Vibration compensation for the ARGOS laser up-link path

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Abstract. Present and future adaptive optics systems aim for the correction of the atmospheric turbulence over a large field of view combined with large sky coverage. Thus they use multiple laser beacons on sky. Still usually a guide star for correction of the tilt-aberrations is needed. For some fields even a tilt-star is not available. To still be able to improve the image quality the laser beacons must not be affected by telescope vibrations on their up-link path. For the ARGOS system the jitter of the beacons must be below $0\farcs05$. To achieve this a vibration compensation system is necessary which runs at high speed. In this article the control algorithm for this system and first laboratory tests of the algorithm are presented.

1 Introduction

ARGOS is the future ground layer adaptive optics (GLAO) system for the Large Binocular Telescope (LBT). It is designed to effectively reduce the seeing by a factor of two or better over a wide range of seeing conditions. In Figure 1, a sketch of the ARGOS system (see [1]) is shown. The system should be capable to improve the seeing even without TT-star information. Therefore a good stability of the laser beacons on sky is required. For the ARGOS system the jitter of the laser beacons on sky must be below of $0\farcs05$. From the temporary measurements of the vibrations on the telescope vibration amplitudes of 400 nm are predicted for the laser system which in the worst case correspond to a jitter of 0.55” on sky.
The ARGOS vibration control system (VCS) is designed to detect vibrations on the instrument optical path at a level sufficient to calculate and mitigate the variations in tip and tilt of the different components. The launch path of the lasers is shown in Figure 1. The folding mirrors (LM1, LM2) of the launch telescope are mounted on top of the secondary mirror and the wind-brace. Here the vibrations of the telescope have a big impact, generating tip-tilt-movements on the mirrors which result in displacement of all laser spots on the sky. To mitigate this effect and its impact on the other parts of the instrument, the ARGOS control software has a control loop steering a fast steering mirror (FSM) upstream the launch telescope. The laboratory set-up to test this loop and first results will be described in this article.

2 The concept for vibration compensation

The VCS is supposed to correct for vibrations and deliver a beam stability of 0.05” or better. The concept of the vibration control is shown in Figure 2. The signals coming from 8 accelerometers which are placed on the two folding mirrors of the laser up-link path are fed into the control computer. Here a Kalman filter based recursive controller calculates the voltage to be applied to the FSM. Obviously the system is a feed forward system. Several controllers have been tested for the VCS. From these controllers a model based approach was found to be the most capable. The details of this Kalman filter based approach will be described below.
Some additional features of the VCS which will not be discussed in detail is the possibility to offload large strokes from the FSM to the first folding mirror (LM1) and to continuously monitor the vibration spectrum and change the frequency input for the model based controller.

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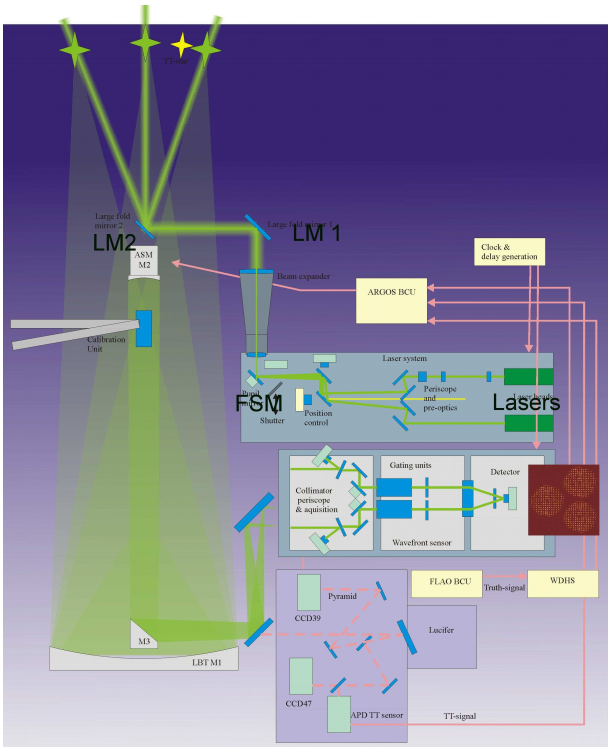

Fig. 1. Sketch of the ARGOS system at the LBT. (Thanks to S.Rabien). The important components of the laser launch path are the fast steering mirror (FSM) and the two folding mirrors (LM1, LM2).

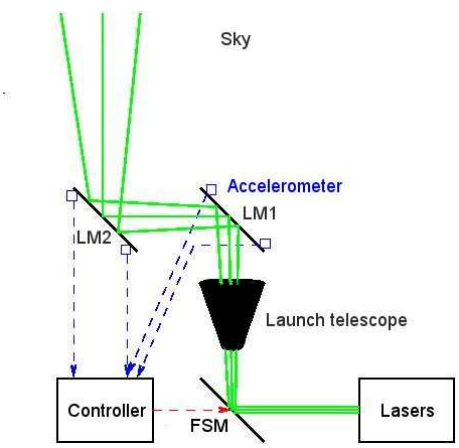

Fig. 2. Set up, of the vibration compensation at the telescope.

2.1 Specifications and laboratory set-up

To achieve the performance of the system stated above the following specifications for the system at the telescope will have to be met (a_{max} = maximum amplitude of tilt typically 400nm, f = frequency typically $\leq$ 30 Hz):

1. a maximum time delay $\delta t < 36/a_{max}[nm]/(2 * \pi * f[Hz])[s]$,e.g., for a_{max}=400 nm and f=30 Hz: $\delta t < 0.5$ ms
2. accelerometer noise $\sigma < 1.41 * 10^{-6} * f[Hz]^2[m/s^2]$

3. accuracy of frequency deduction: $\delta f/f < 18/a_{max}[nm]$,e.g. for a_{max}=400 nm: $\delta f/f < 0.045$
4. accuracy on orientation between mirrors: $\alpha < 0.5acos\left(\sqrt{(1-(36/a_{max})^2)}\right)$, e.g.,for a_{max}=400 nm and f=30 Hz: $\alpha < 2.6$ degrees.

In the lab we build a set up as a scaled down model of the situation on the telescope but yielding the same displacement of the accelerometers as on the telescope. But to minimize the dimensions of the set-up the deflection angle must be maximized. This entails that the accelerometers must be mounted as close as possible to the optical axis: The mirror used will have 12.5 mm diameter. The accelerometers have 25 mm diameter. Thus the acceleration is measured at 20 mm from the axis. As the acceleration on-sky will be measured at 300 mm from the axis one gains a factor of approximately 15 in angle compared to the situation on-sky. This means the maximum tilt angle in the lab is $8\overset{''}{.}25$ and desired tilt angle is $0\overset{''}{.}75$.

2.2 Hardware

The system consists of three main hardware parts:

- the accelerometers
- the control computer
- the FSM for compensation.

Additionally in the lab a mirror to to introduce vibrations on the beam will be used.
As accelerometers we have chosen PSB 393B05 accelerometers due to their small weight and small measurement noise. Still the noise does only allow for frequencies f down to 3 Hz to be measured within the specified accuracy. This does not exactly meet the requirements. Never the less for weight reasons we cannot make use of more sensitive accelerometers. I addition the very low frequency vibrations were measured at larger structures at the telescope. We expect that the mirror and its structure will not exhibit frequencies this low. This expectation is supported by measurements on the tertiary mirror of the LBT which is a twin of the LM mirrors.
The control computer is the NI PXI 1031 chassis with the PXI 4472 input, PXI 6733 output board, and a PXI 8108 controller.
The FSM is the PI S-330 mirror. It has been tested for amplitude and phase response and exhibits a latency 2 ms. So there will be the need of a predictive algorithm to mitigate the latency at least for frequencies larger than 7.5 Hz.
The vibrating mirror which is used in the lab only is a simple mechanical construction excited via a

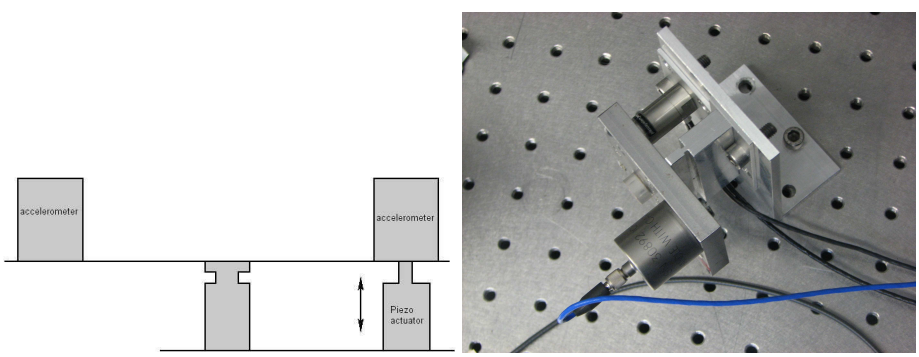

Fig. 3. Left:Principle of the mechanical set-up for the vibrating mirror. right: Picture of the mirror with one accelerometer attached

Piezo actuator (see Figure 3). Due to this scheme it exhibits not only the applied frequency but also several overtones and high frequency noise (see Figure 4). For testing purposes this behaviour is welcome as one can already test the algorithm for several simultaneous frequencies of vibration while only a single frequency sine wave is applied to the Piezo actuator.

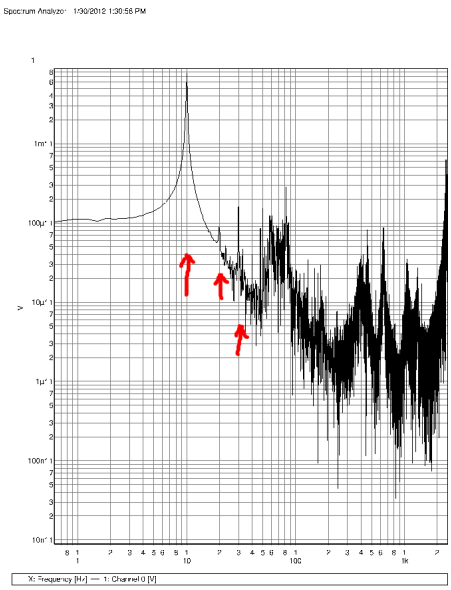

Fig. 4. Power spectrum of vibrating mirror. The scale is logarithmic. The excitation was at 10 Hz the next two overtones and the high frequency noise are clearly visible.

2.3 Control algorithm

The control algorithm for the vibration compensation system is based on a Kalman filter design ([2],[3]). It further exploits the predictive behaviour of the Kalman filter to act as a predictor for more than a single time step into the future.

2.3.1 Kalman filter for vibration

The Kalman filter is a recursive filter to reduce the output noise in a system with linear behavior. In our case the linear system can be described as in [3]. If the vibration has a single frequency ω_r with sinusoidal behaviour and is sampled in time steps Δt the linear connection between present system state $x_n^{\omega_r}$ and past states $x_{n-1}^{\omega_r}, x_{n-2}^{\omega_r}$ is given by

$$x_n^{\omega_r} = 2cos(\omega_r \Delta t) x_{n-1}^{\omega_r} - x_{n-2}^{\omega_r} \tag{1}$$

So for the Kalman filter equation the state X_n of the system is given by a two element vector: $X_n = [x_n^{\omega_r}, x_{n-1}^{\omega_r}]$ and the linear relationship can be written as:

$$X_n = AX_{n-1} \tag{2}$$

with the following expressions for A for a single frequency ω_r and a sampling interval Δt:

$$A = A_{\omega_r} = \begin{pmatrix} 2cos(\omega_r \Delta t) & -1 \\ 1 & 0 \end{pmatrix} \tag{3}$$

For multiple frequencies $\omega_1 ... \omega_m$ the vector X_n and the matrix A turn to

$$X_n = [x_n^{\omega_1}, x_{n-1}^{\omega_1}, ..., x_n^{\omega_m}, x_{n-1}^{\omega_m}, x_n^{tot}] \tag{4}$$

The $x_n^{\omega_k}$ are the states for single frequencies and x_n^{tot} is the state including all signals with different frequencies. This is the line where within the Kalman filter the measurement is introduced. The matrix

A then reads

$$A = \begin{pmatrix} A_{\omega_1} & 0 & \dots & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & 0 & A_{\omega_m} & 0 \\ e_2 & \dots & \dots & e_2 & 0 \end{pmatrix}. \tag{5}$$

With the two element vector $e_2 = [1, 0]$. The last line is needed to construct the full signal with multiple frequencies from the single frequency models.

2.3.2 Prediction with Kalman filter

To construct a filter which is predictive over multiple sampling times the recursive relation (Eqn. 1) must be repeated several times. For example for a second time step starting from:

$$x_n = 2cos(\omega_r \Delta t) x_{n-1} - x_{n-2} \tag{6}$$

one can derive:

$$x_{n+1} = 2cos(\omega_r \Delta t) x_n - x_{n-1} = (4cos^2(\omega_r \Delta t) - 1) x_{n-1} - 2cos(\omega_r \Delta t) x_{n-2}. \tag{7}$$

This prediction can obviously be carried further to an arbitrary number of predictive steps.
To implement prediction the state vector must get an additional line for every frequency ω_r thus for k predictive steps the state vector reads:

$$X_n = [x_{n+k}^{\omega_1}, x_n^{\omega_1}, x_{n-1}^{\omega_1}, ..., x_{n+k}^{\omega_m}, x_n^{\omega_m}, x_{n-1}^{\omega_m}, x_n^{tot}, x_{n+k}^{tot}] \tag{8}$$

The additional line for the every matrix A_{ω_r} corresponding to the k-fold prediction at frequency ω_r,i.e., $[p_1^{\omega_r}, p_2^{\omega_r}]$, can be calculated by:

$$\begin{pmatrix} p_1^{\omega_r} \\ p_2^{\omega_r} \end{pmatrix} = (1, 0) \times \begin{pmatrix} 2cos(\omega_r \Delta t) & -1 \\ 1 & 0 \end{pmatrix}^{k+1} \tag{9}$$

The matrix A then reads:

$$A = \begin{pmatrix} A_{\omega_1} & 0 & \dots & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & A_{\omega_m} & 0 & 0 \\ e_{03} & \dots & e_{03} & 0 & 0 \\ e_3 & \dots & e_3 & 0 & 0 \end{pmatrix} \tag{10}$$

with $A_{\omega_r} = \begin{pmatrix} 0 & p_1^{\omega_r} & p_2^{\omega_r} \\ 0 & 2cos(\omega_r \Delta t) & -1 \\ 0 & 1 & 0 \end{pmatrix}$, $e_3 = (1, 0, 0)$, $e_{03} = (0, 1, 0)$

2.3.3 From acceleration to displacement

To derive the displacement y_n from the measurement by the accelerometers every frequency component corresponding to frequency ω_r has to be multiplied by a factor of $-1/\omega_r^2$ (see [4]) This means an additional line is required for the state vector X_n which then reads:

$$X_n = [x_{n+k}^{\omega_1}, x_n^{\omega_1}, x_{n-1}^{\omega_1}, ..., x_{n+k}^{\omega_m}, x_n^{\omega_m}, x_{n-1}^{\omega_m}, x_n^{tot}, y_{n+k}^{tot}] \tag{11}$$

Note that only the last input is new compared with Eqn. 8. The matrix A now reads:

$$A = \begin{pmatrix} A_{\omega_1} & 0 & \dots & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & A_{\omega_m} & 0 & 0 \\ e_{03} & \dots & e_{03} & 0 & 0 \\ e_{\omega_1} & \dots & e_{\omega_m} & 0 & 0 \end{pmatrix} \tag{12}$$

With $e_{\omega_r} = (-1/\omega_r^2, 0, 0)$ and A_{ω_r} and e_{03} as before. Here only the last row changed compared to Eqn. 10.

3 First laboratory results

3.1 Laboratory set up

A test set up was built to mimic the behavior on the telescope. The set up is shown in Figure 5. A laser

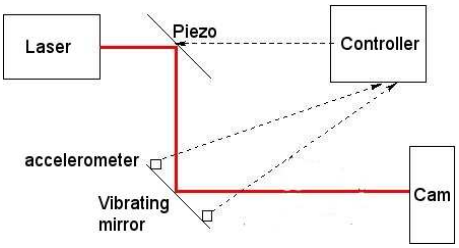

Fig. 5. Laboratory set up: The light from the laser is deflected off the FSM then off the vibrating mirror which introduces the 'telescope vibrations' into the beam and then monitored on a CCD .

beam is deflected by the FSM, then by a mirror which can be excited for vibration by a Piezo actuator (see Section 2.2) and which has 4 accelerometers attached. The position of the beam is measured with a CCD device.

3.2 Calibration of the system in the lab

For an efficient compensation several open parameters must be calibrated. In our case these are five parameters:

1. the frequencies of the vibrations
2. the orientation between the vibrating mirrors and the FSM
3. the loop gain
4. the Kalman gain
5. the time delay introduced by the system.

These parameters are obtained as follows: The frequencies at which the system must compensate can be deduced from the power spectrum of the accelerometer signals.
The rotation angle between the vibrating mirror and the FSM is obtained in two steps. First the laser movement on the CCD is measured with system off. Then the system is run with a large gain and the angle between the mirrors is changed in the controller until the laser jitter is parallel to the original movement.
The loop gain is obtained via switching on the system and measuring the laser jitter with different gains. A linear fit yields the optimum gain.
The Kalman gain is obtained by comparing the accelerometer data with the output of the VCS. This output must yield sensible results.
The time delay can be directly measured by comparing accelerometer data with the data of the positioning sensor in the FSM.
All the parameters and the calibration methods are listed in Table 1.

3.3 Measurements

First measurements were obtained recently. A 10 Hz sinusoidal signal with an amplitude corresponding to $0\farcs5$ on sky was applied to the vibrating mirror. The accelerometers were read out at a sampling rate of 100 kHz. For initial noise suppression 50 data values were averaged so the sampling rate was

Table 1. Parameters to calibrate

Parameter	Obtained via
Frequencies to compensate	Find Peaks of the power spectrum of vibrations
Rotation angle between FSM and vibrating mirror	compare spot movement between system on and system off with a large gain
Loop gain	swipe through different gain factors and use linear regression to find optimum
Kalman gain	Compare input and sensor data from VCS
Time delay	Compare input and sensor data from FSM

effectively reduced to 2 kHz. Due to the latency of the mirror we applied 2 ms prediction. The spectrum of the vibrating mirror showed significant peaks at 10 Hz, 20 Hz, and 30 Hz. We corrected at these bands. The orientation angle between the mirrors was deduced to be 40.11 degrees.
Using this parameter set we were able to reduce the movement of the beam on the CCD from initially 7.″5 root mean square (RMS) by a factor of 11 to < 0.″7 RMS corresponding to 0.″047 on sky. This value surpasses the value which will be needed on sky. However, it was achieved for a convenient frequency with large amplitude. So further testing with smaller amplitudes and frequencies is necessary.

4 Conclusions and outlook

We presented the concept and first laboratory results of the ARGOS vibration control system for the laser up-link path. After a general overview of the system and the requirements we have to meet, which include a time delay of < 0.5 ms, an orientation between the single mirrors of < 1 degree, and well deduced frequency bands of the vibrations, the hardware components and the controller for the system were presented. The system has three main parts:

- the accelerometers measuring the vibrations
- the control computer
- a fast steering mirror (FSM) for compensation of the laser jitter.

The control algorithm we use is a modified Kalman filter which is capable to predict the system behavior several milliseconds into the future and convert the acceleration measurements into tilt information for the FSM.
First laboratory results which use all features of the controller were very promising. The jitter of the laser beam of 7.″5 root mean square error was reduced by a factor of approximately 13 to below 0.″7. This reduction factor meets the specifications of the system.
Never the less we have to perform more extensive tests applying multiple frequency signals as vibrations and test the sensitivity of the system for small vibration amplitudes.

References

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