Merit function regression method for efficient alignment control of two-mirror optical systems

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Abstract: The precision alignment of high-performance, wide-field optical systems is generally a difficult and often laborious process. We report a new merit function regression method that has the potential to bring to such an optical alignment process higher efficiency and accuracy than the conventional sensitivity table method. The technique uses actively damped least square algorithm to minimize the Zernike coefficient-based merit function representing the difference between the designed and misaligned optical wave fronts. The application of this method for the alignment experiment of a Cassegrain type collimator of 900mm in diameter resulted in a reduction of the mean system rms wave-front error from 0.283λ to 0.194λ, and in the field dependent wave-front error difference from ±0.2λ to ±0.014λ in just two alignment actions. These results demonstrate a much better performance than that of the conventional sensitivity table method simulated for the same steps of experimental alignment.

OCIS codes: (110.6770) Telescopes ; (120.4820) Optical systems ; (220.1140) Alignment

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1. Introduction

The precision alignment of the optical systems of relatively small fields of view (e.g. less than 0.1 degree) can be achieved efficiently by measuring the on-axis interferogram. However, it becomes a lengthy and time consuming task to align optical systems with relatively large fields of view or those with off-axis components. For example, when aligning two mirror systems, the wave-front error (WFE) observed from the extreme edge of its field of view can be large, even though it exhibits low RMS WFE from the on-axis measurement. This is because two mirror systems feature certain coma-zero conditions in which the misalignment is not noticeable from on-axis measurement but amplified with the off-axis measurement [1].

Many researchers have developed the reverse-optimization algorithm for the purpose of aligning off-axis systems such as Three Mirror Anastigmat (TMA) or the wide-field optical system [2-5]. The method attempts to discover the misalignment of the components by measuring the system WFE from several different fields. It then applies the theoretical Zernike sensitivity table to the misalignment parameters and the measured Zernike coefficients of the sample optical system under the disturbed alignment. This technique has been well-developed and has already been implemented in optical design software such as Code V. If the Zernike coefficient sensitivity to the misalignment parameters is sufficiently linear, the technique can bring relatively high accuracy and convergence to the reverse estimation of misalignment state.

In the research described below, we report a new reverse-optimization algorithm that uses the merit function (MF) regression instead of the sensitivity table. The technique uses the MF minimization consisting of the measured and model Zernike coefficients of the target optical system. The regression process employing the actively damped least square method adjusts the misalignment parameters of the model optical system until the smallest MF value is obtained. We then applied the technique for alignment experiments for the KRISS two-mirror optical system.

Section 2 describes the optical characteristics of the KRISS collimator. This is followed in Section 3 by an analysis of the shortcomings of the existing sensitivity table method and the theoretical basis of the new MF method.. The performance limitations of the new MF methods in practical application are studied in Section 4. The alignment simulation and experiment presented in Section 5 demonstrates the superior performance of the new MF method to that of the sensitivity method. This leads to Section 6, where the implications for practical application are discussed.

2. KRISS Collimator

We are currently developing a collimating optical system shown in Fig. 1 [6]. It is a Cassegrain telescope of 900 mm in diameter, 0.14 degree in full field of view and 11 in f-ratio. The system has an aspheric primary mirror (PM) of which the conic constant is -1.013 and a secondary mirror (SM) of 200 mm in diameter and -2.121 in conic constant. The radii of PM and SM are 3433 mm and 784 mm respectively. Figure 2 shows the measured WFEs of PM and SM. Some deformation of PM is noticeable, mainly due to the mounting stress. The rms WFEs of PM and SM are 0.19λ and 0.03λ, respectively. The distance of 1392 mm between the PM and SM is maintained using a carbon-composite metering structure of near zero CTE (Coefficient of Thermal Expansion). The alignment tolerances of SM were defined as 0.04 mm in decenter and 0.005 degree in tilt angle, which degrades the rms WFE less than 0.01λ. The SM assembly is equipped with manual actuators for micro adjustment of the alignment

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parameters (i.e. 5 degrees of freedoms) within the tolerances. This collimator was used for simulations and experiments described in the subsequent sections.

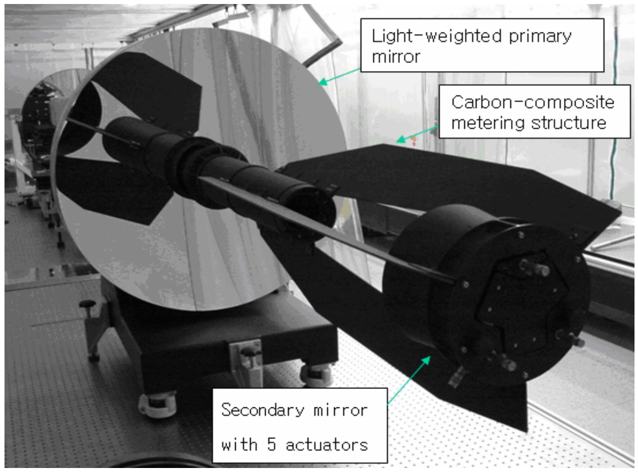
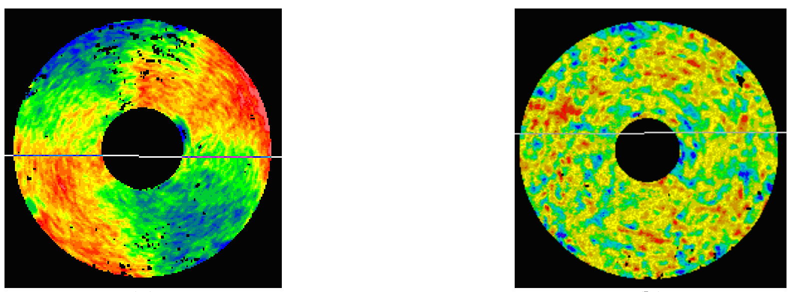


Fig. 1. Picture of the KRISS 0.9-m collimator.



(a) (b)

Fig. 2. Measured rms WFE of primary (a) and secondary mirror (b) before integration

3. Theoretical Basis of Merit Function Regression Method

3.1 Concept and limitations of conventional sensitivity table method

Assuming that the Zernike coefficients are linear to misalignments, each Zernike coefficient can be derived from the linear combination of different misalignment parameters with relevant Zernike sensitivities as expressed in Eq.1.

$$\Delta Z = A\Delta D \tag{1}$$

, where

$$\Delta Z = \begin{bmatrix} \Delta Z_1 \\ \vdots \\ \Delta Z_n \end{bmatrix} = \begin{bmatrix} Z_1 \\ \vdots \\ Z_n \end{bmatrix} - \begin{bmatrix} Z_{1o} \\ \vdots \\ Z_{no} \end{bmatrix}, A = \begin{bmatrix} \frac{\delta Z_1}{\delta x_1} & \cdots & \frac{\delta Z_1}{\delta x_1} \\ & \vdots & \\ \frac{\delta Z_m}{\delta x_n} & \cdots & \frac{\delta Z_m}{\delta x_n} \end{bmatrix} \text{ and } \Delta D = \begin{bmatrix} \Delta x_1 \\ \vdots \\ \Delta x_n \end{bmatrix} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} - \begin{bmatrix} x_{1o} \\ \vdots \\ x_{no} \end{bmatrix}$$

Here, ΔZ is the differences of Zernike coefficients between the measured and model WFEs. A is the Zernike sensitivity table that is calculated from the ideal configuration model. ΔD represents the amount of disturbances in the alignment parameters (x_i) such as displacement,

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tilt or decenter. *m* and N are the total number of Zernike coefficients fitted and the total number of alignment parameters, respectively. This equation is commonly solved for ΔD using singular value decomposition technique [6].

As shown in the previous studies [4, 7], this method tends to bring high accuracy to the estimation of the misalignment parameters as long as the linearity of the Zernike coefficient sensitivity to the alignment perturbation is maintained. If the misalignment range were large, the non-linearity of the Zernike sensitivity would be a major factor for the residual error after applying this method. In addition, the problem can be further aggravated due to the fact that, since the sensitivity table A is generated from the ideal model configuration, the measured Zernike coefficients with some field errors can also serve as an additional residual error source. The linearity dependency and this field error effect are discussed further in the following sections.

3.2 Merit function regression method

The MF, commonly used in optical modeling software, is defined as follows:

$$MF^2 = \frac{\sum W_i (V_i - T_i)^2}{\sum W_i} \quad , \tag{2}$$

where V_i and T_i are the current and target values of chosen parameter that are the Zernike coefficients in our case. W_i is the weighting factor. Many commercial optical design software use the actively damped least square method to minimize the MF value to produce the best-fit parameters [8, 9]. Like the sensitivity table method, the MF regression method also uses a kind of least square method to fit the data; however, the main difference between two methods is that the MF regression method does not rely on the predetermined trends of variation of the Zernike coefficients (sensitivity). Since the MF regression method deals with current and target values only, the estimation of misalignment is not affected by the amount of initial misalignments.

In order to effectively use the MF regression, we wrote a program using the macro language of commercial optical design software and it carries out the following tasks;

1. Read the Zernike coefficients from the interferometric measurements. They are T_i which represents the misaligned system WFE.
2. Assign the ideal model Zernike coefficients to V_i, which represents the current alignment status (i.e. wave front) of the designed optical system.
3. Run the optimization algorithm (e.g. damped least square technique [8, 9]) embedded in the software to minimize the MF. This operation varies the alignment parameters so that V_i approaches T_i as closely as possible.
4. When MF is minimized, read the alignment parameters that indicate the misalignment state of the optical system.

Using both the sensitivity table and MF regression methods, we estimated the prediction accuracy for the known misalignments (two tilts, two decenters, and despace) of SM of the KRISS collimator. Both methods considered five low order terms (Z_5 :Astig X, Z_6:Astig Y, Z_7:Coma X, Z_8:Coma Y, and Z_9:Spherical) of Fringe Zernike polynomials at 5 different fields (on-axis and 4 extreme fields). The weighting factor for the MF regression method was set to unity for all variables. The results are summarized in Table 1. The sensitivity table method resulted in accuracy of prediction worse than that of the merit function minimization method, and the estimation error increases with the magnitude of misalignment perturbation. This can be caused either by the nonlinearity of the Zernike coefficient sensitivity to the alignment parameters and/or by cross-coupling among the alignment parameters, as explained in the earlier study [7]. In practice, therefore, the sensitivity table method tends to give slow

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convergence in iterative alignment processes, when the initial alignment state is far from the design tolerance range of the target optical system.

On the other hand, the MF regression method showed the extremely small calculation errors of less than 10^{-5} even with Dx = Dy = 1 mm and Tx = Ty = 1 deg. This indicates that the MF regression method can provide fast convergence in iterative alignment processes, even if it starts from the misalignment state that is initially far from the design tolerance of the target optical system.

Table 1. Misalignment calculation results using the sensitivity table method and MF regression method for several misalignment cases applied to the SM of KRISS collimator. We denote Dx and Dy for the decenters in X-axis and Y-axis, Tx and Ty for the tilts about X-axis and Y-axis and Df for the defocus of SM. Error indicates the difference between the actual misalignment and calculation. Note that the machine precision is 10^{-16} in double precision, when looking at error terms.

Case	*Parameter*	*Misalignment*	*Sensitivity table method*		*MF regression*	
			Calculation	Error	Calculation	Error
Case1	Dx (mm)	0.2	0.180	0.020	0.200	$<10^{-5}$
	Dy (mm)	-0.2	-0.184	-0.016	-0.200	$<10^{-5}$
	Tx (deg)	0.2	0.197	0.003	0.200	$<10^{-5}$
	Ty (deg)	-0.2	-0.204	-0.004	-0.200	$<10^{-5}$
	Df (mm)	0.2	0.201	-0.001	0.200	$<10^{-5}$
Case2	Dx (mm)	0.5	0.398	0.102	0.500	$<10^{-5}$
	Dy (mm)	-0.5	-0.407	-0.093	-0.500	$<10^{-5}$
	Tx (deg)	0.5	0.483	0.017	0.500	$<10^{-5}$
	Ty (deg)	-0.5	-0.519	0.019	-0.500	$<10^{-5}$
	Df (mm)	0.5	0.508	-0.008	0.500	$<10^{-5}$
Case3	Dx (mm)	1	0.694	0.306	1.000	$<10^{-5}$
	Dy (mm)	-1	-0.708	-0.292	-1.000	$<10^{-5}$
	Tx (deg)	1	0.948	0.052	1.000	$<10^{-5}$
	Ty (deg)	-1	-1.058	0.058	-1.000	$<10^{-5}$
	Df (mm)	1	1.032	-0.032	1.000	$<10^{-5}$

4. Error Sources of the MF Regression Method

4.1 Effects of number of measurement fields

Theoretically, the MF method requires single field interferometric measurement for the estimation of the misalignment state for the two-mirror system, as 5 Zernike coefficients (Z_5 ~ Z_9) extracted from the single field measurement can be used to solve Eq. 2 for the 5 misalignment parameters. However, the interferometric measurement has, in general, several error sources including air turbulence and vibration. Such error sources can produce inaccurate Zernike coefficients, hence leading to increased error in estimating the misalignment parameters. This can be improved by taking multiple field measurements, as it tends to average the effects of the interferometric measurement error sources out, but at the expense of stretching the process overhead.

We used the KRISS collimator design parameters to simulate the accuracy of MF regression with the number of measurement fields changed and with the maximum 10% random fluctuation in the Zernike coefficients. The starting misalignment parameters were set to the same values as those in case 1 in Table 1 and the Z_5~Z_9 coefficient terms were used to fit the optical path difference map from each field measurement. Figure 3 shows the field numbering that the measurement sequence followed in this simulation.

The simulated Dx and Ty are plotted against the total number of measurement fields used in Fig.4. Each data point in the figure is averaged over 20 simulation runs and comes with the corresponding standard deviation. We note that the standard deviation of Dx decreases from ±0.131 mm to ±0.032 mm as the number of fields increases from 1 to 9. A similar trend takes

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place for Dy as well. These results confirm that the influences of interferometric measurement error sources onto the Zernike coefficients are reduced as the number of fields used is increased. As for the actual alignment experiment using the KRISS collimator, explained in a later section, we used the 5 measurement fields for its process throughput, whilst the standard deviations of Dx and Ty are ±0.039 mm and 1 arc min, respectively, according to Fig. 4, and they are well within the system tolerance.

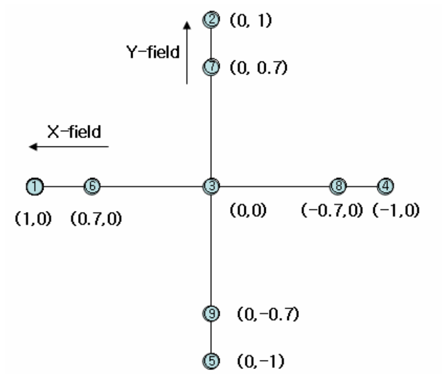

Fig. 3. Measurement field numbering at the image plane. The number in parenthesis indicates the relative incident angle.

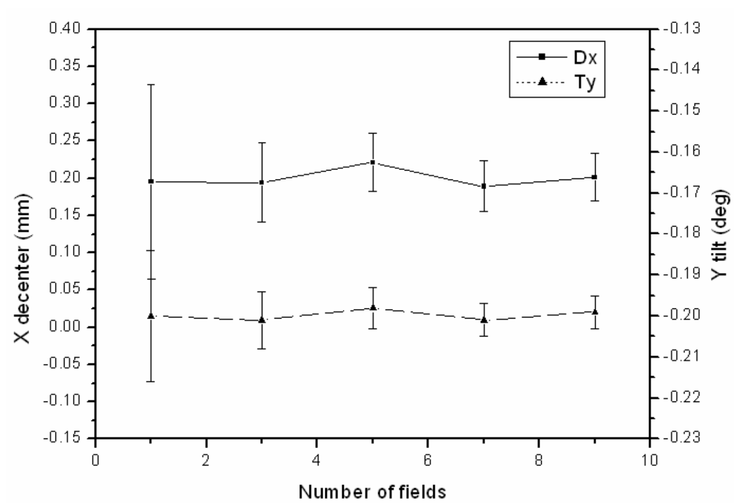

Fig. 4. Effect of the interferometric measurement errors on decenter in X axis and tilt about Y axis. Note that the standard deviation decreases with the increase in the number of measurement fields.

4.2 Effects of field positioning error

In order to measure the WFE at the specific measurement field angle, the reference spherical wave from the interferometer should be focused onto the exact field position with respect to the telescope focal plane. Often, in alignment practice, finding the correct field position corresponding to each field is difficult and tends to leave the residual positioning error. This resulting error serves as the estimation error source for the given alignment state, when the sensitivity table is generated from the optical design with no field errors.

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First, we investigated the performance of the sensitivity table method by simulating the effect of this error with the whole field shifted about 0.02 degrees along the X-axis, which corresponds to 28.6% of the total field positioning error. The misalignment parameters were set to the same as in case 1 in Table 1. Equation 1 was then solved with the Zernike sensitivity table generated from the KRISS collimator optical design that does not have the field positioning error. The resulting estimation error was 0.184 mm in Dx and 0.034 degree in Ty, which are nearly 10 times larger than the 0.02 mm and -0.004 degree obtained without the field errors, as shown in Table 1. This demonstrates the critical weakness of the sensitivity table method, in that its performance is severely degraded with the presence of the field positioning errors unavoidable in alignment practice, and that it also lacks a built-in capacity to predict the field positioning error.

Second, as shown in Table 1, the MF method can accurately estimate the misalignment state, provided the measurement field position is well known. Hence, under the same simulation conditions, we ran the MF regression method to compute the shifted field position of 0.02 degrees mentioned earlier. Fig. 5 shows the results of the MF regression runs for the field position varied from -0.1 degrees to +0.1 degrees on the X-axis with the interval of 0.01 degree. The MF value approaches nearly zero at 0.02 degrees, confirming that it is the shifted field position it was looking for. In summary, these simulation exercises indicate that the MF regression can be an extremely useful tool for computing the field positioning error and the misalignment parameters simultaneously and accurately, whilst the sensitivity table method requires precise field position, as a necessary pre-condition for accurate estimation of the alignment state.

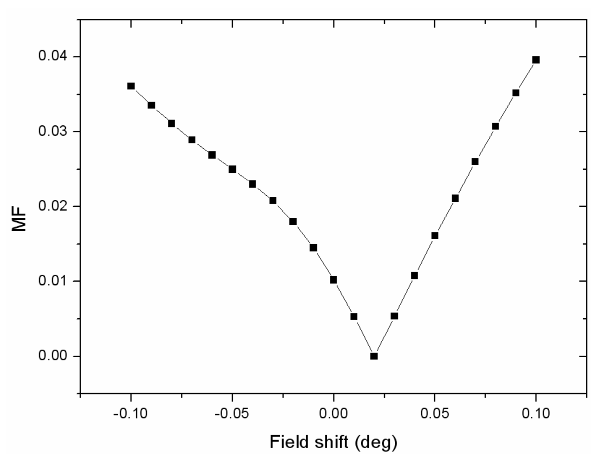

Fig. 5. The variation of MF as the field is shifted 0.02 degrees on the X-axis.

5. Alignment Experiment with KRISS Collimator

Using the KRISS collimator, the actual alignment experiment proceeded with the MF regression method. Figure 6 shows the experiment results, this being the mean WFE and maximum WFE difference plotted against the alignment action number. Figure 7 shows the field error calculated by the MF regression run. Figure 8 shows the "center field" measurements of WFE at each alignment action. In this case, the information about the deformation of PM, shown in Fig. 2, was input to the optical design under which the MF regression run is executed. Four parameters (i.e., X- and Y- decenters and X- and Y- tilts) were used for the alignment action. Initially, the optical system was aligned, by means of manual adjustment, according to the engineer's estimate, down to the mean rms WFE of

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0.286λ and the maximum rms WFE difference of 0.2λ, these being obtained from 5 measurement fields as suggested earlier in subsection 4.1.

At this stage, the MF regression method was employed and information about the field error and misalignment of SM was obtained. With this information, the optical design software predicted that the state of the system (i.e. before the 1st alignment action) was the mean rms WFE of 0.257λ and the maximum rms WFE difference of 0.18λ. The difference between the prediction and the measurement indicates some errors in the MF regression run. The main reason for such difference might be from the errors in the WFE measurement that could be much more than 10 %, as explained in section 4.

Following these predictions, the 1st alignment action (i.e. correction of field error and misalignment of SM) was performed and produced the measured WFE (i.e. solid square symbol) of "1st alignment" in Fig. 6. The measured mean rms WFE and the maximum rms WFE difference was reduced to 0.259λ and 0.102λ, respectively. The MF regression run in this state showed 0.222λ in mean rms WFE and 0.076λ of maximum rms WFE difference, which shows some calculation errors from the MF regression run. After the 2nd alignment action, the measurement result shows 0.194λ in mean rms WFE and 0.014λ in maximum rms WFE difference. Considering that the final rms WFEs observed both from Fig. 6 and 8 come mostly from the deformation of PM and thus cannot be improved by continuing the alignment step, the KRISS collimator was successfully aligned. It is also shown in Fig. 7 that the field error was reduced from 0.05 degrees to 0.01 degrees. The field error of 0.05 degrees is about 70 % of a half field of view. Since this large error was decreased to 14% after two alignment actions, the MF regression method must be an effective tool in alignment, even with a large initial field error.

However, the final MF regression run showed 0.041λ in maximum rms WFE difference, which means that another alignment action would be necessary. This discrepancy comes from the errors in Zernike coefficients and thus we would have some fluctuation in the measured mean rms WFE above 0.19λ if we performed the further alignment. We believe that if the environmental conditions were much more stable during the alignment, we would achieve a more accurate alignment using the regression method.

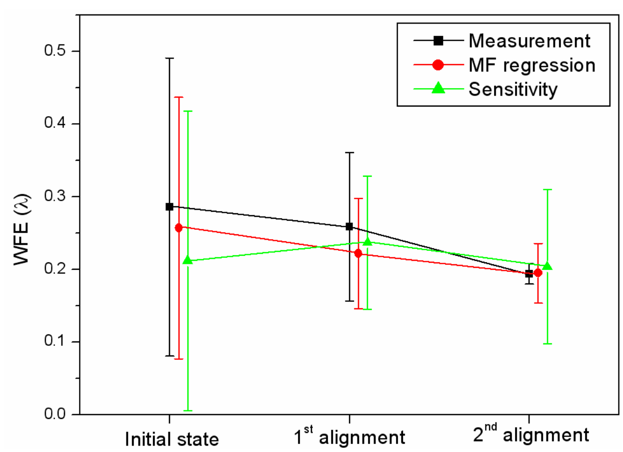

Fig. 6. Alignment results at each alignment action. Each point is the mean WFE for 5 fields and the error bar is the maximum rms WFE difference (λ = 633 nm).

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The simulation of the above mentioned alignment process using the sensitivity table method was performed for comparison and exhibits much larger maximum rms WFE difference and error in mean values at each stage of alignment as shown in Fig. 6. This is caused by the measurement field error that the sensitivity table method cannot remove on its own and the errors in the Zernike coefficients that are similar to the MF regression. It is clear from this comparison that the MF regression method is much more effective and accurate in the alignment of two mirror optical systems than the conventional sensitivity table method.

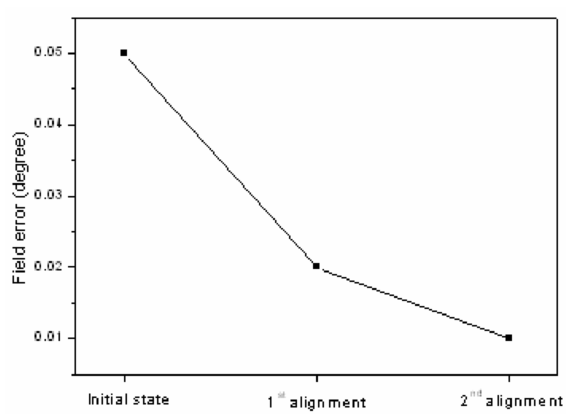


Fig. 7. Field error calculated from MF regression run.

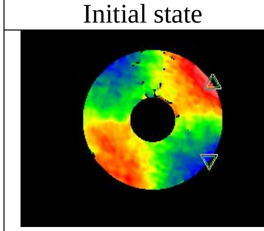
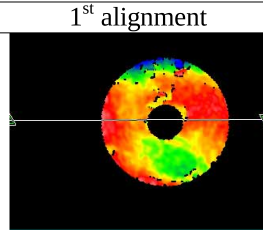
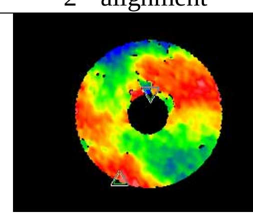
Initial state	1^{st} alignment	2^{nd} alignment
		
RMS=0.283λ	RMS=0.236λ	RMS=0.192λ

Fig. 8. On axis rms WFEs of the KRISS collimator at each alignment action (λ = 633 nm).

6. Concluding Remarks

We report a new alignment control technique that is based on the merit function regression. The method utilizes the merit function consisting of Zernike coefficients representing the misaligned WFE, and attempts to minimize MF using actively damped least square algorithm in order to estimate the misalignment states. The underlying concept and theory exhibit strength in simplicity and, because of that, their “shop-floor” application tends to be straightforward. From both simulations and experiments, we proved that, for practical application, this new method can be more effective and accurate than the conventional Zernike coefficient sensitivity table method.

In particular, when the misalignment state is presented together with the measurement field positioning error, the MF regression method shows its capability to estimate both of them simultaneously, while the conventional sensitivity method tends to provide unacceptable estimates of the alignment state, not to mention its inability to track the field positioning error. We successfully adapted this method to align the KRISS collimator of 900 mm in diameter. We believe that the MF regression based alignment control technique, such as the one reported here, can bring higher convergence in alignment processes for a wide range of optical systems that require a wide field of view and/or off axis components including three mirror Korsh telescopes. Extending the MF regression method to the alignment of multiple mirror systems would be greatly benefited from the use of a new theoretical frame that can describe higher order wave fronts in a more effective manner. The complex function representation [10] recently published has the potential to be a fair example of such a theoretical frame. With this in mind, we will report a further investigation on extending the MF regression method and its practical limitations for the multiple mirror system alignment in our next paper [11].

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