Procedures to measure the Interaction Matrixes

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1 Change Record

Issue	Date	Section/ Paragraph Affected	Reasons / Remarks	Name
1.0	06 Oct 2013	all	created	LB, AP

2 Scope

This technical note has been created to provide indications about the implementation of the calibration procedures of the ARGOS systems.

3 Applicable documents

No.	Title	Number & Issue
AD 1	Required sequence of operations for the optical WF recontruction process and proposed implementation	486f015e
AD 2		
AD 3		
AD 4		
AD 5		
AD 6		

4 Definitions

ASM system: ASM + its electronic cabinets, M2 hexapod, AdSec SW and TCS SW (expecially OSS, MCS and AOS).

LGSW system: the ARGOS LGSW unit and dichroic unit, its electronic rack, the dx-lgsw SW.

Calibration Unit system: the ARGOS calibration unit, including the swing arm, the electronics and all the HW and SW needed to move the unit in position and project the three 532nm off-axis LGS spots and the "white" on-axis NGS spot.

5 General consideration about the use of ASM from the ARGOS point of view

5.1 Real Time Reconstructor

In ARGOS (as in other LBT AO systems) the Real Time Reconstructor (RTR) is implemented on board of ASM electronics. The ASM accepts as input a vector of 1600 slopes via the optical-fiber link (aka FastLink) that connects the ARGOS LGSW BCU to the ASM Switch-BCU.
A simplified scheme of the RTR (see AD1 for a complete description) is the following:

$$\mathbf{m}^{(t)} = \mathbf{g}\,\mathbf{R}\,\mathbf{s}^{(t)} + \mathbf{m}^{(t-1)}$$

$$\mathbf{z}^{(t)} = \mathbf{M2C}\,\mathbf{m}^{(t)}$$

$$\mathbf{c}^{(t)} = \mathbf{z}^{(t)} + \mathbf{d}^{(t)}$$

The slope vector at time t $\mathbf{s}^{(t)}$ is multiplied by the Reconstructor Matrix **R** and by the gain vector **g** to obtain a differential modal-command that is summed to the modal-command at the previous step $\mathbf{m}^{(t-1)}$ to give the total modal-command at time t $\mathbf{m}^{(t)}$.
A Modes-To-Commands matrix **M2C** multiplies the modal-command to projects the command from the modal-space onto the zonal-space. The resulting vector $\mathbf{z}^{(t)}$ contains the command (in meter) for each ASM actuator.
As a last step, a disturb vector **d** can optionally be summed to the zonal vector **z** to obtain the command vector **c** (in meter) actually sent to the ASM actuators. This feature is used during daytime operations to simulate an atmospheric turbulence and to acquire the AO interaction matrix as described below. The disturb vector **d** is a column of a matrix **D** containing up to 4000 temporal steps (columns) and can be applied synchronously with the vector $\mathbf{z}^{(t)}$ or in oversampling (e.g. disturb vectors **d** are applied by the ASM at 1kHz with the WFS sending slopes at 500Hz).
Note that setting a null gain vector **g** and closing the AO loop is the way of applying the disturb as-is to the actuators and realize an "open-loop with disturb".

Customarily, the slope vector **s** has 1600 elements, the reconstructor matrix **R** is (1600 cols, 672 rows), the gain vector **g** has 672 elements, the **M2C** matrix is always 672x672 and the disturb matrix **D** is (4000 cols, 672 rows). **m**, **z**, and **c** are vectors of 672 elements. All these variables are padded with zeros if their size is smaller than the default size.

To summarize, the ARGOS control SW has to produce, store and upload to the ASM the following variables:

- The reconstructor matrix **R**, obtained by pseudo-inversion of the Interaction Matrix **IM**
- The gain vector **g**
- The modal basis **M2C**
- The disturb matrix **D**

Note that the ASM has no knowledge at all about the variety of wavefront sensors used in the ARGOS system: it is up to the ARGOS control software to combine the calibrations of the various wavefront sensors to obtain a single reconstructor matrix. The ARGOS control software must also provide a way of tuning at run-time the AO loop gain indepentently for the various modes.

5.2 Slope computer – ASM synchronization

CCD frames are received by the ARGOS LGSW BCU slope computer, which computes a slope vector for each CCD frame and generates a frame counter. The frame counter is continuously incremented, regardless of the open or closed loop status.
In open loop, no data and therefore no frame counter are sent to the ASM. Only during closed loop operation, slope frames and frame counter are sent to the ASM via the FastLink connection on the optical fiber and stored in a memory buffer.
The memory buffer is used as a circular buffer, where data is stored starting from the last used location and is overwritten from the first location when the buffer is exhausted. Therefore, the signature of a close loop event is a jump (discontinuity) in the frame counter. This information can be used to recover the position of the first frame of a closed loop in the circular memory buffer.

6 General considerations on ARGOS's AO Interaction Matrix

The Interaction Matrix (IM) is the main calibration needed by the AO loop. From the IM one can compute one or more reconstructor matrix to be used in the AO control loop. An IM matrix is assembled by applying a set of shapes ("modes") to the ASM, measuring the corresponding signals ("slopes") on the WFS and pulling together the signal vectors into the column of the IM matrix.
To improve the measurement quality one can use the so-called push-pull technique: apply with the shortest interval a mode with a given positive amplitude and the same mode with negative amplitude. The differences between the signals will reject slowly varying noise terms like telescope oscillations or dome turbulence.
The disturb feature of the ASM is used to rapidly change the shape of the mirror. The disturb matrix is created in such a way that each mode is "push-pulled" at high frequency for a few cycles. (typically the square wave's period is 10ms).

The reconstructor matrix is obtained as the pseudo-inverse of the IM. A reduced number of columns of the IM can be used to obtain a reconstructor with a reduced number of modes.

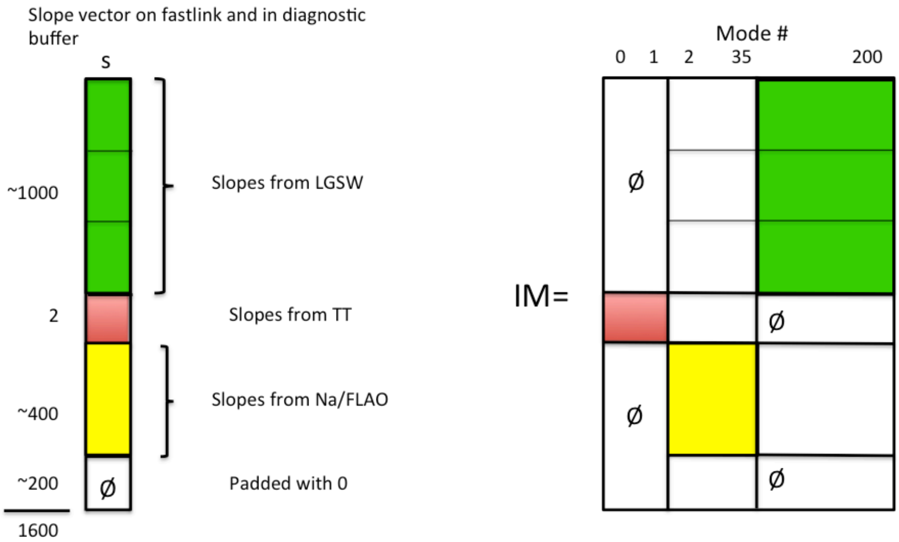

Figure 1 The AO Interaction Matrix is made of 3 blocks, corresponding to signals measured on LGS WFS, TT-sensor and FLAO (or Na-LGS) sensor. In this generic example the Tip/Tilt modes (0 and 1) are measured by the TT-sensor, modes from 2 to 25 are measured by the FLAO WFS and all the other modes up to 200 are measured by the LGSW. A different approach can be used. The baseline is having the Tip/Tilt sensed by TT-sensor and modes from 2 to 151 sensed by the LGSW.

In the current ARGOS scheme the IM matrix is composed of 3 blocks: a first block contains the slopes generated by the LGSW, a 2nd block the slopes generated by the TipTilt unit, a 3rd block contains the slopes optionally coming from the FLAO pyramid WFS or from the future sodium-LGS WFS.

The 3 blocks must be measured separately. A software tool to reassemble the blocks in a single IM matrix before doing the pseudoinversion is needed.

7 Measurement of the LGSW-ASM Interaction Matrix

This section covers the measurement of the LGSW-ASM Interaction Matrix.

Prerequisites:

a. ASM system, LGSW system and calibration unit are fully functional.
b. Optical alignment of the above-mentioned subsystem has been realized.
c. Optical Fibers are properly routed.
d. The M2C matrix (modal base) has been computed (or extorted from FLAO's guys!) and is stored in the ARGOS calibration tree.
e. The Switch BCU input port is set on "ARGOS"
f. The ASM is set and ready. A flat-wavefront (deviation from nominal wf <400nm rms?) is delivered to the LGSW.
g. The LGSW is in state AllLaserAcquired, the sensors delivers sensible measurement.
h. The telescope environment is "quiet" (HBS is on, no fan, no people on the telescope, lights off)

Output:

A disturb matrix and an Interaction Matrix (1600 rows x NModes cols) stored as FITS files in the appropriate folder of the ArgosArbitrator calibration tree. The FITS header must have a set of keywords that describe completely the parameters used for the generation of the disturb, for the IM acquisition and for the IM processing into the REC.
Note: the IM is related to the M2C used to measure it and to the subaperture definition

Procedure:

The procedure can be splitted in 3 independent steps:

1. Generation of the disturb matrix D
2. Measure of the IM and storage of raw data.
3. Data processing and storage of the IM

7.1 Generation of the disturb matrix

1. Choose the modal base to use. This identifies the matrix **M2C** and a file amp_envelope.fits
2. Create a vector of modal amplitudes **modamp**:
    a. Create a vector of 672 elements
    b. Assign to each element a value that is the amplitude (in meter rms) of the corresponding mode. It will be refined empirically to obtain a good SNR yet not saturating the WFS. In the example below, mode #1 and 2 will be acquired with an amplitude of 2.7e-8m and mode #3 5.4e-8m.
    amp_envelope.fits contains a 672-elements vector. Each element is the maximum amplitude (in meters rms) that the mirror can apply for the corresponding mode in the KL matrix (i.e. if element #2 value is 1e-6, the mirror can only apply 1e-6 meters rms of mode #2 in the KL matrix). This limitation comes from the actuator force limit, and is generally very relaxed for low-order modes (tens of microns) and progressively stricter for higher-order modes, down to a few nanometers at mode #600. Force limits are checked anyway when the disturbance file is loaded on the ASM, so a mistake in the amplitude has no safety consequences.

3. Create a matrix **MH** (4000 cols x 672 rows) with the modal disturb history. See Figure 2 for an example. The input parameters are **modamp**, the number of push-pull per cycle (4 in the example) and the number of step up and down (3 in the example)

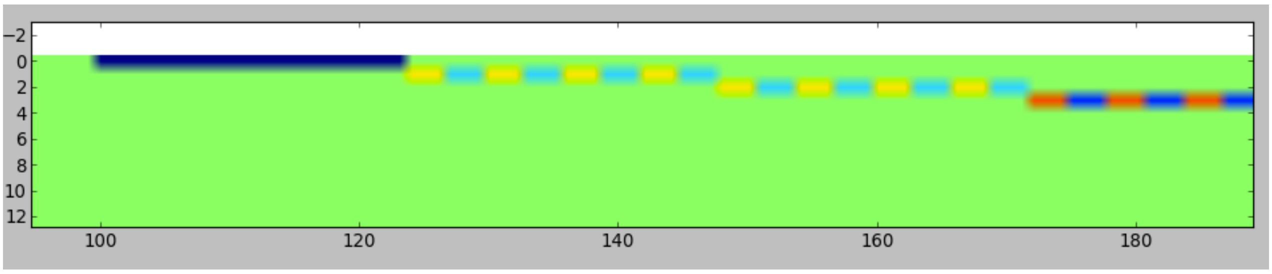

Figure 2 Example of modal disturb matrix MH (20130916_220840). At temporal step 100 the mode #0 is applied for 24 steps. After tha 4 cycles of push-pull on mode #1 with an amplitude of 2.7e-8 and a period of 6 steps (3 positive + 3 negative) are applied. Then the same pattern is repeated for mode #2 with the same amplitude. Mode #3 is applied with an amplitude of 5.4e-8. The disturb matrix goes on with the following modes. In this example last mode in the MH is #152 at time-step 3770 (not visible in the figure). (WHAT'S MODE 0?)

4. Convert **MH** to the actuator base to obtain the disturb matrix: **D = M2C MH**
5. Store **D, MH, modamp** as FITS files, with all the relevant parameters into the header's keywords.

7.2 Measure of IM and store of raw data

This is the only phase in which the system is actually used.

1. Set & flat the ASM.
2. Acquire the calibration sources on the LGSW.
3. Enable the pupil-centering loop in the LGSW and wait until convergence.
4. Load push-pull history on ASM memory. (It can be done either manually using the ASM engineering GUI, or from a script using the ICE interface)
5. Close a "fake" loop (or a "real low-gain" loop, if iterating the procedure).
    a. Load a zero gain file on the ASM (or a low-gain one, if iterating the procedure)
    b. Load a null reconstructor matrix on ASM (or a "real" one, if iterating the procedure)
    c. Start sending slopes to the ASM over the fastlink. Activate the "start bit" in the instrument BCU to activate the push-pull sequence. The command to start the loop is a bit in the param block selector of the slope computer BCU.
6. Wait for data accumulation on the ASM memory (The time needed in seconds is 4000/ loop frame rate in Hz)
7. Stop sending slopes to the ASM, otherwise the ASM memory buffer will be overwritten.
8. Download the ASM memory buffer. The ICE interface provides two methods to read the slope buffer from the ASM. The result is a history of the slopes as they have been sent from the slope computer BCU and stored on the ASM.
9. Save the slope history data on disk as a FITS file.

7.3 Data processing and storage of the IM

1. Read slope series data file from FITS file.
2. Detect close loop event using the frame counter information (see section 5.2)
3. Build the interaction matrix:
   a. For each mode:
      i. Average contiguous slope values in the "push" or "pull" position, and subtract them.
      ii. Normalize the differences by the applied modal amplitude in meter
      iii. Average all "push-pull" differences corresponding a mode.
      iv. The resulting "signal per meter" vector fills a column of the interaction matrix
4. Store the IM as a FITS file.
5. Save a picture where each column of the IM is re-arranged in 2D (a reordering table is needed). For diagnostic purpose.
6. Go to section 8 to invert the interaction matrix and obtain the reconstruction matrix.

Once a first reconstruction matrix has been obtained, we are able to close the loop.
All the steps before can be repeated to generate a better matrix, using the last computed reconstruction matrix to close the loop during the measurement with a very low gain just to correct slow drifts. The procedure is identical to the one outlined before, with the exception of point 5, where the last computed reconstruction matrix is used in place of a zeroed-out one, and a gain vector with low values (such as 0.05) in place of the zero gain vector.

8 Generation of the ARGOS Reconstructor Matrix

Prerequisites:

a. The IMs of LGSW, TT sensor (and optionally FLAO/Na sensor) are available. They must have been measured using the same M2C matrix.

Output:

A global IM matrix (1600 rows x 672 cols) and a Reconstructor Matrix (672 rows x 1600 cols) stored as FITS files in the appropriate folder of the ArgosArbitrator calibration tree. The FITS header must have a set of keywords that describe completely the parameters used for the creation of the global IM and its processing into the REC.

Procedure:

1. Create the global IM matrix by composing the blocks with the IMs of LGSW, TT sensor and FLAO/Na (all 3 of them, or a subset)
2. Pseudo-invert the matrix using a SVD technique. A parameter allows to specify the number of modes (columns of the IM) to be used in the SVD: this is needed to create a REC with a reduced number of modes.
3. Save the following graphs:
    a. A plot of the eigenvalues of the IM
    b. A modal plot of:
        i. The fraction of zero-signal subapertures
        ii. The fraction of saturated subapertures
        iii. The rms of slopes
4. Store the global IM and the REC on disk as FITS files, with all the relevant parameters into the header's keywords.

9 List of acronyms

AGW	Acquisition Guiding and Wavefront sensing
AIP	Astrophysical Institute Potsdam
AOS	Adaptive Optics System
APD	Avalanche Photo Diode
ASM	Adaptive Secondary Mirror
BCU	Basic Computational Unit
DM	Deformable Mirror
DMD	Deformable Mirror Diagnostics
FLAO	First Light Adaptive Optics
FWHM	Full Width Half Maximum
GLAO	Ground Layer Adaptive Optics
IDL	Interactive Data Language
IIF	Instrument InterFace
LBT	Large Binocular Telescope

LBTO	LBT Observatory
LGS	Laser Guide Star
LGSF	LGS Facility
LGSW	LGS Wavefront Sensor
LUCIFER	LBT Near Infrared Spectroscopic Utility with Camera and Integral Field Unit for Extragalactic Research
NGS	Natural Guide Star
PID	Proportional, Integral and Differential
PSF	Point Spread Function
RLGS	Rayleigh Laser Guide Star
RMS	Root Mean Square
RON	Read Out Noise
RPC	Remote Procedure Call
RTC	Real Time Control
SH	Shack Hartmann
SNR	Signal to Noise Ratio
SR	Strehl Ratio
SVD	Single Value Decomposition
TBC	To Be Confirmed
TBD	To Be Defined
TCS	Telescope Control Software
TT	Tip Tilt
TTW	Tip Tilt Wavefront sensor
WFS	WaveFront Sensor

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