PAUCam readout electronics assembly, integration and test (AIT)

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ABSTRACT

The PAUCam is an optical camera with an array of 18 CCDs (Hamamatsu Photonics K.K.) and up to 45 narrow and broad band filters. The camera will be installed on the William Herschel Telescope (WHT) in the Canary Islands, Spain. In order to fulfill with the specifications for the camera readout system, it was necessary to test the different readout electronics subsystems individually before to integrate the final readout work package, which is composed of 4 MONSOON (NOAO) front-ends, 6 fan out boards (MIX), each one driving up to 5 CCDs signals and a pre-amplification stage (PREAMP) located inside the cryostat. To get the subsystems integration, it was built a small camera prototype using the same technology as used in the main camera: a carbon fiber cryostat refrigerated by a cryotiger cooling system but with capacity to allocate just 2 CCDs, which were readout and re-characterized to measure the electronics performance as conversion factor or gain, readout noise, stability, linearity, etc. while the cross-talk was measured by using a spot-light.

The aim of this paper is to review the whole process of assembly, integration and test (AIT) of the readout electronics work package and present the main results to demonstrate the viability of the proposed systems to be use with the PAUCam camera.

Keywords: readout electronics, CCD, AIT, pre-amplification, characterization

1. INTRODUCTION

The PAUCam camera is composed of 18 Hamamatsu K.K. scientific-grade CCDs, type S10892-04 of 2k x 4k pixels, back-side illuminated and fully depleted, which are distributed in 8 central CCDs with an unvignetted area, 8 CCDs in the edges and partially vignetted (60%) and 2 guiding CCDs in the top and bottom corners of the focal plane. This CCDs distribution demands us to design a customized internal (vacuum side) and external (atmosphere side) electronics with 2 main requirements: low noise, low power dissipation and low cross-talk. As our previous experience just reading a couple of CCDs in our test-bench and fulfill these requirements was a huge task, thus readout the whole camera focal plane would be a really "colossal mission". On that way, it was launched the "PAUCam Readout Electronics" work package, whose first approach was presented at the SPIE 2012 [1] and then the focus was put to get working 2 setups: one to characterize the scientific-grade CCDs and the other devoted to AIT issues. The CCDs characterization was started at the end of 2012 in a fully tested setup [2] at the IFAE facilities using a prototype of the internal and external boards. Later, the AIT process was launched to demonstrate the viability of the proposed designs but working on a realistic scenario with a carbon fiber cryostat and similar conditions as expected on the main camera concerning the cooling, pumping and the grounding connections. On other hand, working with the readout electronics system allowed us to get enough know-how to deal with the full system once integrated on the camera.

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2. READOUT ELECTRONICS DESIGN: FIRSTS STEPS TO AIT

Several designs were proposed in order to fulfill the requirements of the camera, many of them demanded a lot time in to be software simulated and check for its viability, while others were directly discarded. The process of design was split in two main branches: internal boards (PREAMP) and external boards (MIX), both with the same restriction: to fit with a MONSOON (NOAO) electronics front-end due it was selected as the standard to readout the PAUCam`s CCDs, mainly because the IFAE's staff had a previous experience using it due the DES and DECam collaboration [3].

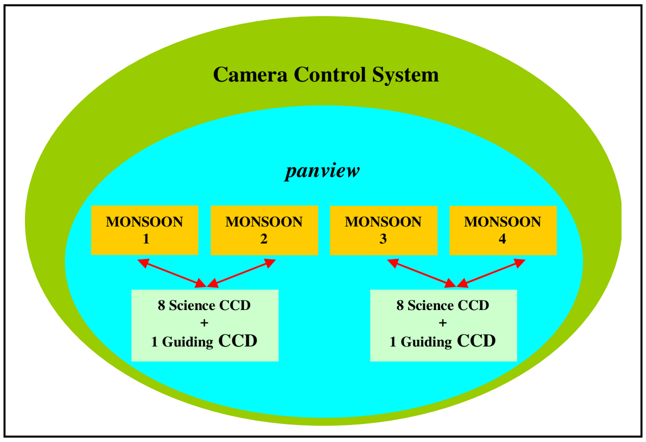

Fig 1. PAUCam readout electronics scheme.

2.1 PREAMP

The PREAMP board is located inside the cryostat (vacuum) and devoted to connect the signals coming from the CCD and route them by means a D-SUB 50 pins feed-through connector to the MIX board. The final PREAMP design is based on a fully differential pre-amplification stage with configurable gain (actually G=1) that process the four CCD's video outputs and one CCD at a time. The board has 12 layers in order to separate bias, clocks and video signals while shielding layers were included to avoid the electrical coupling. A gold-coating finishing was used in order to reduce the thermal radiation and the outgassing, thus all used connectors meets with the NASA-RP-1124 requirements.

The PREAMP was designed at IFAE in order to provide low readout noise (≤ 25 uV RMS), a moderated cross-talk (≤ 5/10.000), reduced power consumption and power dissipation (≤ 200mW) and low-to-moderated outgassing and thermal radiation.

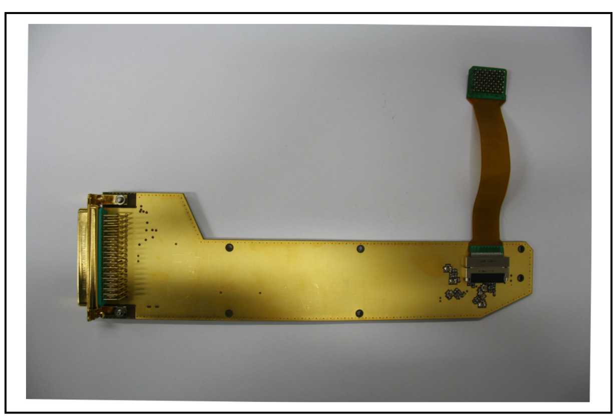

Fig 2. Actual view of the PREAMP board with a Hamamatsu CCD cable.

2.2 MIX

The MIX board resides outside the cryostat (atmosphere) just behind the D-SUB 50 pins feed-through connector. Its main aim is to fan out the CCD signals coming from the PREAMP board and route them toward the MONSOON front-end. The MIX board collects bias, temperature and video signals and is able to drive up to five CCDs on the MIX5 version or up to three CCDs using the MIX3.

The MIX board was designed at the CIEMAT following the camera specifications.

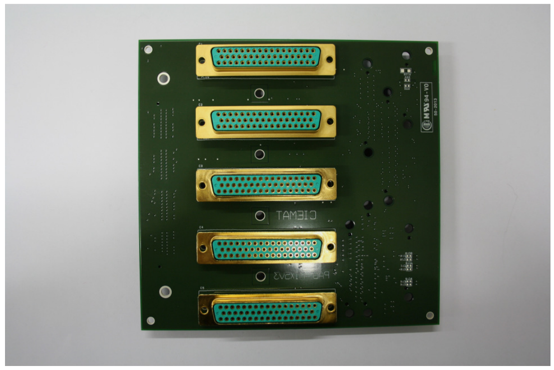

Fig 3. Actual view of the MIX5 board.

3. READOUT ELECTRONICS ASSEMBLY

Both, PREAMP and MIX boards were manually assembled at IFAE facilities. Once ready, the MIX boards were redirected to the CIEMAT for its tests while the PREAMP boards were tested at the IFAE.

Here, the PREAMP boards were tested electrically for short-cuts, open circuit, cold solders and any other defect produced during the PCB's manufacturing or the assembly. Once they were electrically working, they were tested considering its performance concerning readout noise, linearity, readout speed noise and signal stability. In order to do that, the own MONSOON front-end was used as a pixel generator by using a clock signal with the same level as expected in the CCD (i.e.: ~100 mV for a bias level) and synchronized with the correlated double sample (CDS) of the video board. On that way, PREAMP boards with low performance were discarded.

3.1 Stability Test

Signal stability test look for any variation caused for instance by the electronics over-heating. The test was performed by taking 100 consecutive flat-simulated images with different delay times (Fig 4.a). Afterwards, the mean signal over a region of interest (ROI) of 100 by 100 pixels was calculated and plotted to show the stability of the signal over the whole set of images. As demonstrated, the stability is better that 1% along a set of 100 images, which means more than 1 hour taking images on a non-stop regimen.

3.2 Linearity Test

The linearity test was performed by using the pixel generator and modulating the pixel amplitude. Due that Hamamatsu CCDs have a typical node sensitivity of around 5 uV/e-, the worse case pixel amplitude is produced at the typical CCD's full well of 150 ke- [4], then the linearity was measured from 100 mV up to 800mV (Fig 4.b). The linearity performance was measured by the coefficient of determination (R^2) from the mean signal versus the input voltage, which demonstrated to be pretty good for almost all PREAMP boards.

3.3 Readout Noise Test

The readout noise was measured from 10 bias-simulated images. The images were processed in order to calculate the standard deviations for every video channel (Fig 4.c). The readout noise value calculated from this test was just used as reference in order to select the "best" boards from the PREAMP batch.

3.4 Readout Noise vs Readout Speed Test

The aim of this test was to quantify the readout noise at different readout speeds. Using the pixel generator with a bias signal level, the readout speed was increased step by step until to reach the maximum camera pixel rate of 200 kpixel/second (200 kHz). As showed in the figure (Fig 4.d), the readout noise was reduced proportionally while increasing the readout speed. It is because while increasing the readout speed, also was reduced the integration time at the correlated double sampling stage, consequently reducing the mean signal.

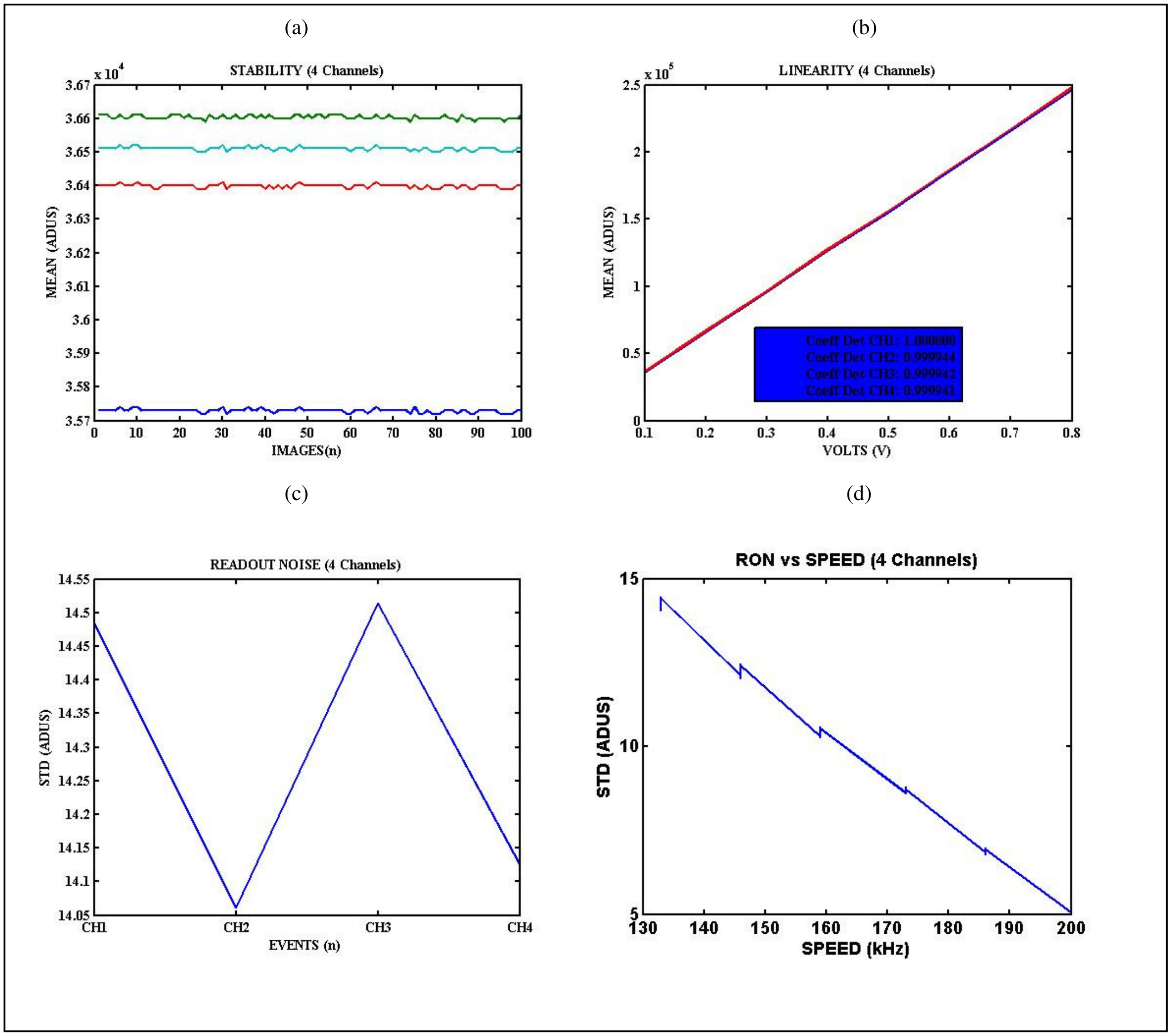

Fig 4. PREAMP test plots: (a) mean signal stability, (b) signal linearity, (c) readout noise, (d) readout speed vs readout speed.

4. READOUT ELECTRONICS INTEGRATION

Once all the subsystems were tested individually, it was time to test all working together. In order to integrate the whole readout electronics system, a cryostat prototype was build with almost the same technology as expected for the main camera. Also, it gave the chance of integrate and test other pieces that never have been joined before and which performance at that time was still uncertain, as the case of the carbon fiber cryostat and the full cryo-vacuum system. On that way, a couple of CCDs was installed on an aluminum focal plane and connected to the cryotiger's cold head by means few thin copper straps. A 50W heater was located on the thermal link to control the CCD temperature at 173ºK ± 0.1 ºK. A suitable vacuum level of 1e-6 mbar was reached using a turbomolecular pump directly attached to the carbon fiber.

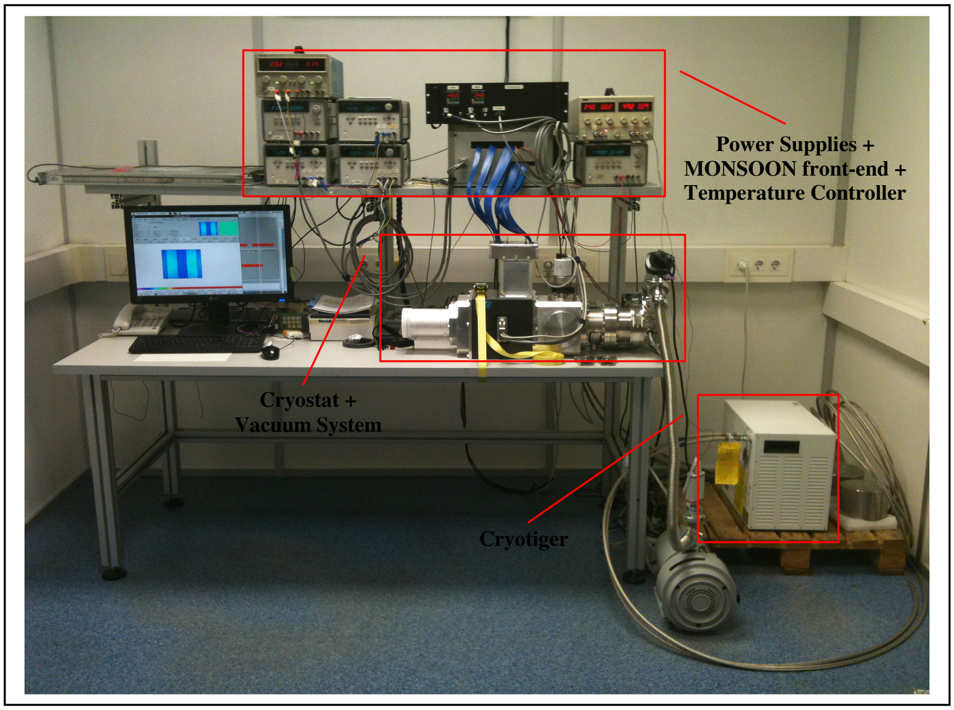

Fig 5. The carbon fiber cryostat and its cryo-vacuum system. On the top bracket, the MONSOON front-end, the power supplies and the temperature controller.

In order to readout the CCDs, a MONSOON front-end was integrated with one video board (ACQB) and one clock board (CB) plus a master control board (MCB). It was also the chance to measure the power consumption and currents needed to feed a MONSOON front-end and estimate these values for a plenty of boards crate as demanded by the camera. Special care was put concerning the grounding connections in order to keep them as close is possible to the proposed scheme for the camera. Grounding loops are not desirables while the cables gauge size is also an important issue.

The PREAMP boards were installed inside the cryostat and connected to the CCD through the rigidflex kapton cable already included with every CCD.

Finally, the whole cryostat and its cryo-vacuum system plus a couple of PREAMP boards for the 2 CCDs were integrated. After 12 hrs pumping and baking out the cryostat and the CCDs, the cryotiger was switched on and the CCDs were cooled down up to the temperature set-point.

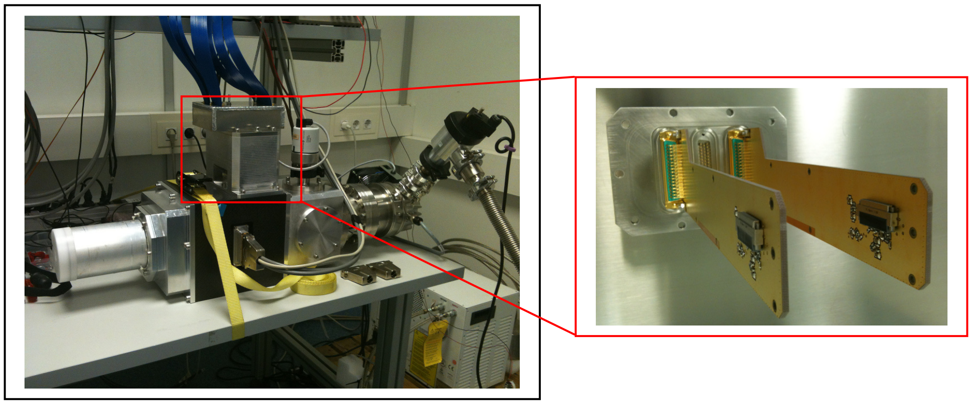

Fig 6. Close up of the cryostat, allocating inside the couple of CCDs and its PREAMP boards.

5. READOUT ELECTRONICS TESTS

Once configured all the bias and clocks signals in the MONSOON front-end through its *panview* interface and with the couple of CCDs cooled, it was time to get the first light and start getting the whole set of images to test the readout electronics system. In order to do that, it was proposed to re-characterize the CCDs, which were previously tested on the characterization setup [5], by run some standard CCD tests as *Photon Transfer Curve* (PTC), *Readout Noise* (RON) and *Cross-Talk.* Also, it was re-run the *stability test* in order to look for some image or overscan gradient. The images were captured with an automatic process by using a TCL/TK scrip while the data reduction and image analysis was performed by a customized IDL application. Afterwards, these software tools were used during the whole process of CCDs characterization. The CCDs readout was performed with 2 readout speeds: 133 kpixel/sec (low speed) and 200 kpixel/sec (high speed). Low speed feature was proposed as the main speed for central and edges CCDs located on the focal plane and because this configuration offers the best relationship between CCD’s readout noise and CCD’s readout time (busy-time) while the high speed was mainly proposed for guiding CCDs were readout time has the priority over the readout noise.

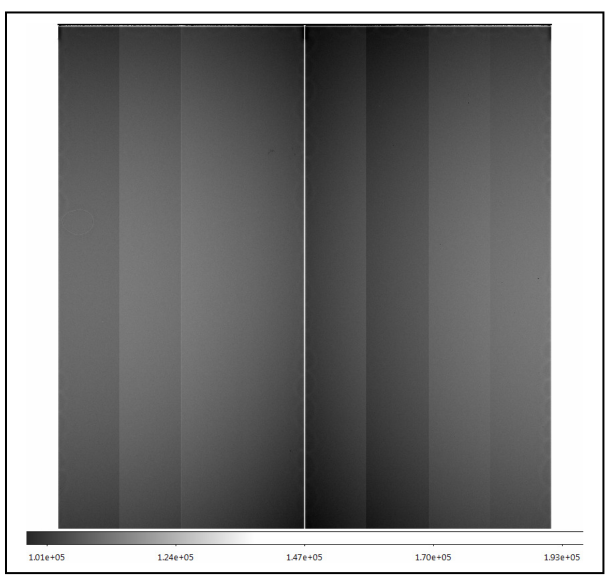

Fig 7. First flat-field image (unbiased) from the readout electronics test. It is possible to observe some cosmetics defect, for instance, the assembly patterns over the detector edges.

5.1 Photon Transfer Curve (PTC)

The *photon transfer curve* is a powerful tool that shows relevant parameters as the *conversion factor* or *gain* (e-/ADU) from the whole video chain and the CCD's *full well*. Roughly, the PTC test is performed by taking several illuminated images (flat-field) with different exposure times, for instance, it was took using an exposure time with increments of 1.122 sec until 40 sec, which was enough to reach the CCD's *full well*. The main results from this test are presented below.

Table 1. PTC main results.

@ 133 kpixels/sec	***CH1***	***CH2***	***CH3***	***CH4***
Conversion Factor (e-/ADU)	0.695	0.674	0.659	0.660
*Full Well (e-)**	145 k	141k	138k	138k
@ 200 kpixel/sec	***CH1***	***CH2***	***CH3***	***CH4***
*Conversion Factor (e-/ADU)***	1.085	1.066	1.051	1.043
Full Well (e-)	162 k	159k	157k	156k

* *Full well* value limited by the video board ADC. Fixed on the final release.

** ACQ board with gain x 2 selected by software.

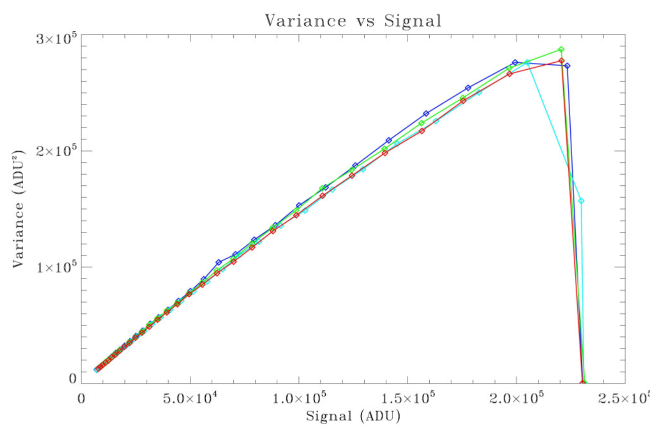

Fig 8. *Photon Transfer Curve* plot at 133 kpixel/sec. The conversion factor or gain is calculated as the inverse of the slope between the variance and the mean signal trends.

5.2 Readout Noise (RON)

The readout noise was measured by calculating the standard deviation on the overscan region from 10 bias images. The value measured at this time would be considered quite realistic for the whole readout electronics systems, but despite that it was designed and integrated to reach the lowest readout noise, there is a CCD noise pedestal, whose value while reading at 133 kpixel/sec, is not better than 5 e- RMS. The main results from this test are exposed below.

Table 2. Readout noise main results.

RON	*CH1*	*CH2*	*CH3*	*CH4*
@ 133 kpixel/sec	5.4	5.3	5.3	5.3
@ 200 kpixel/sec	7.7	7.8	7.7	7.6

5.3 Cross-Talk

Fine cross-talk between video channels is not easily measurable due the weak nature of the signals. On that way, an optical setup was build in order to create a very bright but small spot-light with ~1 mm of diameter and able to be exchanged between CCD channels, one at a time. Approximately, the procedure consisted in to put the spot-light over the desired channel and took several images. Then, the data reduction is focused to look for any faint spot-light over the neighbors channels and quantify its relationship. The main results from this test are exposed below and it shows quite positive results since the worse case cross-talk measured between CCD channels is ≤ 3 /10000 e-, that means, for any tens of thousand electrons, there will be three electrons on the neighbors channels.

Table 3. Worse case cross-talk between channels.

CROSS-TALK	*CH1 to CH4*
@ 133 kpixel/sec	≤ 3/10000
@ 200 kpixel/sec	≤ 2/10000

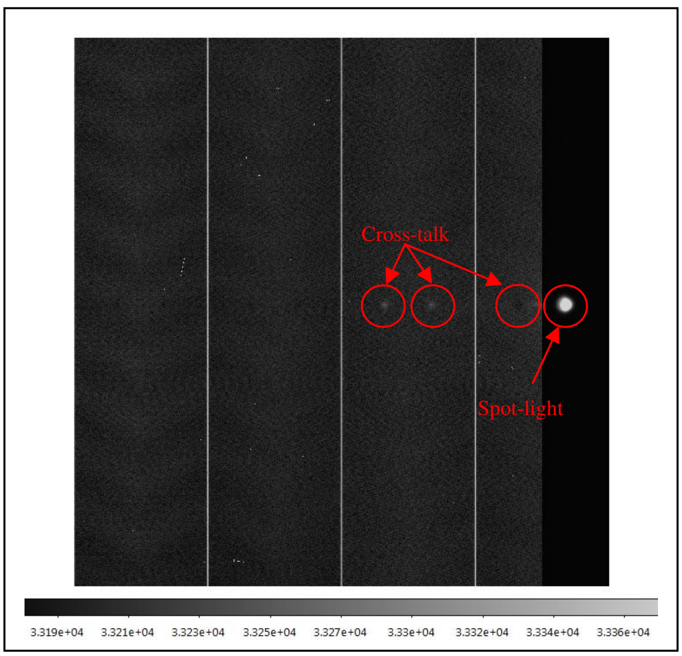

Fig 9. Cross-talk image. It is possible to see the spot-light over the right channel and a weak cross talk on the previous three ones while the first four channels, from the other CCD, are not affected.

5.4 Stability

This test was run previously during the preliminary PREAMP tests and it demonstrated that stability signal was pretty good. Now, signal came from CCD video outputs and also, it was analyzed for any gradient on the image and over the overscan region. The main results from this test are exposed below and confirm the electronics stability.

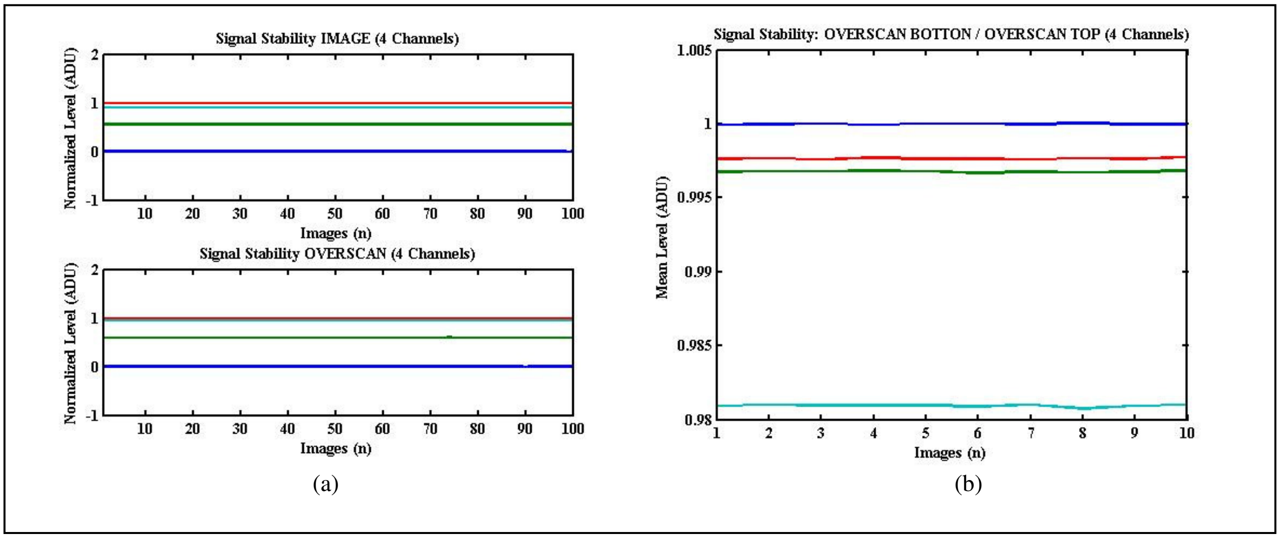

Fig 10. Stability test plots. (a) The signal stability from the image area (top), the horizontal overscan (bottom) and vertical overscan (b).

6. CONCLUSIONS

As exposed on this paper, the readout electronics system proposed for the PAUCam camera was designed, assembled, integrated and tested. It also gave us the chance to get enough know-how with the hundred of details that it would include and to learn how to deal with them.

After several tests and based on the results exposed here, it is possible to confirm the viability of the proposed readout electronics work package for the PAUCam camera.

7. ACKNOWLEDGEMENTS

We would like to thanks to all the people involved on this work package and whose duties were not always visible despite that they worked really hard…without their effort it would not have been possible.

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