Analysis of crosstalk in the DES CCDs

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1 Introduction

We studied the crosstalk problem that has been observed in the *Dark energy Camera* DECam CCDs that are currently being tested at *Silicon Detector Facility,SiDet* (Fermilab) for the *Dark Energy Survey*(DES) project. We present first some definitions and theoretical characterizations of crosstalk in electronic devices. Then we make a description of the problem observed and finally we comment about the procedures followed and show the measurements done for understandig the problem, along with the results obtained.We will see how the requirement that the crosstalk be less than 0.01% is barely satisfied in some cases and that further work needs to be done in order to achieve this. This percentage comes from the fact that it is planned to analize (by the *Data Management* team of *DES*) the two readout channels of each of the 62 *DECam* focal plane CCDs separately by using a cluster of 124 computers. For the problem to be ignored, it has been therefore calculed that it is necesary to have a crosstalk not greater that 0.01%.

It is important for the project to try to correct for this problem and to satisfy this requirement. Ghost images originated due to crosstalk would affect the analysis of the data. For example, it would affect the number of galaxies in a cluster or it would create a particular lenght scale that would affect statistics for describing the structure of the Universe (e.g., the two-poit correlation function).

Finally, we present some conluding results that summarize the work so far done.

1.1 Objectives

- To understand the nature of the crosstalk observed between the two readout channels of the DES CCDs.

- To make measurements that allow us to characterize the magnitude of the crosstalk and to identify its sources (electronics,CCDs,...). These studies would allow to have a better understanding of the problem in order to correct for it in the future 12-channel Monsoon adquisition board that is being designed for the project.

- To establish if the amount of crosstalk observed is below of what is technically required for the problem to be ignored (0.01%).

2 Crosstalk

According to the definition given by the *Federal Standard 1037C* , the crosstalk is the "undesired capacitive, inductive or conductive coupling from one circuit, part of a circuit or channel, to other". Alternatively, we can say also that crosstalk is "any phenomenon by wich a signal transmitted on one circuit or channel or a transmission system creates an undesired effect in another circuit or channel".

Capacitive coupling is the transfer of energy between circuits due to the mutual capacitance of them. In the same way, *inductive coupling* refers to the transfer of energy caused by the mutual inductance of the circuits involved.Finally,when we have*conductive coupling*, the energy is passed between circuits through physical contact. Sometimes these coupling are deliverate, but in other cases they may be undesired, like in our case. Capacitive coupling favors higher frecuencies. On the other hand,inductive coupling favors low frecuencies. Conductive coupling favors those componets of all frecuencies.

3 Description of the problem

The *Lawrence Berkeley National Laboratory* (LBNL) CCDs that will be used in the *Dark Energy Camera* and are being tested at *SiDet* possess each one two readout channels. When analysing the images, it has been observed that if one has an intense signal in one of these two channels, like a bright pixel, we note that a some sort of ghost image is formed in the other one, in a possition that mirrors that of the source but with a lower intensity.

In Figure 1 we can better appreciate the nature of this problem.

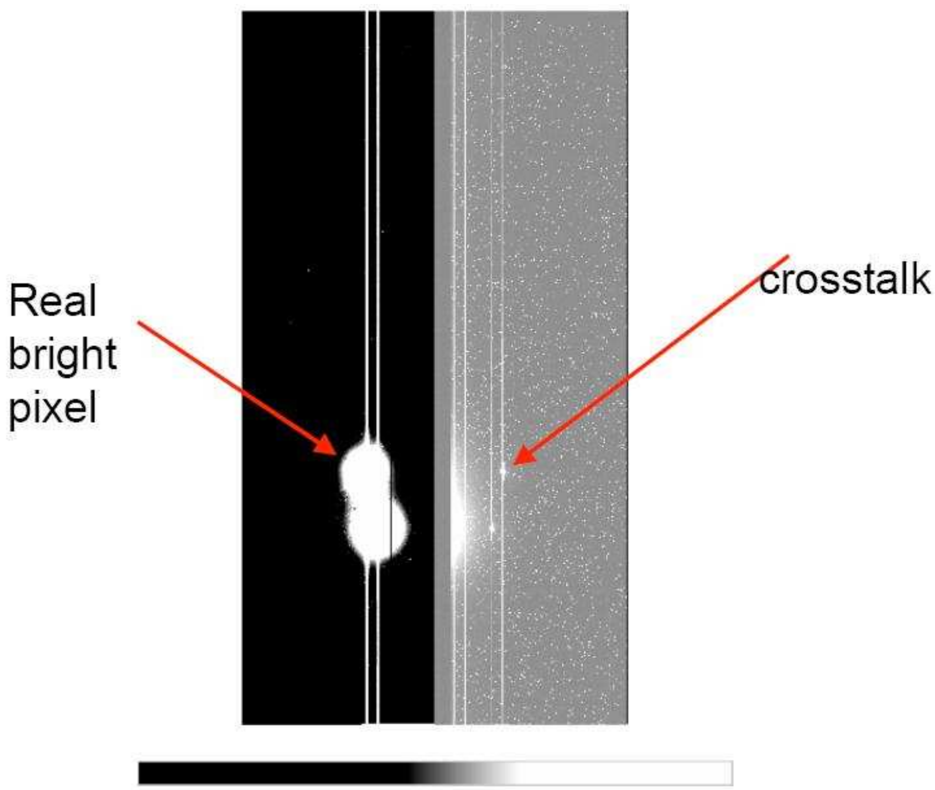

Figure 1: Crosstalk observed in *DECam* CCDs

We want to make a cuantitative description of this problem in order to study ways to solve it in order to satisfy the *DES* scientific requierements.

4 Measurements and Results

4.1 Sine wave signal and long cable

4.1.1 Equipment

- Pulse generator.

Channel number	Crostalk (%)
2	5.6 ± 0.1
3	5.8 ± 0.1
4	1.4 ± 0.1
5	0.5 ± 0.1
6	0.4 ± 0.1
7	0.4 ± 0.1
8	0.4 ± 0.1

Table 1: Crosstalk between channel 1 and the rest at $11MHz$.

- Oscilloscope Tektronix TDS5054B-NV-T
- Long cable.
- Monsoon 1.
- CCDACQ SN 021

4.1.2 Procedure

We generated a sine wave using the pulse generator(i.e., there was no CCD plugged).This signal was connected to the CCD transition board of the CCDACQ SN 021. It is worth to remember that, by default, the two readout channels of the CCD are connected to channels 1 and 3 of the CCDACQ board and so the signal coming from the pulse generator goes through these two channels,too. First we measured the crostalk between channel number 1 and the rest (from 2 to 8) at a fixed frequency ($11MHz$). After that, we analized the crosstalk dependence on frequency between channels 1 and 3. Data were taken observing the output signals amplitudes on the oscilloscope, so errors in the appreciation of the values are present.

4.1.3 Results

Crosstalk between channels at $11MHz$

We note that the highest crosstalk is seen between channels 1, 2 and 3 (around 6%). The minimum value of crosstalk is found in the channel that is physically farthest to channel 1, that is to say, channel 8. The crosstalk in here is around 0.5%, which is still a high value. (See Figure 2).

Crosstalk dependence on frequency

The amount of crosstalk in channel number 3 was analized. The sine wave was located in channel number 1.

Frequency(MHz)	Crosstalk (%)
0.1	0.11 ± 0.005
0.3	0.16 ± 0.005
0.5	0.22 ± 0.005
0.7	0.21 ± 0.005
0.9	0.24 ± 0.005
1	0.26 ± 0.005
3	0.69 ± 0.005
5	1.09 ± 0.005
7	2.30 ± 0.005
9	3.39 ± 0.005
11	6.18 ± 0.005
13	12.86 ± 0.005
15	23.38 ± 0.005
17	16.85 ± 0.005
19	9.12 ± 0.005
21	9.09 ± 0.005

Table 2: Crosstalk dependence on frequency. Channels 1 and 3. Long cable.

In this case (Figure 3) we can note how the crosstalk changes with frequency. We see that the crosstalk has a very high peak of 23% at an also high frequency of $15MHz$. It is worth to mention here that it was observed in the crosstalk signal in the oscilloscope a change of phase of $\frac{\pi}{2}^{\circ}$ with respect to the input signal. We can say therefore that we are observing in this case a sort of transition between *capacitive coupling* and *inductive coupling.* The minimun value of crosstalk (0.1%) was found at $0.1MHz$.

4.2 Sine wave signal and short cable

4.2.1 Equipment

- Pulse generator.

- Oscilloscope Tektronix TDS5054B-NV-T
- Short cable.
- Monsoon 1.
- CCDACQ SN 021

4.2.2 Procedure

We used again the sine wave of the pulse generator. This time we changed the cable that goes from the pulse generator to the transition board of the CCDACQ SN 021 and used a shorter one. First we measured the crosstalk between channel number 1 and the rest (from 2 to 8) at a fixed frequency ($1.1MHz$). After that, we analized the crosstalk dependence on frequency between channels 1 and 3. Data were taken observing the output signals amplitudes on the oscilloscope, so errors in the appreciation of the values are present.

4.2.3 Results

Crosstalk between channels at $1.1MHz$.Short Cable.

Channel number	Crostalk (%)
2	2.09 ± 0.020
3	0.06 ± 0.0005
4	0.06 ± 0.0005
5	0.04 ± 0.0005
6	0.04 ± 0.0005
7	0.03 ± 0.0005
8	0.04 ± 0.0005

Table 3: Crosstalk between channels 1 and the rest at $1.1MHz$.Short cable.

We note (Figure 4) that the highest crosstalk is seen between channels 1 and 2(around 2%).We can start to appreciate here that the amount of crosstalk diminished with this shorter cable.

Crosstalk dependence on frequency

The amount of crosstalk in channel number 2 was analized. The sine wave was located in channel number 1.

Frequency(MHz)	Crostalk (%)
0.1	1.21 ± 0.013
0.3	1.70 ± 0.006
0.5	1.83 ± 0.006
0.7	1.98 ± 0.004
0.9	2.17 ± 0.003
1	2.22 ± 0.006
3	5.18 ± 0.007
5	11.74 ± 0.007
7	5.50 ± 0.010
9	3.13 ± 0.016
11	4.21 ± 0.017
13	2.82 ± 0.019
15	3.39 ± 0.030
17	3.23 ± 0.027
19	2.89 ± 0.032
21	2.06 ± 0.038

Table 4: Crosstalk dependence on frequency.Channels 1 and 2.Short cable.

Again we can appreciate the crosstalk dependence with frequency (Figure 5). This time the crosstalk was lower and we found a peak again but at a lower frequency, indicating perhaps some kind of inductive coupling. We see that at all frequencies the crosstalk was higher than 1%.

4.3 Sine wave signal and short cable with resistors

4.3.1 Equipment

- Pulse generator.
- Oscilloscope Tektronix TDS5054B-NV-T
- Short cable with $20k\Omega$ resistors.
- Monsoon 1.
- CCDACQ SN 021

4.3.2 Procedure

Now we added $20k\Omega$ resistors to the floating channels in the short cable that we used above. We measured then the dependence on frequency betwenn channels 1 and 2 and between channels 1 and 3.

4.3.3 Results

Crosstalk dependence on frequency between channels 1 and 2.

Frequency(MHz)	Crostalk (%)
0.1	0.11 ± 0.0014
0.3	0.38 ± 0.0023
0.5	0.64 ± 0.0022
0.7	0.89 ± 0.0026
0.9	1.20 ± 0.0026
1	1.35 ± 0.0012
3	3.53 ± 0.010
5	5.54 ± 0.0095
7	9.54 ± 0.0077
9	17.67 ± 0.0057
11	7.48 ± 0.0113
13	3.60 ± 0.0085
15	3.14 ± 0.0092
17	4.03 ± 0.0096
19	3.59 ± 0.0089
21	4.58 ± 0.0091

Table 5: Crosstalk dependence on frequency. Channels 1 and 2. Cable with resistors.

We find a peak of 18% approximately at $9MHz$. The mimimum value is at $0.1MHz$(0.1%). (See Figure 6).

Crosstalk dependence on frequency. Channels 1 and 3. Cable with resistors.

The amount of crosstalk in channel number 3 was analized. The sine wave was located in channel number 1.

Frequency(MHz)	Crostalk (%)
0.1	0.076 ± 0.0006
0.3	0.092 ± 0.0005
0.5	0.090 ± 0.0005
0.7	0.083 ± 0.0008
0.9	0.082 ± 0.0008
1	0.80 ± 0.0016
3	0.80 ± 0.0015
5	0.139 ± 0.0022
7	0.138 ± 0.0049
9	0.538 ± 0.007
11	0.523 ± 0.007
13	0.440 ± 0.008
15	0.409 ± 0.006
17	0.499 ± 0.007
19	0.446 ± 0.010
21	0.499 ± 0.010

Table 6: Crosstalk dependence on frequency.Channels 1 and 3. Cable with resitors.

We can see (Figure 7) that in this channel we find a lower crosstalk than in channel number two. The maximum value is nearly 0.5% between 9 and $11MHz$. We don't find this time a definite peak.

4.4 Measurements with the LEACH system

4.4.1 Equipment

- Short cable.

- Pulse generator (No CCD).

- Oscilloscope

4.4.2 Procedure

Before making further tests, we wanted to make some measurements using the *LEACH* system instead of *Monsoon*. Leach has only two readout channels, so we connected the input signal coming from the pulse generator to the first channel and studied the crosstalk present in the second one with the help of the oscilloscope.

4.4.3 Results

Frequency(MHz)	Crosstalk (%)
0.3	0.40 ± 0.002
0.5	0.80 ± 0.002
0.7	0.96 ± 0.002
0.9	1.07 ± 0.002
1	1.08 ± 0.002
3	1.10 ± 0.002
5	1.08 ± 0.002
7	1.07 ± 0.002
9	1.09 ± 0.002
11	0.91 ± 0.002
13	0.99 ± 0.002
15	1.03 ± 0.002
17	1.03 ± 0.002
19	1.03 ± 0.002
20	1.03 ± 0.002
21	0.99 ± 0.002

Table 7: Leach system. Crosstalk dependence on frequency. Channels 1 and 2. Short cable.

As a main feature, we can appreciate (Figure 8) that the crosstalk is almost the same (average: 0.98%) at all frecuencies. We observe too that it is relatively low compared with the results obtained so far for the Monsoon system in similar conditions.

4.5 Synchronized Signal

4.5.1 Equipment

- Short cable with $2k\Omega$ resistors in the free channels.

- Monsoon 1.

- CCDACQ SN 021, CCDACQ SN022

4.5.2 Procedure

Instead of making the measurements with the pulse generator, now we used a synchronized signal originated from the clockboard of the Monsoon system . The generating code of the syncronized signal was modified by Juan Estrada so that the images taken of the readout channels show four vertical fringes or regions: the signal, the left hand side pedestal, the right hand side pedestal and the crosstalk of the signal.By doing this, the analysis of the images was easier.In figure number 9 there is an example image of what we have just described.

First, we analized the crosstalk between channels using both CCDACQ SN021 and CCDACQ SN022. In this case, the input signal (synchronized) was connected to channel 1 of the boards (simulating one readout channel of a CCD). After that, we decided to change some parameters in the *TCL* software that controles the signal (parameters such as the integration window and summing well widths) and looked for changes in crosstalk. We found, in fact, that we could manipulate the amount of crosstalk measured by changing those parameters, concluding therefore that using the this kind of synchronized signal is not adecuate for our purposes.

4.5.3 Results

CCDACQ SN021

Channel	Crosstalk (%)
2	-0.002
3	0.0003
4	-0.0004
5	-0.0015
6	-0.0014
7	-0.0016
8	-0.0043

Table 8: Crosstalk between channel 1 and the rest. Synchronized signal. CCDACQ SN021

We can see that this time we got values much smaller than when we used the pulse generator. This time all values are less than 0.005%. (Figure 10)

The minus sing on the percentages values of table number 8 just reminds us that we got a negative crosstalk. This feature will be importart in the analysis below.

CCDACQ SN022

Channel	Crostalk (%)
2	-0.0046
3	0.0862
4	-0.0005
5	-0.0012
6	-0.0013
7	-0.0013
8	-0.0014

Table 9: Crosstalk between channel 1 and the rest. Synchronized signal. CCDACQ SN022.

Again we can find relatively low values.We see almost no difference with the CCD SN021 adquisition board. We note also that all values of crosstalk are negative (except in channel number 3). Now, as mentioned above, we changed some parameters in the signal and found crosstalk changes (See Figure 11).

Change of parameters in the synchronized signal.

In Figure 12 we find the oscilloscope image of the two integration windows of the Monsoon system (green), the synchronized signal originated from the Clock and Bias board of Monsoon (yellow, channel 1) and the crosstalk that is created by this last signal (blue, channel 2).

A priori, by looking at this image shown in Figure 12, we can imagine that it is possible to manipulate the amount of crosstalk that is seen by the integration windows if we change the relative phase between them and the synchronized signal(this can be achieved by changing parameters in the signal generating code). That is to say, the integration window sometimes takes into account a high peak of the crosstalk, sometimes a low one or sometimes a positive or a negative part of it. This leads us to think that there exists some sort of ambiguity by using this sinchronized signal to study the crosstalk problem. We changed, therefore, the *integration window* and *summing well* widths in the TCL code that generates the signal. Here are the results we obtained:

Parameters changed. Example 1

- CCDACQ SN 021

- No CCD (Synchronized signal). Channels 1 and 2.

- Summing well width : 0 (normally 8)

- Integration window width: 10 (normally 20)

In this case we obtained a crosstalk of 0.008%. What is important in this is that we have a *positive crosstalk* between these two channels. Remember that (table number 8) we had obtained, for this acquisition board and this channel, a negative value of crosstalk. So *we managed to change the sign of the crosstalk by changing the SW and integration window widths.*

Parameters changed. Example 2

- CCDACQ SN 021

- No CCD (Synchronized signal). Channels 1 and 2.

- Summing well width : 0 (normally 8)

- Integration window width: 5 (normally 20)

In this case we obtained a crosstalk of 0.01%. Again we got a positive crosstalk, meaning that we could change the sign of it by manipulating the integration window and summing well widths.

As we can appreciate in Figure 13, the real CCD video signal is *quite* different from the synchronized signal we used for making these last measurements.So we considered that for getting a better idea of the real situation we had to work with a CCD connected.

4.6 Measurements with a CCD connected

The two output channels of the CCD were connected initially to channels number 1 and 3 in the CCD aquisition board. We made measurements with both CCDACQ SN021 and CCACQ SN022. But, after taking the data, we discovered there was a problem in the gain given by the amplifier we used (so one output channel of the CCD had twice the gain than the other).Nevertheless, even though the quantitative results were wrong, qualitatively we noticed the important(but not at all unexpected) fact that the channels with the farthest spatial separation(1 and 8) presented a relatively low percentage of crosstalk. So, if we connected the two readout channels of the CCD to these two low-crosstalk channels, we could separate the board contribution to crosstalk from the CCD contribution, having in this way a better characterization of the problem.
Besides this, for improving the results and trying to lessen the magnitude of the crosstalk, $5k\Omega$ resistors were put in the floating(free) channels(2-7) of the transition boards of both CCD ACQ boards.

4.6.1 Results

Crosstalk in the boards:

We studied the crosstalk in both CCDACQ SN 021 and CCDACQ SN 022 boards. The most important thing to note (see Figures 14 and 15) is that only the two channels that are physically closest to to the two video channels of the CCD presnt a percentage above what is required.We can condlude that the $5k\Omega$ resistors in the floating channels helped to lessen the magnitude of the crosstalk in the board. Now we proceed to analize the crosstalk between channels 1 and 8 (0 and 7 according to the MEC-*Monsoon Engineering Console*-numeration), so we can better appreciate the crosstalk due only to the CCD.

Crosstalk in the CCD:

Taking the ratio of the two peaks visible in the two plots shown in Figure 16, we obtain a crosstalk of $0.07 \pm 0.02\%$ (this last uncertainty comming from the noise). For these channels, we had previously obtained a crosstalk of approximately 0.004% due to the board, which in this case is negliglible (as we had assumed!). At this point it is worth to note that this is not only the crosstalk caused by the CCD (though mainly it is) but to other stuff coming from the CCD to the CCDACQ like cables and amplifiers.

We can summarize our results as follow:

Crosstalk in physically opposite channels of the board	$\approx 0.08\%$
Crosstalk in physically non-opposite channels of the board	$\approx 0.006\%$
Crosstalk due to the CCD and stuff (cables, amplifiers,...)	$\approx 0.07\%$

Table 10: Summary or results

After all these measurements, at this point we can say that there are now two choices:

- **To connect the CCD to physically opposite channels (1-2, 3-4,...)** By doing this we would get a crosstalk of $\approx 0.15\%$ (board plus CCD) and the crosstalk between channels would be very low, making in this way possible software corrections easier (we wouldn't have to deal with crosstalk crossterms).

- **To connect the CCD to physically non-opposite channels (1-3,2-4,...)**

  In this case we would have a reduced crosstalk of about 0.07% (which is mainly the contribution of the CCD,because the contribution of the board would be negligible) , but now software corrections would be more complicated because each channel would be talking with two more channels and therefore there would be different CCDs involved.

5 Conclusions

- We tried differents approaches for studying and analizing the nature of the crosstalk problem: fequency dependence, synchronized signal, real signal comming from a CCD. The synchronized signal is not the best way for investigating this problem. We found that we could manage to change the crosstalk that was measured by changing the synchronized signal parameters. So this does not mirror exactly the real situation that concerns us and the best option is to make our measurements using a real CCD signal.

- Crosstalk is sensitive to the different frequency components of the signals. This is an important feature that should be taken into account in further studies of crosstalk.

- The adition of resistors to the free channels of the transition board of the CCDACQ board reduced the amount of crosstalk observed.

- We managed to separate the CCD and board contribution to crosstalk. The main quantitavive results are summarized in **table 10**.

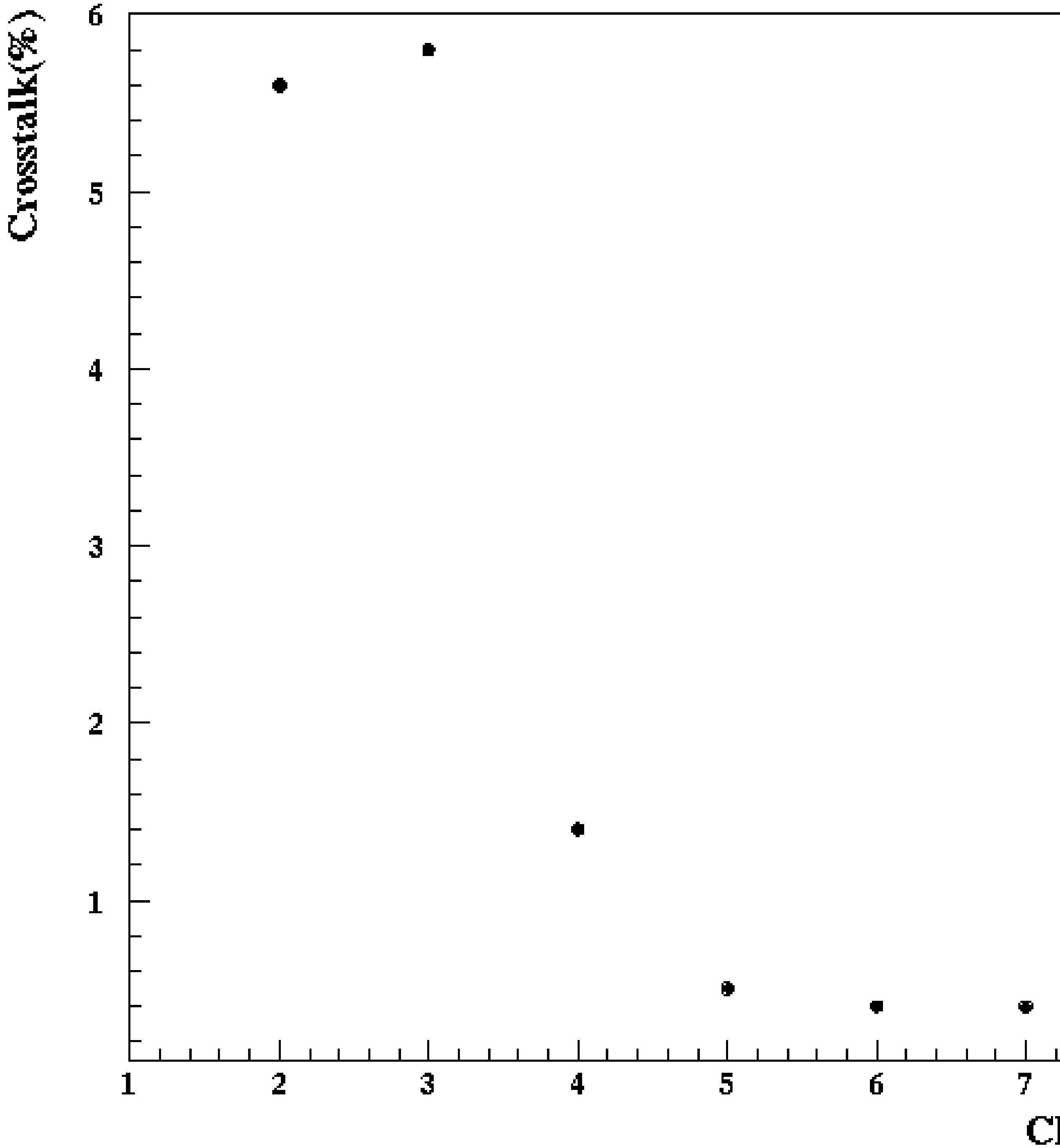

Figure 2: Crosstalk between channels 1 and the rest at 11MHz

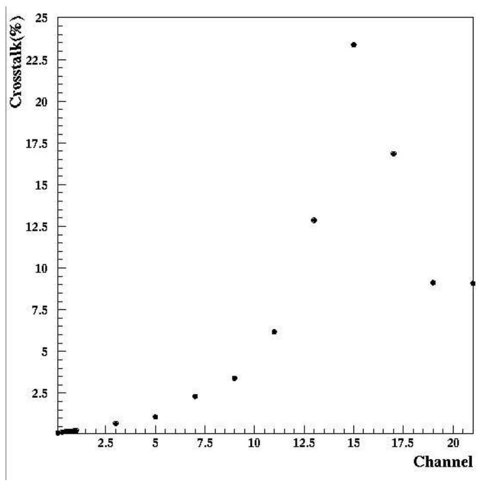

Figure 3: Crosstalk dependence on frequency. Channels 1 and 3. Long cable.

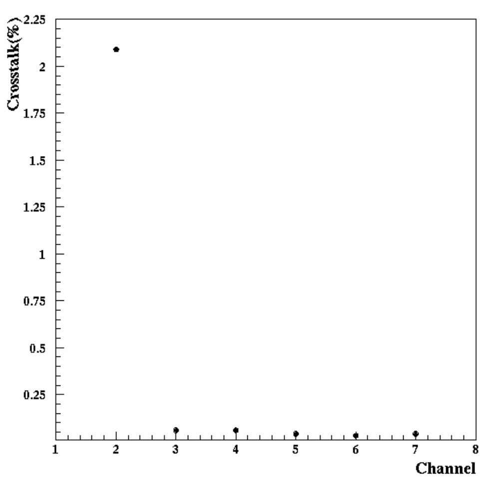

Figure 4: Crosstalk between channels 1 and the rest at 1.1 MHz. Short cable.

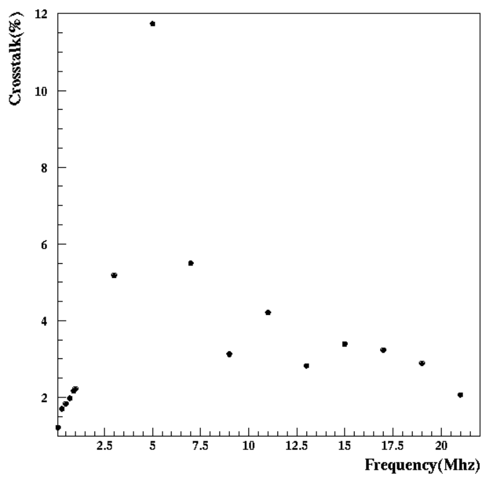

Figure 5: Crosstalk dependence on frequency.Channels 1 and 2.Short cable.

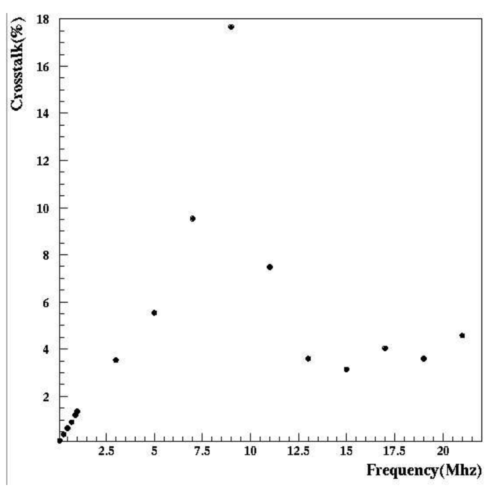

Figure 6: Crosstalk dependence on frequency. Channels 1 and 2. Cable with resistors.

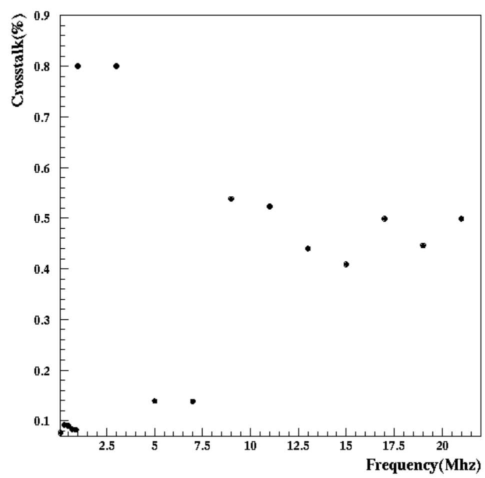

Figure 7: Crosstalk dependence on frequency.Channels 1 and 3. Short cable.

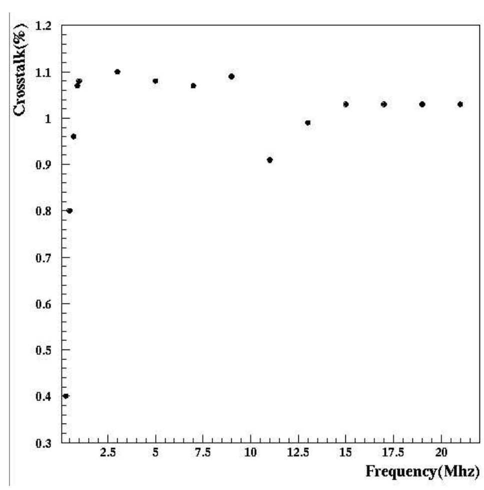

Figure 8: Leach system. Crosstalk dependence on frequency.Channels 1 and 2.Short cable.

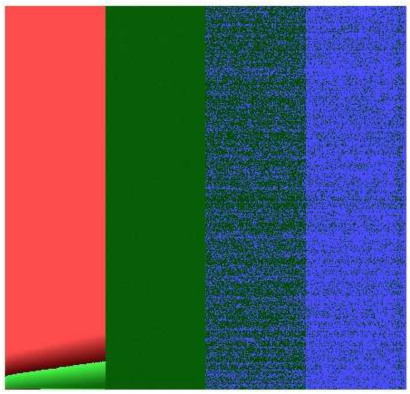

Figure 9: Syncronized signal. The first and fourth fringes represent the signal and its crosstalk in the other channel.The second and third, the pedestals.

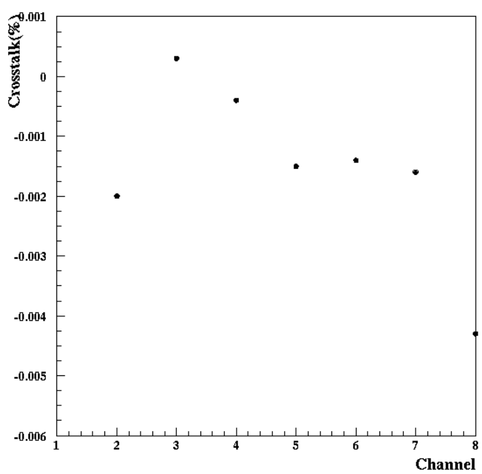

Figure 10: Crosstalk between channel 1 and the rest. Synchronized signal. CCDACQ SN021

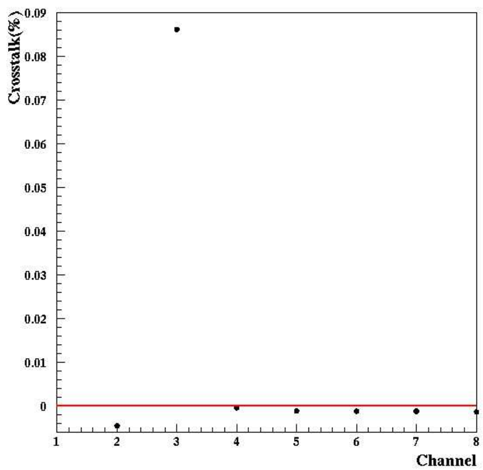

Figure 11: Crosstalk dependence on frequency.Channels 1 and 3.Short cable.

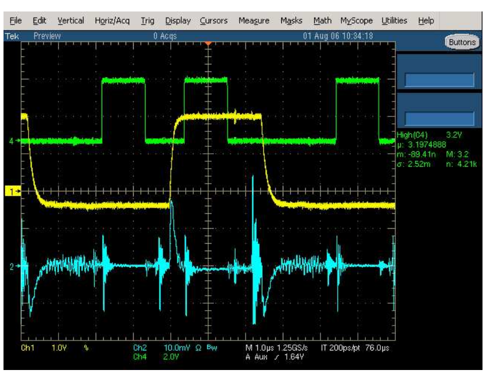

Figure 12: Oscilloscope image of the integration windows of Monsoon (green), the synchronized signal (yellow, ch.1) and the crosstalk due to this last signal(blue, ch.2). At the bottom of the image are the scales of each one.

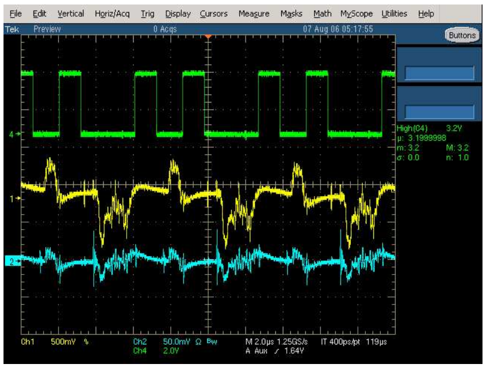

Figure 13: Yellow: CCD (500 mV). Blue: crosstalk (50 mV) . Green: integration window.

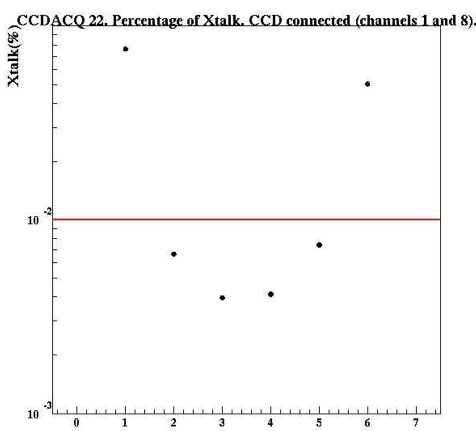

Figure 14: Crosstalk in the board SN 021. Note that the CCD readout channels are 0 and 7(MEC numeration). The red line shows the required 0.01% of crosstalk.

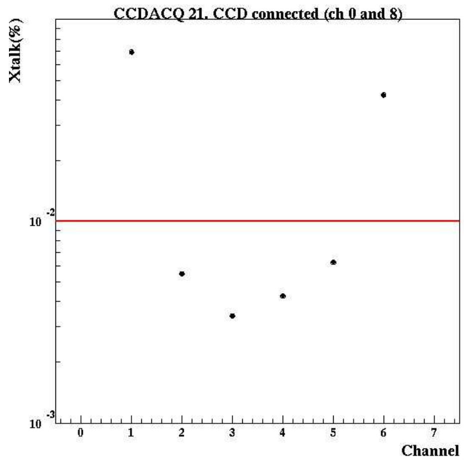

Figure 15: Crosstalk in the board SN 022. Note that the CCD readout channels are 0 and 7(MEC numeration). The red line shows the required 0.01% of crosstalk.

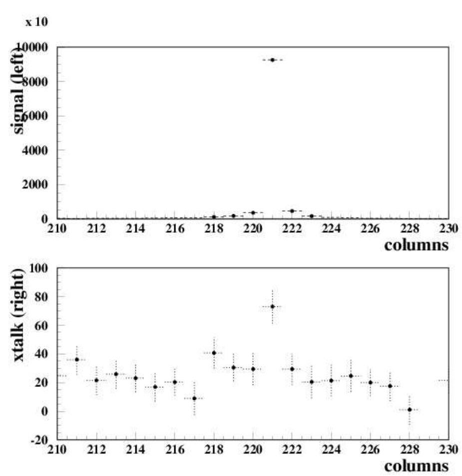

Figure 16: Crosstalk in the CCD. Channels 1 and 8. CCDACQ SN 021