High-Precision Calibration of Flux Measurements for cosmology with SN Ia

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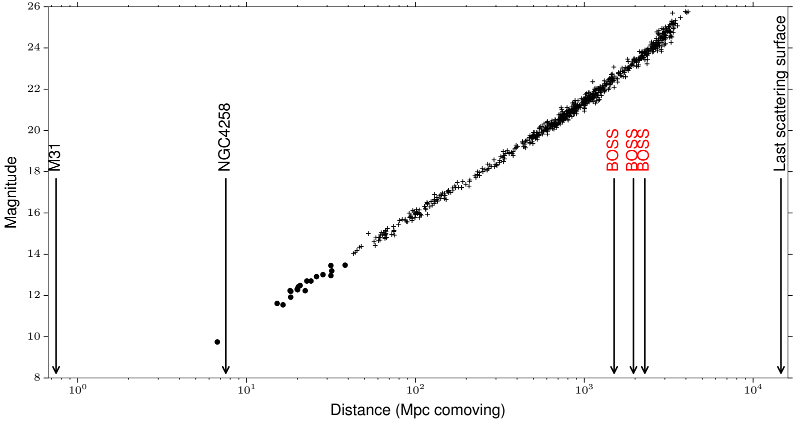
ESAC 2016

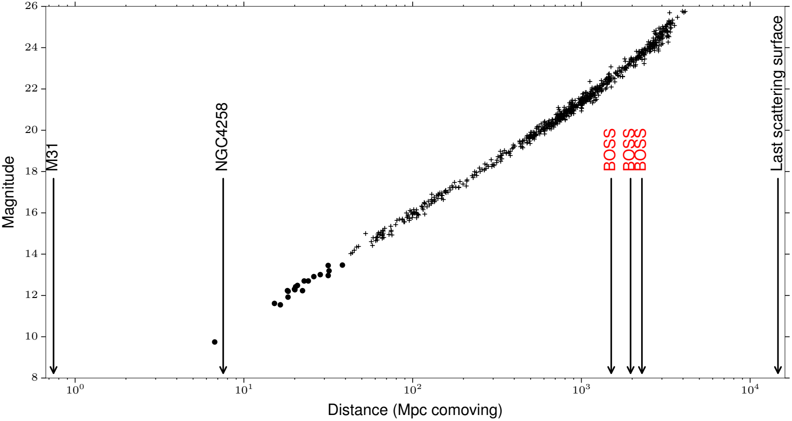
High-precision calibration: A challenge to probe the geometry of the background

Luminosity distances for background geometry



- Efficient way to probe distances from 10Mpc to 3Gpc
- H_0
- $w(z)$

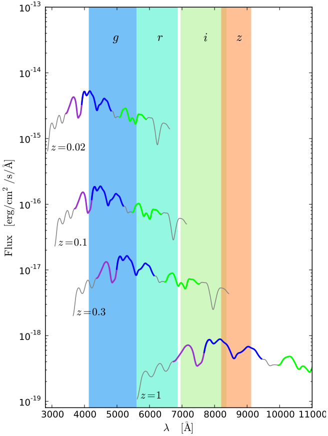
Specific calibration needs for luminosity distances



A relative measurement of fluxes with *wide-field* instruments

- Relative calibration in time
- Relative calibration in space
- Relative calibration accross wavelength

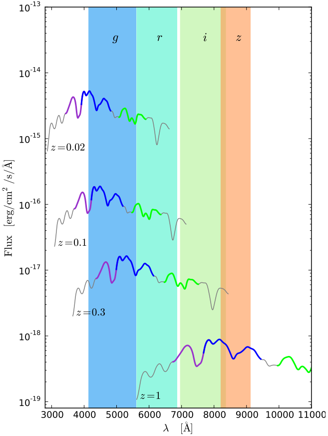
Luminosity distances from SNe Ia: a flux and color comparison accross redshift

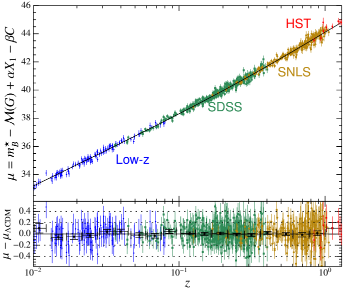


- Flux measurement in comparable ‘rest-frame’ passbands
- However we look at ‘standardizable’ candles
- Many possible sources of differential extinction
- Color also matters:

$\mu = m - M - \beta c$
for type Ia supernovae:
$\beta \sim 3$

Required precision: back of the enveloppe computation





Let us divide the HD in 2 bins

- $\sigma^{stat} \sim 0.008$ mag $\rightarrow \sigma(\Delta_\mu) \sim 0.011$

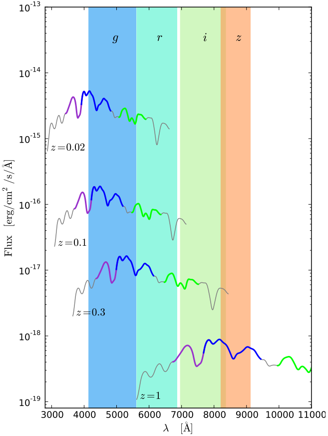
and assume that

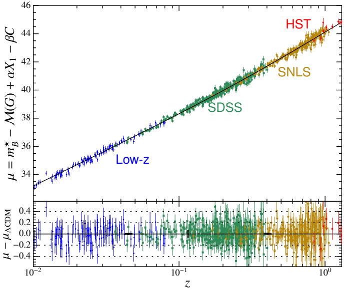
- $m_1 \sim \langle g \rangle$ and $c_1 \sim \langle g \rangle - \langle r \rangle$
- $m_2 \sim \langle i \rangle$ and $c_2 \sim \langle i \rangle - \langle z \rangle$

$$\begin{aligned} \Delta\mu &\sim m_1 - m_2 - \beta(c_1 - c_2) \\ &\sim 2\langle g \rangle - 2\langle i \rangle + 3\langle r \rangle - 3\langle z \rangle \end{aligned}$$

$$\Rightarrow \sigma(\Delta\mu)_{cal} \sim \sqrt{10}\sigma(cal)$$

Required precision: back of the envelope computation





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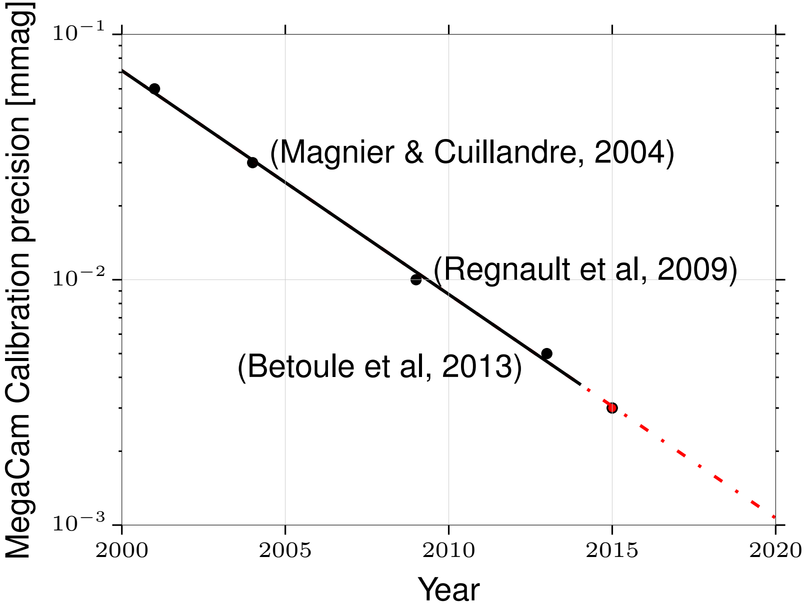
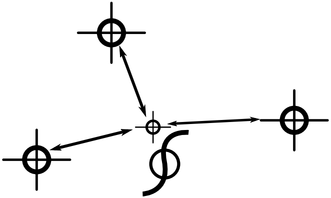
Calibration accuracy of the wide MegaCam instrument over the last decade

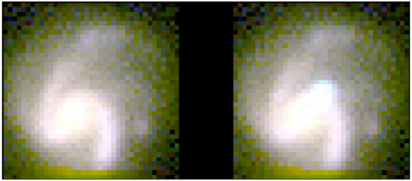


The quest for an accurate calibration transfer to supernovae flux

Differential photometry

Measurement of SN/stars **flux ratios** in a collection of images





The flux expected for image i at pixel p, reads:

$$M_{i,p} = [f_i \times \phi_i(x_p - x_{SN}) + G\left(T_i(x_p)\right) \otimes K_i + S_i]\, R_i$$

Well under control. Two potential traps (see Astier et al. 2013)

- Different weighting schemes for the bright and faint object would turn PSF errors into a bias
- The heart of the PSF is wavelength dependent

SN flux are relative to in-situ calibration references

The SNLS 2014 calibration references were build using

A position dependant model of the instrument response $T(\lambda, x)$

- Scans of the filter transmission curves
- Measured transmission curves of the other elements
- Flatfield maps build every lunation from twilights
- A correction of the response (measured every 6 months)

A slightly evolved aperture photometry methods

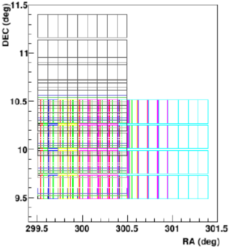
- Large IQ-scaled apertures
- With specific handling of the background contamination

A specific set of observations of standard stars

- Short observing blocks
- Looping between science and calibration fields
- At similar airmass
- Relative aperture corrections corrects for systematic PSF differences between science and calibration

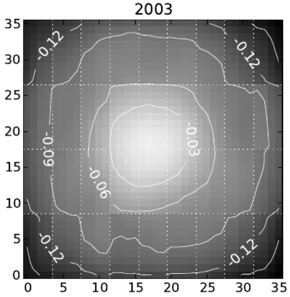
Mapping the instrument response

(see Magnier & Cuillandre 2004, Regnault 2009)



Dithered observations of dense stellar fields

- 13 exposures
- Logarithmically increasing steps from 1.5' to 1/2 deg
- 4-10 independent grid datasets /band
- $\rightarrow$ measure a correction δzp to the twilight flat-field



Observation model

$m_{\mathrm{ADU}}(x, star) =$
$m(x_0, star) + \delta zp(x) + \delta k(x)(g - i)$

- $m(x_0) \sim 100000$ nuisance parameters
- $\delta zp \sim 100$ parameters

Wide-field specific effects corrected in this procedure

Flat-field pollution (∼8%)

- Plate-scale variation (∼3-4%)
- Ghost-pollution (5%)

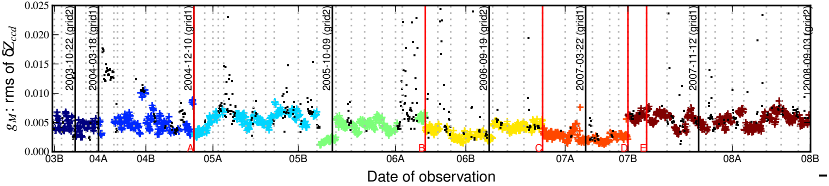
Variation of the filter transmission

- 4% (color-dependent)

Variation of the aperture correction (1%)

Internal consistency of the reference catalog

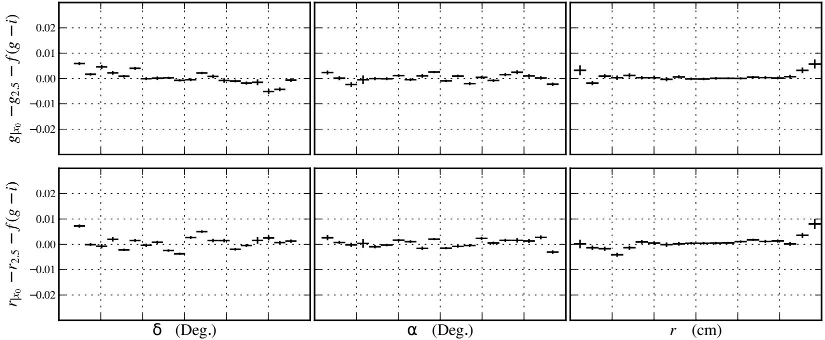
RMS of the zero point variation across the focal plane in each of the 5 years survey images with respect to the average



Typically, an individual survey image agrees with the reference catalog to the 5 mmag level

External cross-check: Uniformity

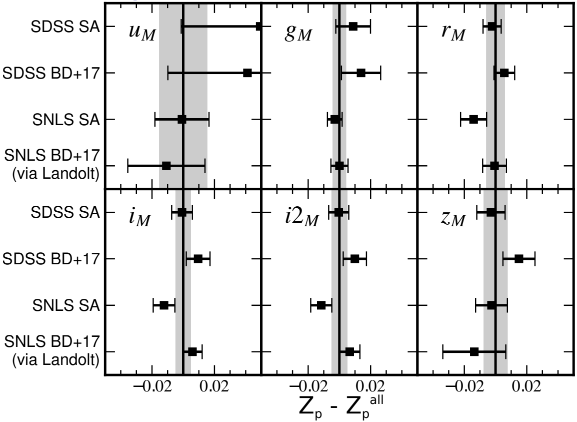
Comparison with SDSS



- The rms of the points in any of the panel is less than 3mmag

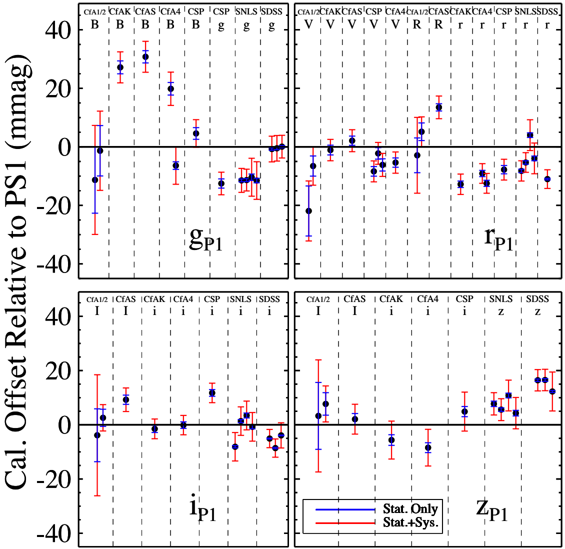
External cross-check: relative band calibration

Comparing 4 different paths



- We claimed that the combination of the different path should be accurate to the 5mmag level

A recent confirmation (Scolnic et al. 2015)



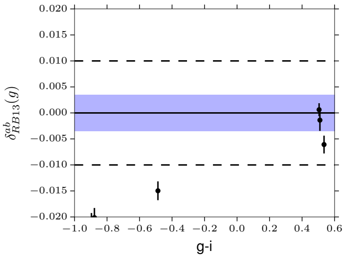
Limitation in the 2013 calibration

1) Statistics: the 2013 calibration relied on a small data sample

- 3 standard stars (~5 nights)
- now experiencing mmag accuracy transfer: 6 stars / 40 nights

2) Filter knowledge (again)

- Independant ZP determination on 6 stars
- With currently assumed filters (left)
- Shifting the g band filter by 1.6 nm (right)



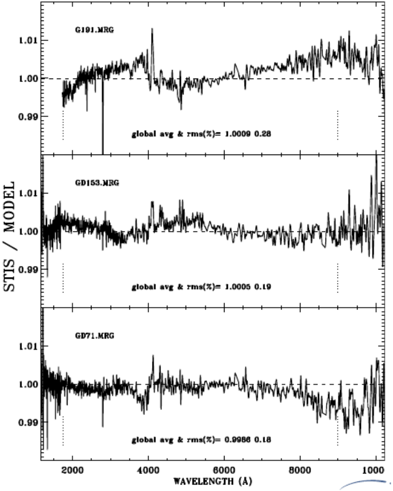
But the real limitation now is the cross-wavelength calibration reference

Bohlin, Gordon & Tremblay 2014

- Rauch et al 2013 NLTE model
- 3 DA WD: G191B2B, GD153, GD71

The average defines the HST/STIS calibration

- Residuals at the percent level in the visible range



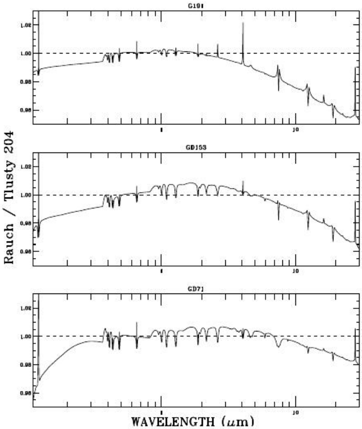
But the real limitation now is the cross-wavelength calibration reference

Uncertainty estimate based on:

- difference between 2 models
- implementing similar physics
- Amount to 4 mmag in color for $300 < \lambda < 1000$nm

What about unaccounted physics ?

- Metal lines found in high resolution spectrum of G191B2B
- Lyman/Balmer lines problem
- Other ?



(Bohlin et al. 2014)

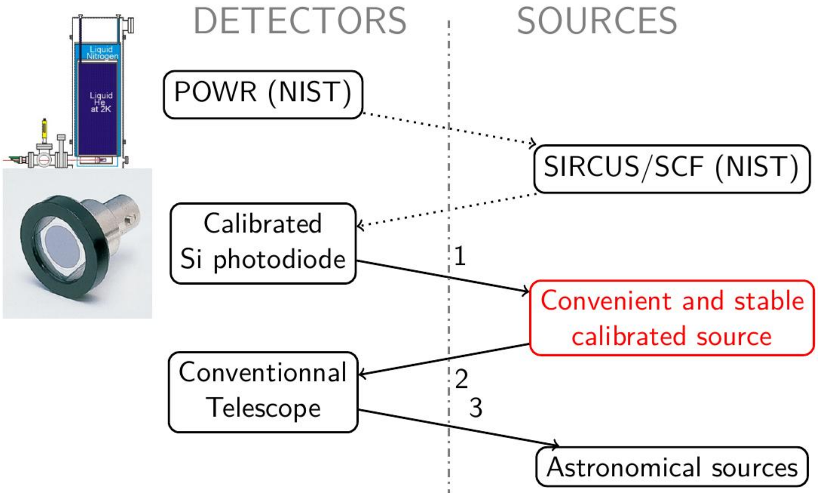
Looks like we'll get calibration issues sorted in the end

- We think that we have achieved calibration transfer from white dwarfs to Supernovae with an accuracy better than the accuracy of the white dwarf themselves
- But all this was reverse engineering
- And the current accuracy level of the white dwarfs is insufficient for future supernovae science

Let's try to do things in the right order

Toward a complete understanding of the spectrophotometric calibration path: the DICE experiment

The whole idea is to replace white dwarfs with POWR

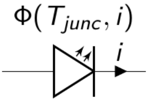


The DICE experiment

We have build an experimental light source (Regnault et al. 2015)

To calibrate CFHT+MegaCam response

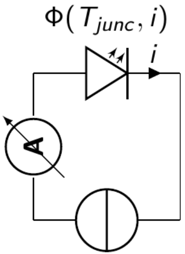
Design choice 1: LEDs



Quantum emmiter, emmission depends on:

- junction temperature
- current

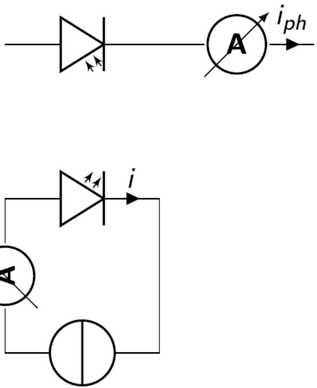
Design choice 1: LEDs



Monitor:

- Junction temperature
- Current
- Current source temperature

Design choice 1: LEDs



Redundancy

- Photodiode current

Design choice 2: no optics

Optics could be used to

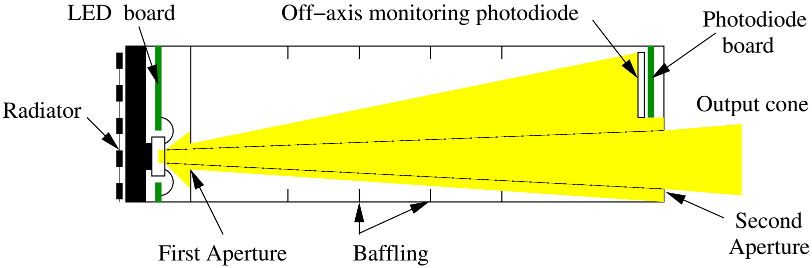
- Change the shape of the beam
- Select Wavelength

But would make the thing harder to control

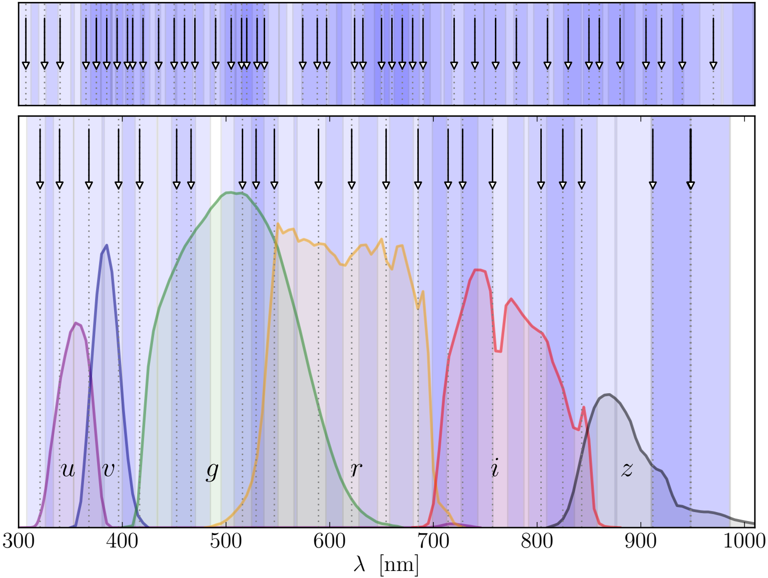
Other solutions

- Use geometry to get the beam you want
- Precise knowledge of the source narrow spectrum

This gives the following design for a single channel:

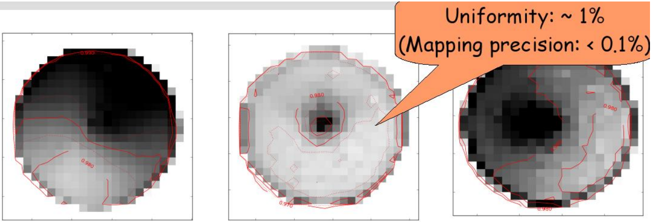


And we use 24 of them to cover the wavelength range:

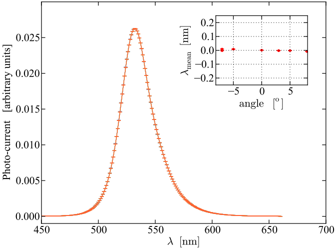


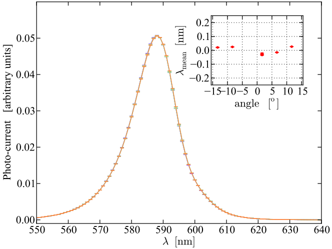
The source was precisely characterized

Flux

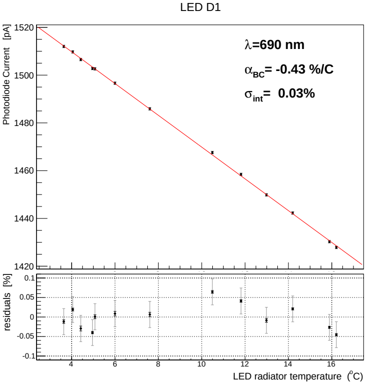


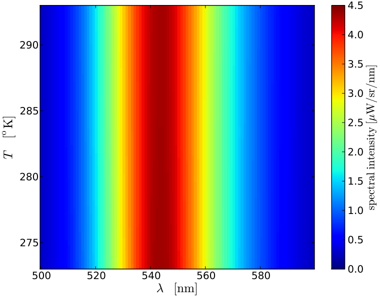
And spectrum



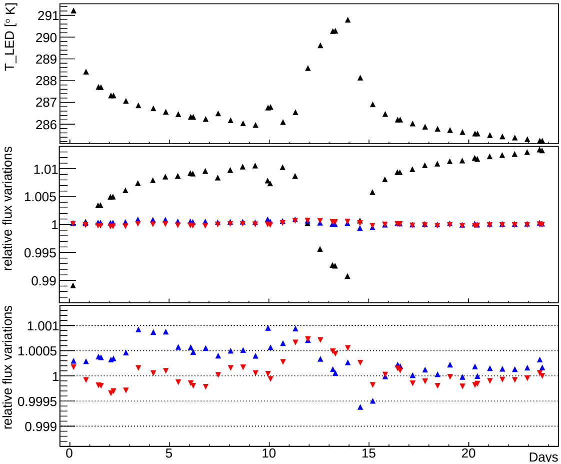


Measurement III: In a temperature range



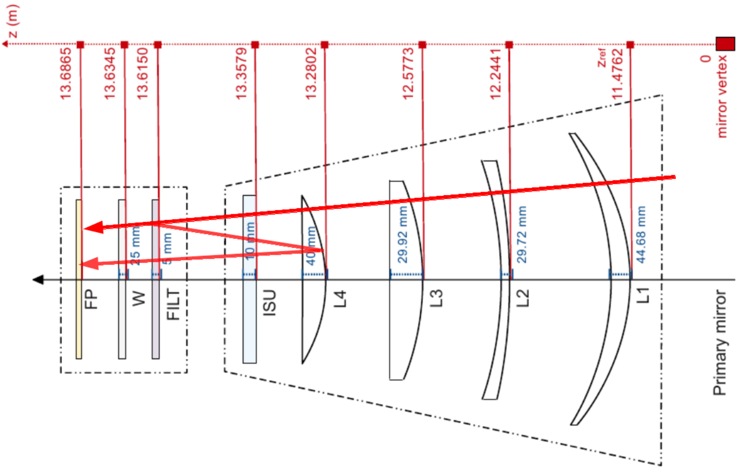


A convenient/extremely stable light-source: Done

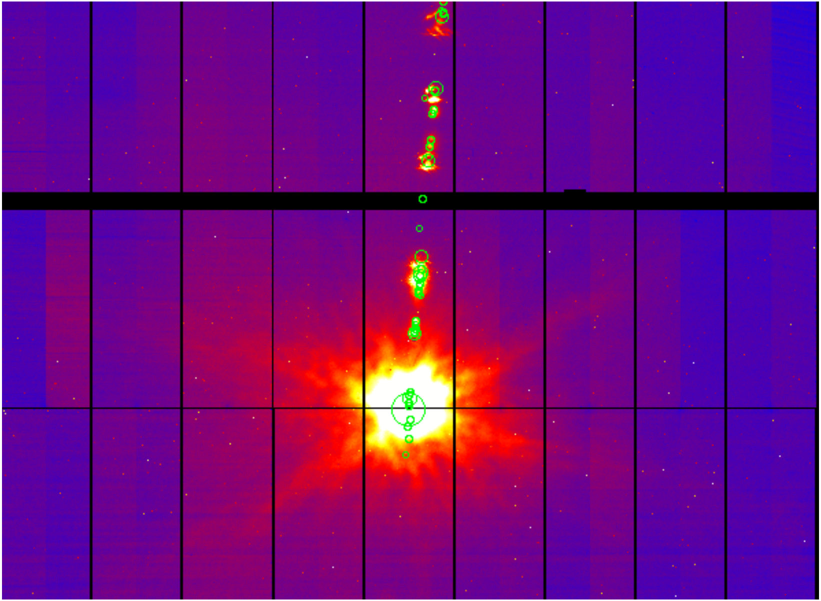


Let's shoot with that in

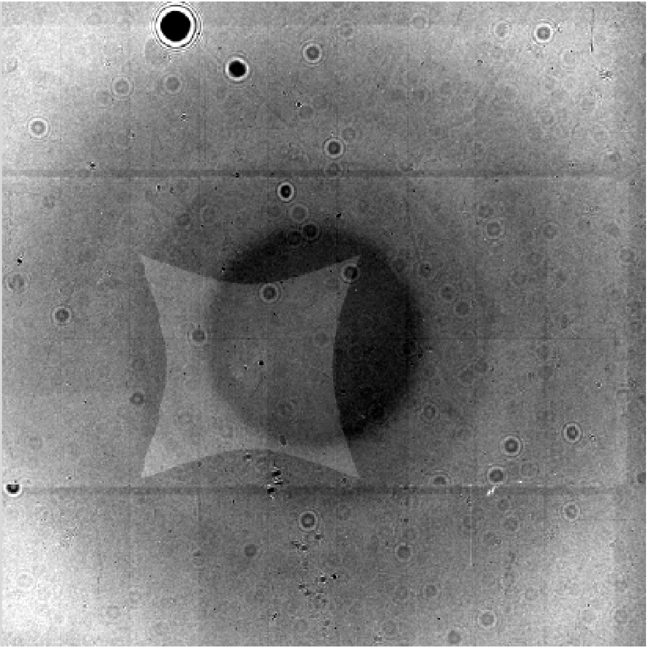
MegaCam optics



An alignement beam

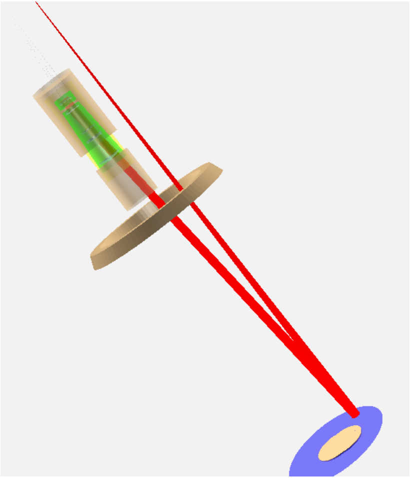


A flat-field illumination



Toward a complete model of the instrument

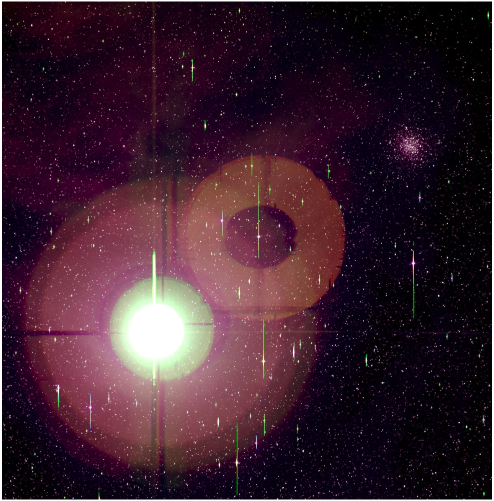
- There's a lot of information in these images
- And the feature are distinct
- There is hope that they can be used to constrain a model of the instrument



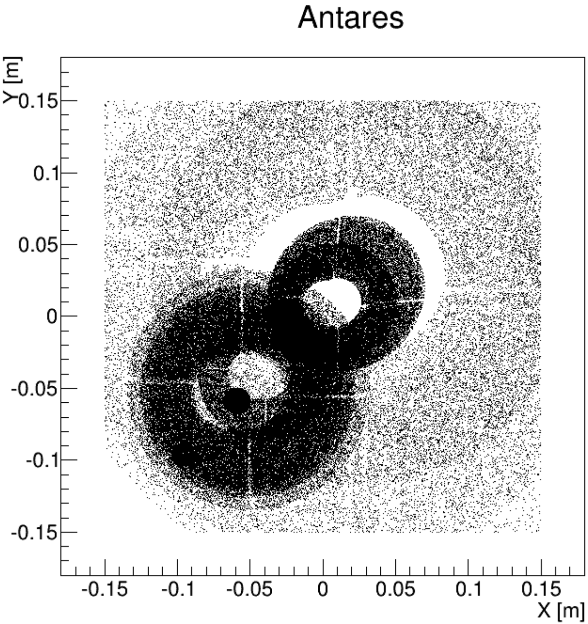
We settled on developing such a model of MegaPrime

- predict ghosting in stars, galaxy and DICE images
- at all wavelengths

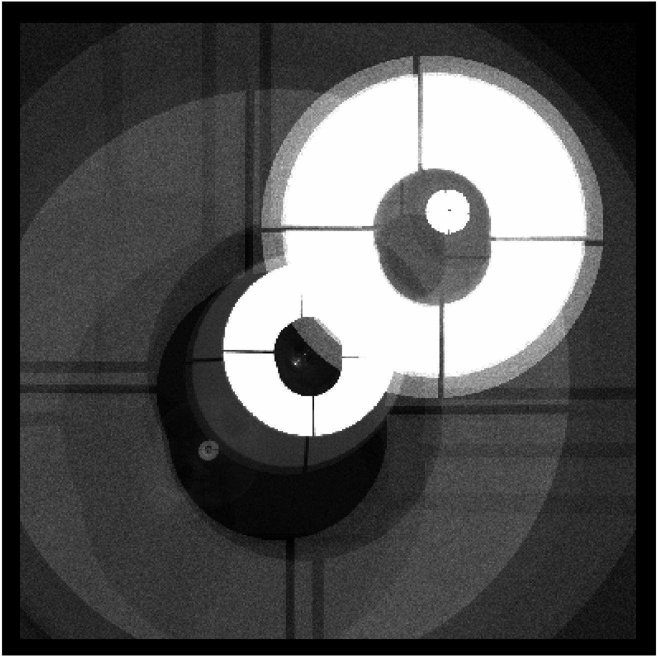
A test picture of Antares (from JCC)



Raytracing results looks promising



Let's move the star



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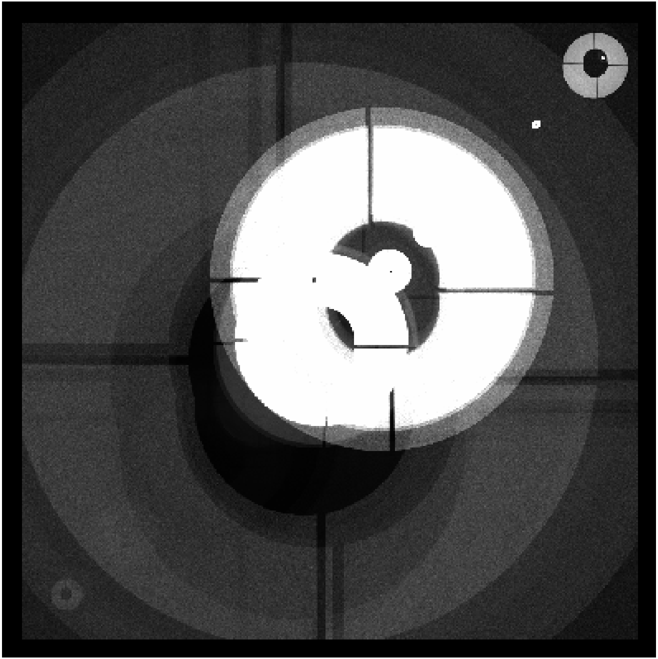

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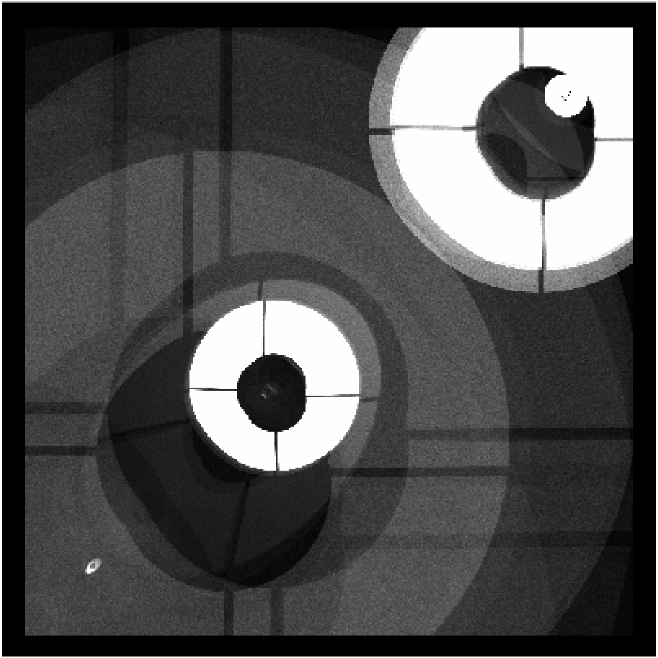

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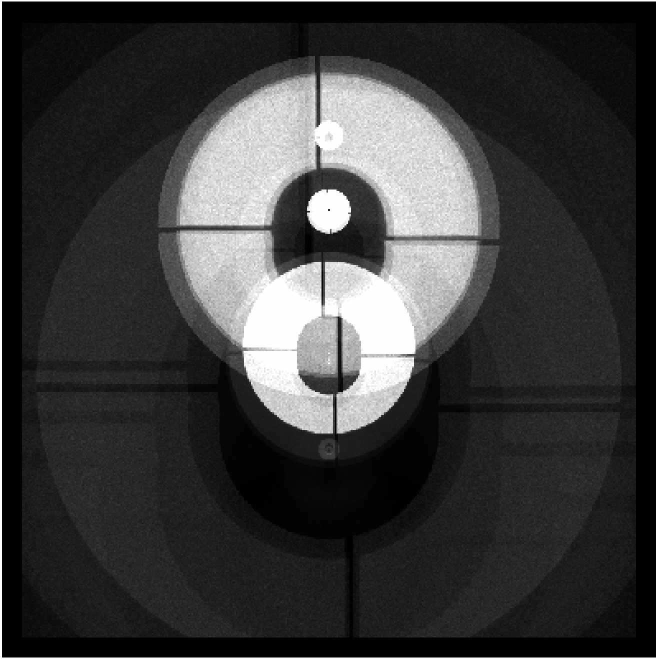


Raytracer ?

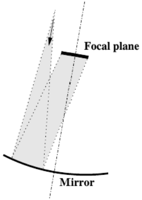
Monte-Carlo with a raytracer is conceptualy simple, but

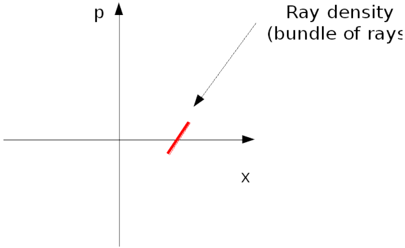
- $O(10^3)$ rays / second
- $O(300 10^6)$ rays needed (with 64x64 superpixels)
- $\sim$ 3-4 days / exposure (1 core)
- too slow !
  (remember : we need effective transmissions $=>$ scans in λ)

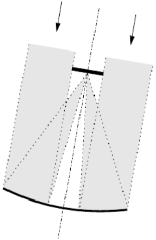
Why ?

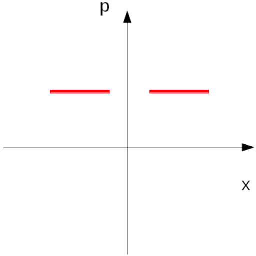
- Many rays / many paths / large memory needed
- ray-surface intersection tests computationaly intensive
- We need $\sim O(10^5)$ rays / s / core to be effective

The beams in phase space...





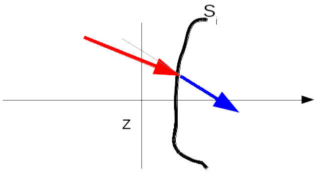




… have a simple structure

- So, we can propagate the ray densities in phase space, instead of the individual rays.
- We can model propagation / reflection / refraction of paraxial rays using linear optics

$$\mathbf{M}_i \cdot \begin{pmatrix} x \\ y \\ p_x \\ p_y \end{pmatrix} = \begin{pmatrix} x' \\ y' \\ p'_x \\ p'_y \end{pmatrix}$$



- The transfer function of the full system is the product of the individual M_i matrices.
- Attenuation is modeled with scalar modulation functions.

Then propagation through a path translates to products with precomputed matrices

Our first tests show that with

- simple beam structures (stars or collection of stars)
- linear optics

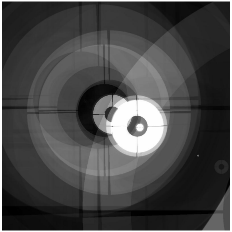
One can deal with O(100) paths per second

- (using 1 single core and 64 x 64 superpixels)

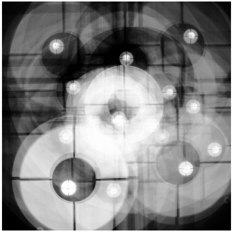
Non-linear (polynomial optics Hullin et al. 2012)

- provide a straitforward
- but slower extension
- ongoing work

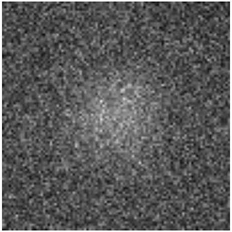
Exemples



Etoile simple
10000 ghosts
2 minutes

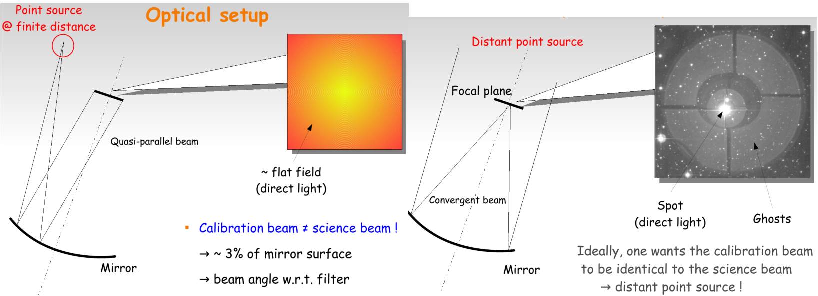


17 étoiles
10000 ghosts
34 minutes



Flatfield
Monte-Carlo (10^7 rayons/*ghost*)
30 minutes

StarDICE@OHP: doubling the model-based calibration



- Differences between calibration and sience beam makes us eavily dependant on the optics model

A calibrated artificial star can be build using only geometry

- If the telescope is small enough
- We called that StarDICE

StarDICE in a nutshell

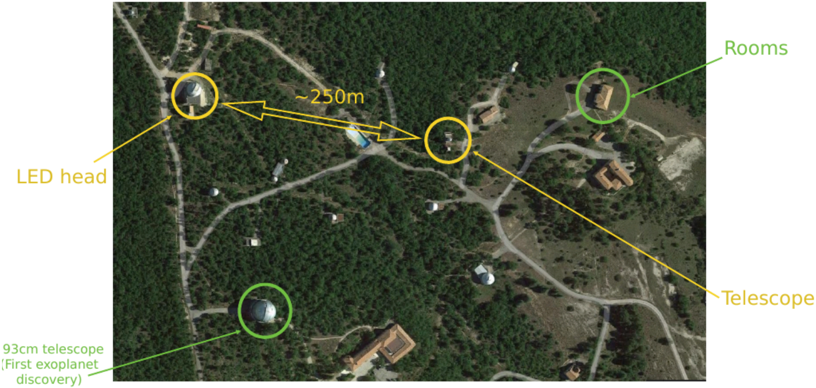
Use a telescope

- Small enough that a small source at 200m illuminates the entire pupil and appears point-like
- Large enough that it can reach CALSPEC WD (mag 13)
- Sweet spot for 16" telescopes

A dedicated one

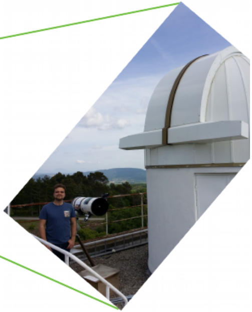
- Repeat the measurements as long as necessary to get rid of atmosphere
- If LIDAR and dedicated spectro are available on site that could help

Proof of concept with a test setup @ observatoire de haute provence



OHP site

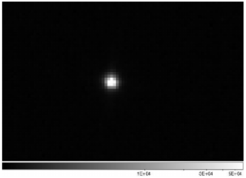
Window for control devices wires



LED head pointing to the telescope

Beam width at 250m : ~9m

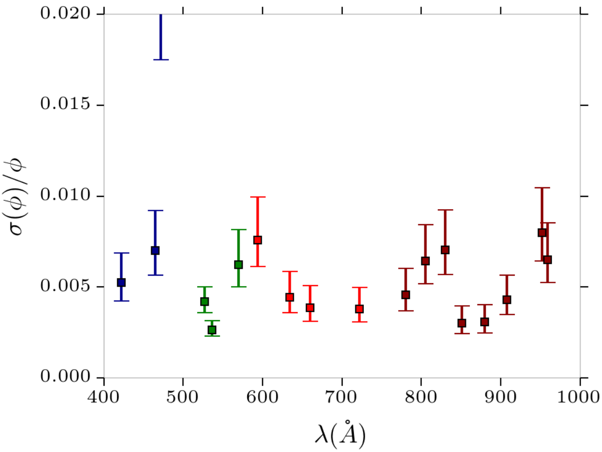
Easily illuminating the whole telescope



OHP first light from a LED

We took images of LEDs with different filters and images of 19 UMi with green filter

Repeatability of artificial sources photometry



- Short time goal is to the NIST-Star loop at the percent level
- Upgrade to something able to reach better accuracy if that succeed

Conclusion

Getting calibration issues fixed for 2nd generation survey proved harder than anticipated

- Comparison and collaboration with different instrument proved useful

A lot going on to get readier for 4th generation

- Gaia is going to make ‘reverse engineering’ much easier anyway
- Hopefully we will have a working solution for ‘absolute calibration’ for the next Euclid calibration workshop