Simple alignment of complex laboratory optics using a HASO3 wavefront sensor

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The aberration free alignment of optics for custom built setups in University and R&D laboratories are often underestimated in regards of time and labor consumption. The use of several beamsplitters, lenses, mirrors and filters is evident for any complex optical setup used for fundamental research or during an industrialization phase in corporate research. Consequently, all these optical elements will introduce significant aberrations in the system, deteriorating the quality of the used light source, the focus or laser beam shape.

Imagine Optic designed a new method to quickly decrease aberrations within a complex optical alignment. It is based on using simple optical holders available in any lab in combination with a wavefront sensor. In the example below, we show how to align two triplets in order to obtain an afocal lens system with a minimum of aberration. We are targeting the aberrations focus, astigmatism and coma.

The setup in Figure 1 is an example, which needs to be aligned in order to reduce the main aberrations (focus, astigmatism and coma). We have three actuators for each optical mount of the triplets, thus three degrees of freedom on each mount. Each actuator modifies the afocal alignment which can be visualized and measured by a wavefront sensor. The wavefront sensor, we are recommending to use a HASO3 32 with an absolute accuracy of λ/100, is able to acquire the transmitted wavefront in real time. All measurements done in the optimization process are referenced on the wavefront measured before introducing the triplets into the system, only using the collimator in the setup. This allows for only measuring the aberrations of the afocal lenses.

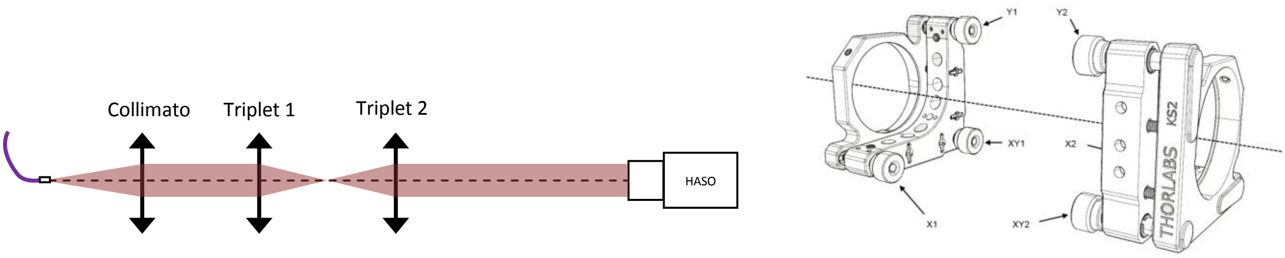


Figure 1: Basic set-up to be aligned.

The simple approach is based on three main steps

1. Measurement of the Interaction matrix:

The measured wavefront is calculated by a modal reconstruction based on Zernike polynomials. If you are not familiar with the Zernike polynomial, you can have a look here: http://en.wikipedia.org/wiki/Zernike_polynomials

In this particular case the wavefront is projected on 8 Zernike coefficients. The software HASOv3 (always included with all HASO3 wavefront sensors) calculates the PV value of each aberration. We are using the value of focus, astigmatism at 0 °, astigmatism at 45 °, coma at 0° and coma at 90°. The initial value of each coefficient is recorded with the HASOv3 software. This gives us the initial vector $\vec{v_i}$. Then we execute the following steps for each actuator:

1. Screw in one turn
2. Record the Zernike coefficients and the number of turn.
3. Screw out one turn

After these three steps, we obtain 6 vectors of 5 coefficients. We subtract the initial values vector $\vec{v_i}$, measured in the beginning and rearrange the data in a 6x5 matrix [M], where each column of the matrix represents the influence of each actuator on the wavefront. This matrix is called interaction matrix [M], it represents the answer function of the movement of all six degrees of freedom within the lens system.

We have to inverse this matrix [M] in order to find the solution matrix of this linear system. But this matrix is rectangular. In our case, we have only 5 equations with 6 degrees of freedom meaning that the system is under-determined. We can easily avoid this problem if we consider that within the system, all degrees of freedom allow to do a complete translation of the afocal, thus we do not change the wavefront by doing so. Therefore, to find a solution that does not change the afocal position, we can add a constraint related to the complete transition: the sum of all the displacements must be equal to 0. That constraint adds the missing line in the 6x5 matrix [M] and imposes that the solution must be 0. The completed matrix is then noted: [M*]
The linear system to be solved is then as following:

$$\begin{pmatrix} \text{Focus} \\ \text{Astig } 0° \\ \text{Astig } 45° \\ \text{Coma } 0° \\ \text{Coma } 90° \\ 0 \end{pmatrix} = \begin{bmatrix} a_{0,0} & \cdots & a_{0,5} \\ \vdots & \ddots & \vdots \\ a_{4,0} & \cdots & a_{4,5} \\ 1 & & 1 \end{bmatrix} \cdot \begin{pmatrix} \Delta X_1 \\ \Delta Y_1 \\ \Delta XY_1 \\ \Delta X_2 \\ \Delta Y_2 \\ \Delta XY_2 \end{pmatrix}$$

2. Calculation of the control matrix.

By inverting the interaction matrix [M*] we obtain the control matrix $[\overline{M*}]$ of the system. This matrix can be easily calculated with Labview or Matlab.

3. Calculation of the actuator displacement amount

The five aberration coefficients and the afocal lenses translation (0) constitute the settings vector $\vec{V}_{S_{1,6}}$. The needed displacements for each actuator are in the Displacements vector $\vec{V}_{D_{1,6}}$. This vector is calculated with a multiplication between the Settings vector $\vec{\boldsymbol{V}}_{\boldsymbol{S}_{1,6}}$ and the control matrix $[\overline{M*}]$.

$$\vec{\boldsymbol{V}}_{\boldsymbol{S}_{1,6}} \times (\overline{\boldsymbol{M}*})_{6,6} = \vec{\boldsymbol{V}}_{\boldsymbol{D}_{1,6}}$$

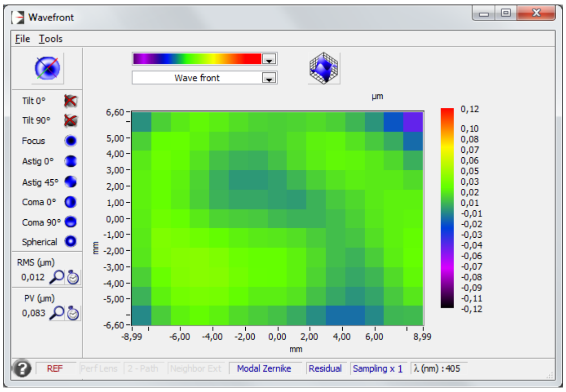
The vector $\vec{V}_{D_{1,6}}$ contains the displacement of each actuator (turns of the actuators) which is needed to generate the current aberration without translates the afocal. So we just have to do a reverse displacement to delete the aberrations. All the needed displacements are listed in the displacements vector. In our example, we defined our own convention: Screwing in is a positive displacement.
For example, if the calculation results in a displacement vector $\vec{V}_D = [+0.5;\ -0.7;\ +0.1;\ +1.2;\ -1.0;\ -0.1]$ these are the settings to do:

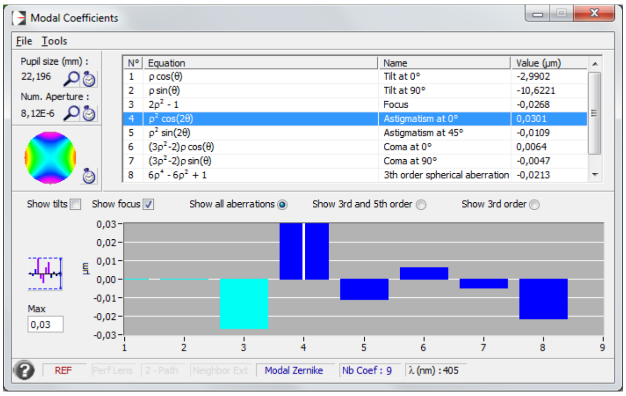
Triplet 1	Settings	Triplet 2	Settings
ΔX_1	Screw out 0.5 turn	ΔX_2	Screw out 1.2 turn
ΔY_1	Screw in 0.7 turn	ΔY_2	Screw in 1.0 turn
ΔXY_1	Screw out 0.1 turn	ΔXY_2	Screw in 0.1 turn

Now a new wavefront must be acquired. If the results are satisfying, the setting is done. If not, you need to restart with step 1 by using the new settings vector $\vec{V}_{S_{1,6}}{}'$ with the updated aberrations.
The three previous steps define one single iteration. The resulting wavefront after each iteration has to be enhanced. If this is not the case, you should reevaluate your interaction matrix.

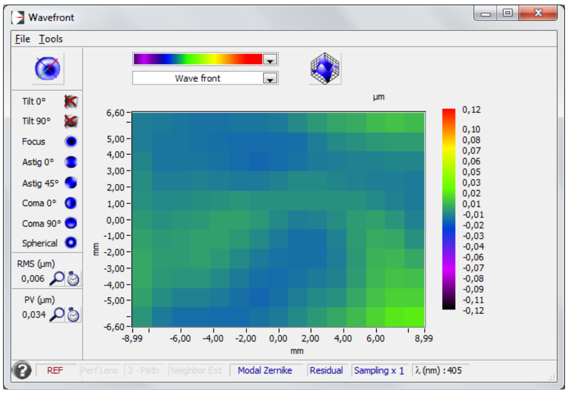
RESULTS OF THE EXAMPLE

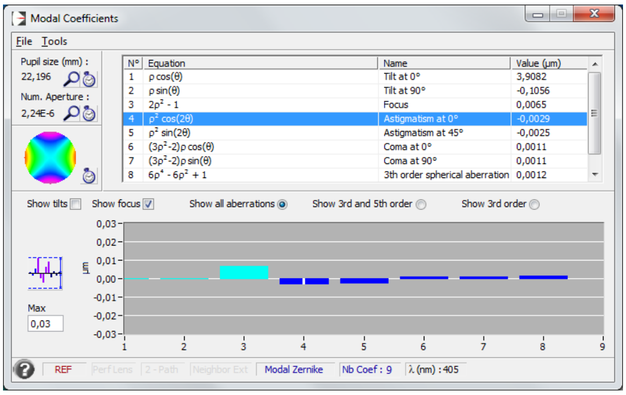
Initial condition of the optical system measured by the HASO HP 16 wavefront sensor:





Result after 4 iterations:





	Initial wavefront	Wavefront after 4 iterations
Focus (nm PV)	-26.8	6.5
Astigmatism 0° (nm PV)	30.1	-2.9
Astigmatism 45° (nm PV)	-10.9	-2.5
Coma 0° (nm PV)	6.4	1.1
Coma 90° (nm PV)	-7.4	1.1
Total (nm RMS)	**11.5**	**6.4**
Total (nm PV)	**83.2**	**34**