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Matthias Erdmann

Dominique Pierot

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The Optical Alignment of the two GAIA Three Mirror Anastigmatic Telescopes

Matthias Erdmann
Directorate of Science and Robotic Exploration
ESTEC – European Space Research & Technology Centre
Noordwijk, Netherlands
matthias.erdmann@esa.int

Dominique Pierot
Optical Instruments
Astrium SAS
Toulouse Cedex 4 France
dominique.pierot@astrium.eads.net

Abstract— **Gaia is an ambitious ESA mission to chart a three-dimensional map of our Galaxy, the Milky Way, in the process revealing the composition, formation and evolution of the Galaxy. Gaia will provide unprecedented positional and radial velocity measurements with the accuracies needed to produce a stereoscopic and cinematic census of about one billion stars in our Galaxy. The payload consists of 2 Three Mirror Anastigmat (TMA) telescopes (aperture size ~1.5 m x 0.5 m), 3 instruments (astrometer, photometer and spectrometer) and 106 butted CCDs assembled to a single 0.9 Giga-Pixel focal plane. In this paper we are describing the optical alignment of the two Gaia telescopes and the tooling that was used.**

Keywords-telescope alignment; Tree Mirror Anastigmat; TMA; 2D-Legendre coefficients; Shack-Hartmann wave front sensor; optical alignment

I. INTRODUCTION AND SCOPE

Inherited from the proven principles from Hipparcos, the purpose of the GAIA mission is to provide a three-dimensional map of about one billion stars throughout the Galaxy and beyond. It will give the detailed physical properties of each star, gathering basic observational data to tackle a large range of problems related to the origin, structure and evolutionary history of our Galaxy. The principal and most prominent feature of the Gaia mission is the high precision optical payload, whose development is under the scope of the spacecraft prime contractor.

The Gaia Pay Load Module (PLM) consists of a ceramic torus main structure from Silicon Carbide (about 3.5 m diameter) as primary structure. Two Tree-Mirror-Anastigmatic-Telescopes (TMA) with an aperture size of about 1.5x0.5 m are installed on the torus structure. Each telescope has a focal length of 35 m. The optical design of each telescope provides an intermediate focus (image after the primary and secondary mirrors M1, M2) and a real exit pupil after the tertiary mirror M3. The tertiary mirror reproduces the intermediate focus on the focal plane with a reduction ratio of about 4. As Gaia is a scanning system the optical design of the telescopes consists of a so called "$f\theta$-design". This means that a pincushion distortion is intrinsic to the design such that the image size $\hat{y}$ is a linear function of the object angle ($\hat{y}$ rather than $\hat{y} = f \cdot \tan(\alpha)$). At the exit pupil of each telescope two quaternary mirrors M4 are located such that the optical beams of each telescope are combined to be directed to a single common focal plane. The two telescopes are mounted on torus with a height difference of 75 mm to provide the space for the two M4 mirrors. Via a system consisting of two precisely polished flat mirrors (M5, M6) the beams of both telescopes are focused on the same focal plane (Focal Plane Assembly FPA). Mirrors M5 and M6 are forming a periscope that folds both telescope beams on the opposite side of the torus and provides the correct optical path length at the focal plane. Figure 2 shows the view of the unfolded optics; Figure 3 shows one telescope Astro 2 including all folding optics in the 3 planes of the PLM reference coordinate system.

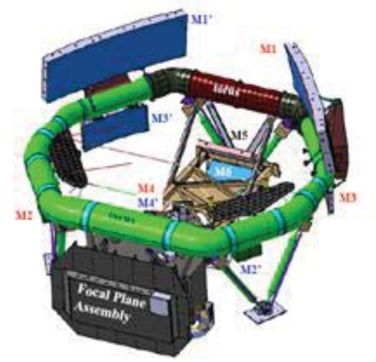


Figure 1: GAIA PLM overview

The Focal Plane Assembly (FPA) consists of 106 CCDs butted together on a Silicon Carbide structure. In front of the focal

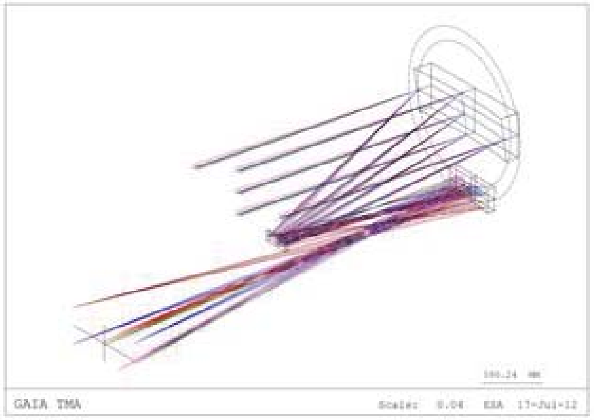


Figure 2: Telescope Optical Lay Out (without Folding Optics)

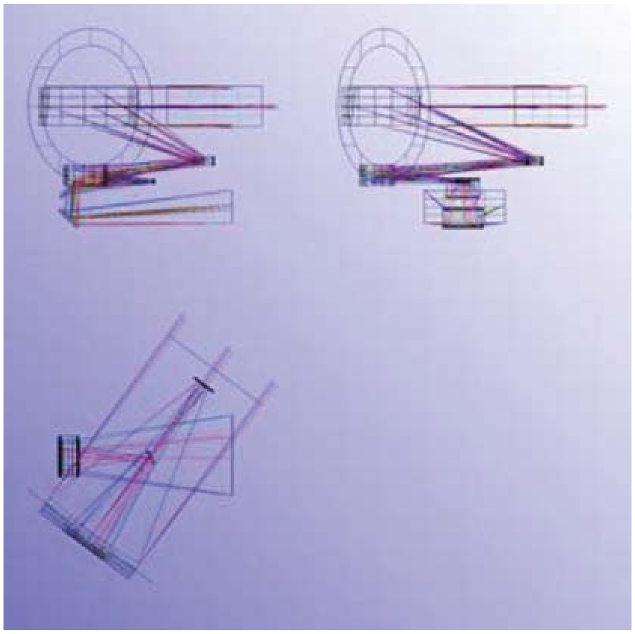


Figure 3: One of the Gaia Telescopes Including Folding Optics

plane three instruments are installed:

- The Radial Velocity Spectrometer RVS is used to analyse the Doppler shift of stars by analysing the spectral shift of a spectral signal of the star. 12 of the 106 CCDs are dedicated to the RVS.
- The Blue Photometer BP measures the photometric blue spectrum of each observed star.
- The Red Photometer RP measures the photometric red spectrum of each observed star.

Each photometer consists of 7 CCDs in the focal plane.

In addition to the instruments, the Gaia PLM includes a number of sensors.

- The Star Mapper registers every object entering the focal plane. Each telescope has its own star mapper and 7 CCDs are dedicated to each Star Mapper.
- Two Wave Front Sensors (WFS) are installed on the FPA that can measure the WFE of each telescope for a number of bright stars in orbit.
- Two of the CCDs are used to monitor the Basic Angle. The basic angle of 106° is the angle between the Lines of Sight of the two telescopes. This angle is the reference for the star position measurement and is therefore precisely monitored by the Basic Angle Monitor (BAM) based on an interferometry principle. Two CCDs are dedicated to the BAM.

Figure 9 shows a complete lay out of the FPA. The detector locations associated to the different instruments and sensors can be seen.

Beside the optical components and their mounts the GAIA PLM consists as well of two mechanisms that actuate the secondary mirrors in 5 Degrees of Freedom. These self-locking high precision mechanisms can be actuated via the two controllers that are part of the GAIA PLM. It is therefore possible to align the two telescopes after launch in orbit based on the measurements of the WFE performed by the Wave Front Sensors (WFS) in the focal plane. During the alignment of the telescopes on ground the two mechanisms were used as well.

Diffraction limited image performance is an elementary requirement for the two telescopes to provide the angular resolution for the star mapping. In addition to that the optical alignment of the two telescopes has to take into account other requirements coming from co-alignment aspects of the two telescopes working simultaneously as front end for the three Gaia instruments:

- Angular magnification differences to be less than 8E-5 between the two telescopes.
- Back focal length of the two telescopes must be the same as they are focused on the same focal plane.

For the optical alignment both telescopes were auto-collimated on two full aperture size flat mirrors (ACflat). As the two ACflats represented a Wave Front Error (WFE) reference for the alignment they have been polished flat to a high level of precision (WFE<20 nm RMS). Each ACflat was supported by an actively controlled and extremely precise tilting mechanism that allowed to steer each ACflat to any angle in the telescope object space that would be represented by any field point in the focal plane of about 1 m x 0.5 m in size.

During alignment the focal plane was replaced by the Focal Plane Scanning device that was able to support and actuate an optical bench in 5 Degrees of Freedom (see Figure 7). Various sensors and sources were installed on this bench during alignment allowing to measure different optical stimuli in auto-collimation to characterize the optical alignment status of each telescope with the required precision.

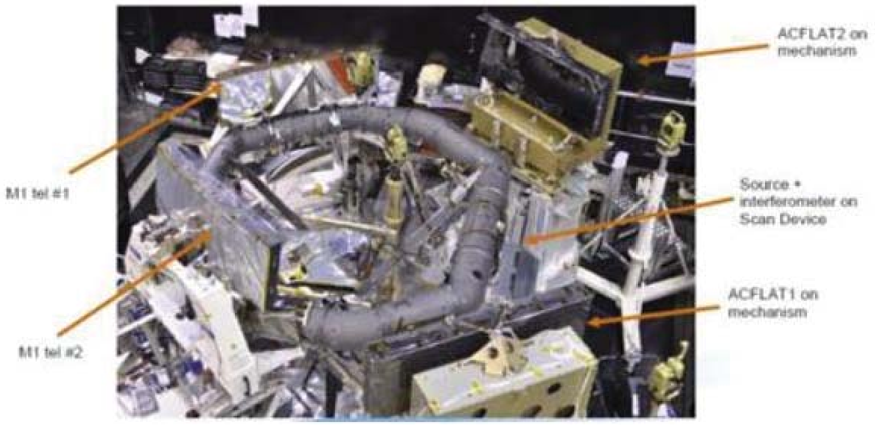


Figure 4: GAIA PLM during optical alignment

II. CHRONOLOGY OF THE OPTICAL ALIGNMENT

Starting in September 2011, the optical alignment of the two telescopes was performed.

A. *Alignment of all flat mirrors*

Figure 6: Focal Plane Scanning device

All flat mirrors were aligned and bolted to the PLM structure. Their nominal positions and orientations were measured by Laser Tracker and theodolite.

B. *Coarse alignment of all mirrors with optical power*

Then all mirrors with optical powers (M1, M2, M3) were integrated on the torus. The Secondary Mirror which fits onto the Secondary Mirror Mechanism (M2M) was integrated directly at the interface bracket at the torus. The M2M could move the secondary mirror in 5 DOF.

M1 and M3 were installed on the torus via a Mechanical Ground Support Equipment (MGSE) that allowed to actuate each mirror by 6 DOF. The actuation of these mirrors was done manually with micrometer screws integrated on the MGSE. In addition to that the MGSE includes, counter weights and levers to compensate for gravity deformation of the torus, the mirrors or the mirror mounts as much as possible.

At the delivery of the Flight Model (FM) mirrors each mirror was equipped with a number of laser tracker target supports. The position of these supports was characterized with respect to the optical vertex position and orientation of the component by the mirror polisher company. By means of these targets the mirror were nominally positioned with respect to the PLM reference coordinate system by Laser Tracker measurements.

The two ACflats were aligned in front of the two telescopes. A Hartmann-Shack sensor (HASO from Imagine Optics) with an integrated diode laser point source was installed on the optical bench of the Focal Plane Scanning device. The Focal Plane Scanning device allowed moving the optical bench and the HASO sensor unit in 5 Degrees of Freedom (DOF) by motorized drives. All drives were equipped with position encoders and therefore any position in the focal plane could be addressed with the HASO in a convenient manner by computer control.

The HASO generated an image of the laser with the telescopes f-number. This image was auto-collimated via the Telescope on the ACflat (see Figure 6). In front of the HASO at the nominal image position the set up consisted of a high precision support for the installation of a spherical ball of about 1 cm in diameter. When a ball was installed in this mount the center of the ball was located at the HASO focus point. For the WFE and focus calibration of the HASO a polished ceramic ball was used as target. The ball could then be replaced by a Laser Tracker Alignment Target of the same diameter. Therefore the focus position of the HASO during measurement could be transferred directly into the PLM reference coordinate system with the Laser Tracker. Once the setup was calibrated the Wave Front Error (WFE) of the telescopes at any field point in the focal plane could be measured by auto-collimation in an effective, reliable and convenient way. The calibration concept of the HASO WFE reference and the transformation in the PLM reference coordinate system by Laser Tracker is illustrated in Figure 8. In this configuration the first WFE of each telescope was measured in the centre of the Field of View (FoV). The values reached at the first WFE measurement were in the order of 200 nm RMS (see Figure 5).

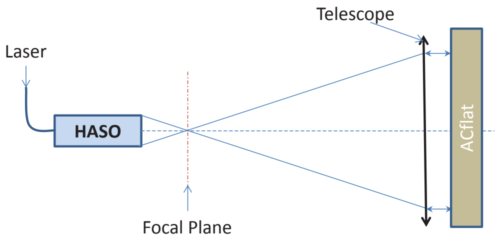


Figure 7: HASO Measurement Principle

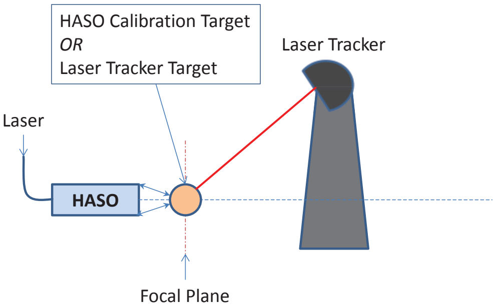


Figure 8: Calibration of HASO and Calibration of the Measurement Point

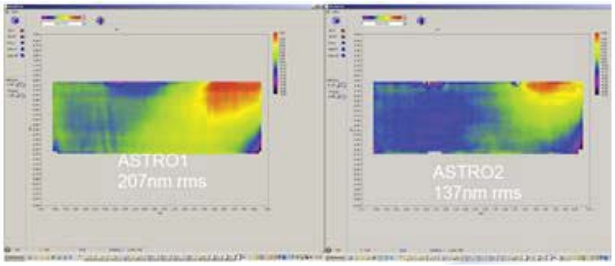


Figure 5: Telescopes WFE after coarse alignment

C. Fine alignment based on WFE measurements and normalized Legendre decomposition to match a Code V model prediction

The WFE was measured for each telescope in 5 field points of the astrometry field of view ($P_1 .. P_5$ see Figure 9). Each measured map was decomposed into 19 normalized 2D-Legendre coefficients ($L_1 .. L_{19}$). Only the following Legendre coefficients were used for the alignment: $L_4 .. L_{10}$.

Basis for the alignment was the sensitivity of the Legendre coefficients with respect to each alignment Degree of Freedom. These sensitivities were derived by analysis (Code V) and verified by measurements on the telescope. The Primary Mirror M1 was used as reference; all other mirrors were aligned with respect to M1. Therefore the alignment was based on 8 alignments DOF which were referred to as ($DOF_0 .. DOF_7$):

- Secondary mirror translation in 3 DOF (M2x, M2y, M2z)
- Secondary mirror rotation in 2 DOF around x- and y-axis (M2a, M2b)
- Tertiary mirror translation in 3 DOF (M3x, M3y, M3z)

The first step of this alignment was based on the 5 reference points in the Astrometric Field of View. The location of the 5 points can be seen in Figure 9. The complete sensitivity matrix consisted therefore of 56 coefficients (7 Legendre coefficients, 8 alignments DOF): $\frac{\partial L_i}{\partial DOF_j} \begin{cases} i = 4..10 \\ j = 0..7 \end{cases}$

It was then possible with the 56 sensitivities to synthesize a WFE map as a function of an alignment vector S assuming a simplified linear model. This vector consists of 8 components each representing an alignment DOF. The synthesized WFE describes the change of the measured WFE as a function of the actuation as defined by the vector:

$$WFE_{synth} = \sum_{i=4}^{10} \sum_{j=0}^{7} S_j \, \frac{\partial L_i}{\partial DOF_j}.$$

This synthesized WFE was then added to the measured WFE at every field point and the result was a prediction of the corresponding telescope WFE at each of the 5 reference field points which would be obtained if the telescope mirror positions and orientations were modified according to the solution vector.

At that stage it was easy to construct a Figure of Merit (FoM) to make the measured WFEs in the 5 reference points converge to a target WFE as calculated by the Code V model:

$$WFE_{synth} + WFE_{measured} = WFE_{predicted} + residual$$

And

$$FoM = \sqrt{\sum_{P=1}^{5} residual_P^2}$$

A solution vector was calculated simply by minimizing the FoM. For each alignment step a number of solution vectors were calculated with a limited set of DOF. This was done to investigate the most effective alignment DOF at the actual alignment status of each telescope and to avoid miss-alignments caused by cross-couplings. The chosen solution vector was actuated at the telescopes and the WFE was measured again and the fidelity of the simplified linear model could be assessed. It turned out that the actual telescopes response was very well in line with the predictions of the model.

This part of the telescope alignment was implemented in an Excel spread sheet that was called Telescope Alignment Tool (TAT). A screen shot of the TAT can be seen in Figure 10. The table consists of 4 fields: ‘Target’, ‘Synthesis’, ‘Difference’, ‘Solution’. For the first three each row represents a field point (P1..P5) and each column represents a normalized alignment Legendre term (L4..10 in this example). ‘Target’ describes the WFE that is desired e.g. the WFE of the prediction model, ‘Synthesis’ describes the WFE changes caused by the ‘Solution’. The synthesized WFE is based on the alignment Degrees of Freedoms and the sensitivities which are not shown in the figure. ‘Difference’ is the difference between ‘Target’ and ‘Synthesis’ and represents therefore the residuals that are used for the Figure of Merit. As the Legendre coefficients are normalized the resulting RMS of the WFE can be calculated easily as the Root Sum Square (RSS) of the Legendre coefficients.

In the example shown in Figure 10 the target WFE is 75 nm RMS. An alignment as shown in the solution vector,

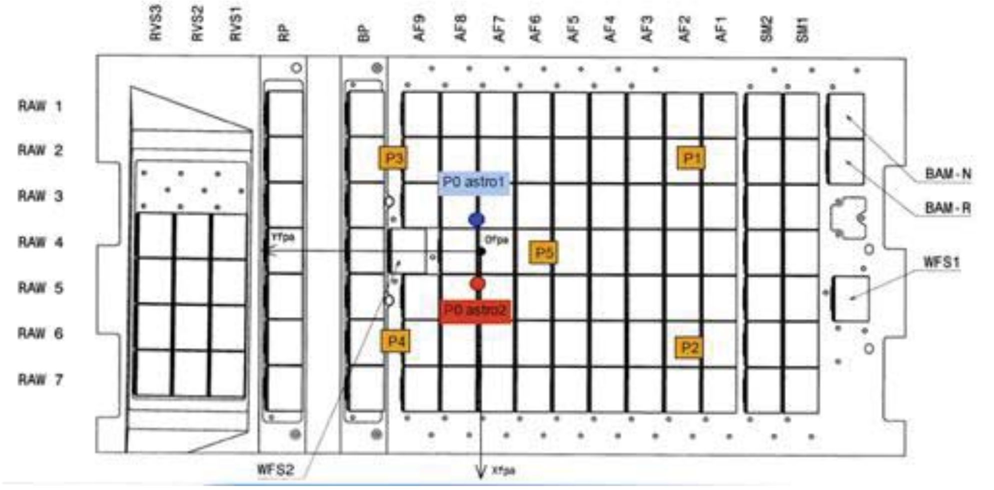


Figure 9: Focal Plane with the Astro field alignment reference points

consisting of an M2x actuation of -2, would lead to 56.4 nm RMS residual WFE

According to the chosen solution of the TAT, the mirrors positions and orientations were actuated accordingly and new WFE measurements were done. This process was repeated two or three times until an optimum was reached. When the optimum in this configuration was reached, the load transfer of the mirrors from the MGSE to the torus was foreseen. But before that was done it was important to measure the co-alignment of the two telescope focal lengths first to make sure that the co-alignment can be reached without moving any of the Primary Mirrors.

1) Fine adjustment of the two telescopes angular magnifications

The Delta Focal Length OGSE (DFOGSE) consisting of a double slit target with precisely known distance and a large flat auto-collimation mirror with MGSE support was installed (diameter > 300 mm). This auto-collimation mirror coupled the two telescopes such that telescope 1 could see the slits image of telescope 2 and vice versa. As both telescopes were observing the same focal plane the two slits represented a reference target of an identical image size for both telescopes. Therefore the slit separation Δ_0 generated two images as seen by telescope 1 ($\Delta_1 = \frac{\Delta_0}{f_2} f_1$) and telescope 2 ($\Delta_2 = \frac{\Delta_0}{f_1} f_2$). Hence by measuring the differences of the two slit image separations, the focal length difference of the two telescopes (f_1 focal length telescope 1 and f_2 telescope 2) could be measured precisely and could be matched to the requirement:

$$\frac{2(f_2 - f_1)}{f_2 + f_1} \leq 8 \cdot 10^{-5}$$

The slit separation was measured with sub-pixel interpolation by a CCD camera installed in the focal plane. The measurement precision provided a comfortable margin with respect to the required resolution.

The absolute focal length was based on the encoder readings of the two full size auto-collimation mirror mechanisms which were sufficiently precise for the alignment of the absolute focal length of the telescopes of 35m±1%.

D. Load transfer of M1 and M3 from MGSE to PLM torus support structure

After the angular magnification (focal length difference) between the two telescopes was adjusted the load transfer of mirrors M1 and M3 from MGSE to the torus and bolting was done. The M1 and M3 mirrors were then supported by the Invar bipods Isostatic Mounts (ISM). To control parasitic forces on the mirror each ISM was instrumented with a number of strain gauges. Analysis showed that the allowable strain in each ISM was so low that unexpected WFE errors induced by parasitic mechanical force could be excluded. At that stage the MGSE gravity compensation was de-coupled and the WFE was dominated by gravity (almost 300 nm RMS). This was reflected by an update of the target WFE of the TAT for the alignment. As M1 and M3 were no longer installed on the MGSE all further alignments of the telescopes was made by only moving the secondary mirror with the M2M.

1) Alignment with constant Legendre sensitivities

The procedure of measurement and alignment was repeated with the new WFE targets including gravity deformation of the mirrors and the payload until an optimum was reached. This optimum for telescope Astro1 was in the requirements for the astro field of view but not for the RVS field of view. Astro 2 was marginally non-compliant in the astro field of view.

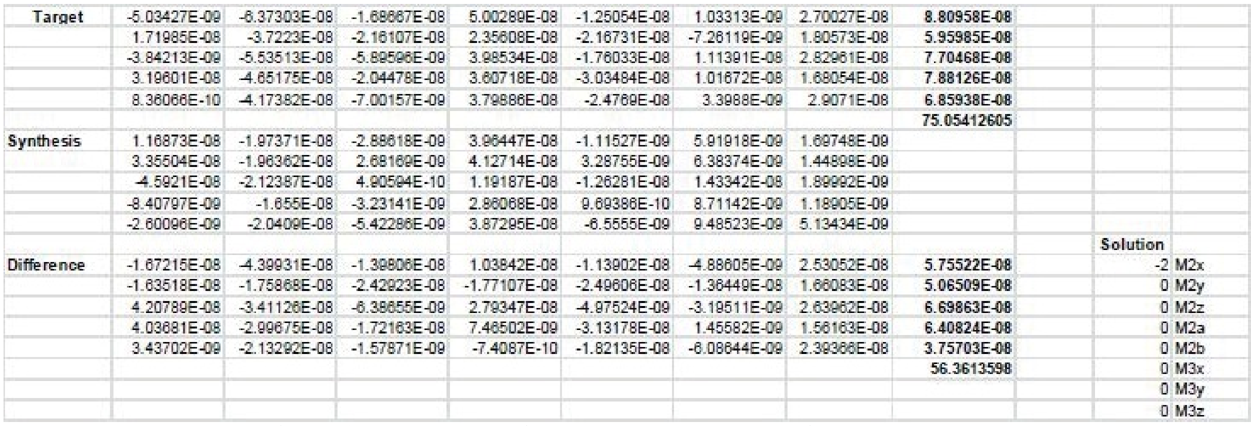
2) Finalization of the alignment utilizing Legendre sensitivity gradients

The alignment result of the two telescopes based on constant Legendre sensitivities for all field points resulted in a performance status that was compliant with the requirement in the Astro Instrument Field of View (FoV), but there was a small non-conformity in particular L5 (45° Astigmatism) at the far field edge of the RVS instrument. The RVS instrument bends the light towards the field centre. Without RVS instrument in place, which was the telescope alignment condition, the RVS field points are lying outside of the nominal focal plane. Therefore it was investigated if Legendre sensitivity gradients existed and if they can be utilized to correct the RVS Field of View without compromising the overall good image performance of the telescopes in the centre FoV.

LEGENDRE SENSITIVITY AND GRADIENT ANALYSIS USING PERL AND CODE V

A careful assessment of sensitivity gradients was performed in this phase to analyse the potential use of Legendre sensitivity gradients in the focal plane for the alignment. For this assessment the Code V prediction models WFE were analysed on a large field scan in the focal plane. One analysis consisted of several thousand of WFE files generated by Code V:

- A set of WFE files characterizing the reference Code V prediction model at each field point.



Target	-5.03427E-09	-6.37303E-08	-1.68667E-08	5.00289E-08	-1.25054E-08	1.03313E-09	2.70027E-08	**8.80958E-08**			
	1.71985E-08	-3.7223E-08	-2.16107E-08	2.35608E-08	-2.16731E-08	-7.26119E-09	1.80573E-08	**5.95985E-08**			
	-3.84213E-09	-5.53513E-08	-5.89596E-09	3.98534E-08	-1.76033E-08	1.11391E-08	2.82961E-08	**7.70468E-08**			
	3.19601E-08	-4.65175E-08	-2.04478E-08	3.60718E-08	-3.03484E-08	1.01672E-08	1.68054E-08	**7.88126E-08**			
	8.36066E-10	-4.17382E-08	-7.00157E-09	3.79886E-08	-2.4769E-08	3.3988E-09	2.9071E-08	**6.85938E-08**			
								75.05412605			
Synthesis	1.16873E-08	-1.97371E-08	-2.88618E-09	3.96447E-08	-1.11527E-09	5.91918E-09	1.69748E-09				
	3.35504E-08	-1.96362E-08	2.68169E-09	4.12714E-08	3.28755E-09	6.38374E-09	1.44898E-09				
	-4.5921E-08	-2.12387E-08	4.90594E-10	1.19187E-08	-1.26281E-08	1.43342E-08	1.89992E-09				
	-8.40797E-09	-1.655E-08	-3.23141E-09	2.86068E-08	9.69386E-10	8.71142E-09	1.18905E-09				
	-2.60096E-09	-2.0409E-08	-5.42286E-09	3.87295E-08	-6.5555E-09	9.48523E-09	5.13434E-09				
										Solution	
Difference	-1.67215E-08	-4.39931E-08	-1.39806E-08	1.03842E-08	-1.13902E-08	-4.88605E-09	2.53052E-08	**5.75522E-08**		-2	M2x
	-1.63518E-08	-1.75868E-08	-2.42923E-08	-1.77107E-08	-2.49606E-08	-1.36449E-08	1.66083E-08	**5.06509E-08**		0	M2y
	4.20789E-08	-3.41126E-08	-6.38655E-09	2.79347E-08	-4.97524E-09	-3.19511E-09	2.63962E-08	**6.69863E-08**		0	M2z
	4.03681E-08	-2.99675E-08	-1.72163E-08	7.46502E-09	-3.13178E-08	1.45582E-09	1.56163E-08	**6.40824E-08**		0	M2a
	3.43702E-09	-2.13292E-08	-1.57871E-09	-7.4087E-10	-1.82135E-08	-6.08644E-09	2.39366E-08	**3.75703E-08**		0	M2b
								56.3613598		0	M3x
										0	M3y
										0	M3z

Figure 10: Telescope Alignment Tool (TAT), version M. Erdmann

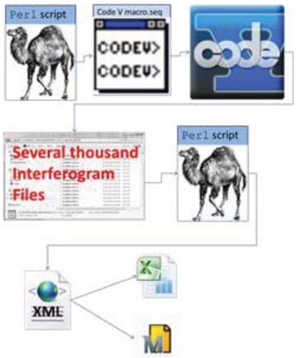


Figure 11: Legendre gradient analyses logic. CODE V is a registered trademark of Synopsys, Inc.

- A set of WFE files characterising the Code V prediction model at the same field points but with an "infinitely small" actuation of the alignment DOF in the model

This exercise was performed for all relevant alignment DOF and for all Legendre coefficients that were relevant for the alignment.

Obviously this kind of analysis cannot be done manually; therefore a script language was utilized to generate the analysis cases as an executable Code V macro. The script allowed easy configuration of parameters like field size, sampling distance, parameters for the Interferogram files to be dumped and so forth. Perl was used in our case but any other programming language can be used for this.

In the next step the script was then processed by Code V and thousands of INT files were dumped on the hard disk. The image coordinate associated to each individual INT file was encoded in the file name.

A second Perl script was coded to read all the INT files. Each file was processed as follows:

- Legendre decomposition over 19 Legendre coefficients was performed.
- The RMS wave front error was calculated.
- The number and percentage of valid data points was calculated.

All the results were then written in an XML file that could be directly imported for further analysis and visualization.

An example is shown in Figure 12, the fluctuation of the L5 component as a function of a scan in the focal plane can be seen. This kind of fluctuation is normal and it is caused in particular by the polishing maps of the optical components which are located at some distance to the pupils. The effective WFE seen in the telescope measurement is caused by sub-pupils on the components. As the field point is moved fluctuations occur.

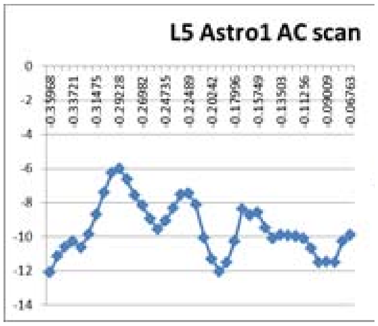


Figure 12: Fluctuation of L5 during field scanning [nm]

It proved also very useful to cross correlate Legendre fluctuations with the percentage of valid pixels. This analysis highlighted for example that one of the polishing maps consisted of a small area of missing data points. As the pupil on that element was quite small it resulted in an increased noise of the prediction as calculated by Code V. This defect caused a periodic modulation of certain Legendre coefficients as the defect was crossing the pupil. After the cause of the anomaly was identified, the prediction model was updated accordingly.

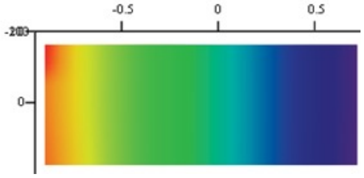


Figure 13: Gradient L5 M2ade. Scale -54..80 nm per arcmin

But also a comparison of the model predictions with a line scan measurement on the telescopes proved to be very useful because it uncovered an unexpected and hidden WFE in a small area of an optical component caused by the coating process.

The analysis of the Legendre sensitivity gradients showed that indeed a number of alignment DOF were good candidates to improve the alignment. Figure 13 shows the gradient of the M2ade movement. The scaling is not symmetrical because the field analyzed was not symmetrical.

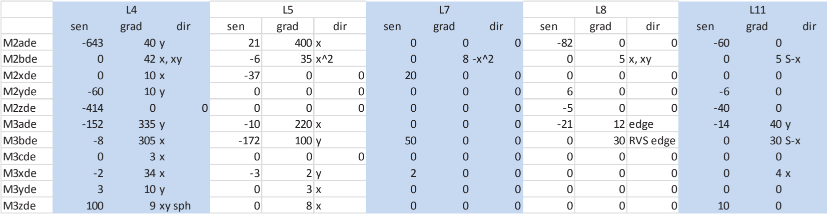
A summary of all sensitivities and gradients can be found in Figure 14. On the left side are the alignment DOF. Then the sensitivities and gradients and the shape of the gradients of L4, L5, L7, L8 and L11 are given. The sensitivity and gradient is in nm RMS per unit displacement. The gradient is given for the extreme field points in x and y direction (including the RVS field). Example: A tilt around the optical x-axis of the M2 mirror (M2ade) of one "unit displacement" produces 400 nm RMS of L5 at the extreme field point in the x-direction. This sensitivity scales linearly from the center of the field, where it is zero, to the edge. These gradients extend the solution space if additional field points are included in the TAT, because there are solutions which have no effect (or can be compensated by another actuation) in the center of the field of view but become effective in outer field points.

The utilization of the sensitivity gradients allowed deriving a well-balanced and compliant alignment of the two telescopes.

E. In Orbit Performance Prediction

Obviously for the in orbit telescopes performance prediction the measured WFE on ground needs to be processed. The on ground WFE measurements are dominated by contributions coming from gravity, atmospheric turbulence and ground vibration. For the performance prediction in orbit the following modifications were applied to the on-ground prediction models:

- All gravity maps were removed from the mirror and optical element surfaces. All mirror polishing maps were already corrected to zero-g maps by the mirror polishers. These maps were derived by calculating the zero-g map from a +1g and -1g map.



	L4			L5			L7			L8			L11		
	sen	grad	dir	sen	grad	dir	sen	grad	dir	sen	grad	dir	sen	grad	dir
M2ade	-643	40	y	21	400	x	0	0	0	-82	0	0	-60	0	
M2bde	0	42	x, xy	-6	35	x^2	0	8	-x^2	0	5	x, xy	0	5	S-x
M2xde	0	10	x	-37	0	0	20	0	0	0	0	0	0	0	
M2yde	-60	10	y	0	0	0	0	0	0	6	0	0	-6	0	
M2zde	-414	0	0	0	0	0	0	0	0	-5	0	0	-40	0	
M3ade	-152	335	y	-10	220	x	0	0	0	-21	12	edge	-14	40	y
M3bde	-8	305	x	-172	100	y	50	0	0	0	30	RVS edge	0	30	S-x
M3cde	0	3	x	0	0	0	0	0	0	0	0	0	0	0	
M3xde	-2	34	x	-3	2	y	2	0	0	0	0	0	0	4	x
M3yde	3	10	y	0	3	x	0	0	0	0	0	0	0	0	
M3zde	100	9	xy sph	0	8	x	0	0	0	0	0	0	10	0	

Figure 14: Alignment sensitivity gradients summary

- Positions and orientations of elements cause by gravity were corrected to zero-g conditions.
- Positions, orientations and WFE distortions coming from the cryogenic orbital environment of the telescopes in orbit were taken into account.

Statistical WFE variations caused by ground vibration and atmospheric turbulence were compensated by a huge number of measurements (about 600 phase maps per measurement were integrated).

In the last step of the optical alignment and performance prediction the two ACFLATs (auto-collimation mirrors and mechanisms) in front of the telescopes were exchanged. It was now possible to remove the deterministic part of the two ACFLATs from the performance prediction maps and take this into account for the final alignment step at the Secondary Mirror Mechanism. The final performance prediction of the two telescopes after the final alignment is as follows:

Table 1: Optical Performance Summary

	Telescope 1	Telescope 2
Auto collimator mirror 1	47 nm RMS	46 nm RMS
Auto collimator mirror 2	51 nm RMS	53 nm RMS

Therefore the alignment was considered as accomplished within the requirements of 50 nm RMS.

III. CONCLUSION

The optical alignment of the two Gaia Telescopes was accomplished according to the requirements. The coarse alignment was done by laser tracker and provided already quite a good image. The fine alignment was performed by WFE measurements of the full aperture size auto-collimated telescopes with a Shack-Hartmann sensor. The fine alignment was based on 2D Legendre sensitivities. For the final fine adjustment and a performance balance over the entire telescope field of view Legendre sensitivities gradients were successfully used.

The focal length difference between the telescopes was measured and aligned by a double slit target in the focal plane and a coupling of the two telescope apertures with a large flat mirror.

The complete duration of activities was about 10 month. This included the installation and alignment of all instruments and sensors on the PLM and the alignment of the Basic Angle. Considering the size of the two telescopes, the diffraction limited image performance and the restriction of the alignment (same focal length *and* same back focal length) this duration is considered as quite effective.