Vibration control for the ARGOS laser launch 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. To achieve this goal the telescope is equipped with multiple laser beacons. Still, to measure tip-tilt aberrations a natural guide star is used. For some fields such a tilt-star is not available and a correction on the laser beacons alone is applied. For this method to work well the laser beacons must not be affected by telescope vibrations on their up-link path.

For the ARGOS system the jitter of the beacons is specified to be below 0.″05. To achieve this goal a vibration compensation system is necessary to mitigate the mechanical disturbances. The ARGOS vibration compensation system is an accelerometer based feed forward system. The accelerometer measurements are fed into a real time controller. To achieve high performance the controller of the system is model based. The output is applied to a fast steering mirror. This paper presents the concept of the ARGOS vibration compensation, the hardware, and laboratory results.

Keywords: Vibration control, laser guide star, adaptive optics

1. INTRODUCTION

1.1 ARGOS

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 Gässler[1]) is shown. The main parts of the system are three Rayleigh laser beacons, a tip tilt (TT)-wavefront sensor and a high order laser-fed wavefront sensor. The lasers are pulsed and the beacons are, with the use of Pockels cells in front of the wave front sensor, caught at 12 km altitude.

The system is designed to improve the seeing even without TT-star information. Therefore a good stability of the laser beacons on sky is required.

1.2 The ARGOS vibration control system

For the ARGOS system the jitter of the laser beacons on sky is specified to be below of 0.″05. From the contemporary measurements of the vibrations on the telescope root mean square (RMS) amplitudes of 400 nm are predicted for the laser system which, in the worst case, correspond to a jitter of 0.″5 on sky. Thus the system must correct the tilt by a factor of 10 or better.

The ARGOS vibration control system (VCS) is designed to detect vibrations in the instrument's 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 the wind-brace and on top of the secondary mirror. Here, the vibrations of the telescope have a big impact, generating tip-tilt-movements on the mirrors which result in displacement of the laser spots on the sky.

A fast steering mirror (FSM) upstream the launch telescope is used to mitigate this tilt. In the following section the control concept of the VCS will be described. Section 3 describes the laboratory set up, the specifications of the system, the hardware components, and gives first results of the control system in lab. In section 4 we will draw conclusions and give a further outlook for the system.

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Adaptive Optics Systems III, edited by Brent L. Ellerbroek, Enrico Marchetti, Jean-Pierre Véran, Proc. of SPIE Vol. 8447, 84474J · © 2012 SPIE · CCC code: 0277-786/12/$18 · doi: 10.1117/12.926042

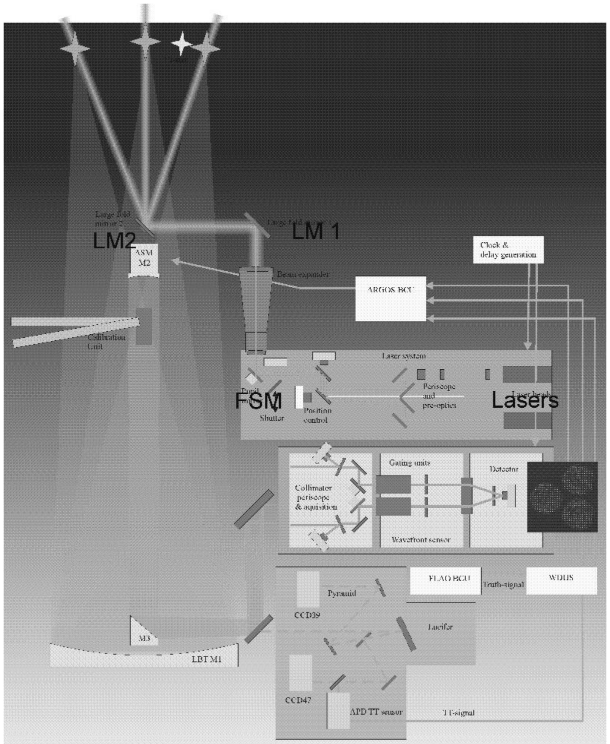

Figure 1. Sketch of the ARGOS system at the LBT. (Thanks to S.Rabien). The important components of the laser launch path are the fast steering mirror (FSM) and the two folding mirrors (LM1, LM2).

2. THE CONCEPT FOR VIBRATION CONTROL

The VCS is supposed to correct for vibrations and deliver a beam stability of $0\overset{\prime\prime}{.}05$ or better. The concept of the vibration control to gain this correction is shown in Figure 2.

The signals coming from 8 accelerometers which are placed on the two folding mirrors (LM1/LM2) 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. The system is a feed forward system.

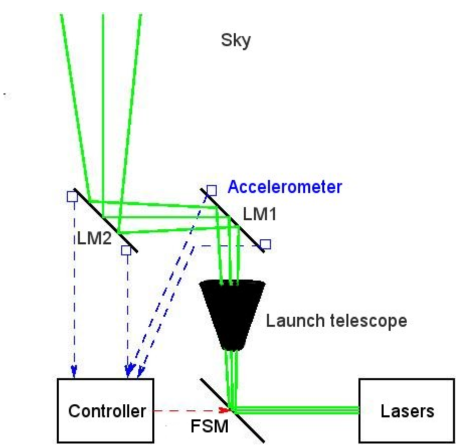

Figure 2. Set up, of the vibration compensation at the telescope.

2.1 Specifications

To achieve the performance of the system of 0.″05 RMS residual tilt from originally 0.″5 tilt the following specifications for the system at the telescope will have to be met (a_{max} = maximum amplitude of tilt, typically 400nm RMS, f = frequency, typically ≤ 30 Hz):

1. maximum time delay $\delta t < 36/a_{max}[nm]/(2\pi f[Hz])[s]$,e.g., for a_{max} 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}: $\delta f/f < 0.045$
4. accuracy on orientation between mirrors: $\alpha < 0.5acos\left((1-(36/a_{max})^2)^{0.5}\right)$, e.g.,for a_{max}: $\alpha < 2.6°$.

To achieve this rather strong requirements a model based approach is used for the control algorithm.

2.2 The Kalman filter based controller

The control algorithm for the vibration compensation system is based on a Kalman filter design (Kalman,[2] Petit[3]). It exploits the predictive behavior of the Kalman filter to act as a predictor for more than a single time step into the future. This feature can also be used to take into account any phase shift between input and output.

The Kalman filter is a recursive filter to reduce the output noise in a system with linear behavior. It connects the system state X_k at time step 'k' linearly to the state X_{k-1} at time step '$k-1$' via the matrix A that is constructed from a model of the system:

$$X_k = AX_{k-1} + w_{k-1} \tag{1}$$

The system itself can additionally have some noise w_k. The measurement z_k with noise ν_k is also linearly connected to the state X_k via a matrix H:

$$z_k = HX_k + \nu_k. \tag{2}$$

For our system with n frequency bands with central frequencies ω_1 to ω_n to be taken into account and a desired double integrated output the state X_k reads:

$$X_k = [x_k^{\omega_1}, x_{k-1}^{\omega_1}, ..., x_k^{\omega_n}, x_{k-1}^{\omega_n}, x_k^{tot}, y_k^{tot}] \tag{3}$$

The $x_k^{\omega_i}$ are the scalar states at time step k belonging to a single frequency oscillator of frequency ω_i. The state x_k^{tot} is the scalar state belonging to the entire system of n-frequencies and the state y_k^{tot} contains the double integrated state. For this system the matrix A reads:

$$A = \begin{pmatrix} A_{\omega_1} & 0 & ... & ... & 0 & 0 \\ ... & ... & ... & ... & ... & \\ 0 & ... & 0 & A_{\omega_n} & 0 & 0 \\ e_2 & ... & ... & e_2 & 0 & 0 \\ e_{\omega_1}^s & .. & .. & e_{\omega_n}^s & 0 & 0 \end{pmatrix} \tag{4}$$

with:

$$A_{\omega_r} = \begin{pmatrix} 2cos(\omega_r \Delta t) & -1 \\ 1 & 0 \end{pmatrix} \tag{5}$$

$$e_2 = [1, 0] \tag{6}$$

$$e_{\omega_r}^s = p(\omega)/(\omega_r)^2 \times (1,0) \times A_{\omega_r}^{s+1} \tag{7}$$

the symbols have the following meaning: $p(\omega)$ = frequency dependent amplitude
ω_r = central frequency of band

Δt = time step.
the matrix H reads:

$$H = [0, 0, ..., 0, 0, 1, 0] \tag{8}$$

As output the value y_k^{tot} is used. It is the displacement calculated from the input acceleration data. The double integration is replaced by a multiplication with the factor $1/(\omega_r)^2$ (see Stalcup and Powell[4]). A phase shift corresponding to s time steps Δt and also a frequency dependend amplitude $p(\omega)$ is applied. Note that this scheme is slightly modified from the description in the paper by Peter and Gässler.[5]

3. LABORATORY RESULTS

In the following the hardware components, calibration of the system, and lab measurements will be presented.

3.1 Laboratory set up

In the lab we build a set up resembling a scaled down model of the situation on the telescope yielding the same accelerations as on the telescope. 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: In our case 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.″25 RMS and desired tilt angle is 0.″75 RMS. The set up is shown in Figure 3. A laser beam is deflected by the FSM, then by a single mirror which can be excited for vibration by a Piezo actuator in 1 axis only (see Section 3.2) and which has 4 accelerometers attached. The position of the beam is measured with a CCD device.

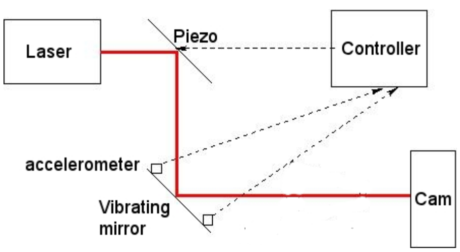

Figure 3. Laboratory set up: The light from the laser is deflected off the FSM, then off the vibrating mirror which introduces the 'telescope vibrations' into the beam, and finally monitored on a CCD .

3.2 Hardware

3.2.1 Accelerometers

As accelerometers we have chosen PCB 393B05 accelerometers due to their small weight and small measurement noise. Still the noise does only allow for frequencies f down to ≈ 1.5 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. In 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.

3.2.2 Control computer

The control computer is the NI PXI 1031 chassis with the PXI 4472B input board, PXI 6733 output board, and a PXI 8108 controller.
The input card, as it needs to have analogue input, contains a high pass filter with a cut off frequency of 0.5 Hz. Thus there is a frequency dependent phase shift which has to be taken into account. The frequency dependent phase shift is shown in Figure 4. For our specifications the phase shift becomes important for frequencies below 5 Hz.

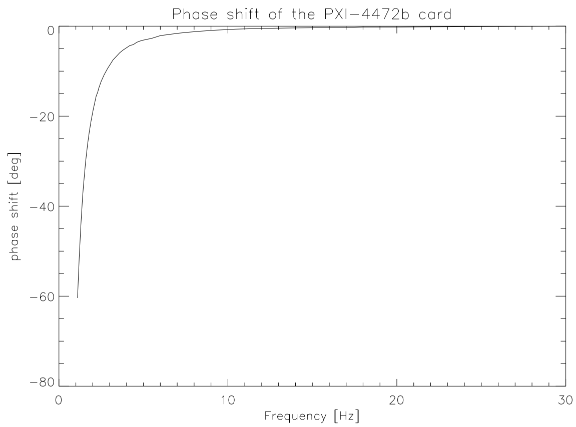

Figure 4. Frequency dependence of the phase shift of the PXI-4472b card

3.2.3 Fast steering mirror

The FSM is the PI S-330 mirror. It has been tested for amplitude and phase response and exhibits a phase shift of 2 ms for sine-like excitations at all relevant frequencies. From the specifications one can calculate that there will be the need of a predictive algorithm to mitigate the latency at least for frequencies higher than 7.5 Hz. An important feature of this mirror is the frequency dependent amplitude and phase response which has to be taken into account. See Figures 5 and 6.

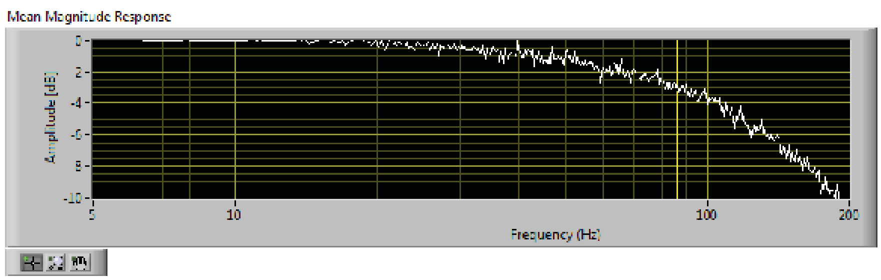

Figure 5. Frequency dependence of the amplitude response of the PI-mirror.

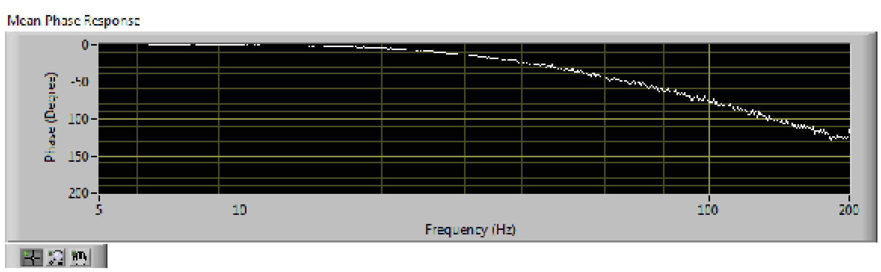

Figure 6. Frequency dependence of the phase shift of the PI mirror.

3.2.4 Vibrating mirror

The vibrating mirror (VM) is used in the lab to mimic the vibrating mirrors at the telescope. It is a simple mechanical construction excited with a Piezo actuator (see Figure 7). Due to this scheme it exhibits not only the applied frequency but also several overtones and high frequency noise (see Figure 7). For testing purposes this behavior is welcome as one can test the algorithm for several simultaneous frequencies of vibration while only a single frequency sine wave is applied to the Piezo actuator.

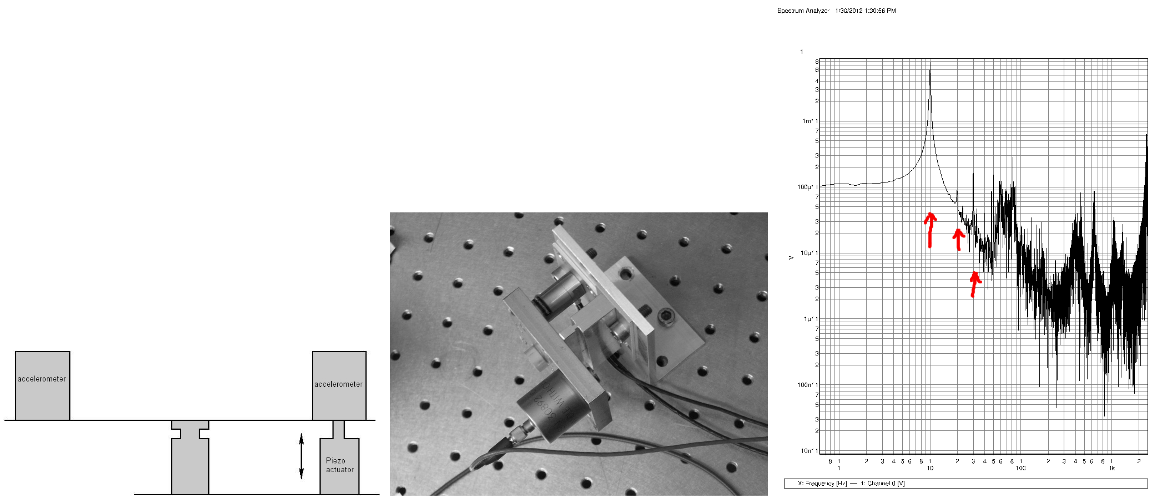

Figure 7. Left:Principle of the mechanical set-up for the vibrating mirror. Center: Picture of the mirror with one accelerometer attached. Right: Power spectrum (acceleration) of vibrating mirror. The scale is logarithmic. The excitation was at 10 Hz the next two overtones and the high frequency noise are clearly visible.

3.2.5 CCD camera

To record the movement of the laser beam a Prosilica GC1350 was used. It has a pixel size of 4.65 μm and a full frame rate of 20 Hz. As we need a higher frame rate the camera was binned 2x2. for the lab set-up the resolution is 1″.5/pixel, i.e. 3" in the case of 2x2 binning

3.3 Stand alone test of the algorithm

In a first attempt the control computer was tested stand-alone. The input was generated by two signal generators. The output was measured with a Data translation data logger DT 9837A.
As the input is an acceleration but the output a displacement signal, for the comparison the input data was artificially integrated twice.
The controller was tested with single and multiple frequencies between 1Hz and 30 Hz and amplitudes between 0.01 and 1 V input. The residual error was always below 1 % of the maximum of the signal which would correspond to 4 nm RMS.

3.4 Calibration of the system in the lab

For an efficient compensation four parameters must be calibrated:

1. the frequencies of the vibrations to compensate
2. the time delay and (frequency depended) phase shift introduced by the system.
3. the orientation of the axis of the vibrating mirrors with respect to each other and the FSM
4. the loop gain

These parameters are obtained in the lab by the following procedure:
1. The frequencies at which the system must compensate can be deduced from the power spectrum of the accelerometer signals.
This data was taken in advance with the data logger directly from one of the accelerometers. 2. The frequency dependent part of the phase shift and the time delay were measured once by applying voltage to the controller and comparing the input signal to the data of the position sensor in the FSM. This calibration can be performed comfortably in the lab with a good signal to noise ratio.
3. The orientation of the axis of the vibrating mirror and the FSM is obtained once by tilting each mirror along

each mirror axis. The difference in position of the laser spot on the CCD yields the desired angles.
4. 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.
All the parameters and the calibration methods are listed in Table 1.

Table 1. Parameters to calibrate

Parameter	Obtained via
Frequencies to compensate	Find peaks of the power spectrum of accelerometer measurements
Phase shift/time delay	Compare signal generator input with output from positioning sensor in FSM
Orientation of the mirror axis	measure spot position for different mirror excitations
Loop gain	sweep through different gain factors and use linear regression

3.5 Full system measurements

Finally the system was tested in the lab (see Figure 3). For these first tests only one of the vibrating mirrors was excited and the spot movement was recorded on the camera. In the following this measurement is referred to as 'open' measurement. The compensation was activated and the spot movement was again recorded.
The spectrum of the VM was deduced at an excitation at 10 Hz. To obtain sufficiently good corrections not only the frequency applied to the mirror but also the first two overtones were corrected for (see Figure 7). This correction of the first two overtones was then used at every frequency. To test the limits of the system the VM

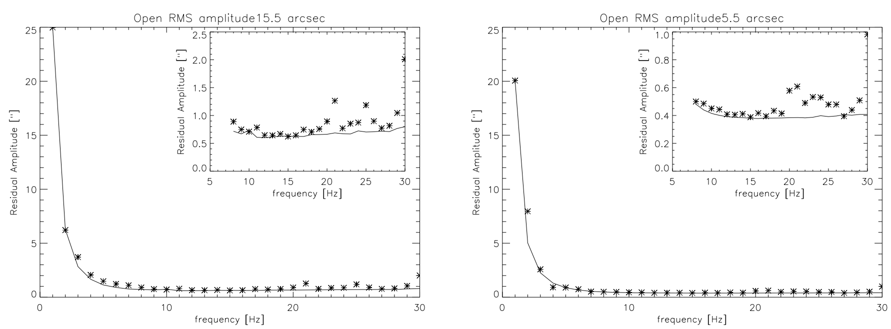

Figure 8. Left: Comparison of the performance of the system for large amplitudes (15.″4 RMS). Right: The same for amplitudes as expected at the telescope (5.″5 RMS). The inlay shows the results for frequencies of 7Hz and higher.

was run with different amplitudes between 1.″14 and 15.″4 RMS. Figure 8 shows the data compared with the theoretically derived error curve $\sqrt{\sigma_{tot}^2}$.
This curve was derived for the signals with amplitude A and frequency f with the following errors:

1. σ_{res}: The finite resolution of the camera of 0.32" RMS
2. σ_{noise}: The external noise on the accelerometers as measured
3. σ_{ang}: the error due to mis-measurement in the angles of the axis by the angle $\phi = 0.5°$: $\sigma_{ang} = A(1 - cos(\phi)$
4. σ_{phase}: the error in phase due to the finite loop frequency i.e. half a loop step ($\Delta t = 0.25ms$) $\sigma_{phase} = A(1 - cos(2 * \pi * f\Delta t))^{0.5}$
5. σ_{gain}: the error due to an error in the gain factor by 3 %: $\sigma_{gain} = 0.03A$

$$\sigma_{tot}^2 = \sigma_{res}^2 + \sigma_{noise}^2 + \sigma_{ang}^2 + \sigma_{phase}^2 + \sigma_{gain}^2 \tag{9}$$

At most of the frequencies above 3Hz the correction is better than a factor of 10 as specified. At a few frequencies, especially at 30 Hz, the correction is not sufficient. We suspect that the deduction of the frequencies (overtone) at which the correction is applied needs to be done more accurately. Here further investigation is necessary.

4. CONCLUSIONS AND OUTLOOK

In this paper laboratory tests of a Kalman filter based approach to compensate the effect of telescope vibrations on the laser launch of the ARGOS was presented.
The controller is based on the Kalman filter for vibrations proposed by Petit et al.[3] The difference to the filter in the paper of Petit et al.[3] is that ours has an extra line to calculate the displacement from the acceleration data. Here also a frequency dependent phase shift and a frequency dependent gain can be applied.
The specifications for the final system aim at a residual root mean square tilt error in the laser position of $0.''05$ on sky. This specification drives the specifications on frequency deduction, time delay/phase shift, and mechanical orientations of the system to values of 0.045%, 0.5 ms, and 2.6° respectively.
The available hardware introduces a latency as well as a phase shift which is larger than the temporal requirement of 0.5 ms. This latency and phase shift has to be mitigated by the control algorithm.
The approach was tested in a lab set-up with a single vibrating mirror which was vibrating in one axis only. The mirror was excited at single frequencies between 1Hz and 30Hz with different amplitudes. Due to its mechanical constuction it also did vibrate at the frequencies of the overtones of the frequency of excitation. Additionally high frequency noise was strongly present. The movement of the beam was measured with a CCD device.
For frequencies higher than 3 Hz the compensated tilt was a factor 8-20 lower than uncompensated. At the frequencies for which the correction was not sufficient we suspect an insufficient calibration of the frequencies to correct as reason.
The limit at 3 Hz for sufficient correction is not due to the internal noise of the accelerometer but to external noise. The limit due to internal accelerometer noise would be at about 1.5 Hz.
The next steps to bring the system to full functionality will be to first find the sources of the error in the case of the too low corrections, then to add a second vibrating mirror which is vibrating in the orthogonal direction and finally to apply different frequencies to these mirrors.

ACKNOWLEDGMENTS

The authors want to thank the entire ARGOS team for their great collaboration and suggestions.

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