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INSTRUMENTAL CALIBRATION OF WIDE FIELD IMAGERS

F. Villa[1] and the SNDice collaboration

Abstract. Photometric calibration is becoming a crucial issue in various cosmological measurements, such as the measurement of the cosmological parameters with Type Ia Supernovae (SNe Ia). To achieve the accuracy level of $\sim$ 0.1% required by future surveys, several collaborations are studying new instrumental calibration strategies. We report on the SNDice project. SNDice is a very stable illuminating system installed at the Canada-France-Hawaii Telescope (CFHT). The goal is to demonstrate that, with such an instrument, it is possible to monitor the instrument response with a precision of 0.01%, and to deliver a flux calibration accurate at the 0.1% level.

Keywords: Type Ia Supernovae, calibration, SNDice

1 Introduction

Type Ia Supernovae are one of the most powerful cosmological probes to study the properties of Dark Energy (Sullivan et al. 2011; Conley et al. 2011; Guy et al. 2010; Amanullah et al. 2010). The next generation of very large surveys (DES, Euclid, LSST) will detect and study thousands of SNe Ia. The measurement of the Dark Energy Equation of State will reach a statistical precision of 1% or better (Abell et al. 2009).

The challenge is now to reduce systematic uncertainties to a comparable level. The dominant contribution to the systematic error budget is the photometric calibration of the imagers. Future surveys will require a flux calibration accurate at the per-mil level. This seems difficult to obtain with the traditional techniques relying on standard star observations. For this reason, supernova surveys are exploring alternative approaches. For instance, the SNLS collaboration began to invest in the SNDice project. SNDice is a demonstrator, designed and built at LPNHE in Paris, which was installed in 2008 in the enclosure of the Canada-France-Hawaii Telescope (CFHT) in Mauna Kea (Hawaii) (Juramy et al. 2008; Barrelet & Juramy 2008). The goal is to show that it is possible to obtain a photometric calibration accurate at the 0.1% level or better.

In what follows, we present the design of the SNDice instrument. We review the many applications of the system, such as the monitoring of the telescope readout electronics, the study of the camera uniformity and the measurement of the imager passbands. Finally, we detail the analysis of the SNDice data and explain how this strategy may be an alternative to the traditional calibration techniques.

2 The SNDice instrument

SNDice (SuperNova Direct Illumination Calibration Experiment) is a photometric calibration device which has been optimized to study the MegaCam imager (Boulade et al. 2003). The instrument consists in a calibrated light source composed of 24 narrow spectrum (Fig. 1 *right*) LEDs ($\delta\lambda/\lambda \sim$7%). Their emission wavelengths cover the MegaCam bandwidth from the UV to the IR. LEDs have been chosen for the stability of their emission and their spectral properties. Each LED emits a 1° wide conical beam which illuminates the whole CCD camera. Each LED beam covers a $\sim$30 cm wide area on the primary mirror and generates a nearly flat illumination on the focal plane. In each LED channel, a calibration photodiode is placed off-axis in front of the LED to monitor the light output as a function of time and input current. Finally, the light source can be oriented to allow one to align SNDice and MegaCam optical axes.

In 2008, a prototype of SNDice was installed in the CFHT enclosure. Since then, SNDice is taking data and two upgrades of the motorization were made.

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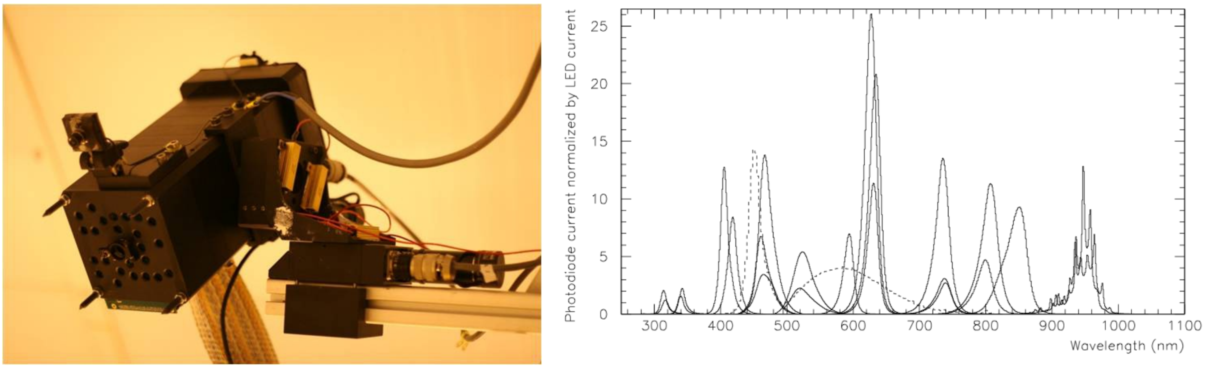

Fig. 1. Left: The SNDice demonstrator in the CFHT enclosure. **Right:** Spectra of the 24 LEDs composing the light source.

3 Test bench studies

Prior to its installation, the SNDice instrument has been characterized and calibrated on a precision test bench at LPNHE. The main products of these studies are:

- maps of the radiant intensity of each LED beam, accurate at the 0.1% level,
- spectra of each LED, measured with a similar precision.

The calibration was performed on short range and long range distances. The short range measurements have been done on a 2.5 m test bench enclosed in a black box. A 12 m-long black tube was used for the long range calibration. In both configurations, the light source was placed at a fixed position in the black box. The photometric calibration of each LED was done using a NIST (National Institute of Standard of Technology) photodiode. This photodiode was mounted on a 3D motorization including a 1.5 m-long axis for motion parallel to the light source axis. Each LED beam was mapped in a $30{\times}30$ cm^2 region perpendicular with respect to the source axis. The short distance setting allowed us to map each LED beam, whereas the long distance configuration was necessary to reproduce the study at a distance similar to CFHT focal length. LED spectra have been calibrated to determine their variations as a function of temperature.

The illuminating system has been proved to be stable at the 0.01% level.

4 The monitoring of MegaCam

The response function of MegaCam is likely to change over time. First, the gains of the readout electronics are subject to variations over time scales of a few hours. Second, the transmission of the instrument degrades slowly over time. This affects the zero points of the instrument, as well as the flat-field structure. Given its 0.01% stability, SNDice is a good tool to measure these effects.

As an example, the gains of the 72 amplifiers of the MegaCam CCDs have been measured throughout one year of data acquisitions. The average values of the gains for 2010 are showed on the left panel of Fig. 2. Since the SNDice illumination of the focal plane is uniform, the amplifier gains have been obtained through the variance of the Poissonian distribution of the fluxes measured in each pixel. The monitoring of the readout electronics reached a precision such that it was possible to study the gain variability from one run to another. Variations up to 1% have been highlighted. The values for February 2010 and July 2010 are showed on the right panel of Fig. 2. The gain variations are correlated for the nearby amplifiers.

5 The SNDice exposures

Fig. 3 (*left*) gives an example of a SNDice exposure. As we will see in this section, each exposure encodes a lot of information on the imager internals.

First, one can see differences from amplifier to amplifier. These are due to the gain differences from one amplifier to another, and also to variations of quantum efficiencies from one CCD to another. By requiring that

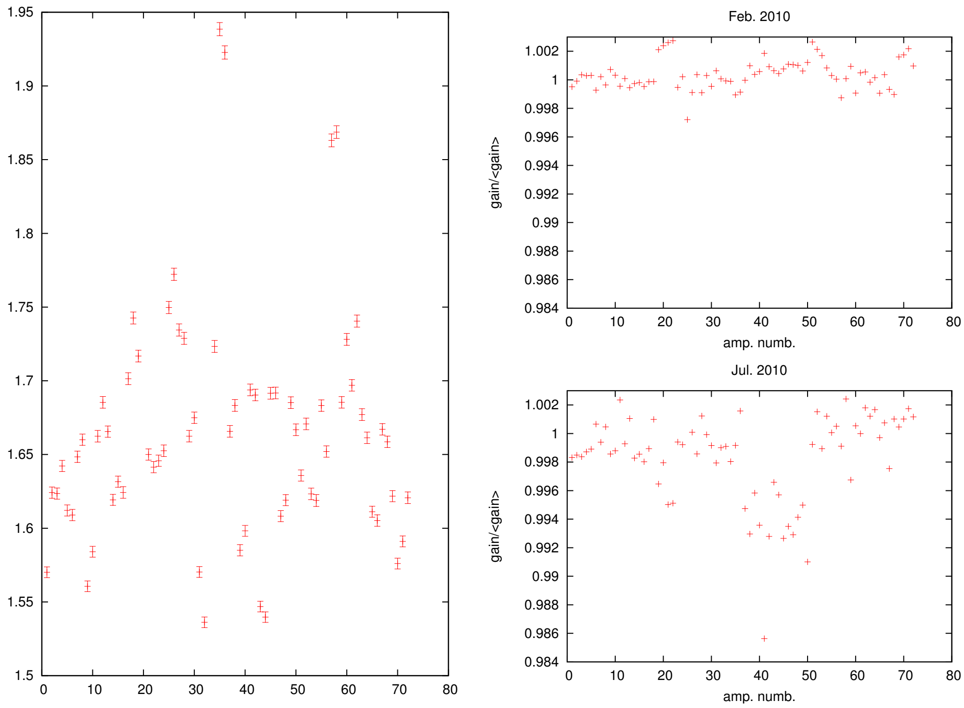

Fig. 2. Left: The gains averaged over time for the 72 amplifiers. **Right:** On the top panel, the gain values for data taken on February 2010; on the bottom panel, gains measured on July 2010. The precision of the SNDice system allowed one to study gain variations at the 0.1% level with respect to the average value over the year. Correlations between nearby amplifiers have been found.

the focal plane illumination is continuous, it is possible to determine the relative ratios of the gains and CCD quantum efficiencies and to monitor their variations.

The diffraction patterns caused by imperfections and dusts settled on the optics are another feature present on raw images. Fortunately, it is quite easy to deal with this effects by resampling the images in "superpixels" and by calculating the median of the fluxes in each "superpixel".

Once these sources of non-uniforimities are accounted for, one can see that the exposure integrates not only the direct light, but also the light from internal reflections within the imager. As an example, in Fig. 3 (*right*) one sees clearly the reflexion of the focal plane on the cryostat window. Also, it is easily visible the "pincushion" due to light reflected by the filter and lens L4 of the wide field corrector. Depending on the focal plane position and on the illuminating LED, the indirect light may represent 0.5% to 20% of the direct light. Hence, we need a model to disentangle the direct and indirect light. Note that any flat-field is similarly affected by internal reflections. However, due to the very simple design of SNDice, it is possible to build a model of the reflections, that can predict the illumination on a point (x,y) of the focal plane. This model can be written as:

$$\Phi_{\mathrm{ADU}}(x, y) = g_{\mathrm{amp}} \int \varepsilon_{\mathrm{CCD}}(\lambda) \cdot \mathrm{T}(\lambda, \mathbf{x}) \cdot \mathcal{B}(\lambda, \mathbf{x}) \mathrm{d}(\lambda) + \mathrm{reflections}(\mathbf{x}) + \mathrm{dust\ diffractions}$$

where $\mathcal{B}(\lambda, \mathbf{x})$ is the model of the LED quasi-Lambertian beam.

6 Modeling the focal plane illumination

The determination of the illumination $\mathcal{B}(\lambda, \mathbf{x})$ on the focal plane depends on the measurement of the LED beam at the source and on its propagation through the optics. The illumination delivered by SNDice is well known thanks to the test bench. To predict the beam shape after the optics, it is necessary to simulate the propagation. To do this, the main tool is a very simple ray-tracer simulating the SNDice-MegaCam system. This software is based on `C++` CERN ROOT libraries. As shown in Fig. 4 (*left*), it is able to reproduce MegaCam optics and to model direct and secondary paths of the SNDice light propagation through them. Finally we are able to simulate

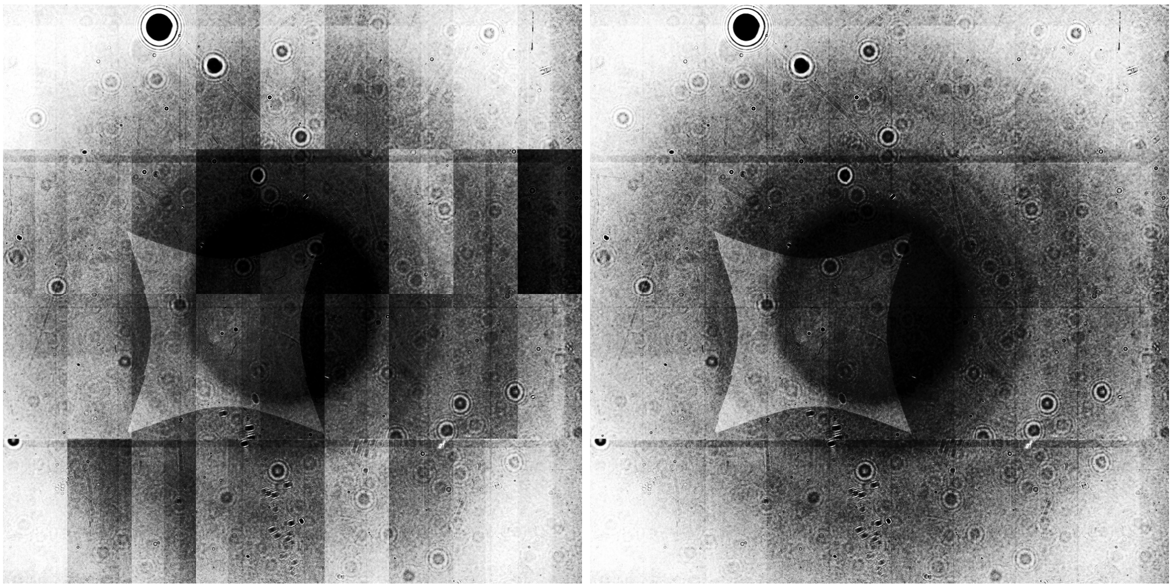

Fig. 3. Left: Raw SNDice exposure: the dominant effect are the differences from an amplifier to another. These non-uniformities are caused by the different gains of the readout electronics and the variations of the quantum efficiencies from a CCD to another. The diffraction patterns caused by dusts or imperfections on the optical path are visible too. **Right:** SNDice exposure after the correction for the gains and the CCD quantum efficiencies. The correction highlights other effects due to reflections in the optics (the central "pincushion" due to the light reflected by the curved surface of lens L4, the reflection of lens L3 on the lower left corner of the focal plane) as well as the radial variation of passband transmission.

an exposure to distinguish between direct illumination, see Fig. 4 (*center*), and reflection contamination, shown in Fig. 4 (*right*), (which can reach up to 20% of the direct light intensity). The determination of the direct

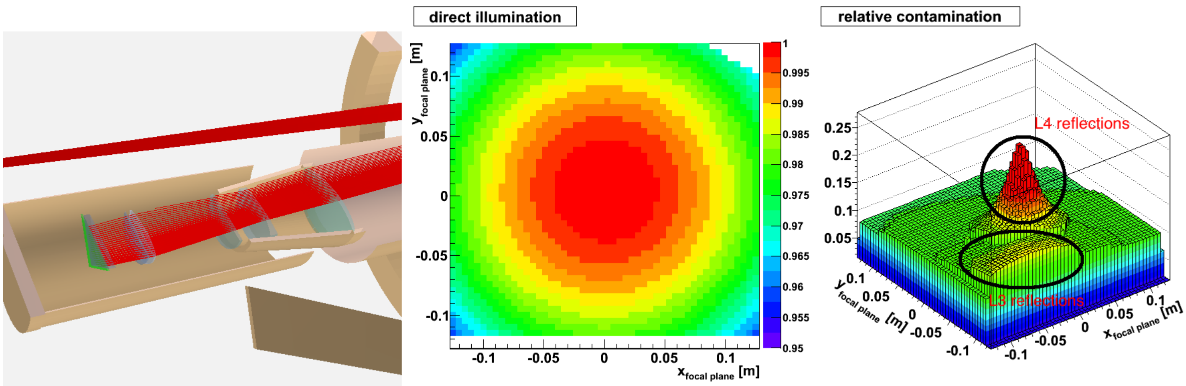

Fig. 4. Left: Simulation of the SNDice beam illuminating the primary mirror. **Center:** The direct illumination of the focal plane. Determining the amount of the direct contribution is a crucial point to gain in precision. **Right:** Spatial distribution of the internal reflection relative contamination on the MegaCam focal plane. The hugest contributions are the reflections due to the curved surfaces of L4 and L3 lenses.

illumination on the focal plane is the crucial measurement to improve the precision of the photometric calibration through the optimization of the flat-fielding technique.

7 Conclusions and perspectives

The analysis of SNDice exposures is an ongoing work. Once the determination of the reflection contamination is achieved, next steps will be the study of the MegaCam focal plane uniformity and the optimization of the flat-fielding procedure with SNDice exposures.

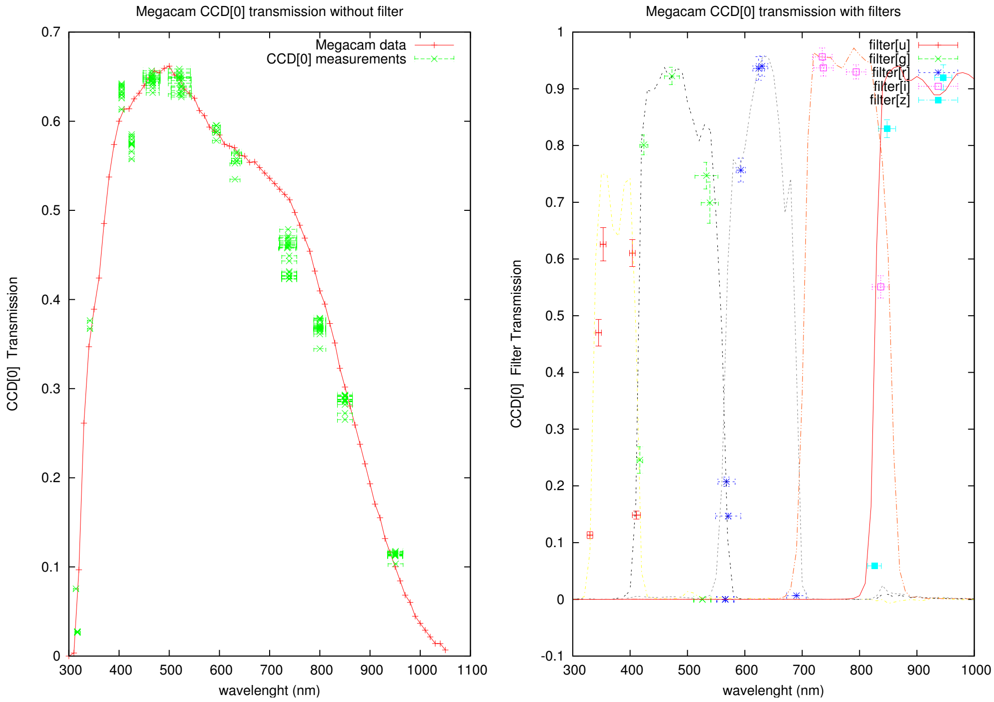

Fig. 5. Left: Open transmission. **Right:** Filter responses: the curves are the theoretical transmissions, the points are the measurements of the 24 LEDs fluxes.

Furthermore, there are ongoing studies on the determination of the normalized transmissions of the imager passbands. Preliminary results are shown in Fig. 5. On the left, the open transmission of the MegaCam is displayed: it has been obtained comparing the MegaCam flux on CCD #0 to the flux measured by the control photodiode mounted in front of the LED. The plot in Fig. 5 (*right*) shows the filter transmissions measured on CCD #0 as the flux ratio of an exposure taken with filter over one without filter. The aim of the study on the filters is the extraction of normalized passband transmissions with an accuracy better than 1%. The achievement of this analysis depends on the measurement of the variation of LED spectra as function of temperature (test bench studies at LPNHE).

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