3) = -0,5mm		
ZERNIKE	0	2’	4’	0	2’	4’	0	2’	4’
5	0,0000	0,1553	0,8547	0,0000	0,1553	0,8554	0,0000	0,2063	0,8531
6	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
7	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
8	0,0000	-0,1647	-0,1538	0,0000	-0,6144	-1,0611	0,0000	0,0585	0,7438
9	**-0,0509**	**-0,2075**	**-0,4979**	**1,1582**	**0,9845**	**0,6829**	**-1,3234**	**-1,4652**	**-1,6761**
10	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
11	0,0000	0,0253	0,2118	0,0000	0,0251	0,2113	0,0000	0,0249	0,2119
12	0,0000	-0,2385	-0,8650	0,0000	-0,2389	-0,8658	0,0000	-0,2391	-0,8676
13	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
14	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
15	0,0000	0,0621	0,0174	0,0000	0,0211	-0,0564	0,0000	0,1069	0,0997
16	**0,1687**	**0,1762**	**0,1431**	**-0,6303**	**-0,6116**	**-0,6385**	**0,9633**	**0,9603**	**0,9303**
WFE-rms	0,076	0,118	0,487	0,183	0,322	0,501	0,203	0,316	0,743
E_50%	0,031	0,032	0,109	0,077	0,095	0,126	0,116	0,119	0,175
E_80%	0,064	0,081	0,172	0,148	0,166	0,262	0,217	0,23	0,301
(thi s1)	*12829,67*			*12828,818*			*12830,522*		

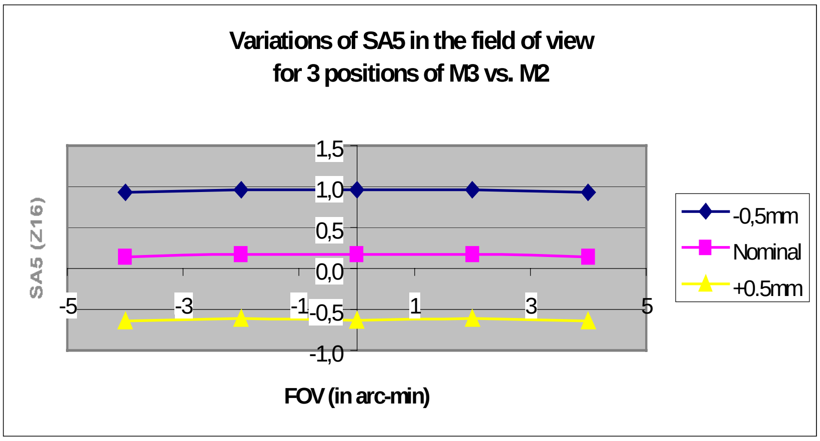
Following informations can be derived from above data :

- in the nominal (aligned) system, the field-dependent aberrations are mostly the astigmatisms AST3 (Z5) and AST5 (Z12). They are not affected by the M3 displacement.
- when axial perturbations are introduced, the major aberrations that show out are the spherical aberrations, Z9 and Z16, as expected;
- but note that large amounts of 3rd order coma (Z8) show out in the FoV.
-

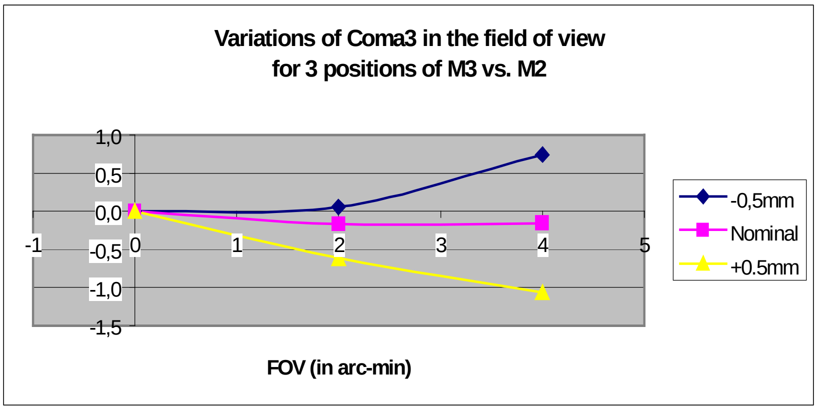
The variations of the third order spherical aberration (SA3) in the FOV are not affected, but the average value increases linearly with the M3 displacement :



The situation is the same for the fifth order spherical aberration (SA5) : the global variations are always stable in the FoV, but the average value is strongly dependent on the M3 displacements :



And although 3rd order coma is always 0 on axis, as it could be expected, its variations are much more important in the FoV of the perturbed system than in the nominal design :



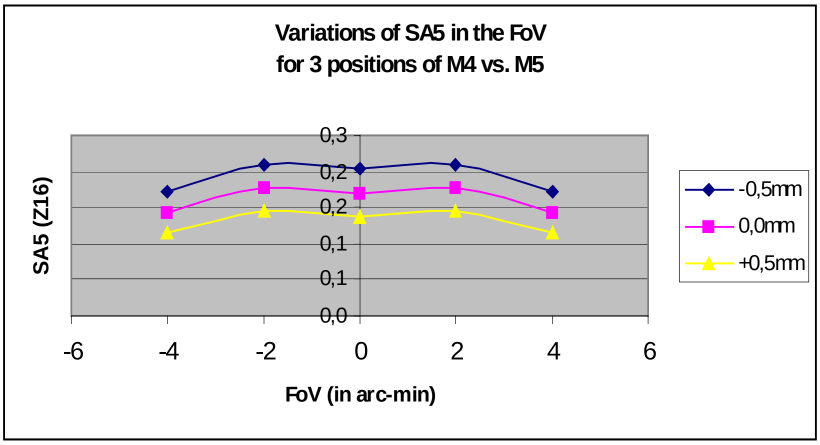
5.3.2 Sensitivity to the displacements of M4 w.r.t. M5 :

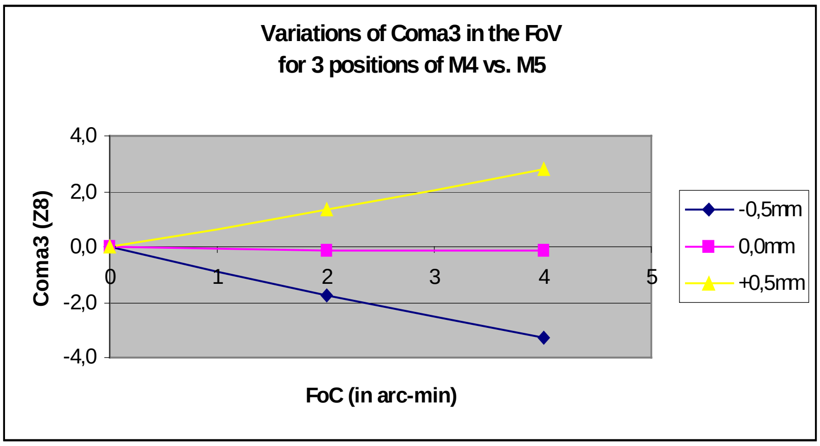
In the following table, we have computed the Zernike terms up to the 5th order (Z16) for the 3 fields :

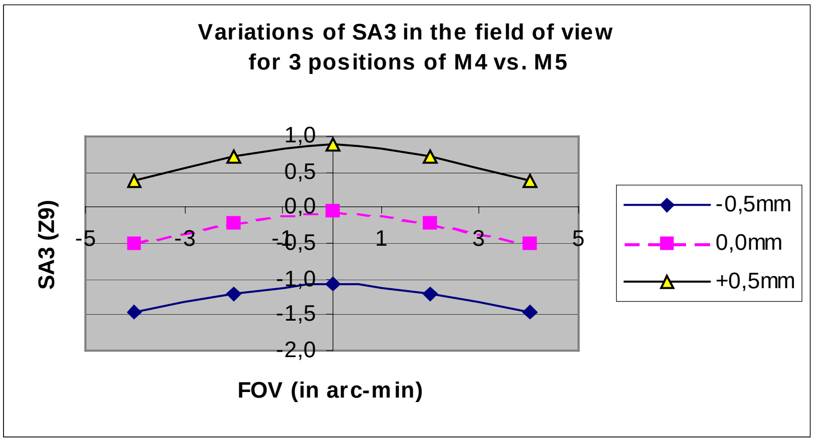
		Nominal system			δ(M4-M5) = -0,5mm			δ(M4-M5) = +0,5mm		
	Zi	0	2'	4'	0	2'	4'	0	2'	4'
AST3	5	0,0000	0,1553	0,8547	0,0000	0,5247	2,3071	0,0000	-0,2010	-0,5468
AST3	6	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
COM3	7	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
COM3	8	0,0000	-0,1647	-0,1538	0,0000	-1,7525	-3,2741	0,0000	1,3437	2,8198
SA3	9	-0,0509	-0,2075	-0,4979	-1,0757	-1,2161	-1,4590	0,8813	0,7054	0,3758
	10	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
	11	0,0000	0,0253	0,2118	0,0000	0,0230	0,1918	0,0000	0,0274	0,2285
AST5	12	0,0000	-0,2385	-0,8650	0,0000	-0,2518	-0,9206	0,0000	-0,2267	-0,8145
	13	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
	14	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
	15	0,0000	0,0621	0,0174	0,0000	0,0910	0,0815	0,0000	0,0401	-0,0354
SA5	16	0,1687	0,1762	0,1431	0,2034	0,2107	0,1731	0,1358	0,1463	0,1148
	WFE-rms	0,076	0,118	0,487	0,27	0,693	1,61	0,309	0,645	1,564
	E_50% (")	0,031	0,032	0,109	0,125	0,184	0,296	0,119	0,108	0,321
	E_80% (")	0,064	0,081	0,172	0,195	0,347	0,533	0,292	0,339	0,66

As for the displacements of M3, following informations can be derived from above data :

- in the nominal (aligned) system, the field aberrations are mostly AST3 (Z5) and AST5 (Z12), that are much affected by the M4 displacement,
- the spherical aberrations SA3 (Z9) increases as well, but, by contrast with the M2-M3 case, SA5 is not much affected by the M4 displacements,
- the field-dependent 3rd order coma is dramatically increased ;


Variations of SA5 in the FoV
for 3 positions of M4 vs. M5
SA5 (Z16)
0,3
0,2
0,2
0,1
0,1
0,0
-6
-4
-2
0
2
4
6
FoV (in arc-min)
-0,5mm
0,0mm
+0,5mm


Variations of Coma3 in the FoV
for 3 positions of M4 vs. M5
Coma3 (Z8)
4,0
2,0
0,0
-2,0
-4,0
0
1
2
3
4
5
FoC (in arc-min)
-0,5mm
0,0mm
+0,5mm


Variations of SA3 in the field of view
for 3 positions of M4 vs. M5
SA3 (Z9)
1,0
0,5
0,0
-0,5
-1,0
-1,5
-2,0
-5
-3
-1
1
3
5
FOV (in arc-min)
-0,5mm
0,0mm
+0,5mm

5.4 SENSITIVITIES TO ERRORS ON RADII

The radius of curvature of the blanks will be measured via mechanical profilometry after the fine grinding stage. Subsequent polishing operations will not contribute to any noticeable variations of the radius. The typical precision on the sags determination is about 5µm, but a relaxed tolerance up to 10µm may be wished for. We have evaluated what could be the contribution of that tolerance.

We start with the following hypothesis :

- radii tolerances correspond to a 10µm error of the sag over the clear aperture,
- compensators are :
  - the distance M1-SAC (thi s1)
  - the distance M2-M3 (thi s2)
  - the distance M4-M5 (thi s6)

The back-focal distance is frozen, since we understand that the SALT instruments operate at a fixed focus.

On axis, the results are quite good, and the following CODE V listing shows that the WFE is virtually unaffected by above set of tolerances; the WFE varies from 0.053 λ-rms to 0.060 λ-rms, provided suitable compensators are used :

```
                                P E R F O R M A N C E   S U M M A R Y
                               POLYCHROMATIC RMS WAVEFRONT ABERRATION

                              Spherical Aberration Corrector for SALT

  ------------------------------------------------------------------------------------------------
                                                                          WAVELENGTH   WEIGHT
                                                                           633.0 NM      1
  ----------------------------------------------------------------------------------------------------
         RELATIVE     WEIGHT    DESIGN  DESIGN  COMPENSATOR RANGE (+/-) *
          FIELD                         + TOL
                                                  DLT S1               DLT S2   C   DLT S6   C
                                                                       DLT S3   C   DLT S7   C
                                                                       DLT S4       DLT S8

        0.00, 0.00      1.00     0.053   0.060    7.880059             0.444813     2.840579
  -------------------------------------------------------------------------------------------------
```

The situation is quite different in the field of view.

```
                                P E R F O R M A N C E   S U M M A R Y
                               POLYCHROMATIC RMS WAVEFRONT ABERRATION

                              Spherical Aberration Corrector for SALT

  ------------------------------------------------------------------------------------------------
                                                                          WAVELENGTH   WEIGHT
                                                                           633.0 NM      1
  ----------------------------------------------------------------------------------------------------
               RELATIVE     WEIGHT    DESIGN  DESIGN  COMPENSATOR RANGE (+/-) *
                FIELD                         + TOL *
                                                       DLT S1       DLT S2   C    DLT S6   C
                                                                    DLT S3   C    DLT S7   C
                                                                    DLT S4        DLT S8

             0.00, 0.00      1.00     0.076   1.007    2.713982     0.853662      0.361722
             0.00, 0.50      1.00     0.117   1.027    2.713982     0.853662       0.361722
             0.00, 1.00      1.00     0.486   1.239    2.713982     0.853662      0.361722
  ----------------------------------------------------------------------------------------------------
      * The change in RMS is a mean plus 2 Sigma value (97.7 percent)and assumes a uniform
distribution of manufacturing errors over the range for all tolerances.
```

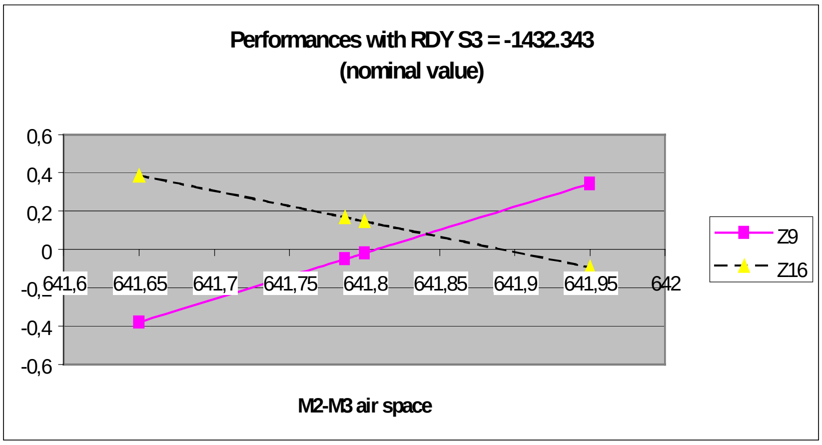
It turns out that there is no combination of compensators that correct the effects of tolerances on radii in the FOV. The aberration residuals are fairly high, even on axis …

We can see which tolerance is responsible of this situation :

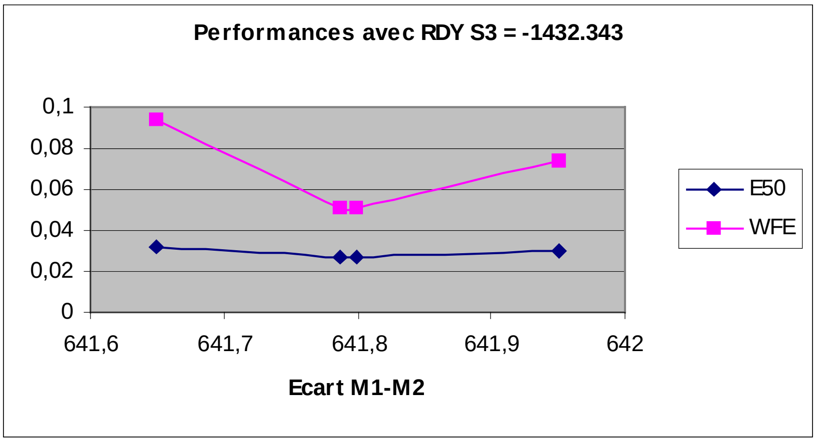
```
                                        I N V E R S E   S E N S I T I V I T Y
                                       POLYCHROMATIC RMS WAVEFRONT ABERRATION

                                       Spherical Aberration Corrector for SALT

----------------------------------------------------------------------------------------------------
                                                              WAVELENGTH   WEIGHT   NO. OF RAYS
    FIELD (X,Y) = ( 0.00, 0.00)MAX, (  0.00,   0.00)DEG        633.0 NM       1         648
    FIELD WEIGHT =  1.00

       NOMINAL RMS              =  0.076
---------------------------------------------------------------------------------------------------
    MANUFACTURING ERROR          CHANGES IN RMS FOR          COMPENSATING PARAMETERS
                                   PLUS AND MINUS
   TYPE              CHANGE      MANUFACTURING ERRORS         DLT S1          DLT S2   C     DLT S6   C
                                                                              DLT S3   C     DLT S7   C
                                                                              DLT S4         DLT S8

   DLS S3         0.0100000        0.993     0.925            2.298917       -0.735594      -0.278292
   DLS S4         0.0100000        0.003     0.053           -0.393584        0.070051       0.018880
   DLS S7         0.0100000       -0.015     0.020           -0.285268       -0.022630       0.131320
   DLS S8         0.0100000        0.004    -0.004            0.054494       -0.006061      -0.055535

    PROBABLE CHANGE IN RMS         0.931

             PROBABLE CHANGE OF COMPENSATORS (+/-)            2.713982        0.853662       0.361722

    Units - linear dimensions in mm.    angles in radians,
            fringes in wavelengths at 633.0 nm.
            RMS is in wavelengths at 633.0 nm.
```

There is clearly a problem with the M2, since its contribution (DLS S3 = DeLta Sag M2) makes up the entire performance degradation.

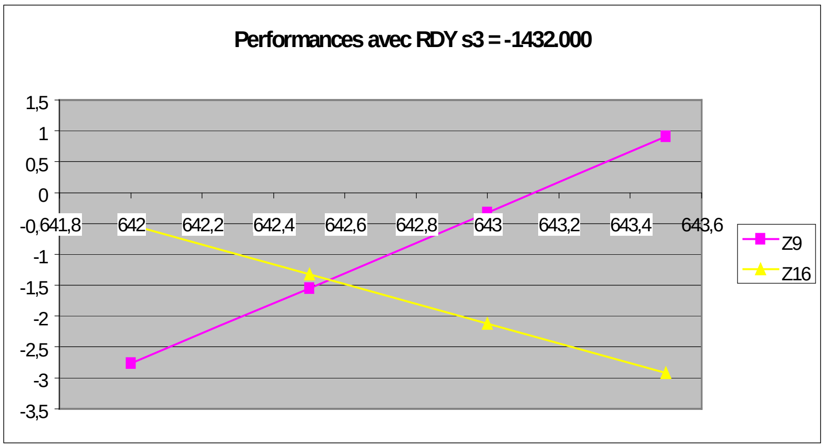
We will study in the following why the SAC is so sensitive to the radius of curvature of M2. We have traced the variations of the Spherical Aberration of the 3rd and 5th order as a function of the M2-M3 spacing, a possible compensator :

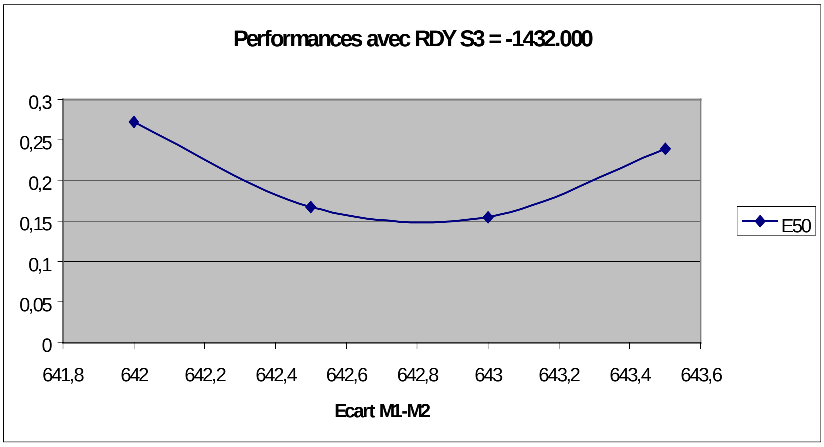


Both aberrations cross the y-axis close to M2-M3 = 641.800, and indeed the optical performances have a good optimum at the thickness of 64.787, which is the nominal value of the M2-M3 distance :



But let us consider the case for which the radius of M2 is –1432mm, that corresponds to a “delta-sag” of about 10µm. We see that for the perturbed design, there is no value of the M2-M3 distance that could compensate both spherical aberration Z9 and Z16 : indeed Z9 would be compensated at about M2-M3 = 643.1, while Z16 is null at about M2-M3=641.8. Therefore, the energy concentration EE(50) has a minimum somewhere in between, at a poor value :





It is interesting to note that the variations of Z9 and Z16 are very close to the sensitivities computed in the previous chapter, for the nominal design, namely :

$$\frac{\partial Z9}{\partial (thiS2)} = 2.45$$

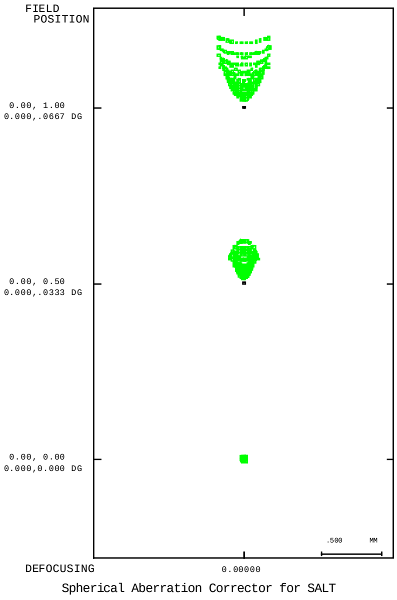
$$\frac{\partial Z16}{\partial (thiS2)} = -1.6$$

Since the M2-M3 space is not sufficient for the correction of SA3 and SA5 on axis, one should envisage the use of the M4-M5 space. Since we already know the sensitivities of the Zernike Z9 and Z16 to these parameters, and keeping in mind that we have to work at a fixed focal position (the compensator for focus is the distance M1-M2, not the back focal distance), we readily arrive to the following parameters :

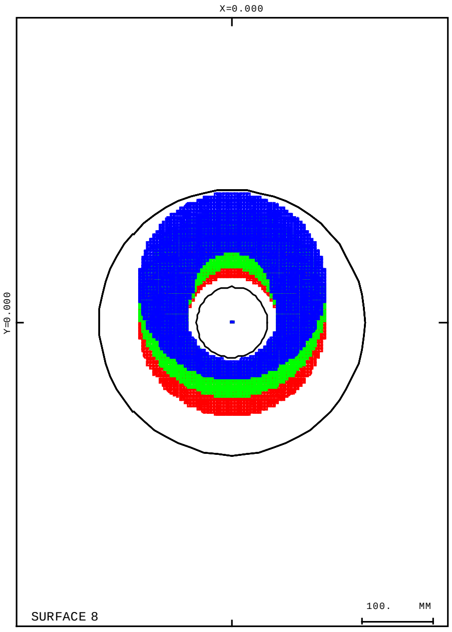
Parameter	Nominal	Compensated
M2 radius	1432.343	1432.00
Distance M2-M3	641.787	641.6695
Distance M4-M5	171.595	173.961
EE50 on axis	0.027’’	0.028’’
EE80 on axis	0.055’’	0.049’’

Since the 2 mirror spaces are the only available parameters suitable to compensate the 2 aberrations, that is all we can do for compensating the error on the M2 radius.

The problem is that this configuration works extremely poorly in the science FOV. At 4’, the spot diagram is larger than 0.500mm; primary aberration is visibly coma (the amplitude of the Z8 term is larger than 12…) :



Our interpretation of this behavior is the following : with computed sensitivities, the compensation of the error on the M2 radius implies a severe displacement of the M4 w.r.t. the M5. This is OK on axis, but we must realize that the displacement of the useful beams over the M5 surface are relatively large, so the aberrations compensation is no more correct in the FOV.



Footprint on M5

Fig. Position of the beam over the M5 surface (footprint)

A special study is therefore needed for the tolerancing of the M2 radius. We have seen that the tolerances with the 3 other radii could be relatively large.

We may mention in passing that this tolerance cannot be compensated with the M3 (in the polishing sequence, the M3 is the last mirror polished, and could be used as a compensator for some aperture aberrations). This is because the M3 is conjugated with the pupil, so by definition its contribution is the same for all the point of the field of view.

Following table summarizes different hypothesis for the M2 tolerancing. Optical performances are expressed in WFE-rms @ 633nm :

		Tolerance on the M2 radius		
FOV	Nominal	3µm	5µm	10µm
0	0.053	0.322	0.499	0.964
2’	0.122	0.337	0.517	0.992
4’	0.497	0.619	0.773	1.264

We will see in the following which tolerance is best adapted when all parameters are taken into considerations.

6. RELATION BETWEEN ENERGY CONCENTRATION VS. WFE

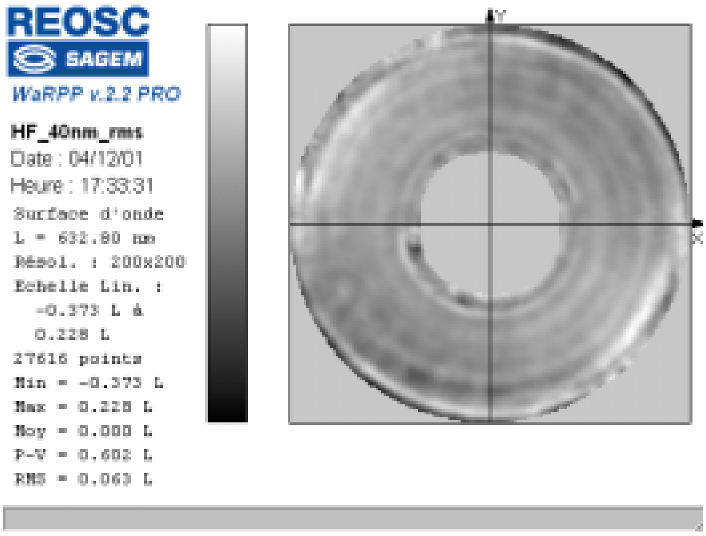
6.1 DEFINITION OF THE PROBLEM

We have seen at Chapter 1 that the determination of the manufacturing and alignment errors shall be established in term of WFE. Contributors to the SAC performances of 2 types. Since these types are of definitely different nature, they will be addressed separately . There are :

- the residuals of polishing errors, at individual mirror level, are defects of high spatial frequencies, that correspond to relatively important local slopes,
- the “modes” corresponding to the misalignments of the SAC, which, as seen in the previous chapter, are essentially Spherical Aberrations of 3rd and 5th order, and 3rd order Coma, that corresponds to slowly varying wavefront errors.

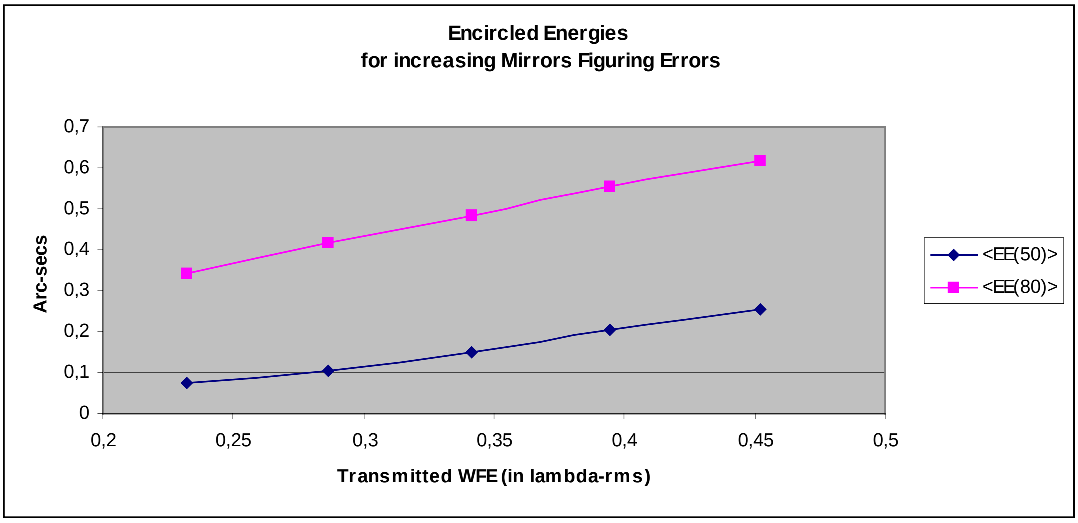
6.2 INFLUENCE OF THE POLISHING ERRORS

A typical example corresponding to a highly aspherized concave mirror is shown hereunder :



```
HF_40nm_rms
Date : 04/12/01
Heure : 17:33:31
Surface d'onde
L = 632.80 nm
Résol. : 200x200
Echelle Lin. :
  -0.373 L à
  0.228 L
27616 points
Min = -0.373 L
Max = 0.228 L
Moy = 0.000 L
P-V = 0.602 L
RMS = 0.063 L
```

We have introduced this type of perturbation in our SAC model and we have computed the <EE50> and <EE80> corresponding to wavefront errors of increasing magnitude. The results are the following :



<EE80> is visibly much more sensitive to high-frequencies wavefront errors than <EE50>. This can be understood : since high spatial frequencies correspond to rays that are diffracted far from the specular direction, the « feet » of the image tend to spread far away, when the FWHM is relatively less affected.

NB : these are wavefront errors, so the tolerances on the mechanical surfaces shall be divided by 2.

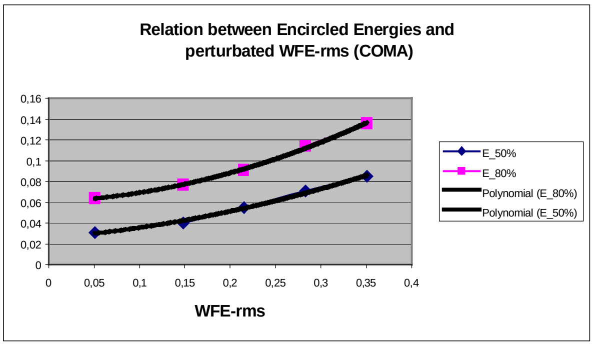
6.3 SENSITIVITY TO MISALIGNMENT ERRORS :

We have seen in chapter 4.6 that the aberrations introduced by the mirrors tilts and decenters consisted almost entirely in coma (Zernike polynomials Z7 and Z8), while spacing errors introduced rotationally symmetric terms : Spherical Aberrations (third : Z9 and fifth order : Z16). Therefore, only those terms will be considered for the elaboration of the alignment budget.

6.3.1 Sensitivity to Coma

Following table give the energy concentration corresponding of coma term of increasing amplitude :

Z7, Z8	WFE (in λ-rms @ 633nm)	EE50 (in arc-sec)	EE80 (in arc-sec)
0.0	0.051	0.031	0.064
0.2	0.086		
0.4	0.148	0.040	0.077
0.6	0.215	0.055	0.091
0.8	0.283	0.071	0.114
1	0.351	0.085	0.136

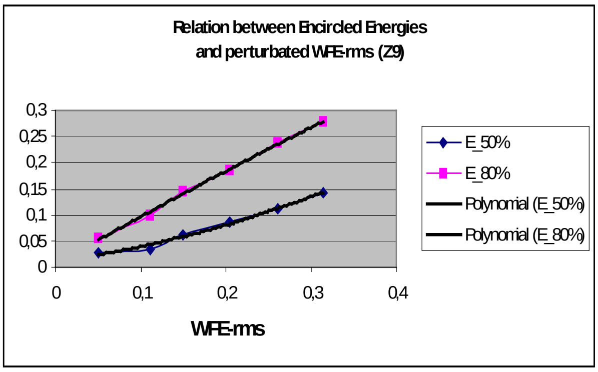


Some kind of quadratic relations can be guessed, and indeed following relations fit above data fairly well :

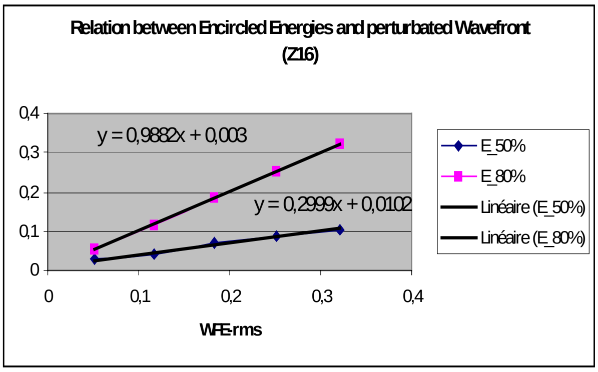
$$EE50^2 = (0.031)^2 + 0.05 * WFE\text{-}rms^2$$

$$EE80^2 = (0.050)^2 + 0.13 * WFE\_rms^2$$

6.3.2 Sensitivity to third order Spherical Aberration (Z9)



6.3.3 Sensitivity to fifth order Spherical Aberration (Z16)



7. RIGID BODIES TOLERANCING

In this chapter, we evaluate the performances of the SAC for the following hypothesis :

- starting from a « perfect » SAC (i.e., the nominal design), uniform and random perturbations are applied at the mirrors mechanical interfaces. For reasons of simplicity, we will define « δ » as this uniform tolerance. Corresponding tilts are derived from the expression « Tilt » = δ/ « Mechanical Diameter » for that mirror.

- no compensators are applied.

This will result into an estimation of the long-term stability of the instrument

We have seen at Chapter 3.6 that the tilts-and-decenters aberrations consisted essentially in Coma3. We will first evaluate the contribution of those tolerances, expressed in terms of WFE-rms, then translated into Energy Concentration. The contribution of the axial tolerances consist in SA3 and SA5, for which the conversion factor WFE/Energy Concentration is different. This will be addressed separately.

Following table lists the tilt and decenter sensitivities for each mirrors, ie. their contribution to Z8 for δ = 1(mm). Data are taken from Chapter 3.6. The sensitivity to M2 tilt, for example, is computed from the angular sensitivity : since $dZ8/d\alpha = 2335$/deg. . Over a diameter of 600, a displacement « d » would introduce a tilt equal to $(1/600)*(180/\pi)$ deg. , corresponding to Z8 = 223, etc…

	M2	M3	M4	M5
Decenter	-98.4	10.6	21.7	23
Tilt	223	8.6	45.8	18

Clearly, the dimensioning contributor to the SAC stability is the M2. The expected coma for a given « generic » stability of δ is the quadratic sum of all above terms, and we have :

<u>Z8 = 250*δ</u>

For example, a dimensional stability of 4µm would translate into a Zernike term Z8=1, that this would correspond to following performances :

Parameter	Error Budget	Nominal	δ = 4µm
EE(50)	0.24’’	0.050’’	0.175’’
EE(80)	0.42’’	0.094’’	0.257’’

We see that the extremely tight tolerance of 4µm on the M3 is about the 75% of the total budget. If no compensator can be found, this situation could not be accepted.

7.1 EVALUATION OF THE SAC AS A GLOBAL COMPENSATOR :

We have studied the aberrations introduced by a transverse displacement of the SAC. Following table gives the 16 first Zernike polynomials on axis, and at 2' and 4' FoV. Clearly, the only perturbed aberration is coma (Z8). For a given displacement, the variations of Z8 are very uniform within the FoV, better than 1%.

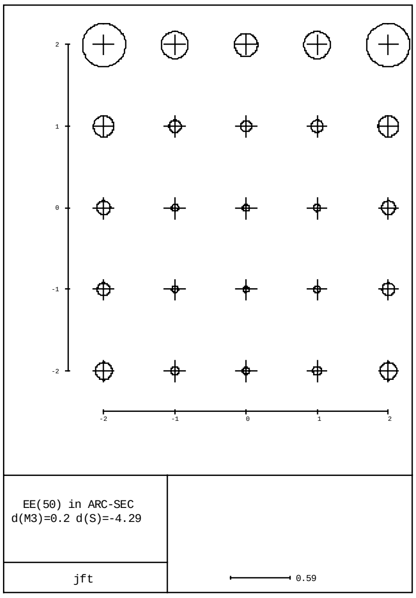
The scale factor is : $\boldsymbol{\delta Z8 = 0.49 * \delta Y_{SAC}}$

In the following, we investigate up to which level we can take advantage of this compensator for relaxing the requirements on the M3 stability.

We have to be concerned by the fact that, because of high order terms that will not cancel each other with sufficient precision, a compensation effective on-axis may not be adequate in the totality of the FoV, and therefore not be acceptable. This issue will put a limit to the SAC compensation, and define the requirements for the Mirrors stability.

For this complex task, we propose the following approach :
- define 25 points in a square FoV for the object field angles (xan, yan) = {-4', -2',0,+2', +4'},
- find the best focal plane for this configuration,
- evaluate the parameter EE(50) for the 25 points

We first start to illustrate qualitatively the situation. We will consider a M3 decenter of 0.2mm. It can be shown that, on axis, the optical quality is virtually restored to its nominal value if a SAC decenter of -4.29mm. However, this is not the case in the whole FoV.



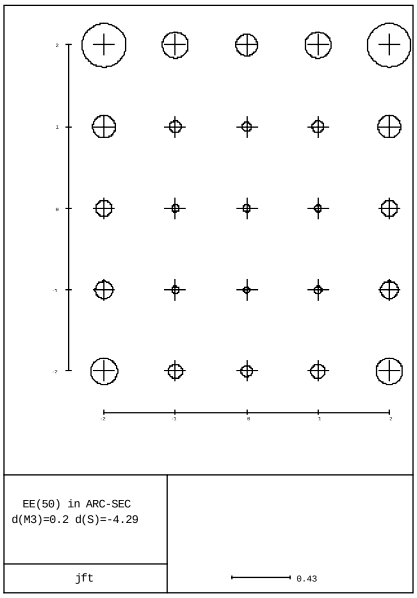
On the above field map, the dimensions of the circles are proportional to EE(50). Data is given in following table : it can be seen that for all the fields close to +4', the energy concentration is unacceptably poor, ranging from 0.23'' to about 0.30'' (we do not consider here the (4',4') points, that are out of the science FoV) :

```
*******************************************************************************
*  YAN (min) *      PERFORMANCES IN THE FOV (XAN = -4′, -2′ .. 4′)          *
*******************************************************************************
*    -4      *    0.1711  *    0.0900  *    0.0700  *    0.0900  *    0.1711  *
*    -2      *    0.1296  *    0.0685  *    0.0594  *    0.0685  *    0.1296  *
*     0      *    0.1386  *    0.0726  *    0.0659  *    0.0726  *    0.1386  *
*     2      *    0.2092  *    0.1238  *    0.1076  *    0.1238  *    0.2092  *
*     4      *    0.4366  *    0.2700  *    0.2305  *    0.2700  *    0.4366  *
*******************************************************************************
```

For a M3 decenter of 0.10mm, the compensation is obtained for a transverse shift of the SAC of –2.15mm, and the situation is the following :

```
*******************************************************************************
*  YAN (min) *      PERFORMANCES  IN THE FOV (XAN = -4′, -2′ .. 4′)           *
*******************************************************************************
*    -4      *    0.1946  *    0.1047  *    0.0820  *    0.1047  *    0.1946  *
*    -2      *    0.1262  *    0.0532  *    0.0438  *    0.0532  *    0.1262  *
*     0      *    0.1165  *    0.0505  *    0.0514  *    0.0505  *    0.1165  *
*     2      *    0.1636  *    0.0836  *    0.0653  *    0.0836  *    0.1636  *
*     4      *    0.3190  *    0.1884  *    0.1558  *    0.1884  *    0.3190  *
*******************************************************************************
```

The EE(50) is more equitably balanced in the FoV than in the previous case :



Therefore, it is justified to consider the lateral translations to the SAC as an effective compensator to 3^{rd} order coma, as far as the perturbations are “sufficiently” small.

SENSITIVITY OF ZERNIKE POLYNOMIALS TO SAC TRANSLATION (vs. M1)

	Nominal			yde s2 0.2			yde s2 -0.2			xde s2 0,2		
	Axis	2’	4’	Axis	2’	4’	Axis	2’	4’	0’	2’	4’
Z1	-0,1629	-0,0526	0,3465	-0,1628	-0,0461	0,3601	-0,1628	-0,0602	0,3322	-0,1628	-0,0533	0,3466
Z2	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	2,0396	2,0396	2,0388
Z3	0,0000	2,5169	4,9722	2,0396	4,5558	7,0095	-2,0396	0,4784	2,9360	0,0000	2,5172	4,9724
Z4	-0,0498	0,1692	0,5792	-0,0497	0,1787	0,5917	-0,0497	0,1624	0,5675	-0,0497	0,1710	0,5790
Z5	0,0000	0,1553	0,8547	0,0000	0,1563	0,8702	0,0000	0,1545	0,8409	0,0000	0,1553	0,8548
Z6	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	-0,0061
Z7	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,9865	0,9867	0,9900
Z8	0,0000	-0,1647	-0,1538	0,9865	0,8237	0,8399	-0,9865	-1,1541	-1,1491	0,0000	-0,1656	-0,1542
Z9	-0,0509	-0,2075	-0,4979	-0,0510	-0,2140	-0,5063	-0,0510	-0,2039	-0,4900	-0,0510	-0,2093	-0,4975
Z10	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0021	0,0083
Z11	0,0000	0,0253	0,2118	0,0000	0,0275	0,2203	0,0000	0,0234	0,2031	0,0000	0,0253	0,2116
Z12	0,0000	-0,2385	-0,8650	-0,0001	-0,2503	-0,8873	-0,0001	-0,2265	-0,8436	0,0001	-0,2382	-0,8651
Z13	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0128	0,0229
Z14	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0058	0,0055	0,0030
Z15	0,0000	0,0621	0,0174	0,0058	0,0661	0,0190	-0,0058	0,0595	0,0174	0,0000	0,0631	0,0175
Z16	0,1687	0,1762	0,1431	0,1687	0,1758	0,1408	0,1687	0,1781	0,1447	0,1687	0,1771	0,1427

EE50	0,031	0,033	0,109	0,088	0,08	0,14	0,088	0,104	0,142	0,088	0,09	0,1260
EE80	0,064	0,081	0,172	0,137	0,132	0,223	0,137	0,148	0,214	0,136	0,147	0,2180

WFE	0,076	0,118	0,485	0,351	0,329	0,667	0,351	0,377	0,485	0,351	0,368	0,6050

▨ = unaffected

8. THERMAL ANALYSIS

8.1 HYPOTHESIS

In this chapter we investigate the sensitivity of the SAC performances with thermal change. As for previous cases, we will use the axial SAC displacement w.r.t. the M1 as a compensator.

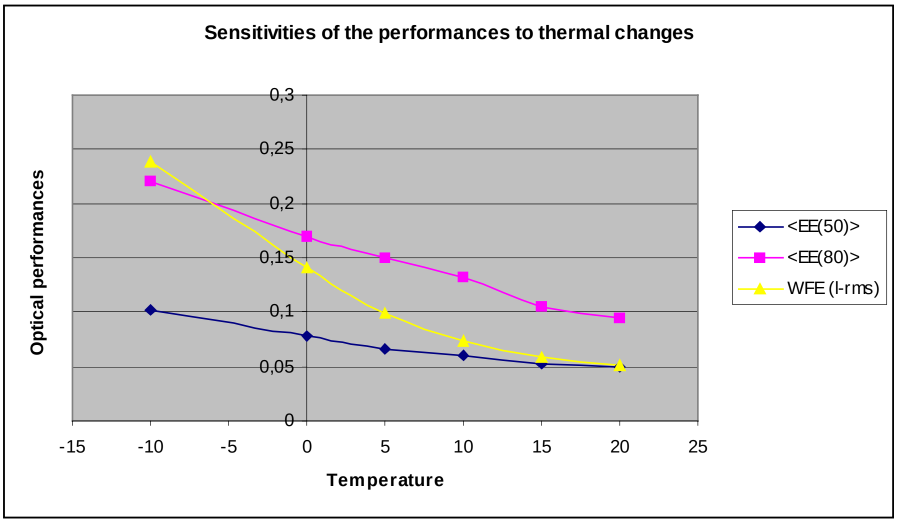
We have anticipated the M1 as a segmented mirror with ZERODUR thin segments assembled on a steel structure. Therefore the « local » radii would be thermally invariant, when the « mean » radius would follow the temperature changes with the steel CTE (coefficient of thermal expansion). We understand this situation is not to be considered, and in any circumstances, the M1 behaves as a solid ZERODUR blank (i.e., the average radius of curvature is actively control).

We have considered the Telescope « tube » made of steel. This has little importance since the axial displacement of the SAC via the tracker is a compensator.

8.2 RESULTS FOR THE CASE ZERODUR/STEEL

In this document, we have considered the case of a SAC Structure made of steel (up to the focal plane) , with a CTE of $173 \cdot 10^{-7}$, up to the focal plane. Mirrors are made from ZERODUR.

Performances are evaluated as the averaged energy concentrations EE(50) and EE(80), with relative weights of 2/1/1 for the scientific fields of 0. 2’ and 4’. In addition, we have computed the wavefront errors (WFE). Results are the following :



Clearly, the system it at his best at 20°C, i.e. the conditions for which it has been optimized, and for which it will be tested. It is clearly not optimized for the domain 0..20°C. The EE(50) and EE(80) vary almost linearly in that domain, and take up almost 20% of the complete error budget :

Parameter	Error Budget	Nominal @ 20°C	Nominal @ 0°C
EE(50)	0.24’’	0.050’’	0.079’’
EE(80)	0.42’’	0.094’’	0.170’’

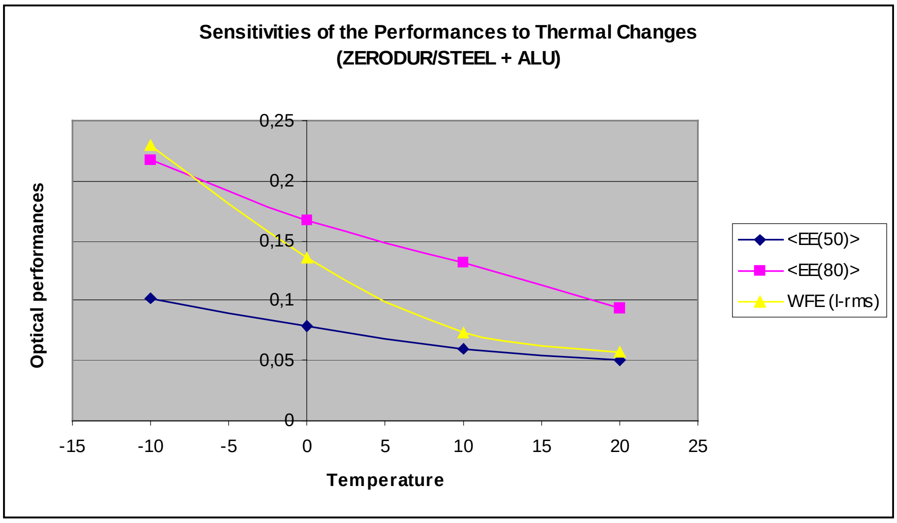
Should this situation be considered as critical, it could be readily alleviated by a small change in the mirror spacings, after the optimum configuration had been found at ambient conditions.

For information, the corresponding SAC refocusing, to be added to the natural tube expansion, is highly linear between –10 and +20°C, and is equal to –0.032mm/C (i.e. the tracker shall take the SAC away from the M1 of 32µm every temperature decrease of 1C.)

One may also notice that at 0°C, the perturbed WFE of about 0.15 λ-rms correspond to encircled energies of EE(50)=0.08'' and EE(80)=0.17'', a situation consistent with the presence of centered (spherical) aberrations (3rd and 5th order).

8.3 RESULTS FOR THE CASE ZERODUR/STEEL-ALU :

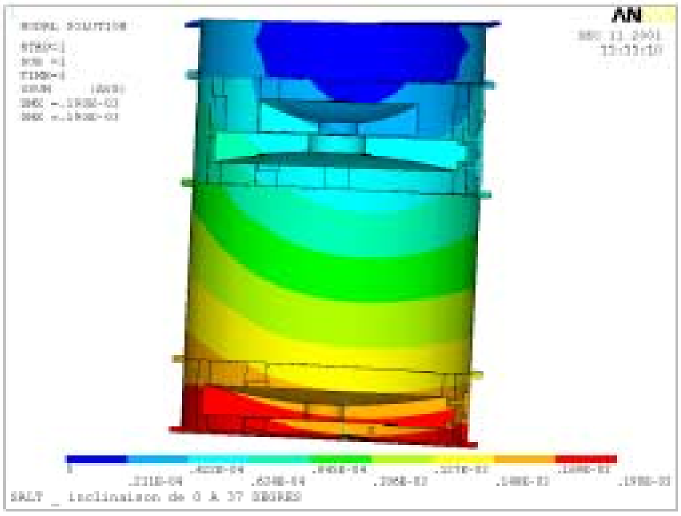
We have investigated the possibility to have the interval between the SAC and the Focal Plane made of Aluminum (CTE $234 \cdot 10^{-7}$). This could be of interest for mass budget considerations. The results are virtually identical to previous configuration, except that the coefficient for the tracker refocus is now –0.033mm/C :



9. SENSIVITY TO GRAVITY

The SAC will be aligned with the axis vertical, and will operate at an elevation angle of 37 +/- 8.5° . The modification of the gravity direction will cause mirror displacements because of the flexure of the SAC main structure, and because of the plays at the mechanical bearings level. It is anticipated that these plays will be compensated during the integration phase, by springs or by levers, so their contributions (about 5µm for the 3 DoF) will not be taken into consideration. However, the mirror deformations due to the load variations at the mechanical interfaces, and the global tube flexure, can not be compensated within the SAC.

The tube deformation, and the mirrors displacements have been computed ; the results are shown hereunder. The sag at the M3 level is about 0.160mm :



9.1 RIGID BODIES DISPLACEMENTS

Following table lists the displacements to be expected at the mirror levels (configuration as illustrated above: ZERODUR-STEEL) during the transition 0° ⇒ 37°, and their corresponding contribution to the aberrations. We have seen in Chapter 4.6 that they consisted almost entirely in Coma3, described by the Zernike polynomial Z8 :

Displacement	M2	M3	M4	M5	***Total***
δy (µm)	-51.6	-162.8	idem M2	-37.2	
δZ8	***5.1***	***-17.0***	***-1.1***	***0.9***	***-12.1***
δα (µrad)	145.5	192.3	‘’	112.4	
δZ8	***19.5***	***-1.0***	***0.7***	***-0.8***	***18.4***

Those contributions are deterministic, so they add algebraically, and not quadratically. The consequence of the transition Vertical => 37° is a **<u>large amount of coma, with Z8 ≈ 6.3</u>**. This result has been cross-checked by introducing above tilts and decenters in the SAC model.

The aberrations due to the tube flexure can be compensated by a global SAC decenter and refocusing. We have applied following procedure :

- start from the centered design
- apply the tilts and decenters to the SAC elements,
- find the best SAC decenter and refocus that optimize the <EE(50)> in the FoV,
- compute the EE(50) and EE(80) over the full FoV.

The perturbed design has no more the rotational symmetry of the centered design, therefore a new definition of the « weighed » energy concentration is needed. Referring to following tables, there will be

The coma can be compensated by a SAC decenter of δy_{SAC} = -1.25mm. A small refocus of 0.003mm has been applied. The performances in the FoV are now the following :

```
 ******************************************************************************
 *  YAN (min) *          EE(50)   IN THE FOV (XAN = -4′, -2′ .. 4′)          *
 ******************************************************************************
 *    -4      *    0.2221  *    0.1226  *    0.0978  *    0.1226  *    0.2221  *
 *    -2      *    0.1317  *    0.0486  *    0.0343  *    0.0486  *    0.1317  *
 *     0      *    0.1192  *    0.0447  *    0.0318  *    0.0447  *    0.1192  *
 *     2      *    0.1755  *    0.1047  *    0.0880  *    0.1047  *    0.1755  *
 *     4      *    0.3115  *    0.2100  *    0.1906  *    0.2100  *    0.3115  *
 ******************************************************************************

Line   YAN = 0     : <EE(50)> = 0.0569′′
Column XAN = 0     : <EE(50)> = 0.0489′′
                   --------------------
Average performance:             0.0529′′
```

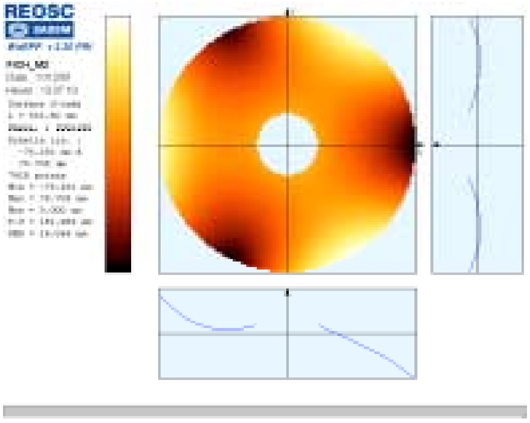
```
 ******************************************************************************
 *  YAN (min) *          EE(80)   IN THE FOV (XAN = -4′, -2′ .. 4′)          *
 ******************************************************************************
 *    -4      *    0.3116  *    0.1891  *    0.1539  *    0.1891  *    0.3116  *
 *    -2      *    0.1971  *    0.0962  *    0.0721  *    0.0962  *    0.1971  *
 *     0      *    0.1891  *    0.0954  *    0.0667  *    0.0954  *    0.1891  *
 *     2      *    0.2572  *    0.1728  *    0.1526  *    0.1728  *    0.2572  *
 *     4      *    0.4186  *    0.2951  *    0.2710  *    0.2951  *    0.4186  *
 ******************************************************************************

Line   YAN = 0     : <EE(80)> = 0.1045′′
Column XAN = 0     : <EE(80)> = 0.1109′′
                   --------------------
Average performance:             0.1077′′
```

For information, the performances of the centered SAC are : **<EE(50)> = 0.0512’’**
<EE(80)> = 0.0963’’

The correction appears satisfactory on axis, were we have almost restored the original performances. In the FoV, we noticed the apparition of a mix of high-order aberrations that could not be compensated by the SAC displacements.

9.2 SURFACE DISTORSION

We have computed the surface deformations due to the transition from the vertical position to 37°. The deformation map of M2 is given hereunder. We have subtracted the tilt, decenter and focus terms, and left the triangular deformation is not compensable.

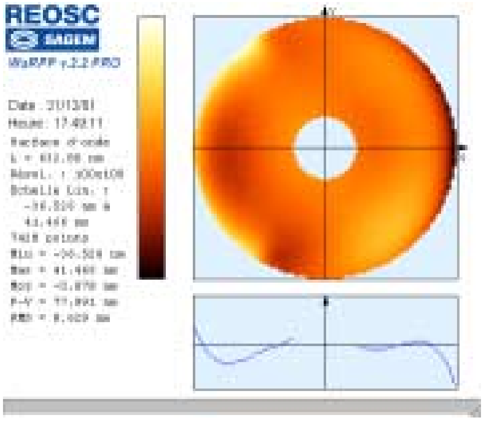


Following table give the gravity-induced deformations for the 4 mirrors during the transition Vertical ⇒ 37° . The contribution of M4 is negligible, given the relatively high stiffness of the substrate :

Mirror	Contribution to WFE-rms
M2	54 nm
M3	51 nm
M4	-
M5	19 nm

The global contribution is the algebraic sum of all the map. A first approximation is to add the contributions of M2 and M3, since the contribution of M5 is relatively modest, and since for each point of the FoV, only one half its aperture contribute to the WFE budget.

Resulting phase map is given hereunder. There is an almost exact compensation since the amplitudes of the gravity-induced sags are almost equal for both mirrors, and the purposely adopted 120° clocking has cancelled most of the contributions :



9.3 CONCLUSION ON THE GRAVITY EFFECTS :

The transition from the vertical position to the inclination of 37° introduces substantial mirrors displacements that could be effectively corrected by a global SAC transverse shift. At the mirror level, the influence of the gravity, and the corresponding variation of constraints at the mechanical interfaces have no noticeable effects on the optical performances.

10. PRELIMINARY ERROR BUDGET :

10.1 SPECIFICATIONS :

The SAC Error Budget is defined at chapter 5.3.1.1 of RD[2]. The image quality over the operational temperature range and at all angles shall be better than :

Image Quality (in arc secs)	
EE(50)	EE(80)
0.24’’	0.42’’

The theoretical performances of the SAC for a perfectly centered system are, respectively :

<EE(50)> = 0.051’’
<EE(80)> = 0.095’’

10.2 THERMAL CONTRIBUTION :

We have seen at Chapter 8 that the non-compensable contributions of the thermal environment is as follows :

Baseline : ZERODUR-STEEL		
T (°C)	<EE(50)>	<EE(80)>
0	0,078	0,170
5	0,066	0,149
10	0,059	0,132
15	0,053	0,104
20	0,050	0,094

On the basis of a quadratic combination of the contributors, we have to allocate 0.0607’’ and 0.1413’’ to the parameters <EE(50)> and <EE(80)>, respectively.

10.3 GRAVITY CONTRIBUTION

Previous chapter has shown that the non-compensable contributions of the gravity increased the <EE(50)> from 0.0512’’ up to 0.0529’’ , and increased <EE80> from 0.0963’’ to 0.1077’’.

On the basis of a quadratic combination of the contributors, we have to allocate 0.0133’’ and 0.0482’’ to the parameters <EE(50)> and <EE(80)>, respectively.

10.4 RESULTS :

Contributor	<EE(50)>	<EE(80)>
Nominal	0.0501	0.0938
Thermal	0.0607	0.1413
Gravity	0.0133	0.0482
Figuring and Metrology	0.226	0.381
TOTAL	**0.240**	**0.420**

We see from the graph of Chapter 7.2 that a contribution of 0.23'' on <EE(50)> corresponds to a Wavefront Error of about 0.42 λ-rms (266nm-rms), when a contribution of 0.38'' on <EE(80)> corresponds to a Wavefront Error of about 0.27 λ-rms (170nm-rms).

Clearly, the dimensioning parameter for the mirrors figuring accuracy is the <EE(80)>.

The compliance to the requirements of [RD1] and [RD2] leads
to a global figuring budget of 170 nm-rms (wavefront) for the 4 mirrors of the SAC.

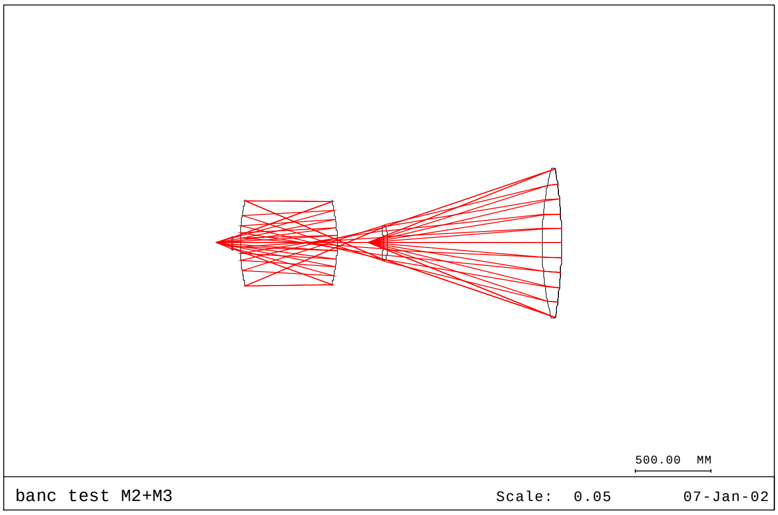
A subsequent analysis will allocate the respective contributions of each mirrors, taking into consideration their intrinsic figuring complexity.

11. SPECIFICATIONS FOR THE INDIVIDUAL MIRRORS

The derivation of the individual specifications is highly dependent on the manufacturing sequence, and in particular with the intermediate matching(s) that will be adopted. This chapter describes a very preliminary sequence. Its scope is only an illustration of the approach that will be adopted.

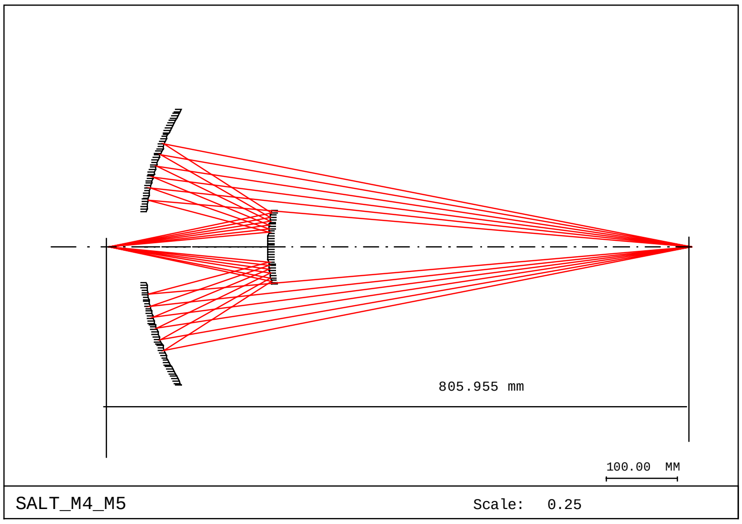
11.1 EXAMPLE OF COMPENSATORS : THE MIRROR PAIR M2-M3

The most critical item of the SAC is the M3, because of its very high degree of aspherisation. The details of the M3 manufacturing will not be addressed here. What is relevant here is that the final test will be performed in association with the M2. This means that the manufacturing errors of the M2 and M3 will be compensated, and will not add quadratically.



11.2 EXAMPLE OF COMPENSATORS : THE MIRROR PAIR M4-M5 :

It can readily be demonstrated that the pair M4-M5 is rigorously stigmatic for a given pair of conjugated points ; the only problem is, that in this configuration where the aberrations are at a minimum, the aperture of the M4 is not adequately covered at the nominal aperture of F/4.2. But increasing the aperture of M5 up to F/2, for example, improves much the situation, the WFE residuals being still negligible, at about 0.0050 λ-rms :



Therefore it is proposed to have the pair M4-M5 tested separately, in their nominal configuration (M4-M5 = 171.597mm.) This would cancel-out the contribution of the relative tilts and decenters of M4 w.r.t. M5, that would be replaced by the tilts and decenter of the pair M4-M5.

This is much less critical : it can be demonstrated that the tolerance on the relative centering of the pair M4-M5, with respect to the pair M2-M3, is at least 0.1mm.

11.3 EXAMPLE OF TEST SEQUENCE AND TOLERANCES ALLOCATION

The fact that the 2 pairs of mirrors can be tested independently leads naturally to a design where the SAC is made up of 2 sub-assemblies. The issue of the relative alignment of those subassemblies has been solved via the following sequence :

- integration of M2 and M5 in their respective sub-assembly,
- mating of the 2 sub-assemblies,
- alignment of M5 vs. M2 with 3D mechanical metrology means,
- disassembly of the SAC, integration of M3 and M4 in their respective sub-assembly,
- matching of M3 in association with M2,
- control of M4 in association with M5 (a refiguring of M4 is not anticipated at that stage)

reassembly and test of the complete SAC.

A preliminary allocation could be as per follows :

M2-M3 Matching	120
M2-M3 Test Bench	60
M2-M3 Sub-assembly	**134**
M4 Figuring	45
M5 Figuring	45
M4-M5 Test Bench	25
M4-M5 Sub-assembly	**68**
SAC Test Bench	**70**
SAC Complete	**166**