Adaptive secondary mirror for LBT and its capacitive sensors: how can we calibrate them?

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\section*{ABSTRACT}

The Adaptive Secondary Mirror (ASM) for LBT arrived in its final characterization phase. In order to use its large stroke performances and high order correction capability, we needed to develop a fast and accurate calibration procedure which use optical measurements and correlates them with signals of capacitive sensors co-located with the actuators. Each capacitive sensor gives a signal related to the local gap between the Reference Body and the Thin Shell of the ASM. The main issue in this implementation is the inverse relationship between mirror position (quantity to be measured) and capacitance (sensed quantity), and the evaluation of the effective reference and stray capacitance for each actuators that affects the calibration parameters. We developed a new method to correlate interferograms optically describing the mirror shape and the shell pistoning: moreover, with a non-linear data fit, we solved the unknown calibration parameters to find the linearization formula to be implemented in the system, giving a optimal solution to the capacitive sensor calibration problem.

\textbf{Keywords:} Adaptive Secondary, capacitive sensor, calibration, raw interferogram, LBT

\section{1. INTRODUCTION}

The first Adaptive Secondary\textsuperscript{1} (AS) for Large Binocular Telescope\textsuperscript{2,3} (LBT) has successfully passed the electronic and mechanical acceptance before arriving in Arcetri observatory in the early April. After a short startup time it will be possible to install it in the Solar Tower test bench\textsuperscript{4} and to perform the optical qualification of the deformable thin shell (TS) in order to proceed the test plan of the Adaptive Optics (AO) system by coupling the AS with the wavefront sensor designed for LBT\textsuperscript{5,6} (AGW unit). To complete this phase and proceed to the commissioning at LBT telescope it is mandatory to have a system with high performances, safely and stably working.

One of the main tasks in this period is to calibrate the position sensor of the internal metrology of AS: in fact a severe mis-calibration can affect the performances of entire Adaptive Optics system of LBT. Here after we describe the path that we followed to obtain a fast calibrated configuration.

\subsection{1.1 The P45 prototype}

We presented the prototype P45 several years ago: it is an AS prototype with a reduced-size deformable mirror and forty-five electro-magnetic actuators and an equal number of capacitive sensors giving each one the relative position of the TS from the Reference Body (RB) (see Figure 1 and the reference\textsuperscript{7} for a more detailed description of the prototype). The P45 was used both as a test bench to characterize the system performances, and to develop the optical calibration method. The latter, which allowed us to obtain full parameters estimation, is reported only for that prototype for schedule reasons. In fact, the optical test on the AS is just started in Arcetri Observatory (ITALY) but it requires the end of the flattening phase before proceed to the capacitive sensor calibration. We experimented in the past another optical calibration procedure,\textsuperscript{8} but we decided to renew the method as explained below in order to improve the speed of the process.
Figure 1. The P45 prototype corresponds to the first three rings of the LBT adaptive secondary. The deformable mirror position is measured by capacitive sensors: one plate is the aluminized back surface of the thin shell (a), the other plate is a conductive deposition on the reference body around the force actuators (b).

Figure 2. The capacitive sensor scheme has to be read from left to right: a square wave (reference signal) is injected into the capacitor formed by RB and TS ($C_{\text{meas}}$) and compared with a reference placed capacitance ($C_{\text{ref}}$). After that, two samplers get the analog data and an amplifier make a differential measurement. The obtained value is inversely proportional to the gap between RB and TS.

2. CAPACITIVE SENSORS

The internal metrology used in the LBT672 unit for controlling the TS shape is based on capacitive sensors and they were fully described in previous articles.\textsuperscript{8,9} They are conceptually based on the scheme reported in Fig. 2.

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The relation between the peak-to-valley voltage amplitude \((V_{IN})\) of the input reference square wave and the output voltage \(V_{OUT}\) is given by the relation (1):

\[
\frac{V_{OUT}}{V_{IN}} = \frac{C_{meas}}{C_{ref}} = \frac{d_0}{d} \rightarrow C_{meas} \propto \frac{1}{d}
\]

in which we have \(C_{meas}\) as the measured capacitance, \(C_{ref}\) as the reference capacitance placed into the capacitive sensor electronical circuit, \(d_0\) is the reference distance, \(d\) the measured distance. The mentioned relation does not consider a stray capacitance contribution, so we can model an additional \(C_{stray}\) term between the signal injection and the operational amplifier as a capacitance which is in parallel to the measured one.\(^8\) By considering the contribution of \(C_{stray}\) we can slightly modify the formula and obtain a more generic one. If we define \(v\) as the ratio between \(V_{OUT}\) and \(V_{IN}\) and \(c\) as the ratio between the \(C_{stray}\) and \(C_{ref}\) terms the equation (1) can be rewritten as:

\[
v = \frac{C_{meas}}{C_{ref}} = \frac{d_0}{d} + c - d = \frac{d_0}{v - c}
\]

Therefore we have a inverse proportional relation between voltage and position and \(d_0\) and \(c\) are the parameters to be calibrated. Typical valued used in the unit are: \(V_{OUT}\) between 0 and 20V, \(V_{IN}\) 10V, \(C_{ref}\) 39pF or 56pF. The distances that we measure are within 50-100 \(\mu\)m with few nanometers (less than five) of accuracy and repeatability. The capacitor plates in our case are made of a thin silver deposition around actuators on one side (the RB one) and a thin aluminum film on the other side (back surface of the TS), which is common to all actuators and which is used to inject the reference square wave signal.

### 3. CALIBRATION PROCESS

The position sensors calibration of a deformable mirror (DM) can be performed comparing the optical measurement of mirror surface acquired with an interferometer with the capacitive sensor electrical signal. In a mis-calibrated system, an high amplitude mode application increases the force pattern and bends the DM at the actuator scale spatial frequency. This behavior is more evident applying rigid modes (such us tip, tilt and piston), because they are not real DM deformation and so they should not require large force application. In general the mis-calibration of position sensors in the AS does not reduce the performances of the AO system but it reduce the AS stroke and it can make unstable the system if the applied forces are not continuously relaxed.

The calibration process is divided in two steps: one is pure electrical and it can be done using internal metrology of the AS, the other is optical and it requires an interferometer which could store raw fringe frames.

#### 3.1 Electronical calibration

As first step we set a working gap between TS and RB and we measured a feed-forward matrix.\(^8\) The feed-forward matrix (FF) relates the static force command pattern corresponding to a given capacitive sensor command vector. The matrix is used in the control loop to perform high spatial frequency deformation and it is the equivalent to the stiffness matrix of TS, but it includes the calibration error of both force actuators and position sensors.

The mirror modal base is given by the right eigenvectors in the Singular Value Decomposition (SVD) of FF and the singular value corresponding to each mode shape represents the stiffness of mode itself. Since the physical piston is intrinsically a position pattern with almost-zero force application (no bending) the SVD of FF identify it as an electrical mode among the very first ones. The shape of piston mode is an evident index of relative mis-calibration between one actuator and the others. It represents, in fact, for each actuator the response of capacitive sensor to common force application. An example is reported in Figure 3. When the piston mode shows a pattern which is not negligible (some percent point difference among the actuator values), we have an electrical mis-calibration. In order to correct this problem we analyzed the piston movement of the TS.

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Let us define some useful symbols to proceed in the algorithm description:

\[
ds(v) = \frac{d_{s0}}{(v - c_s)} \quad (3)
\]

\[
dr(v) = \frac{d_{r0}}{(v - c_r)} \quad (4)
\]

where \(dr, ds\) are the real (physical) and the estimated (electrical) distance, \(d_{r0}, d_{s0}\) the real and the estimated gain for the relation, \(c_r\) and \(c_s\) the real and the estimated ratio between stray capacitance and reference, \(v\) the ratio between output and input voltage. Initially the estimated parameters are set to the nominal values (70 \(\mu m\) for \(d_{s0}\) and 0.1 for \(c_s\))

Formally the goal is to describe the piston given by the feed-forward matrix decomposition in terms of \(d_{r0}, d_{s0}, c_r,\) and \(c_s\). Therefore we get \(v\) from (4) and substitute it in (3):

\[
ds(dr) = \frac{d_{s0}}{c_r - c_s + \frac{d_{r0}}{dr}} \quad (5)
\]

Considering \(dr = dr_I + \Delta dr\) and \(ds = ds_I + \Delta ds\) we can apply the Taylor series develop to \(\Delta dr\) around \(dr_I\) (real measure of working gap). We suppose the piston retrieved by SVD of FF a representation of the true piston \(\Delta dr\) respect to the estimated one (\(\Delta ds\)) and we obtain:

\[
\frac{\Delta d_s}{\Delta d_r} = \frac{dr_0 d_{s0}}{(c_r dr_I - c_s dr_I + d_{r0})^2} \quad (6)
\]

Now we can expand \(dr_I\) using the corresponding voltage ratio \(v_I\) by equation (4) and have:

\[
\frac{\Delta d_s}{\Delta d_r} = \frac{d_{s0} (c_r - v_I)^2}{d_{r0} (c_s - v_I)^2} \quad (7)
\]

This coefficient should be 1 (one) in case of perfect piston application (\(\Delta dr = \Delta ds\)).
The equation (7) give us a way to describe the real reference distance and stray capacitive ratio in terms of estimated quantities. To find a solution for the two variable system we need also another correlation between the real values and the estimated ones.

We found another relation correlating the parameter $d_{r0}$ and $c_r$ by analyzing the working gap with a Zernike polynomial fit application. The choice to use a small small amount of Zernike polynomial (eighteen in our procedure) was suggested considering the optical polishing of the front surface and the manufacturing method (the shell was polished over a blocking body) correct the low frequency mode also in the back surface (in the TS of AS, the aluminized one). As consequence, no low spatial frequency should be present in the back surface.

If we explain the residue $B$ between the working gap mirror shape and the Zernike fitting as:

$$B(v) = d_s(v) - d_r(v) = \frac{d_{s0}}{(v_l - c_s)} - \frac{d_{r0}}{(v_l - c_r)}$$  \hspace{1cm} (8)

here in (8) we have the second relation to complete the electronical calibration. In fact, setting $A$ equal to the piston coefficient in the equation (7) and $B$ from Zernike fitting in the equation (8), we can solve the two variable system and found the parameters $d_{r0}$ and $c_r$. By substitution, we get finally the expressions for the real parameters $c_r$ and $d_r$:

$$d_{r0} = \frac{(B - ds)^2d_{s0}}{ds^2A}$$ \hspace{1cm} (9)

$$c_r = \frac{d_{r0}}{B + ds(v_l)} + v_l$$ \hspace{1cm} (10)

By applying the electronical calibration over the unit (an example is in Figure 4) the surface peaks are smoothed and the shape is going to be continuous, as should be in a optical quality thin mirror.

![Figure 4. Mirror shape modification after calibration](image)

(a) Mirror shape before calibration  \hspace{1cm} (b) Mirror shape before calibration

3.2 Optical calibration

The electronical calibration is an important step because it gives a rough pre-calibration that can be optically refined. In fact the second step of the calibration process uses the optical feedback of the interferometer as independent measurement for correcting the internal position metrology implemented in the AS. The process steps are:

1. Gap selection: it’s necessary to select two different gaps to which command a mirror movement. We choose one position at 40µm mean gap and another position 100µm mean gap in order to characterize the typical working conditions needed for Adaptive Optics and chopping.
2. To flatten the TS at two selected gaps with an interferometer: this step is not strictly required for the calibration process but it is recommended in order to have the smallest number of fringes in the interferograms.

3. Command the piston movement forward and backward: the two movements help to identify the structural features due to model errors with respect to the turbulence noise in the residue analysis.

4. Raw fringe frames acquisition

After started the movement, the visible effect is a pattern of fringes passing from white to black while pistoning until the end of the command. It is important at the point 3 to set the gap increment between the two selected positions considering some factors. First of all we have to take care about the dynamic of the movement: it should be as smooth as possible, in order to avoid overshooting in the control loop which could give wrong measurements. Moreover we have to assure a good sampling rate of the sinusoidal variation of intensity done by the fringes (we used at least ten samples per period). Finally, we have to optimize the power of the interferometer laser in order to both cover the full range of the fringes sensor and to avoid saturation effects. For our measurement we used for example a fringe sampling rate of about 30Hz, a signal peak-to-valley of about one hundred counts between the maximum and the minimum values of the raw interferogram and a time to go from one gap to the other of about 25s.

An example of an acquired frame is reported on Figure 5.

The data set are now ready: we have both mirror movement commands and acquired fringe frames, each one with its own time scale. We can proceed now with the data analysis:

(I) Actuator mapping: the fringe frame comes from the interferometer without any marker. Initially we positioned the AS prototype in order to null the clocking difference between our reference axis in the data visualization and the interferogram. So we proceed with a pupil recognition algorithm matching the external and internal radius. At the end we projected the central spot of capacitive sensor in the image, defining a data set for capacitive sensor on each fringe frame over time (Figure 6).

(II) Start and stop detection: the system cannot be synchronized by an hardware line to the interferometer so we have an uncertainty about the estimation of start mirror movement instant. If we analyze the single actuator fringe history we notice a strong slope variation in the data at start and stop of acquisition. In...
fact the signal passes from a relative slow variation due to the air turbulence to the sinusoidal movement
given by mirror piston mode application. We used that first derivative feature to determine for each actuator the time slot in which could be started or stopped the pistoning process. Organizing the data in a histogram, we were able to determine the exact start and stop instant with the precision of interferometer acquisition time (Figure 7,a). To verify the goodness of the signal-to-noise ratio we compared the signal RMS with the turbulence RMS given by the sample out of pistoning time range and we considered a factor beyond six as good for our measurement scope.

(III) Phase unwrapping. The raw interferogram usage give generally some problem in the estimation of a distance greater than one wavelength. We did an attempt to directly fit the acquired data using trigonometric function but the unstableness of result was clear at once, because small variation in the $d_0$ and $c$ in the equation (2) caused large phase wrap in the trigonometric functions. So we decided simply to consider the span between one peak and a valley in a semi period of sinusoidal signal and give to it the fixed value of a quarter of interferometer wavelength* (Figure 7,b) and we obtained a real displacement history for an actuator movement (Figure 8,a).

(IV) Data fitting and residue analysis: the distance $d$ in the equation (2) is now available after the previous step to be managed. We considered before the single forward and backward step, we made a non-linear fit of equation (2) in order to align the data, we collected all two steps as a single measurement and we re-apply the non-linear fitting with the new data set. The result is reported in Figure (8,a).

It’s important to analyze the residue of fit processing reported in Figure (8,b): the very low absolute values on y axis confirm the model is correct and able to describe the data. In fact they pass from a range of about 55µm to a range of about 250nm. The two data sets corresponding to the forward and backward piston movement are still recognizable between 0.6 and 0.8 and over 1.0 $V_{ratio}$ values. We suppose that behavior as an effect of the turbulence (for example caused by the air convection in the laboratory area). The range between 0.8 and 1.0 $V_{ratio}$ instead has a more systematic pattern. This feature is currently under investigation: the effect is quite negligible for the full range calibration but it could be a good starting point to refine the capacitive sensor model.

4. CONCLUSIONS

We presented in this paper a possible solution to the calibration problem for the AS for LBT that could be applied to any deformable mirror with similar features. The stop time needed for the electrical calibration is few minutes if the feed-forward matrices are available for the gap set. Once done the first step, the optical calibration is long to prepare (the interferometer setup and the mirror flat measures at different mean gaps

*The factor four derives from the reflection of the mirror surface (one micron movement in mirror position corresponds to two microns movement of a plane wavefront) and from the semi-period identification

![Figure 6. Example of actuator movement data.](image-url)
Start time estimation

Figure 7. (a) Histogram on data to retrieve start and end time of mirror movement. (b) Example of maximum/minimum values recognition for rough phase unwrap

(a) Capacitive sensor fit result
(b) Capacitive sensor fit residue

Figure 8. Capacitive sensor fitting. In (a), the white dashed line is the result of the fitting over the point cloud of real data. In (b) the fitting residue.

could be time expensive) but it is fast in data acquisition: in few minutes we can have a large data set that we can elaborate off line.

Moreover, if needed, it is possible to increase the precision of the method improving the sampling of fringes intensity variation during the piston movement or considering the whole capacitive sensors area instead of a single spot in the center of them.

The next step we want to concentrate on will be to deep analyze the model and try to understand if the systematic features correspond to a mis-match of the considered model and, in thus, correct the calibration formula currently implemented in the AS.

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REFERENCES


