Gaia no-nominal configurations performance analysis work-plan for AIM needs

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Introduction

The Gaia telescope layout consists of two identical trains of mirrors, pointing in two directions separated by a basic angle of 106.5°, which are merged in a common path at the exit pupil. The beam combination occurs at M4 mirrors (M4a and M4b for the two telescopes) that fold the light beam collected by the two primaries surfaces of each telescope through the focal plane FP. The two M4s are tuned by ±26.63° (a quarter of the telescopes basic angle of 106,5°) wrt the optical axis normal. The M5 and M6 are flat and common to the two paths and are mounted in a periscope configuration to fold the light in a different plane to avoid any vignetting [1].

As written in the AIM SRS req@CU3-AIM-S-GEN-160 [2] and AIM SDD section 4.3 [3], we need to perform a "sensitivity" analysis over the Gaia optical configuration elements, including the focal plane degrees of freedom and to simulate the identified non-nominal optical configurations.

In order to fulfil the requirement we should also study the thermo-mechanical evolution of the optical configuration and the CCD radiation damage profile variation. As asserted in the SRS req@CU3-AIM-S-AIM-040 and req@CU3-AIM-S-MOD-540, due to the huge amount of the efforts, we will take into account the results from the DPAC Radiation Task Force and will pre-correct the AF raw images using the CDM model calibrated by the CTI mitigation chain.

1 Work goals

Our goals are to increase the reality of AF image simulations and perform an accurate analysis of the image variations due to the identified perturbations, with the aim of identifying and developing diagnostic tools for the AIM data analysis software system.

AIM will use the whole procedure and the images library produced in this study for diagnostic purposes e.g. for retrieving as much information as possible about the optical configuration in case of degradation. A more detailed discussion on this issue is given in dedicated documents [4].

2 Identification of Degrees of Freedom

In Table 1 we outline the potential degrees of freedom (DoFs) deemed as critical for the performance. The red crosses represent the degrees of freedom that in principle must be taken into account, but in reality they don't affect the optical design.

TABLE 1: Telescope 1 and Telescope 2 Degrees of Freedom.

		T_AL	**T_AC**	**T_AX**	**R_AL**	**R_AC**	**R_AX**		
Location	**Element**	$\mathbf{dX_{CV}}$	$\mathbf{dY_{CV}}$	$\mathbf{dZ_{CV}}$	$\mathbf{d\alpha}$	$\mathbf{d\beta}$	$\mathbf{d\gamma}$		
Gaia T1	M1	x	x	x	x	x	x	0	6
Gaia T1	M2	x	x	x	x	x	x	0	6
Gaia T1	M3	x	x	x	x	x	x	0	6
Gaia T1	M4	x	x	x	x	x	x	3	3
Gaia T1	M5	x	x	x	x	x	x	3	3
Gaia T1	M6	x	x	x	x	x	x	3	3
Gaia T2	M1'	x	x	x	x	x	x	0	6
Gaia T2	M2'	x	x	x	x	x	x	0	6
Gaia T2	M3'	x	x	x	x	x	x	0	6
Gaia T2	M4'	x	x	x	x	x	x	3	3
Gaia T2	M5'	x	x	x	x	x	x	3	3
Gaia T2	M6'	x	x	x	x	x	x	3	3
Gaia T2	FPA	x	x	x	x	x	x	2	4
TOTAL								**20**	**58**

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13 optical elements are listed in the table, each one with 6 DoFs and N possible values in the range variation, for a maximum of N^{78}. It is obviously a non-sense to start to simulate all possible no-nominal configurations corresponding to all possible values combinations.
We neglect the Z rotational and X and Y translational degrees of the M4, M5, M6 fold mirrors, since an optical margin of few tens mm is applied along each mirror dimension systematically on the useful optical aperture in order to define the mirror mechanical dimension. The optical surfaces are well oversized respect the footprint dimension.
We also neglect the X and Y rotational degrees of the FPA; the effect is a loss of upper or lower FP edge or an early or delayed entry of the star through the FP.

We propose to simulate about 2000 no-nominal configurations for performing the study and the analysis helpful for AIM goals. That implies a data storage need of about 22 Tb.
We plan to choose the more meaningful and representative configurations sample keeping the essential. At the moment we can not estimate the right number of the effective data until the first and second step of the work planning will be completed. A reasonable starting number could be around 200 configurations for an amount of 2,2 Tb.

3 DoF variation distribution and values

We consider an uniform distribution of each DoFs variation to simulate effects of unexpected perturbations as launch stresses, micro-meteorites, attitude perturbation, since the simulation of DoFs random variation due to uncertainties in mounting, vibrations included in the tolerances ranges are already tested and not so relevant for our investigation.
Of course we plan to insert also those values in the variation ranges but we need to span the all range equally. Discussion about values to be used is given in the following subsection.

3.1 Ranges of variation

Manufacturing, gravity deformations, cool down effects and launch settings, can be in principle considered ([1], pag. 127, 141, 154). In Table 2 and 3 we show the values of the 6 DoFs variation for the launch settings displacements and gravity deformations. They are derived from the ASTRIUM available documents on Gaia Livelink.

During the launch the payload will be subjected to mechanical and thermo-elastical stresses which will set a starting reference configuration of the telescopes different from the design/nominal one.
Such perturbations can in principle be larger than the ranges in Table 2 because of unexpected events. For this reason it should be a good approach to investigate value ranges outside the tolerance ones.
After a deep discussion about which one would be more important for the AIM goals we decided to select the limit values showed in Table 4, which allow us to take into account the possibility that the on-flight starting reference configuration is at the border of the tolerance ranges.

TABLE 2: setting displacements of mirrors for each telescope

	dX_{CV}	dY_{CV}	dZ_{CV}	dα	dβ	dγ
Element	**μm**	**μm**	**μm**	**μrad**	**μrad**	**μrad**
M1	±19	±2	±2,4	±14	±8	±6,2
M2	±4,8	±4,8	±1,3	±23	±23	±62
M3	±9,8	±2	±2,4	±21	±8	±12
M4	±2,5	±4,2	±4	±63	±63	0
M5	±4,2	±4,1	±2,7	±32	±7,1	0
M6	±4,2	±4,1	±2,7	±32	±7,1	0
FPA	±3,5	±1,1	±3,5	±6,8	±2,7	±6,1

TABLE 3: local displacement of optical centres from 0g to +1g gravity - alignment configuration

		dX_{CV}	dY_{CV}	dZ_{CV}	dα	dβ	dγ
Location	**Element**	**μm**	**μm**	**μm**	**μrad**	**μrad**	**μrad**
Gaia T1	M1	±6.5	±29.5	±14.0	±5.4	±5.6	±3.4
Gaia T1	M2	±9.4	±16.1	±4.7	±34.6	±2.6	±15.9
Gaia T1	M3	±10.2	±30.3	±9.1	±5.7	±5.7	±3.8
Gaia T1	M4	±3.7	±31.3	±8.3	±7.8	±0.3	±3.7
Gaia T2	M1’	±6.9	±29.1	±12.5	±3.6	±6.0	±3.8
Gaia T2	M2’	±11.6	±16.7	±4.9	±44.5	±2.5	±16.1
Gaia T2	M3’	±11.1	±29.8	±9.3	±4.0	±5.2	±4.0
Gaia T2	M4’	±5.1	±31.3	±8.0	±1.7	±0.3	±8.4
Gaia T1-T2	M5	±0.4	±25.6	±13.7	±6.3	±4.3	±3.4
Gaia T1-T2	M6	±1.5	±12.0	±27.1	±6.3	±3.4	±4.3
Gaia T1-T2	FPA	±1.1	±7.1	±3.7	±17.5	±0.2	±0.2

TABLE 4: Selected variation ranges for Telescope 1 and Telescope 2

		dX_{CV}	dY_{CV}	dZ_{CV}	dα	dβ	dγ
Location	**Element**	**μm**	**μm**	**μm**	**μrad**	**μrad**	**μrad**
Gaia T1	M1	±25.5	±31.5	±16.4	±19.4	±13.6	±9.6
Gaia T1	M2	±14.2	±20.9	±6.0	±57.6	±25.6	±77.9
Gaia T1	M3	±20.0	±32.3	±11.5	±26.7	±13.7	±15.8
Gaia T1	M4	±6.2	±35.5	±12.3	±70.8	±63.3	±3.7
Gaia T2	M1’	±25.9	±29.1	±14.9	±17.6	±14.0	±10.0
Gaia T2	M2’	±16.4	±16.7	±6.2	±67.5	±25.5	±78.1
Gaia T2	M3’	±20.9	±29.8	±11.7	±25.0	±13.2	±16.0
Gaia T2	M4’	±7.6	±31.3	±12.0	±64.7	±63.3	±8.4
Gaia T1-T2	M5	±4.6	±29.7	±16.4	±38.3	±11.4	±3.4
Gaia T1-T2	M6	±5.7	±16.1	±29.8	±38.3	±10.5	±4.3
Gaia T1-T2	FPA	±4.6	±8.2	±7.2	±24.3	±2.9	±6.3

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We plan to divide the work in four main steps:
1. identification of the most significant degree of freedom and their weights (already done with this document),
2. running Montecarlo simulation with the optical Code like ZEMAX or CODEV,
3. production of one PSFs library for each no-nominal configuration identified by the previous analysis
4. Merit Function (MF) calculation for each configuration and production of maps showing the MF variations from the nominal configuration over the whole astrometric focal plane.

The generation of effective PSFs for each AF CCD for the identified no-nominal configurations and at different wavelengths with CODEV or ZEMAX is too much disk space consuming, e.g. the generation of each optical PSF with CODEV and ZEMAX takes:
- about 11 Mb of disk space with CODEV and about 13 Mb of disk space for ZEMAX,
- about 3-5 seconds of calculation with CODEV or ZEMAX if we use the FFT PSF (one Huygens PSF simulation in ZEMAX takes about 35 min), that means from 40 min to 70 min for simulating 811 PSFs;

so that we propose to produce with CODEV only the WFE maps at λ=600 nm and then to simulate the effective and polychromatic PSFs using the AIM AF image simulator (AIM1) written in Java and C, as explained in section 5.

4 Merit Function
The identification of the MF is a critical issue. Encircled energy, Airy envelope centroid, RMS WFE maps, RMS distortion, are good for us?
Since one goal of AIM is the monitoring and recovery of the instrument status from the Gaia data, looking at the variation of image profile, position and shape, we need to consider some MF that refers to the image on the CCD and not to the WFE as done in other studies. The RMS WFE is not enough for determining the amount of the effect on the image centroid and shape variation as already investigated in A&A 2006.

We plan to split the performance analysis in two steps:
1. running of a preliminary simulation using a simple MF, e.g. centroid of Airy disk in order to have a fast feedback about the most critical DoF and their variation regions;
2. running of a more detailed simulation using a more sophisticated and adequate Merit Function; this will require a larger time and CPU allocation.

During the first step, we propose to consider an user defined MF, being the standard ones, typically used by optical ray tracers i.e. spot diagram, WFE RMS and so on.

During the second step, we will use the photo-center location and higher order moments (FWHM, skewness and kurtosis).
A number of standard techniques exist for estimating the location of a distribution in a robust way, that is, relatively insensitive to outliers which statistically represent the wings of the distribution like ML or LS centroid algorithms already implemented in the Gaia data reduction pipeline [5].
Since we need a PSF model for fitting the images and extracting the MF which is still in development, and since the calculation is time consuming, we plan to start the analysis with the weighted central moments, e.g. as in [6].
Discussion on this issue took place and the proposed schedule has been approved with the recomandation to using for the main analysis the location algorithms implemented in the Gaia data reduction pipeline with a suitable PSF model.

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4.1 Merit Function variation

Another important aspect discussed is the acceptance bounds for the identified MF. How much the MF have to change before considering the values unacceptable?
We outline that the error budget given in ASTRIUM documents might not be enough, being our needs different from those discussed. This remains an open point which needs further discussion.

5 Optical and effective PSFs Library

5.1 WFEs generation

CODE V routine running WFEs simulation is already available.
After the individuation of the critical DOF and the critical values range, the table of the settings values for each mirror and FPA are loaded by the routine and fixed to the corresponding DoF into CODE V language.
The routine can loop over all the wavelengths and give out the corresponding WFE as a .txt file with a header where the description of the parent configuration is given.

WFE maps time consuming and storage size:

- about few ten seconds of calculation
- about 1 Mb for each map
- about 115 Mb for 63 CCD for the two telescopes assuming a single point calculation for each CCD (CCD center)

Each WFE map header shall contain the following informations:

- reference wavelength (600 nm)
- DOF variations in mm (linear decenters) and radians (titls)
- X Field Value, X F-Number
- Y Field Value, Y F-Number
- Reference Sphere Radius
- X Focal Length
- Y Focal Length
- average Increment in Entrance Pupil (DX)
- average Increment in Entrance Pupil (DY)
- array Size
- the index enumerating the no-nominal configuration taking into account

An example of the output file containing the perturbed WFE map is given in Table 5.

The identified no-nominal configurations should be stored in a file with a header where the corresponding variation values of the optical elements are described: one set of variation values for each no-nominal configuration and consequently for each WFE maps set.

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TABLE 5: Example of output file for non-nominal WFE map simulation; only translational degrees are listed in the header, no-rotational degrees variations are applied in this case.

This file contain the WFE map for a perturbated configuration of the GAIA telescope obtained by random generation of decenterings for M1, M2, and M3.

The ranges for the random generation of the DoF variation are loaded from table in par. 5.4.4 of GAIA.ASF.TCN.PLM.00068.

The random valued appied are:

Decentering along scan for M1 : -0.013691 mm
Decentering across scan for M1 : 0.00101874 mm
Decentering along axis for M1 : 0.00125398 mm

Decentering along scan for M2 : -0.000781055 mm
Decentering across scan for M2 : 0.00217529 mm
Decentering along axis for M2 : 0.00103677 mm

Decentering along scan for M3 : 0.0082535 mm
Decentering across scan for M3 : 0.000790833 mm
Decentering along axis for M3 : 0.00165762 mm

PMA data:
Data represents the wave aberration
Wavelength: 600 nm
X Field Value: 0 MM. X F-Number: 24.1377
Y Field Value: 0 MM. Y F-Number: 24.1349
Reference Sphere Radius: 3488.8
X Focal Length: 34999.7 MM.
Y Focal Length: 34995.6 MM.
Average Increment in Entrance Pupil (DX): -6.30538 0.000007 MM.
Average Increment in Entrance Pupil (DY): 0.000003 -6.30463 MM.
Zoom Position: 1 Field Number: 1 Wavelength Number: 1
Defocus: 0 MM.
Array Size: 256
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5.2 PSFs Library generation

We plan to generate a library of images, for all the 63 AF CCDs and for each identified no-nominal configurations. We take into account the optical contribution of the instrument and the CCD electro-optical contributions.

The PSFs production and the performance analysis requires a time and CPU allocation that depends on the resolution and the MF we will use for analysis. We propose an output image with a sampling of 1024x1024 and a step sample of 2 microns.

Each image shall contain in its header the following informations:

- pupil sampling
- image sampling
- focal length
- sample step
- wavelength
- the index enumerating the no-nominal configuration taking into account for the generation of the image; the variation values of the optical elements are stored in the header of the corresponding WFE maps.

The generation of PSFs for each AF CCD for the identified no-nominal configurations and at different wavelengths with CODEV is too much time consuming and not useful, so that we choose to produce only the WFE maps at λ=600 nm with CODEV and then to simulate the images using the AIM simulator written in Java and C.

In the following we list the time allocation for the simulation and the storage needs:

811 optical monochromatic PSFs, time consuming and storage size for one CCD:
- about 20 min of calculation including the storage in .fits format x 2 (telescopes)
- about 3,16 Gb of disk space x 2 (telescopes)

11 optical quasi-monochromatic PSFs, time consuming and storage size for one CCD:
- about 15 min of calculation including the storage in .fits format x 2 (telescopes)
- about 44 Mb of disk space x 2 (telescopes)

11 effective quasi-monochromatic PSFs, time consuming and storage size for one CCD:
- about 30 min of calculation including the storage in .fits format x 2 (telescopes)
- about 44 Mb of disk space x 2 (telescopes)

The total amount for 63 CCD and 2 telescopes (only one configuration and one field per CCD taking into account) is:
- optical monochromatic PSFs about 400 Gb
- optical quasi-monochromatic PSFs about 5,5 Gb
- effective quasi-monochromatic PSFs about 5,5 Gb
- the polychromatic PSFs (the star images) where we can introduce the CCD transit and the CTI degradation and radiation damage are not taken into account for this first estimate; we have to foreseen the storage size and CPU allocation also for such simulation but not before two months. A raw estimate of the simulation time for one polychromatic PSF is of about few minutes without including the radiation damage effect and 4 Mb as storage size. We need 63 image, one for each CCD, and several polychromatic PSFs (for each spectral type, 3 at least, and star magnitude we decide to investigate, 8 at least), for an amount of 5,9 Gb.

Without considering the polychromatic PSFs simulation, the total amount is about 410 Gb of required storage disk for one single configuration during the processing.

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We have to keep in mind that the nominal configuration must be permanently stored and accessible since it will be the reference one, so that about 410 Gb will be permanently filled until the end of the work.
We propose to realize about a thousand of no-nominal configurations for performing the study and the analysis helpful for AIM goals. This implies a data storage need of about 11 Tb, which is a really huge amount of data.
We plan to choose the more meaningful and representative configurations sample keeping the essential. Currently we do not have a clear idea about the final number, being necessary a preliminary simulation run to address the main important DoFs and the MF efficiency.

References

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