

Deflectometric Measurement of Astronomical Mirrors: Comparison of Different Calibration and Evaluation Methods

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Long-working-distance phase-measuring deflectometry (LWD-PMD) in a 2f configuration requires high accuracy over large working distances, placing particular demands on system calibration. This work addresses the gray-value and geometric calibration of such a setup and presents results of an in-situ point-spread-function estimation for the astronomical mirror under test.

1 Introduction

Interferometric methods are an established reference for the high-accuracy testing of optical surfaces. However, their in-situ application to an astronomical mirror already installed in a telescope is technically demanding and may not even be feasible. Therefore, long-working-distance phase-measuring deflectometry (LWD-PMD) in a 2f configuration is investigated for the in-situ characterization of the primary telescope mirror at the observatory of Landshut University of Applied Sciences [1].

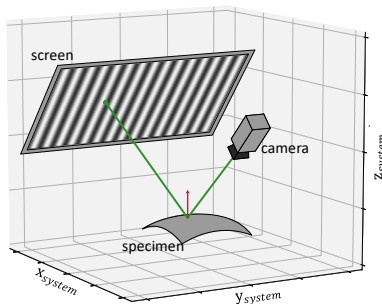


Figure 1. Schematic principle of phase-measuring deflectometry [3].

As illustrated in Figure 1, the measurement is based on the evaluation of reflected phase-shifted sinusoidal patterns, providing correspondences between camera and display coordinates ([2], [3]). Accurate determination of these correspondences requires both correction of the nonlinear response of the display-camera system and precise knowledge of the spatial arrangement of its components. Accordingly, the gray-value calibration and the geometric calibration of the setup are considered.

2 Gray-Value Calibration

To determine the required camera–display correspondences, a conventional phase-shifting algorithm is combined with Gray-code decoding. Since acquisition time is not critical for the present application, the additional pattern sequence required for absolute phase determination is acceptable. To compensate for nonlinearities in the radiometric re-

sponse of the display–camera transmission chain, different fundamental approaches to gray-value calibration and their possible combinations were evaluated, as summarized in Figure 2.

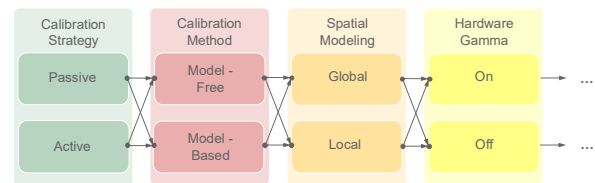


Figure 2. Overview of the investigated gray-value calibration approaches and their possible combinations.

Calibration performance was assessed via contrast image homogeneity. Figure 3 illustrates the difference between **active and passive calibration**. Active calibration compensates *before* the projection of the gray-values so that the overall display–camera response becomes approximately linear, whereas passive calibration corrects the measured camera values *after* acquisition. Since passive correction is applied in camera coordinates, local display information is not directly available and can only be recovered through an iterative approach.

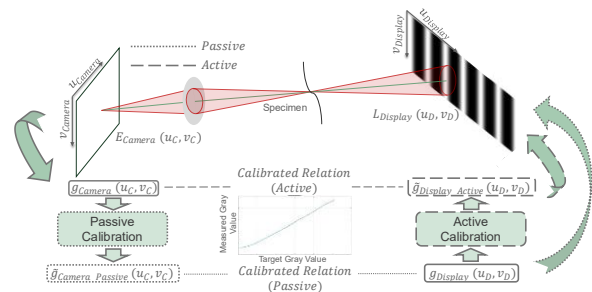


Figure 3. Schematic comparison of passive and active gray-value calibration. Passive calibration corrects the measured camera response after transmission, whereas active calibration precompensates the display signal before projection.

To implement the correction ($g \rightarrow \tilde{g}$), two different **calibration methods** were considered: a **model-free** method via an empirical look-up table and a **model-based** method utilizing a suitable model-function. As

illustrated in Figure 4, both calibration methods reduce nonlinear distortions, but the model-based approach achieves higher contrast because the model-free correction is limited to a restricted operating range.

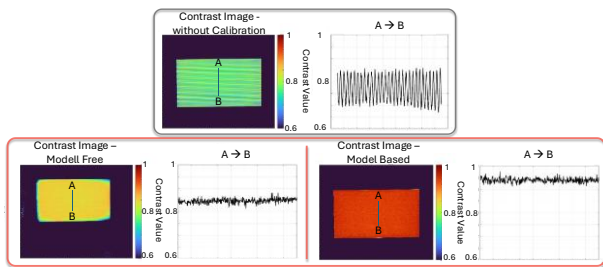


Figure 4. Contrast images and corresponding A–B sections without calibration (top) and after model-free and model-based calibration (bottom).

Local **Spatial Modelling** is recommended because the gray-value response of conventional displays varies considerably across the display area.

3 Geometry Calibration

In conventional geometric calibration, the camera is first calibrated intrinsically, followed by pose estimation of a marker-equipped calibration mirror and subsequent resection of the display [2]. In the investigated 2f setup, however, the working distance is approximately 3.2 m. Relative to the primary mirror, which diameter measures only 0.4 m, the camera chief rays therefore exhibit only weak divergence, rendering the conventional estimation via resection algorithm ill-conditioned, as illustrated in Figure 5. Errors in the mirror pose also strongly affect the subsequent reconstruction of the system geometry, since the physical display appears as a virtual display in the mirror and must be transformed with respect to the estimated mirror pose.

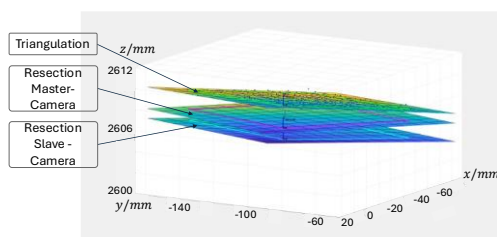


Figure 5. Repeated estimates of the calibration-mirror pose obtained by resection using the master and slave cameras and by stereoscopic triangulation. The mirror remained fixed throughout all measurements; therefore, the observed spread reflects the method-dependent variation of the pose estimation.

For a more stable pose estimation, the calibration mirror is positioned as close as possible to the measurement setup and observed with a stereo-camera system. Its markers are triangulated to form a three-dimensional point cloud, which is then registered to the known marker positions to determine the mirror pose. This pose serves as the basis for the subsequent geometric calibration. The same ap-

proach cannot be applied directly to the display because only a limited number of display points are visible in both cameras. However, the accuracy of the mirror pose is considerably more critical than that of the display pose.

4 Point-Spread Function

The 2f configuration additionally enables a geometrical-optics-based estimation of the point-spread function (PSF) [1]. Interpreting the density of the sight rays' impact positions on the display as brightness, the camera can be considered as an ideal "point source". By holding a real point source (flashlight) next to the camera, the calculated and the actual PSF can be directly compared on the display.

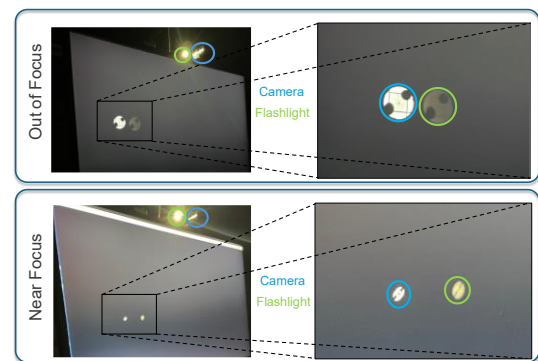


Figure 6. Direct projection of a flashlight positioned next to the camera onto the display for a plane behind the focus (top) and near the focal plane (bottom). The full images are shown on the left, with enlarged views of the two PSFs on the right.

The resulting distribution was determined both for a plane behind the focus and near the focal plane of the mirror under test, as illustrated in Figure 6. The PSF distributions obtained by deflectometry reproduce both the characteristic structure behind the focus and its pronounced reduction in size near the focal plane. The flashlight projections appear smoother, as they can be interpreted as a convolution of the mirror PSF with the finite spatial extent of the flashlight source.

5 Conclusion

The presented results demonstrate suitable approaches for both the gray-value and the geometric calibration of a long-working-distance PMD-setup for the in-situ measurement of astronomical mirrors.

References

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