Requirements for the ARGOS BCU

version 1.3

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Contents

Change Record

- Version 1.0: February 10, 2010
- Version 1.1: June 30, 2010. Modifications and clarification of the interfaces and requested tasks.
- Version 1.2: July 2, 2010. Clarification FLAO interface possibilities.
- Version 1.3: September 8, 2010. Detailing of diagnostics, additional comments (see section 6) and section 5 (handling of asynchronicity, point 16).

Interfaces Description

1 Introduction

We want to describe here the sequence of tasks that the slope computer BCU of ARGOS should perform (see also Figure 1 for the different links).

1. This BCU should receive the data from the wavefront detector unit (at a frame rate of $\sim$ 1kHz), the detector having a 264 by 264 pixels size. Per detector, we have three SH (*Shack-Hartmann*) pupils (3 LGS, *Laser Guide Stars*), each of them has up to 15x15 subapertures of 8x8 pixels. We want to apply several corrections (dark frame, common-mode and flat-field corrections). For each of these subapertures, we want then to compute the centroid (in the 8x8 pixels area) and finally the x and y slopes, creating a slope vector ($\sim$ 350 slopes per LGS, a total (x and y and 3SH) of $\sim$ 1050 slopes).

2. It should also compute the average tip and tilt over the subarpertures of each SH pupil and send, for each of them, these two slopes (tip and tilt) to the corresponding MG HV (*MicroGate High Voltage*) controller at the $\sim$1 kHz (synchronous with the frame rate).

3. Then, the BCU should receive the atmospheric tip/tilt slopes asynchronously from the TT (*Tip Tilt*) unit (firmware from Max-Planck-Institut für Radioastronomie, MPIfR) and stack these slopes to the already computed slope vector.

4. Before the upgrade path, the FLAO BCU will be directly linked to the LGS BCU through an optical link (non permanent link), allowing to stack the NGS slopes to the TT+LGS slope vector (this possibility will not necessarily be used).
   In addition the FLAO BCU will be linked to the ARGOS supervisor (permanent link) for *truth sensing* (slow correction). After integration and computation the ARGOS supervisor will, in its turn, update the slope offsets (point 8. in chapter "Requested Operations").

   In the foreseen upgrade path, the FLAO to LGS BCUs optical link will be replaced by the Na to LGS BCUs optical link. Therefore the LGS BCU will receive asynchronously slopes from the "Sodium" unit (Na BCU) and stack them to the existing vector.
   To keep the possibility to use the FLAO+LGS mode, the FLAO BCU will also be optically linked to the Na BCU, allowing "pipelining" of the FLAO slopes up to the LGS BCU through the Na BCU.

5. Eventually, the BCU has to send the final slope vector to the switch BCU.

The two first tasks and the last one should follow the frame rate ($\sim$ 1kHz), the other tasks may be asynchronous and depend on external specifications.

2 Interfaces

A schema presenting the external interfaces of the BCU (called LGS BCU) is presented figure 1.

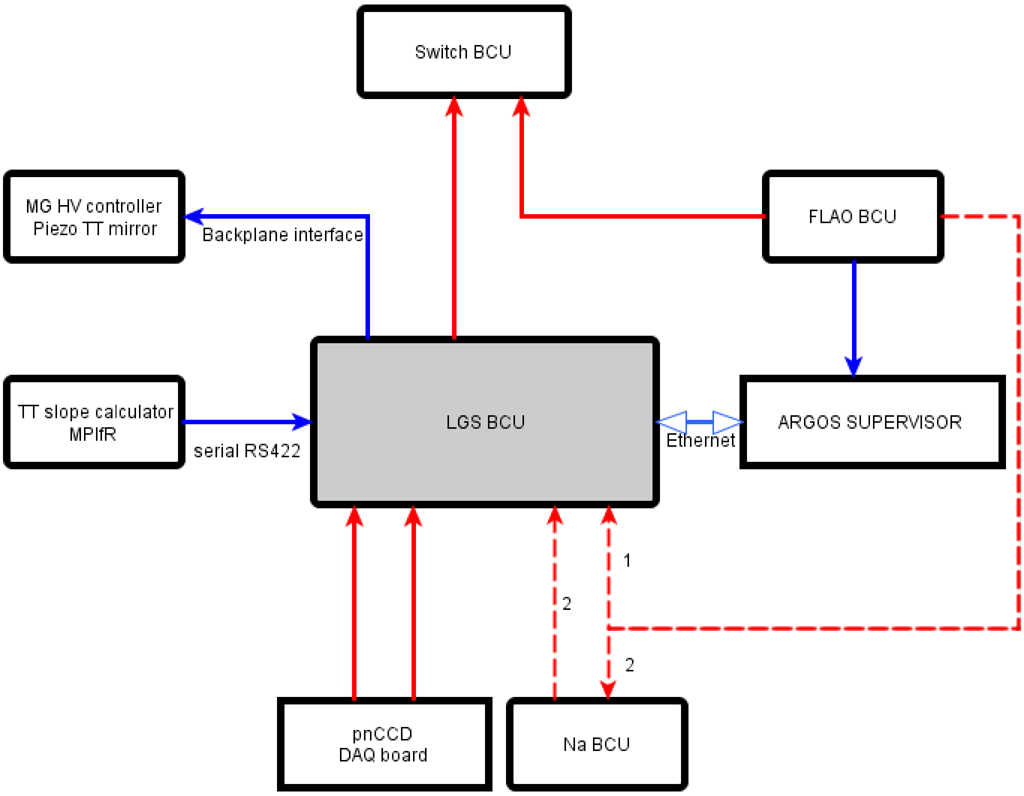


Figure 1: Sketch of the BCU interfaces. The red lines mean fast optical links. Dashed red lines mean non permanent links: (1) before the upgrade path (Na), the FLAO and LGS BCUs will have a direct optical link; (2) once the upgrade path is in place, the Na BCU will be directly linked to the LGS BCU and the FLAO will be linked to the Na BCU allowing "pipelining" of the FLAO slopes up to the LGS BCU through the Na BCU.

Ouputs are :

- Total slopes vector to the switch BCU including frame counters (*optical link*),
- Three slopes vectors (tip and tilt) to the three MG HV controllers (field pointing of the WFS) including frame counter (*backplane interfaces*),
- Diagnostic interface with the ARGOS supervisor (*ethernet*).

Inputs are :

- Inputs from the DAQ board of the detector system. This interface presents by far the highest data flow rate (frame rate of 1kHz, describe hereafter). Protocol is defined in [4]. These inputs will use two Fiber links.
- Inputs from the TT slope calculator from MPIfR. Two slopes, a frame counter and the 4 raw APD counts. Protocol defined below, using a serial RS422 interface (see also [6]).
- Input of low order mode (truth sensing) of the FLAO through the ARGOS supervisor updating slope offsets in the LGS BCU. Slow input. Ethernet interface.

- Inputs from the ARGOS supervisor to operate the LGS BCU. Ethernet link.
- In the upgrade path, the Na BCU unit replacing the direct link FLAO to LGS BCU. The FLAO BCU will then be linked to the Na BCU. Fiber links.

2.1 TT unit to BCU

The interface will be an RS422-Interface at 10 Mbit/s.

Details are given in [6].

2.2 pnCCD to BCU

The interface between the pnCCD and the BCU will be done through two optical links.

The detector format and the foreseen Shack-Hartmann disposition can be seen Figure 2 and Figure 3.

The pnCCD is read columns parallel, in a split transfer mode (two halves of the detector are read resp. to the left and the right, see Figure 2(a)).

The readout electronics is made of 4 units, namely CAMEX. The pixels are read column (or channel) parallel and then multiplexed through two output lines/nodes per CAMEXs.

Therefore, the 2 DAQs (4 ADC per DAQ) receive in total 8 input lines. The data are digitalized and then send to the BCU through two optical links (one per DAQ), following the gigalink protocol [4].

Since the data are multiplexed, the data format arriving to the BCU is, first, all the pixels of the first line, then the second line, etc.

As also represented Figure 2 and Figure 3, they are 4 covered lines and 8 covered channels (or columns) per CAMEX (on the border of the imaging area). These covered pixels can be used for data correction, e.g. the common-mode.

The link

The clock on the fiber (RefClk) runs at 125 MHz, running a 16bit protocol with 8/10bit encoding. This results in 2.5Gbit/s (resp. net speed of 2Gbit/s).

Wirespeed

Data will arrive with small interline/interframe delays (approx. 2μs resp. approx. 40μs) with a speed of –> 12.5MHz x 8 Readout-nodes = = 2 Fibers x 12.5MHz x 4 ADC-words x 2 Byte

Data format

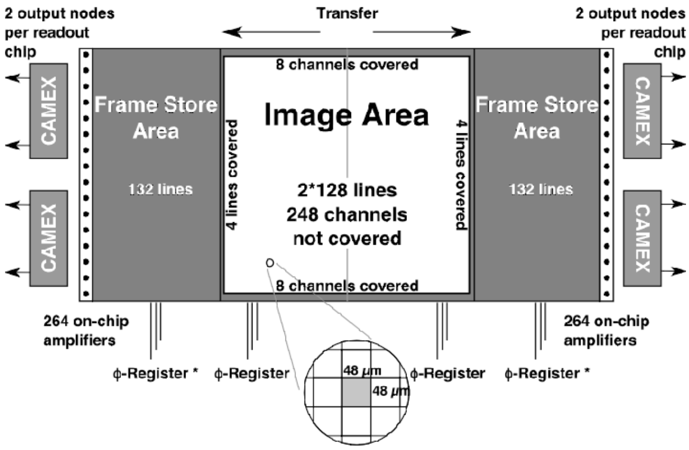
On each fiber channel, data arrives like this 32 bit words, i.e. 4bytes:

```
------------------------------------------------------------------
Spec. Word (spec. char + 3 data bytes)
FrameNumber
TimeStamp_Hi
TimeStamp_Lo
line 0, pix. 66  - line 0, pix. 0
line 0, pix. 198 - line 0, pix. 132
line 0, pix. 67  - line 0, pix. 1
line 0, pix. 199 - line 0, pix. 133
line 0, pix. 68  - line 0, pix. 2
line 0, pix. 200 - line 0, pix. 134
...........
line 0, pix. 131 - line 0, pix. 65
line 0, pix. 263 - line 0, pix. 197
line 1, pix. 66  - line 1, pix. 0
line 1, pix. 198 - line 1, pix. 132
line 1, pix. 67  - line 1, pix. 1
line 1, pix. 199 - line 1, pix. 133
...........
...........
...........
...........
line 131, pix. 130 - line 131, pix. 64
line 131, pix. 262 - line 131, pix. 196
line 131, pix. 131 - line 131, pix. 65
line 131, pix. 263 - line 131, pix. 197
------------------------------------------------------------------
```

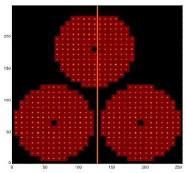
With the following remarks:

- For one half of the image (so data on one fiber link).
- Lines and columns are counted by starting with 0 (i.e. CCD-columns 0 .. 263, CCD-lines 0 .. 131 for half image). The first pixels are also represented Figure 3.

Since all readout nodes of the CCD as well as the subsequent ADC-modules are being operated synchronously, data on both fibers will arrive in parallel; however the fibers itself are independent of each other, i.e. independent RefClks!



(a) pnCCD format.



(b) 3SH.

Figure 2: (*Right*)The 3 foreseen Shack-Hartmann disposition. The middle orange line indicates the separation between the two halves of the read-out (no physical separation).

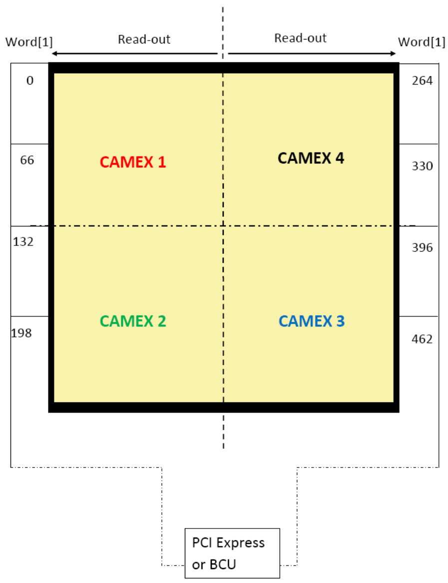


Figure 3: Schematic representation of the data format arriving to the BCU (in-between electronics not shown) through 2 optical links related to 8 output nodes on the CCD. The numbers indicate the pixel number of the first line.

Requested operations

3 LGS slopes computation

1. Read first word : time stamp t and frame counter k.
2. Input of the pixel I_i^k from the CCD. The subscript $i = 1, ..., N_{CCD}$ is the pixel index with N_{CCD} the total number of pixels.
3. Sorting pixels using a user-defined LUT (*Look Up Table*), changeable off-line. As seen, we have three types of pixels: "common-mode" pixels (for CM correction described hereafter, non-illuminated pixels), "slope" pixels (for slope measurements) and possibly "contour" pixels (not for common mode correction, neither slope computation). The latter, if any, are useless pixels. In addition, the "slope" pixels should be referenced to their respective LGS (or equivalently to their SH pupil), l.

   A possible additional operation would take into account cosmic rays by use of a threshold and assigned "contour" instead of normally assigned "common-mode" pixels (so that these pixels do not appear in the common mode correction) :

   $$\begin{aligned} &\forall \text{ \textit{"common mode" pixel i }} : \\ &\quad \textit{if} \quad \textit{common mode}_i^k > \textit{Threshold} \quad \textit{then} \\ &\quad \textit{common mode}_i^k \quad \textit{becomes} \quad \textit{contour}_i^k \end{aligned}$$

   In what follow, we note I_i^k any pixel i (of frame k; "common-mode", "contour" and "slope" pixels), I_{i,a_l}^k any pixel i in sub-aperture a ("slope" pixels) l being relative to one of the LGS, and C_j^k all the "common-mode" pixels of the line j.
4. **Dark/Background correction (DC) :** Correction of offset.

   $$\forall \text{ pixel } i : \quad I_{i;DC}^k = I_i^k - B_i$$

   where B_i is the dark frame (offset map) and needs to be changeable off-line.
5. **Common mode correction (CM).** The common mode consists in a line to line, time dependent variation, as well as CAMEX dependent. Therefore, the common mode correction consists in a line correction for the "slope" pixels. We take the median or the mean ($CM_{j;cmx}$) of a given number of pixels per CAMEX per line. We then subtract to every pixel of the line considered the obtained value, *i.e.*:

   $$\begin{aligned} \forall \text{ line } j : \quad & \forall \text{ pixel } i \text{ of CAMEX } cmx : \\ & CM_{j;cmx} = \text{median}(C_{j;DC}^k) \\ & \text{OR} \quad CM_{j;cmx} = \text{mean}(C_{j;DC}^k) \\ & \forall \text{ sub-ap. } a \text{ of the 3 LGS} \\ & I_{i,j,a;CM}^k = I_{i,j,a;DC}^k - CM_{j;cmx} \end{aligned}$$

This correction cannot be performed directly as the pixels arrived but required all the "common-mode" pixels of one line to be read (which means that a complete line has to be read before applying the common mode correction to the line, creating a latency of 67 pixels).

6. **Flat-field/gain correction (F).** Each "slope" pixels is divided by a proportional factor related to its gain to normalize the pixel to pixel (mostly channel to channel) variations. The flatfield is defined in advance from illuminated images of the CCD. The correction is as followed:

$$\forall i \text{ and } \forall a \text{ of the 3 LGS}: \quad I^k_{i,a;F} = \frac{I^k_{i,a,CM}}{G_i}$$

   Where G is the flat field (gain map). This gain map has to be changeable off-line.

7. **Centroid.** The centroids should be performed using center of gravity (CoG) algorithms. The different variations are reviewed in more details in appendix 1. A general formulation is given hereafter, for each LGS :

$$\forall \text{ sub-ap. } a:$$

$$x_a = \gamma K^{-1} \sum_{i;I_{i,a}>I_{a;T}}^{N} x_i W_{i,a}(I_{i,a} - I_{a;T})^n$$

$$y_a = \gamma K^{-1} \sum_{i;I_{i,a}>I_{a;T}}^{N} y_i W_{i,a}(I_{i,a} - I_{a;T})^n \qquad (1)$$

   with K defined as :

$$K = \sum_{i}^{N} W_{i,a}(I_{i,a} - I_{a;T})^n$$

   where $W_{i,a}$ is a predefined weighting function sub-aperture dependant. If this weighting function is used, a coefficient γ is needed to ensure linear response between estimated and real position, $W_{i,a}$ and γ changeble off-line. The factor n is foreseen to be either 1 or 1.5 (so to weight the pixels by their respective signal to noise ratios [7]), change off-line. The threshold $I_{a;T}$ could be either a constant value for every sub-apertures (changeable off-line), or determined dynamically (on-line) as to be proportional to the maximum pixel value within the sub-aperture considered : $I_{a;T} = \alpha I_{a;max}$, α should be changeable off-line.

8. **Slope calculation.** For each LGS, we have :

$$\forall \text{ sub-ap. } a:$$

$$s_{x,a} = x_a - x_{0,a}$$

$$s_{y,a} = y_a - y_{0,a}$$

   where $x_{0,a}$ and $y_{0,a}$ are the reference x and y position, the slope offsets. These position offsets can be modified during the calibration procedure and *as well on-line* (slow rate: updated by the ARGOS WDHS derived from the FLAO BCU, *i.e. truth sensing*). A slope vector $\vec{s}^k$ is formed containing the x and y slopes of all the three SH patterns.

9. The CCD frame is saved together with the ID frame k_{lgs}, the time stamp t and the slope vector $\vec{s}^k_{lgs}$ to the ARGOS supervisor (WDHS) for diagnostic purpose.

4 LGS tip-tilt slopes and field pointing for the three piezo mirrors in each WFS

To derive the LGS tip-tilt slope is necessary to stabilize the incoming laser beams on the LGS WFS.

10. Define x and y median of slopes for each LGS of the current frame k_{lgs} (more robust to cosmic rays than mean): $\tilde{s}_x$ and $\tilde{s}_y$. These two slopes for each LGS (so a total of 6 slopes) are saved for diagnostic purposes.

    The following steps are either done in the BCU or in the MG HV controller:

11. Projection from frame (image) to piezo TT mirror space.

12. Reconstruction of pixels into voltages and multiply by a gain factor for tip and tilt. The last 2 steps can be summarized into three matrix calculations, one for each LGS:

$$(\delta t_x, \delta t_y) = \mathbf{R_{2x2}}(\tilde{s}_x, \tilde{s}_y)$$

13. (Frame counter k_{lgs} and the time stamp t should also be sent to the MG HV controller at the 1 kHz frame rate for diagnostic purposes.)

    There are three tip-tilt mirrors per WFS (one TT mirrors per SH optical path). The mirrors used are PI-S334 and need 3 voltage lines.

5 Adding additional slopes : TT, FLAO and Na

Adding the TT, FLAO and Na slopes should be switch-able : any combination should be possible (none, one of those, two of those or the three).

14. Input of a the re-rotated x and y TT slopes from the TT slope computer (Bonn unit) $\vec{s}_{tt}^{\,rerot.}$ together with the respective frame counter and the 4 raw APD values. Asynchronous but at $\sim$ 1kHz.

15. Input slope vectors $\vec{s}_{flao}$ from the ARGOS supervisor (itself receiving information from the FLAO BCU) together with frame counter k_{flao} (number of received slopes should be changeable). May be asynchronous, in which case the BCU save these slopes until reception of new ones.

16. Stack these slopes ($\vec{s}_{tt}$ and $\vec{s}_{flao}$) to the previously computed $\vec{s}_{lgs}$. When no new $\vec{s}_{tt}$ and $\vec{s}_{flao}$ slopes inputs, stack either the last received ones or a vector of 0's (the stacking is a synchronous operation).

17. For the upgrade path, same as previously, reception and stacking of the Na sodium slopes (asynchronous).

18. The total slope vector $\vec{s}_{total}$ =[$\vec{s}_{lgs}$; $\vec{s}_{tt}^{\,rerot.}$; ($\vec{s}_{flao}$) ; ($\vec{s}_{Na}$)] is saved together with a frame counter vector $\vec{k}_{total}$ =[k_{lgs}; k_{tt}; (k_{flao}) ; (k_{Na})] and the time stamp t_{lgs} for diagnostic purposes.

19. Finally, the slopes $\vec{s}_{total}$ are transferred to the Switch BCU with $\vec{k}_{total}$ and the time stamp t_{lgs}.

6 Additional comments

Clarifications concerning diagnostics outputs:

- Slopes + ID frames + time stamps should be saved at full rate for diagnostic.
- Median LGS tip-tilt slopes should be saved for diagnostic (point 10).
- The 4 raw APD values should be saved for diagnostic (in addition to the tip-tilt slopes and frame counter).
- Frames, either one full seconds (1 seconds at 1kHz) or at a slow rate $\sim$ 25 Hz (or higher if possible), should be saved for diagnostic. Frames should be by default the corrected ones and optionally the raw frames (instead of corrected ones).
- The diagnostic record should also contain the HVC-related information (commands and strain gauge signals from the 3 piezo mirrors).

Others:

- To have the possibility to inject a "fake" CCD frame (upload a frame from the ARGOS supervisor through ethernet) to debug the software used for the BCU configuration.
- If it does not introduce latencies, instead of having common mode (point 5.) and flat-field correction (point 6) only for "slopes" pixels (pixels in sub-apertures), to have the corrections done for the full frame. In which case, it would not be optional, just modification of point 5 and point 6 (corrections "for all pixels" instead of "for pixels in sub-apertures").

Bibliography

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1 Centroid Algorithms

We choose to only use centroid estimator (and not more complex algorithms like maximum-likelihood estimator, mean-square-error estimator, etc.) as they are easy to implement, less computing time consuming and there is little difference to more complex algorithms provided a sufficient amount of photons (e.g. [8]).

We consider several variations of CoG estimator:

TCoG : the threshold center of gravity. The threshold is subtracted from the spot image and the centroid is computed using only pixels with non-negative values[1]. The threshold used can be either **static** - *i.e.* the same threshold for every subapertures, not depending on the SNR (*Signal to Noise Ratio*), e.g. equals to 3 σ_{RON}, - or **dynamic** - *i.e.* depending on the SNR and defined like $I_T = \alpha I_{max}$, the implications of this dynamic threshold are described by [9][2]. The **dynamic** thresholding requires to determine I_{max} of the sub-aperture before centroid computation.

[1] It is important to subtract the threshold before CoG calculation, otherwise the centroid estimate is biased [8].

[2] This algorithm called "radial thresholding" by [9] should cancelled out most of the errors induced by the LGS spot elongation without altering the centroid accuracy in the presence of noise.

$$\forall \text{ sub-ap. } a :$$
$$x_a = K^{-1} \sum_{i; I_{i,a} > I_{a;T}}^{N} x_i (I_{i,a} - I_{a;T})$$
$$y_a = K^{-1} \sum_{i; I_{i,a} > I_{a;T}}^{N} y_i (I_{i,a} - I_{a;T})$$

with K defined as :

$$K = \sum_{i}^{N} (I_{i,a} - I_{a;T})$$

In its simplest form, the algorithm consider only pixels with positive value ($I_{thres} = 0$).

WCoG : the weighted center of gravity. This algorithm consists in weighting the pixels of the spot image by, e.g., a reference image of the spot (at its nominal position). The gain of this algorithm can be important compared to simple CoG [8]. Nevertheless, as pointed by [9], the CoG of the square of an elongated spot image differs from the actual centre of gravity of that spot, if the spot profile is asymmetric. In our case, we expected the spot to be on average symmetric (thin rayleigh layer, etc.). But higher order turbulences results in short-exposure spots with speckles. Robustness on this effect should be tested.

In addition, a coefficient γ is needed to ensure the linear response between estimated centroid and real position. This coefficient should be computed during calibration procedure.

Previous thresholding may not be needed.

$$\forall \text{ sub-ap. } a : \forall \text{ pixel } i :$$

Possible thresholding like in the TCoG algo

$$x_a = \gamma K^{-1} \sum_{i}^{N} x_i W_{i,a} I_{i,a}$$
$$y_a = \gamma K^{-1} \sum_{i}^{N} y_i W_{i,a} I_{i,a}$$

with K defined as :

$$K = \sum_{i}^{N} W_{i,a} I_{i,a}$$

WWAP : the weighted weighted average pixels. This algorithm weights the intensities to the 1.5th power. Bigger exponents reduce the performance at high flux levels, smaller ones reduce it at low levels without improving the performance in the respective other regimes [7]. The same remark as for WCoG about asymmetric and short-exposure spots holds.

$\forall$ sub-ap. $a : \forall$ pixel i :

Possible thresholding like in the TCoG algo

$$x_a = K^{-1} \sum_i^N x_i I_{i,a}^{1.5}$$

$$y_a = K^{-1} \sum_i^N y_i I_{i,a}^{1.5}$$

with K defined as :

$$K = \sum_i^N I_{i,a}^{1.5}$$

Considering these several variations, we propose a general formulation equation 1.