# Calibration and Spectral Reconstruction for an Art Painting Multispectral Acquisition System

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## Abstract

The CRISATEL system is dedicated to fine art painting digitalization. A specific calibration procedure has been defined and implemented for this system. Some existing spectral reflectance reconstruction methods have been tested and compared. A multispectral image of a Georges de la Tour painting, "Saint Jacques le mineur", has been processed.

## Introduction

This paper presents the management of the multispectral imaging system that is developed within the CRISATEL European project. The CRISATEL system is dedicated to fine art painting digitalization. The hardware system itself is, to our knowledge, the first that combines high resolution and multispectral imaging in a compact camera. A specific calibration procedure has been defined and implemented. Existing methods have been applied and compared for spectral reconstruction.

The CRISATEL approach uses a digital camera with narrow band interference filters. In this system the problem of spectral reconstruction becomes fundamental in order to obtain an image representation independent of the illuminant and able to provide a high fidelity representation of colored surfaces. This general problem has been studied in the community, see for instance the works of Burns and Berns[1] or König and Praefcke[2]. Some examples of application to fine art paintings and pigments spectral reconstruction can be found in the works of Maître et al.[3], Farrell et al.[4] or Haneishi et al.[5]

Prior to this paper an evaluation of the CRISATEL multispectral camera has been done[6], partly with the collaboration of members of the scientific team of *The National Gallery,* London. This evaluation stage provides the necessary knowledge for the definition of a calibration procedure.

Once the system calibrated, 13 single band images (10 on the visible range of the spectrum) at high resolution and high dynamic range are obtained for each acquisition. From these images we are interested in spectral reflectance reconstruction since a representation based on reflectance is independent of the illuminant used in the acquisition stage.

The paper is organized in several sections. First a brief description of the acquisition system is given. Afterwards two main sections describe: i) the calibration system designed and implemented for the CRISATEL system, ii) how spectral reflectance reconstruction is performed for a calibrated multispectral image. A multispectral image of a Georges de la Tour painting, "Saint Jacques le mineur", is finally used as an example to illustrate the operation of the CRISATEL system.

## Brief Description of the Acquisition System

The CRISATEL multispectral camera is a digital camera based on a charge coupled device (CCD) with a 12,000 pixel linear array. This linear array is mounted vertically and precisely mechanically displaced by a step by step motor. The system is able to scan up to 30,000 horizontal positions. This means that images up to 12,000 by 30,000 square pixels can be generated. The current camera is fitted with a system that automatically positions a set of 13 interference filters, ten filters covering the visible spectrum and the other three covering the near infrared. There is an extra position without filter allowing panchromatic acquisitions.

The linear CCD uses two channels for readout operations which process the pixels on the array occupying even or odd positions respectively. In each channel the raw signal coming from the CCD passes through an analog amplifier. Each amplifier has two control parameters, an offset and a gain. The analog signal delivered by the amplifier for each pixel is then quantized into 12 bits by an analog to digital converter (ADC).

For a given scene and lighting, there remain two physical parameters which allow us also to control the amplitude of the signal: the aperture of the optical lens and the exposure time. Both factors can modify the number of incident photons trapped in each individual CCD cells. The aperture of our dedicated optical lens is kept fixed during an acquisition and is therefore not controlled electronically. The exposure time can be automatically setup and changed from 1.3 ms to 200 ms by steps of 0.1 ms.

The focus of the lens is precisely controlled by a stepper motor. Due to the remaining chromatic aberration of the lens, the focal length is not the same for the 13 channels resulting in images of slightly different scale. This multispectral camera provides a displacement system of the full camera body that can compensate these differences in scale for every spectral channel.

## System Calibration

As noted in the introduction an evaluation of the CRISATEL multispectral camera has already been done[6]. Then, the definition and implementation of a calibration procedure is the following natural step. Data collected from the performed experimentation form the basis for this definition. The calibration consists in a series of experiments which will allow us i) to set up the parameters to be used for the acquisition of images and ii) to collect experimental data for the a posteriori correction of the obtained multispectral images. At the end of the procedure, corrections should be applied and the corrected images are expected to have a high dynamic range and good spatial lighting homogeneity. The designed and implemented calibration procedure is composed of the following steps:

- Fixing camera parameters as exposure time, amplifiers gain and offset to obtain a high dynamic range.
- Correction of the inhomogeneous spatial distribution of the illuminants.
- Correction of the inhomogeneities in the physical response of the pixels of the CCD array:
  1. Dark current contribution in each individual pixel.
  2. Individual pixel photosensitivity.

As a prerequisite for calibration a white homogeneous board must be positioned on the plane where paintings will be scanned and the lighting system must be warmed up.

**Fixing Camera Parameters**

The most fundamental part of the calibration system aims to obtain a high dynamic range by appropriately fixing the camera parameters. These parameters are mainly the exposure time and the amplifier gain and offset. In our case two of these parameters, the amplifier gain and offset, can be fixed a priori. Here we must said that there are three preliminary steps that should be performed before calibration:

1. The camera aperture is not electronically controlled. Consequently, this parameter cannot be optimised and should be fixed manually to obtain enough deep of field over the surface we desire to scan.
2. The camera should be on focus for all its channels. This is performed interactively by an in-built software provided by the camera constructor.
3. The hardware correction for inter-channel registration should be done. If this step is not implemented it can be substituted by a postprocessing stage where the registration is performed by software.

The gain can be fixed depending on the quality we want to obtain. Figure 1 shows the relationship between gain, exposure time and the perturbation introduced in the signal (dark noise standard deviation on digital counts, 12bits). There is a non-linear relationship between them. We observe that the gain should be not high as the introduced perturbation augments rapidly with this parameter. Due to our experiment with dark current this relationship is characterized and we know the expected error for every value of the amplifier gain and the exposure time. As a consequence, the amplifier gain can be fixed to a value giving a compromise between low noise and an acceptable acquisition time. We choose this value to be 8dB.

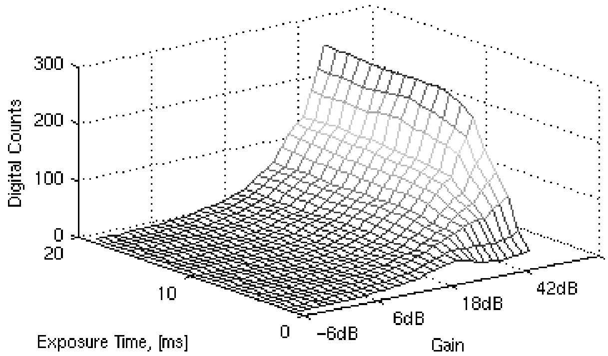


*Figure 1. Standard deviation of the CCD dark noise shown as a function of the exposure time and amplifier gain.*

If the amplifier gain is fixed its offset can be fixed too. Ideally we should choose the smallest possible offset in order to obtain the maximum dynamic range. In practice this is not possible because the level of noise limits the minimal offset that can be used. Using a smaller offset would produce the lost of one part of the information received by the CCD. If we want to keep all noise variability into the image we should consider that in a Gaussian distribution the value of a pixel is on the interval $[m-3\sigma, m+3\sigma]$ with 99.73% probability, where $m$ is the mean of the dark noise distribution and $\sigma$ is its standard deviation. As the level of noise for every value of the gain has been measured and characterized, the values of $m$ and $\sigma$ are then known. Consequently, we can directly choose an appropriate offset by the use of this information.

Once both the amplifier gain and offset are fixed the only free parameter left is the exposure time. Founding the exposure time that gives high dynamic range is to solve a one-dimensional optimization problem. Even if this problem is mathematically affordable, it is unfortunately very delicate in practice. A big part of our calibration system is indeed dedicated to the robust quest for a suitable value of this parameter. This part is complex and we will not provide here its details which are presented in chapter 6 of Ribés' Ph.D. thesis[7]. The procedure is based on dichotomy optimization of the exposure time on images of the white board positioned on the paintings image plane. The optimisation criterium is CCD saturation versus non-saturation. Our procedure involves various spatial analysis that take into account the non homogeneity of the light distribution.

### Spatial Distribution of the Illuminants

Once the camera parameters are fixed, obtaining an image of a white homogeneous board gives us a map that characterizes the spatial inhomogeneity distribution of the light sources. In our case, we take one *inhomogeneity map* per channel because we observed non trivial differences between them. This is due to the use of two lighting systems which have not equal spectral lighting distribution. Then, 13 maps are acquired that will serve to the correction of each channel of the painting images independently.

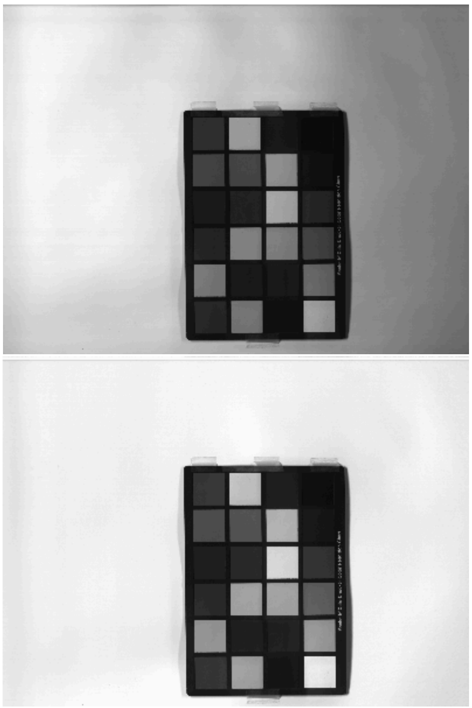

*Figure 2. (upper panel) Raw image of a Macbeth chart obtained from the CRISATEL camera. (bottom panel) same image after illuminant inhomogeneity correction is performed.*

### Per Pixel Dark Current

#### *Experimental Configuration*

The camera lens must be occluded by using an opaque (metallic) cap. In the case of the CRISATEL camera there is a built-in mechanism that allows the occlusion of the camera to be electronically controlled. No direct light reaches then the CCD and we can take black images without switching off the lighting system. This test aims to measure the dark noise contribution per pixel (per cell of the CCD in case of a linear array) along with the possible stray light getting to the CCD.

Figure 3 shows the values of the pixels in a small portion of the CCD array. We clearly see that the variability of dark noise between pixels must be taken into account. In order to do this we take a dark image and calculate the mean and standard deviation of the lines of this image, which correspond to the mean and standard deviation of each pixel of the CCD. Afterwards combining these two statistics we build a pixel dark correction value that will be applied at every pixel of the CCD in the acquisition stage.

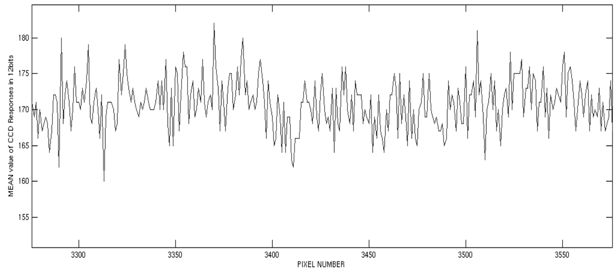


*Figure 3. Mean value of the dark current for some pixels of the CCD.*

### Per Pixel Gain

#### *Experimental Configuration*

A white board must be positioned at the position of the paintings to be scanned and a diffuser introduced in the optical path. Using a diffuser we try all pixels of the CCD to locally receive the same amount of radiant energy. The CRISATEL camera has a built-in electronic mechanism that allows the interposition of the diffuser in the optical path.

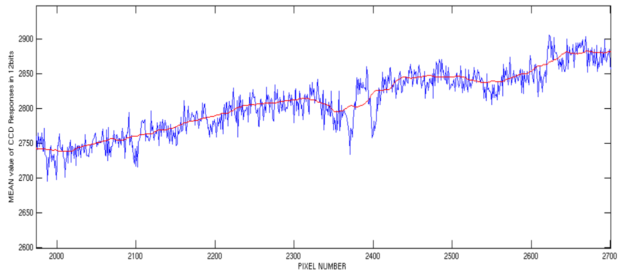


*Figure 4. Mean value of the CCD pixels imaging a white board with a diffuser. Detail of an area of the CCD, note the differences between a pixel (spiky curve) and its filtered value (smooth curve).*

On Figure 4 we show the graph of the mean values of the pixels in a small portion of the CCD. Due to the use of a diffuser, this curve should be smooth, presenting only low frequencies. This is not the case. We observe high frequencies which are due to pixel sensitivity inhomogeneity. We have superimposed the same data after being low-pass filtered. This curve estimates the expected spatial energy distribution of the lighting in the CCD. This part of the calibration aims to collect the necessary data to correct the local differences between both curves.

### Fully Automatic Calibration Procedure

In this section we emphasize the fully automatic character of the CRISATEL calibration system. In fact, this aspect is not a trivial consequence of our design but it was a prerequisite. The calibration procedure has been studied carefully in order to require user interaction as minimal as possible. Let's assume that the camera and the projectors have been properly installed to acquire paintings, the lens aperture selected and the focus properly adjusted for all channels. Then, the user has to proceed to the calibration before starting the multispectral image acquisition. The user is only supposed to warm up the lamps and position a white board in from of the camera before the calibration starts. Afterwards, all the operations performed are transparent for him.

Occluding the camera optics and introducing a diffuser on the optical path are apparently easy manual operations but, on practice, they revealed to be delicate and time consuming. Our collaboration with Lumiere Technologie led this company to integrate two mechanical displacement systems on the camera wich allow occlusion and diffuser introduction to be controlled electronically and make the calibration self-contained

## Spectral Reconstruction

In this section we present comparisons of spectral reflectance curves reconstructed using images acquired by the CRISATEL multispectral system. These comparisons are performed on calibrated and corrected images.

In order to illustrate the spectral reflectance reconstruction capabilities of the CRISATEL system we focus in a simple experiment. For this experiment a multispectral image of the CRISATEL chart was taken. The chart was measured by different spectrophotometers.[8] The CRISATEL chart is composed by 3 sets of acrylic colour patches where one is varnished using matt varnish, another with brilliant varnish and the last one is not varnished. We take the 117 matt varnished patches of the chart and we analyse them to obtain two different kinds of data:

1. A matrix containing 117 columns with the mean camera responses of each colour patch.
2. A matrix containing 117x*S* columns containing non averaged camera responses, *S* being the quantity of pixels analysed into each colour patch.

Based on this data we compare different spectral reflectance reconstruction methods proposed in the literature:

- two methods based on the inversion of the physical measures of the acquisition system, the Smoothing Inverse[9] and the Hardeberg Inverse.[10]
- two interpolation methods using splines and the MDST[11] method are tested.
- four learning based methods are used: SVD Pseudo-inverse,[12] Non-averaged Learning Pseudo-inverse,[13] Non negative Least Square[13] (NNLS) and Mixture Density Networks.[14]

The last above mentioned methods are based on learning over a training set of spectral reflectances and their corresponding camera responses. We then divide the CRISATEL chart into two sets, one will be used for training and the other for testing. This leads to four different sets: averaged train set, non-averaged train set, averaged test set and non-averaged test set. Train and test sets have the same size. The original matrix have been divided into two non intersecting sets by taking even elements for one set and odd elements for the other. We note that the averaged camera responses sets can be considered as less influenced by noise than the non-averaged ones that present a more realistic situation.

**Table 1. Comparing different reconstruction techniques on the CRISATEL chart**

| | Non averaged test set |
|---|---|
| **Smoothing Inverse** | 0.067713 |
| **Hardeberg Inverse** | 0.068442 |
| **Cubic Spline Interpolation** | 0.032080 |
| **MDST Interpolation** | 0.026056 |
| **SVD Pseudo-inverse** | 0.051211 |
| **Non-averaged Learning Pseudo-inverse** | 0.013835 |
| **NNLS** | 0.049253 |
| **Mixture Density Network** | 0.012031 |

In table 1 we present the spectral reconstruction errors, measured with the $L_1$ norm, obtained by using different spectral reconstruction techniques. We just show here results over the non-averaged test set because they are more realistic, including real noisy camera responses.

We first note that direct inversion methods as smoothing inverse and Hardeberg inverse perform badly compared to the rest of the methods. The measures of the CCD and filters used to build the operator are reliable. The transmittances of the CRISATEL filters were carefully measured using a spectrophotometer, the CCD sensitivity curve is issued from an experiment using a monochromator. We believe that this lack of accuracy is justified by the fact that our trainings and tests sets all belong to a painting environment.

In table 1 we also see that methods based on interpolation (MDST and cubic spline) are not the best but they obtain intermediate errors. The smaller errors are obtained by the Mixture Density Networks followed by the Non-averaged Learning Pseudo-inverse method.

### « Saint Jacques le Mineur », A Real Application

In this subsection we show a brief example of spectral reflectance reconstruction on a real art work painting. Images of a painting of Georges de la Tour, “Saint-Jacques le mineur” were acquired at *Musée d’Albi*, Albi, France, on December 2003 by a team of experts of the CRISATEL project; 9 other paintings have been also acquired during this session. In this acquisition the calibration system described on this paper was used. Geometrical and radiometric corrections were performed, the last ones based on the calibration data. In Figure 5 we show a colour image of the acquired painting. The shown image is a highly subsampled version of the original one which was obtained at full resolution of the CRISATEL system (20,000x12,000 pixels). We also note that the colours are not realistic as the visualisation medium you see is not calibrated.

*Figure 5. Painting Saint Jacques le mineur from Georges de la Tour.*

From the image show in Figure 5 we extract a crop of the hand of Saint-Jacques holding the stick. This crop is show in Figure 6. The crop is not in high resolution in order to keep a recognizable shape in the presented image. Much more details in the image are obtained when working at the highest definition.

We performed spectral reflectance reconstruction on pixels of the extracted crop image. Two examples of spectral curves are shown on Figure 6 along with their corresponding positions in the crop image. The reconstruction method used was a simple pseudo-inverse.[7] We use this method because it is sensible to noise, the satisfactory reconstructions shown on Figure 6 illustrate the good image quality obtained by the CRISATEL multispectral system after calibration.

The upper graph of Figure 6 shows a reconstruction on a pixel belonging to a "lightly" zone of the image. At a first glance it can seem that the reconstructed curve are not correct because the pixels shown in the crop image are whiter than it seems on the reconstructed reflectances. But the reconstructed curves are coherent. The image intensity levels have been modified to enhance contrast within this paper for illustration purposes. The original images and the painting itself are very dark; this forms part of Georges de la Tour style.


*Figure 6. Center panel: Crop of the hand of Saint-Jacques holding the stick, greyscale image using a filter centered at 720 n. Top and bottom panels: reconstructed reflectance curves on two pixels of the image. The spectral reflectance curves have been estimated using a pseudo-inverse.*

## Conclusion and Future Work

In this paper we have presented how the CRISATEL digital multispectral acquisition system is used for art works digitalization. The calibration system is described, it provides high dynamic range images and data for a posteriori correction. Once the corrections are performed quality images are obtained. This images can then be used for spectral reconstruction. Several methods have been tested on a simple experiment and Density Mixture Networks appears very promising. We have also illustrated the spectral reconstruction with an image of an art work of Georges de la Tour.

The presented system is at the moment starting its operation stage on art work paintings. The C2RMF (Centre de Restauration des Mussées de France) is in charge of this operations. Further research on high fidelity colour reproduction and virtual restoration will follow our works.

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## Biographies

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