Measurement of telescope response using a Collimated Beam Projector

T. Souverin, J. Neveu, M. Betoule, S. Bongard, S. Brownsberger, J. Cohen Tanugi, S. Dagoret Campagne, P. Fagrelius, F. Feinstein, P. Ingraham, C. Juramy, L. Le Guillou, A. Le Van Suu, P. E. Blanc, F. Hazenberg, E. Nuss, B. Plez, E. Sepulveda, K. Sommer, C. Stubbs, N. Regnault, E. Urbach

Presented by Thierry Souverin

30/11/2022

I. Introduction

Introduction : What is a CBP ?

CBP, for **Collimated Beam Projector**, is a device able to shoot:

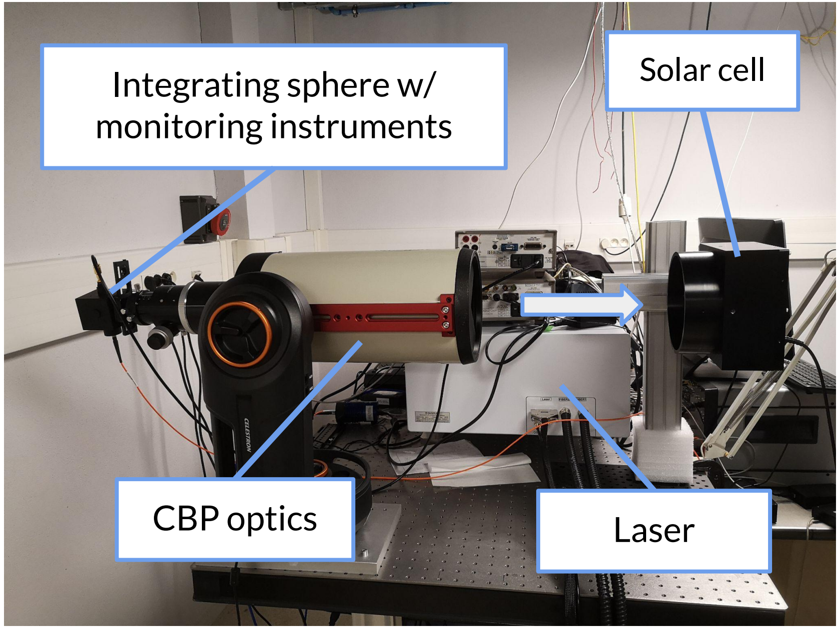
- a **known quantity of photons**
- at a **known wavelength**
- and in a **parallel beam.**

The goal is to mimic a **monochromatic** star of **known flux**, to **calibrate** the **response** of an instrument and its filters.

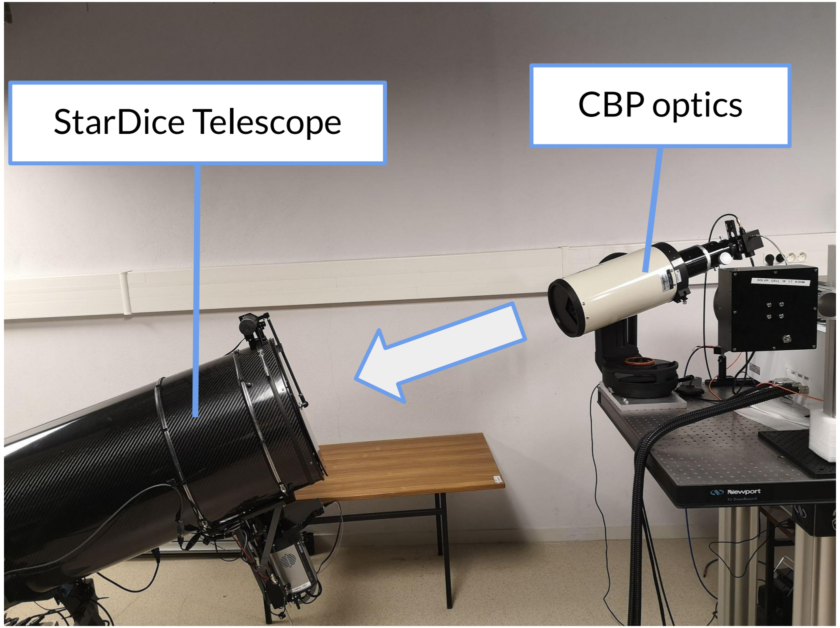
It is composed of :

1. **A tunable monochromatic light**
2. **An optic device able to recreate a parallel beam from a point source**

Setup device



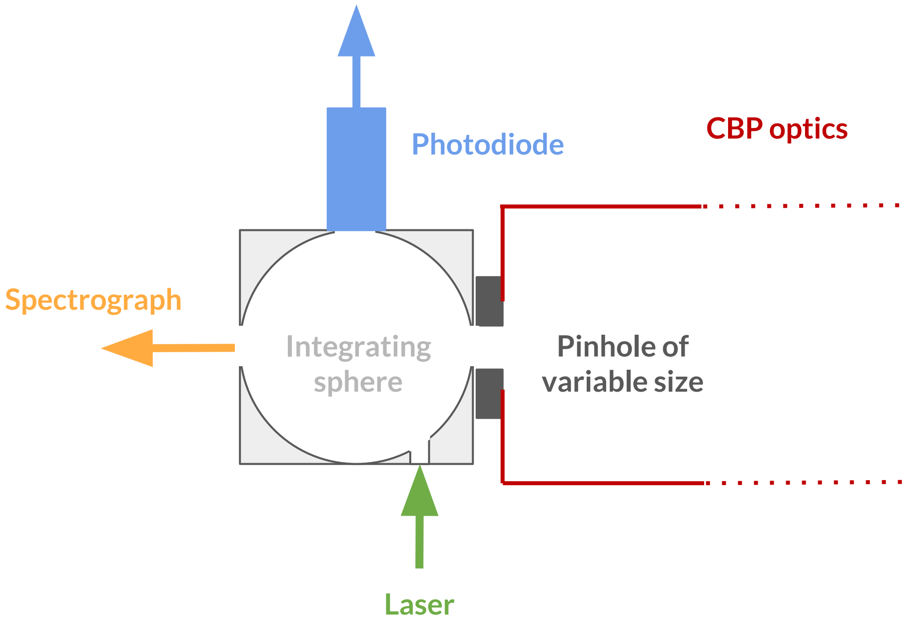
CBP response measurement



StarDice response measurement

II. Instruments

Integrating sphere



Two instruments in the integrating sphere, to monitor the input light :

a. A spectrograph to monitor the laser wavelength
b. A photodiode to monitor the flux quantity

How do we measure our responses ?

CBP response R_{CBP} [γ.C^{-1}]

$$\boxed{R_{\mathrm{CBP}} = \frac{Q_{\mathrm{solar}}}{Q_{\mathrm{phot}} \times \epsilon_{\mathrm{solar}} \times e}}$$

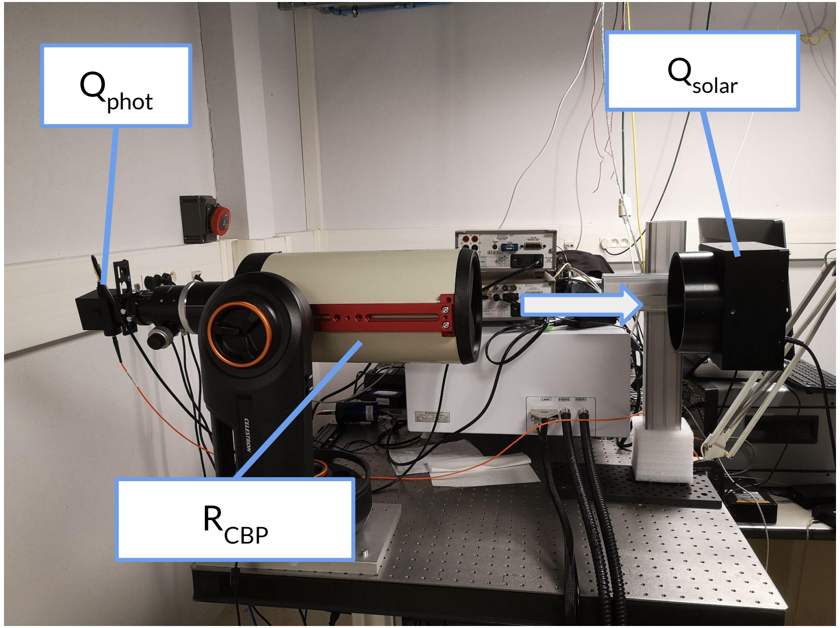
StarDice response R_{SD} [ADU.γ^{-1}]

$$\boxed{R_{\mathrm{tel}} = \frac{Q_{\mathrm{ccd}}}{Q_{\mathrm{phot}} \times R_{\mathrm{CBP}}}}$$

- Q_{solar} : solar cell charges [C]
- Q_{phot} : photodiode charges [C]
- Q_{ccd} : stardice charges [ADU]
- ϵ_{solar} : solar cell quantum efficiency [C.γ^{-1}]
- e = 1.6×10^{-19} [C]

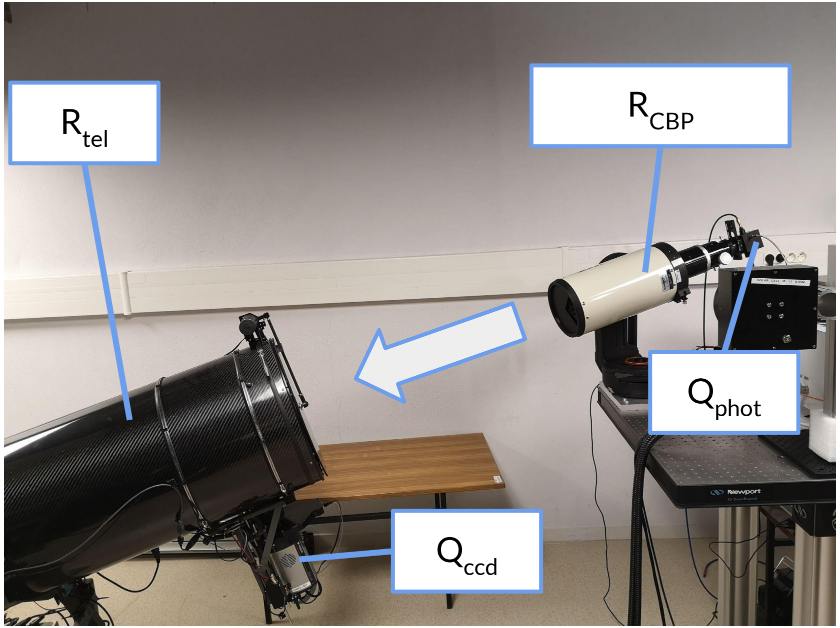
Setup device

CBP response measurement



$$R_{\mathrm{CBP}} = \frac{Q_{\mathrm{solar}}}{Q_{\mathrm{phot}} \times \epsilon_{\mathrm{solar}} \times e}$$

StarDice response measurement

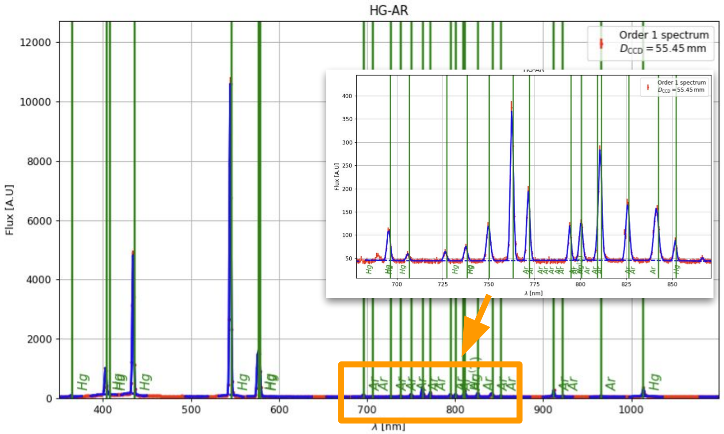


$$R_{\mathrm{tel}} = \frac{Q_{\mathrm{ccd}}}{Q_{\mathrm{phot}} \times R_{\mathrm{CBP}}}$$

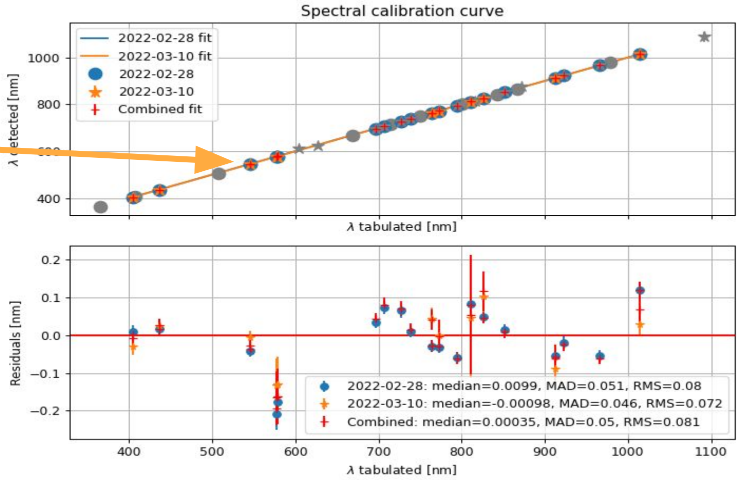
a. Spectrograph

Spectrograph wavelength calibration

- Acquisition of Hg-Ar spectra before and after CBP run
- Apply Spectractor line detection



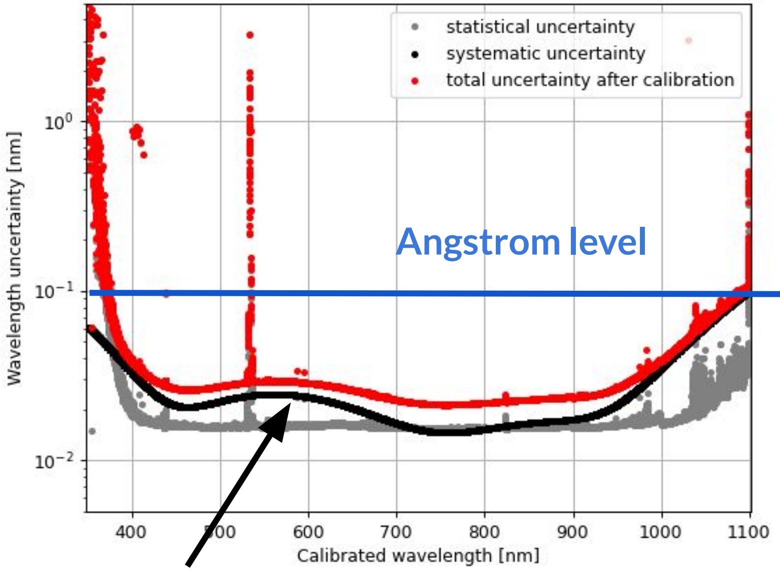
- Fit 3rd order polynom using SNR>20 lines to map detected and tabulated wavelengths, with uncertainties
- Rescale uncertainties to get reduced chi2~1
- Save the polynom coefficients and their covariance matrix



Wavelength calibration total uncertainties

- Total uncertainties globally below 0.1nm

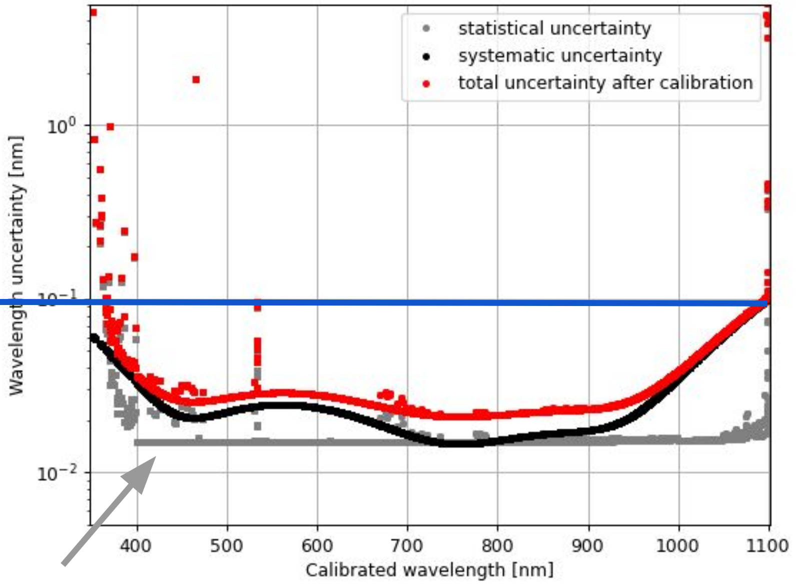
Stardice run



Angstrom level

Calib uncertainties

Solar cell run



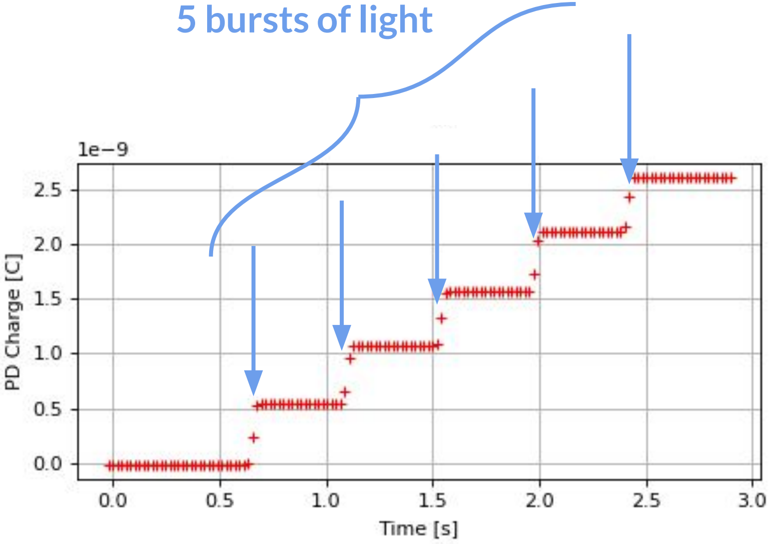
0.015nm floor

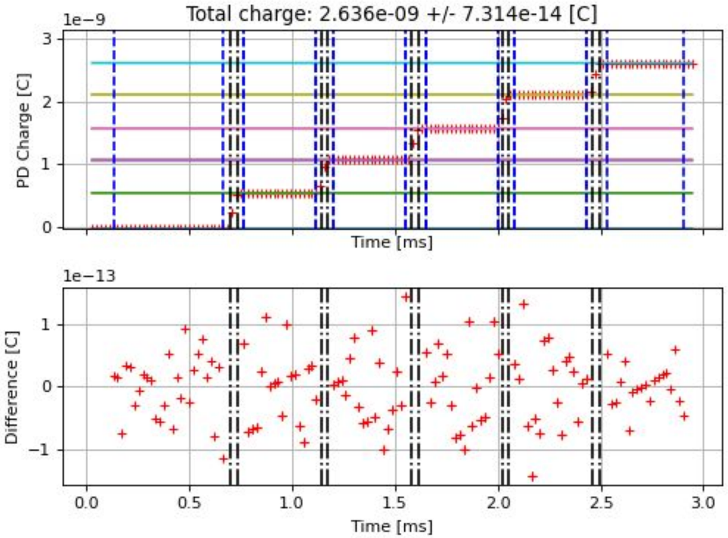
b. Photodiode

Monitoring photodiode

$$R_{\mathrm{CBP}} = \frac{Q_{\mathrm{solar}}}{Q_{\mathrm{phot}} \times \epsilon_{\mathrm{solar}} \times e}$$

- Photodiode plugged to the integrating sphere and connected to a electrometer
- Monitor the total charge collected in the photodiode $\mathbf{Q_{phot}}$ in Coulomb

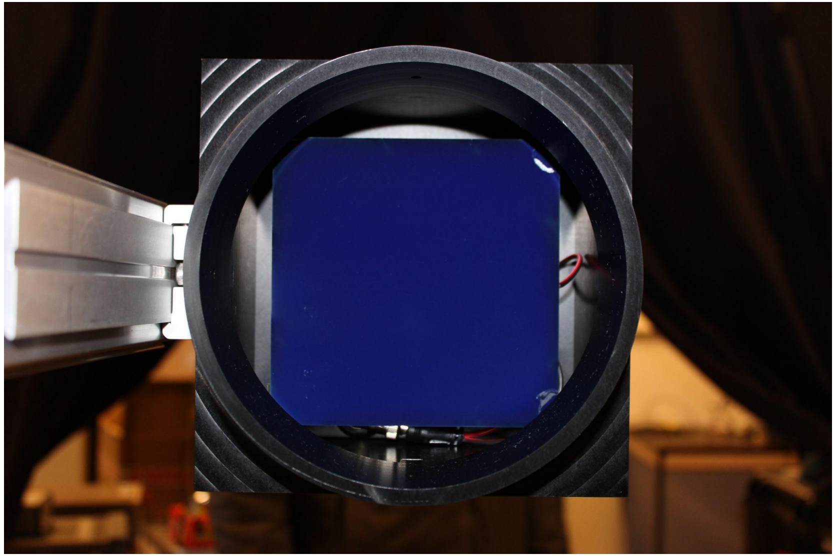

5 bursts of light

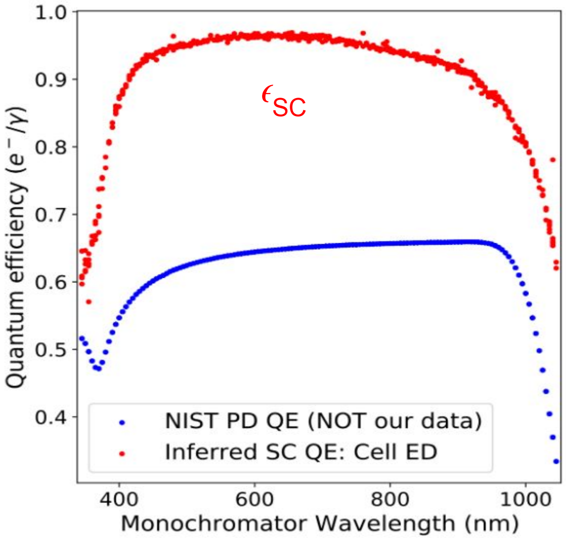


c. Solar Cell

CBP output with Solar Cell

- Large solar cell calibrated with a NIST photodiode
- Measure the photons at the output of the CBP





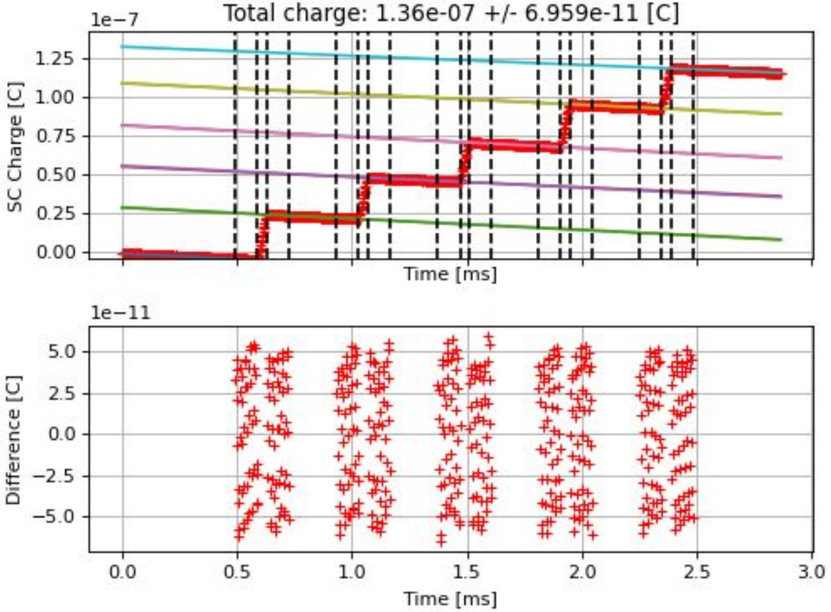
Caption : Quantum efficiency of the solar cell (Measured in Brownsberger et al., 2021)

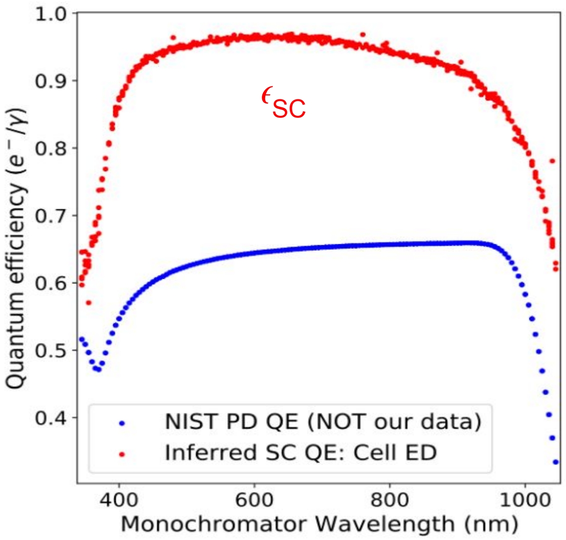
CBP output with Solar Cell

$$R_{\rm CBP} = \frac{Q_{\rm solar}}{Q_{\rm phot} \times \epsilon_{\rm solar} \times e}$$

- Large solar cell calibrated with a NIST photodiode

SC total charge Q_{solar} in Coulomb



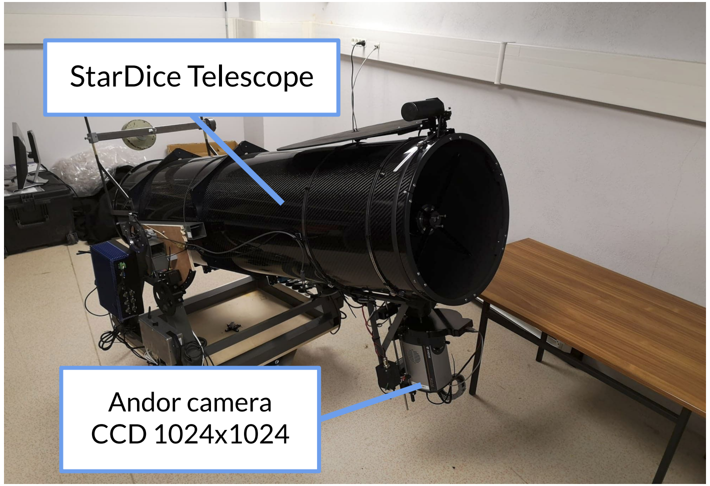


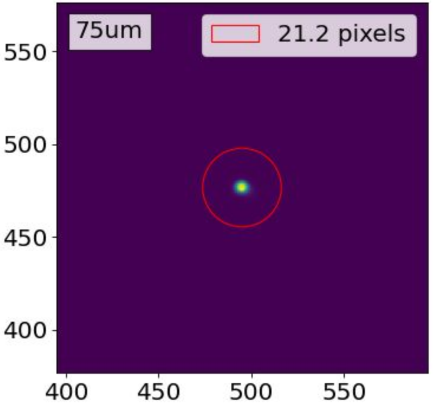
Caption : Quantum efficiency of the solar cell (Measured in Brownsberger et al., 2021)

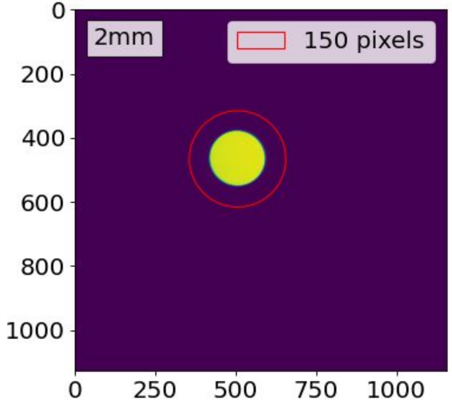
d. StarDice telescope

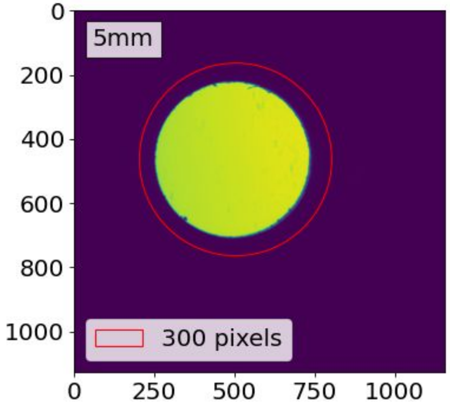
StarDice telescope

$$R_{\text{tel}} = \frac{Q_{\text{ccd}}}{Q_{\text{phot}} \times R_{\text{CBP}}}$$









- **Find spot position on camera**
- **Aperture photometry with dark subtraction**
- **3 pinholes: 75um, 2mm and 5mm**

⇒ Measure Q_{CCD} the photons collected by the camera in ADU

e. Logic timer

Logic timer

Homemade device with 3 inputs to listen to :

- Laser burst trigger
- Solar cell electrometer clock
- Photodiode electrometer clock

⇒ It allows the **synchronization** of all the clocks. This has played a major role in the improvement of the analysis.

III. Measurements

Plan

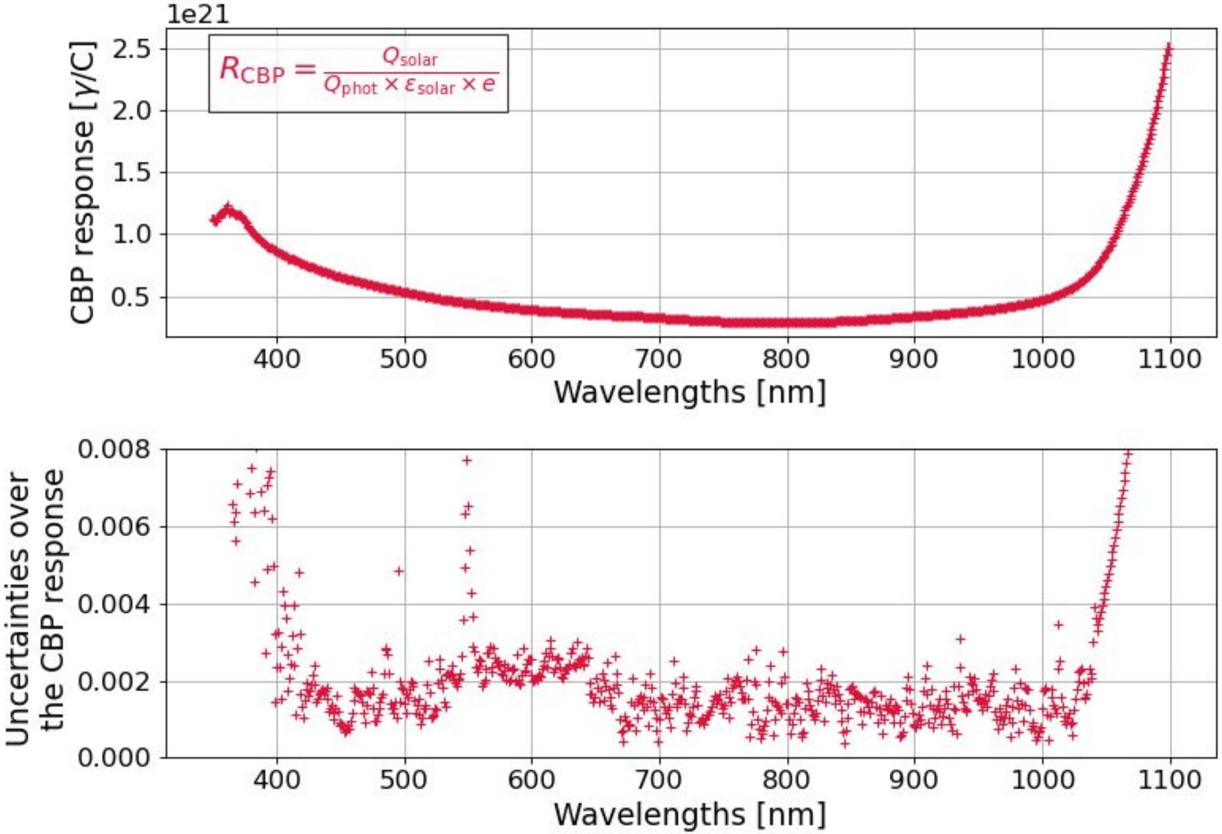
Different measurements have been made :

- Spectrograph calibration
- CBP response :
  - Solar Cell measurement ; 5mm pinhole
  - Long and short distance (~16cm difference) ; 5mm pinhole
  - Cap on the CBP to measure ambient light
- StarDice response :
  - Same position ; every camera filter ; 75μm, 2mm, 5mm pinhole
  - 8 positions on the mirror ; 75μm pinhole (“pupil stitching”)
    - 4 positions on different quadrants but same radius
    - 4 positions at different radius but same quadrant
  - (4x4) positions on the CCD ; 75μm pinhole

a. CBP response

CBP transmission, 5mm

Solar Cell measurement ; 5mm pinhole



Statistical precision

~ 0.2% for [400-1000] nm

b. StarDice response

StarDice response, 5mm

$$R_{\text{tel, 5mm}} = \frac{Q_{\text{ccd}}}{Q_{\text{phot}} \times R_{\text{CBP}}}$$

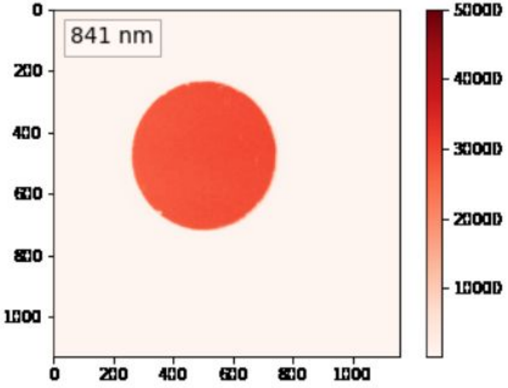
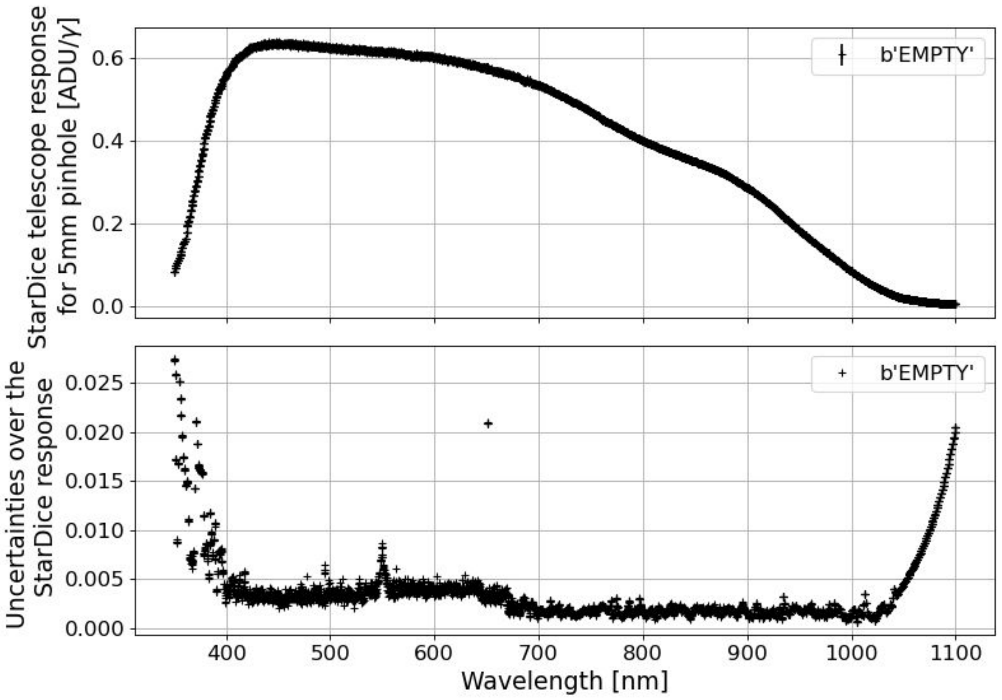


Image for 5mm pinhole for light at 841nm

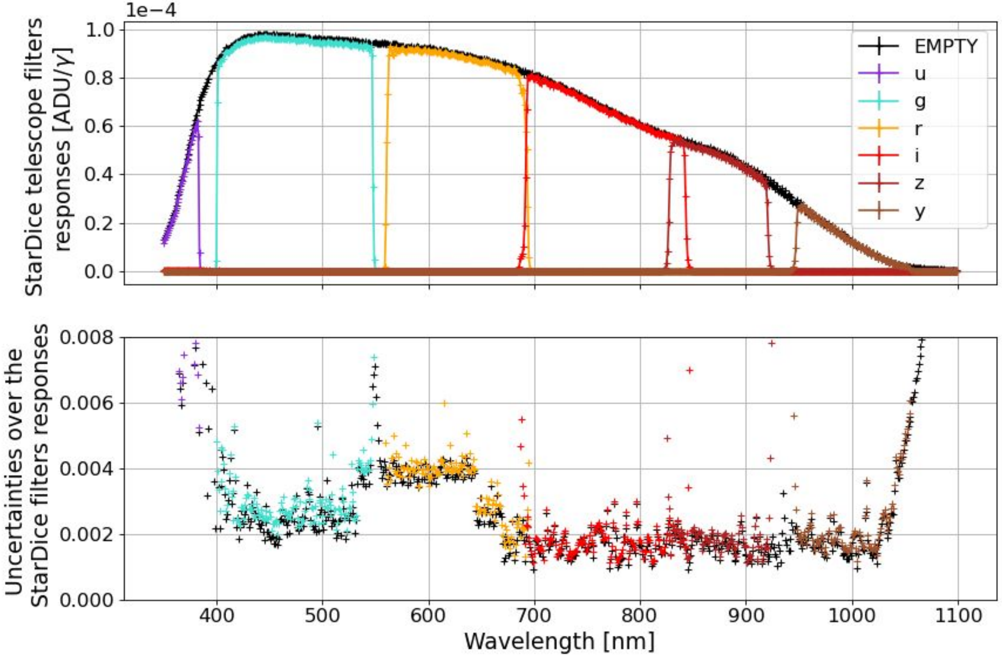


- **Statistical precision around 0.4% for [400 - 1000] nm**

StarDice filters transmission, 75µm

$$R_{\text{tel, }75\mu\text{m}} = \frac{Q_{\text{ccd}}}{Q_{\text{phot}} \times R_{\text{CBP}}}$$

- Precision around 0.4% for every filters in
- Wavelength resolution high enough to see the slopes of the filter edges



StarDice grating transmission, 75µm

Grating → disperse light to observe absorbing rays

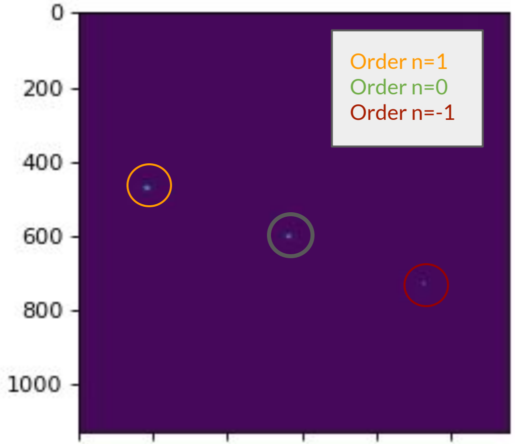
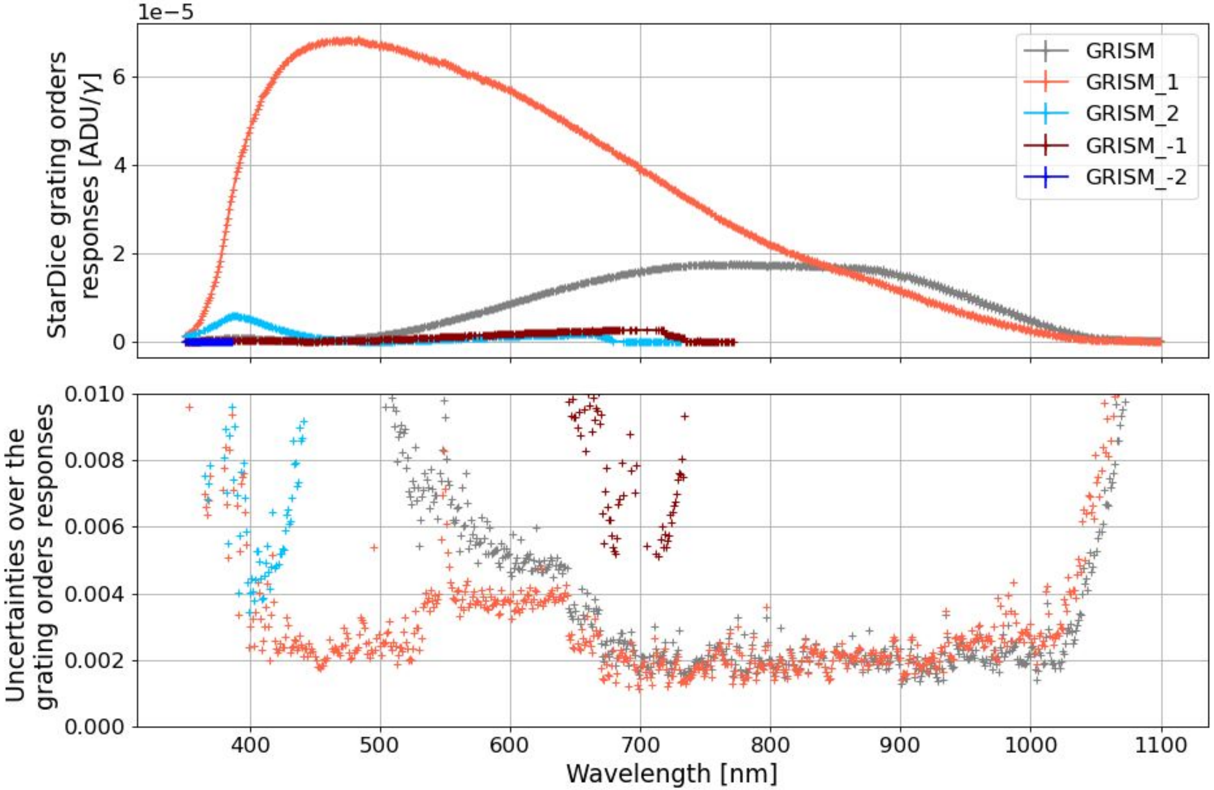


Image for 750 nm



- Uncertainty around 0.3% for 1st order in [400 - 1000] nm range

Summary

- **Good things :**
  - The CBP has converged to a working end-to-end design !
  - Calibration of the CBP itself at the per mil level
  - First time a CBP measures the response of a telescope and its filters at the per mil level

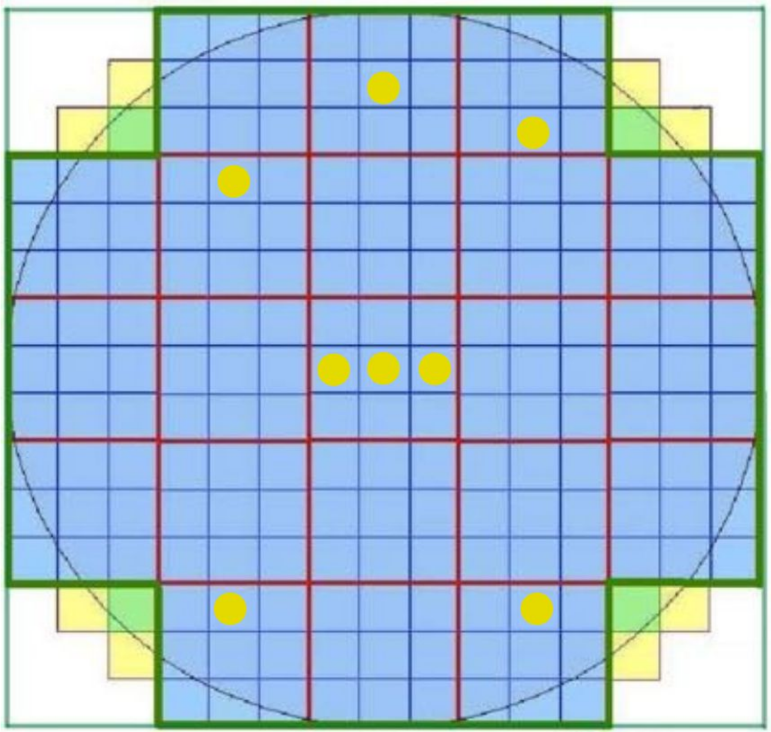
- **Things to do :**
  - Build a model for StarDice response in function of the position on the primary mirror
  - Intercalibration between the 75µm and 5mm pinholes
  - Finish to write the paper

IV. RubinCBP @ Tucson

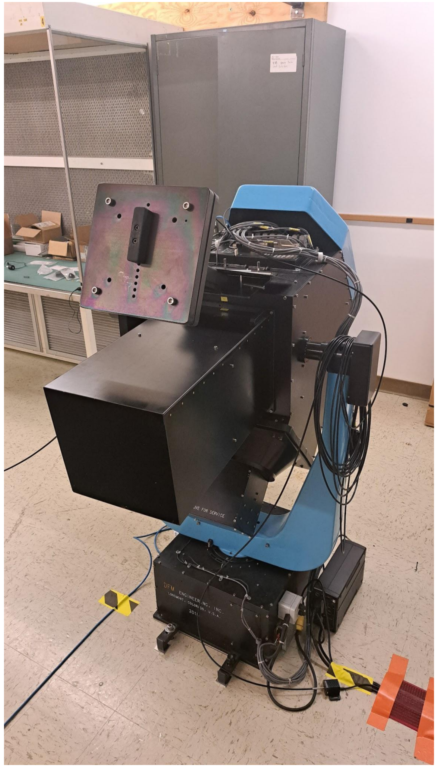
Rubin CBP

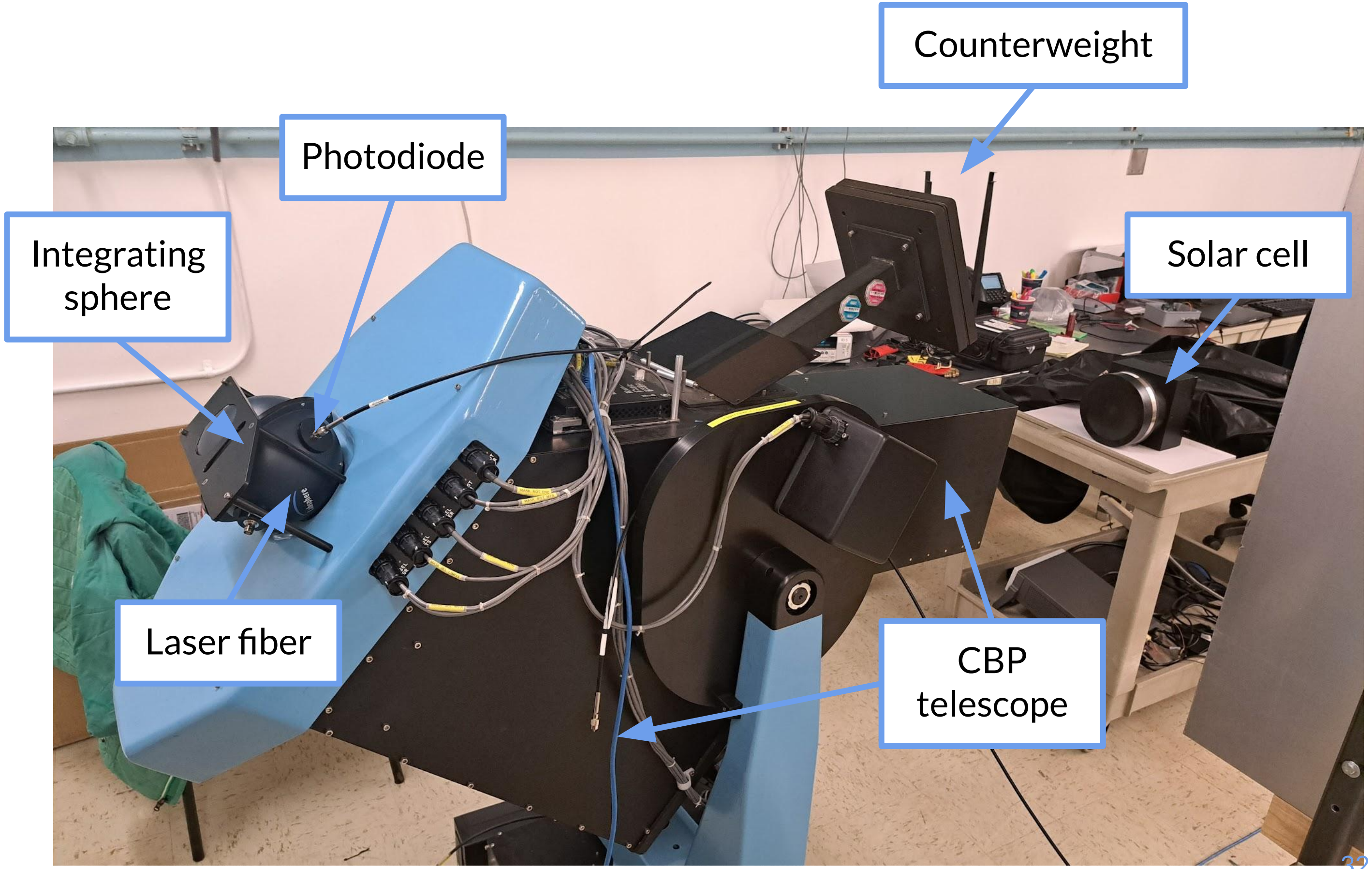
- Collimated Beam Projector to calibrate Rubin telescope : **focal plane and filters responses and uniformities** (artificial star-flats)

- How ? with **artificial constellations of monochromatic stars** calibrated in flux and wavelength: multiple pinhole mask at the focal plane of a small revert telescope, pointing at LSST



Rubin CBP

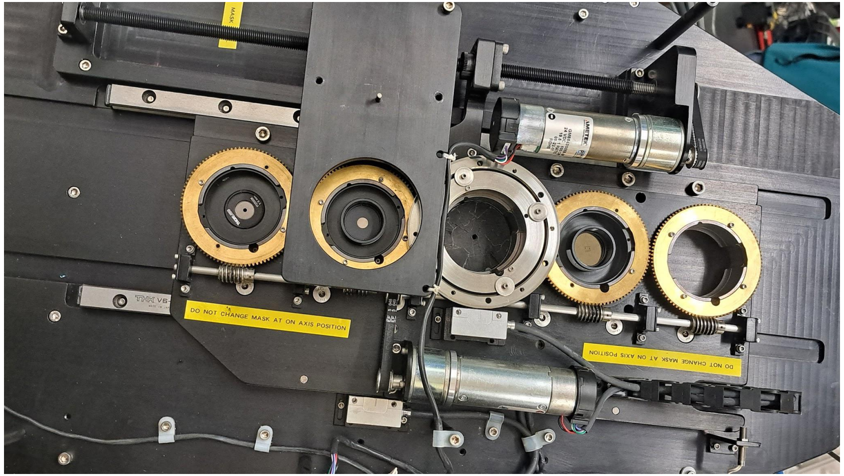



Counterweight
Photodiode
Integrating sphere
Solar cell
Laser fiber
CBP telescope

Rubin CBP masks

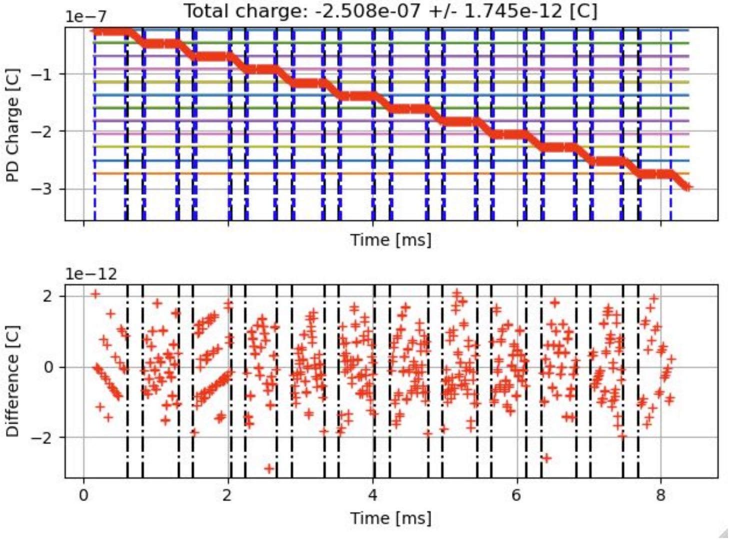
- Masks can be rotated, made by Harvard or Tucson mechanical workshops

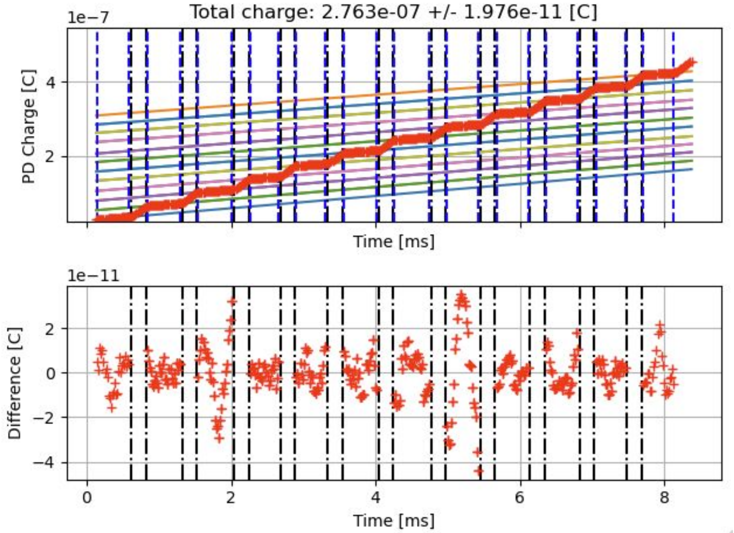
- Still needs to decide how the constellation must look like :
    - a constellation of stars
    - with one star per amplifier/CCD
    - not too small
    - not too big



First data

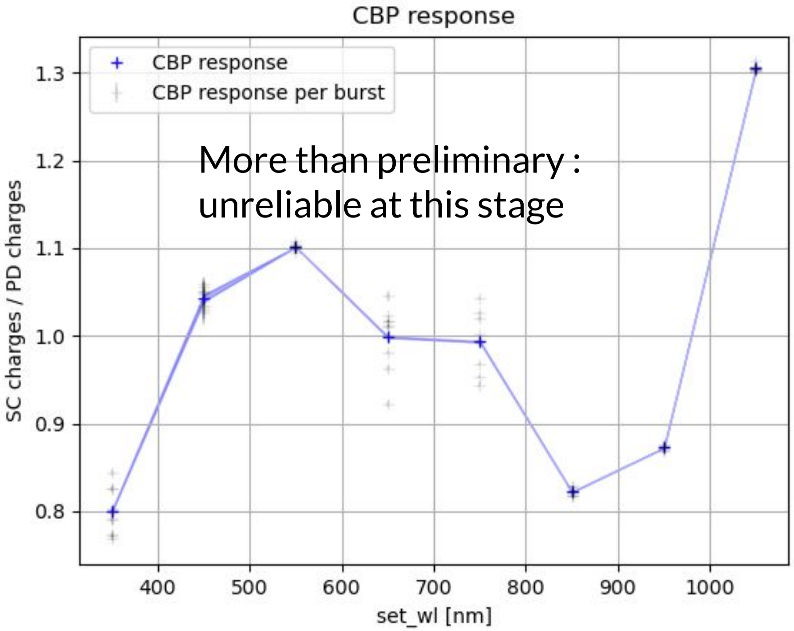
- Visible burst in solar cell with 2.5mm pinhole, 200 laser pulses, at all wavelength
- Burst timings from logic timer device (Arduino) not available for the moment


Photodiode


Solar cell

First data

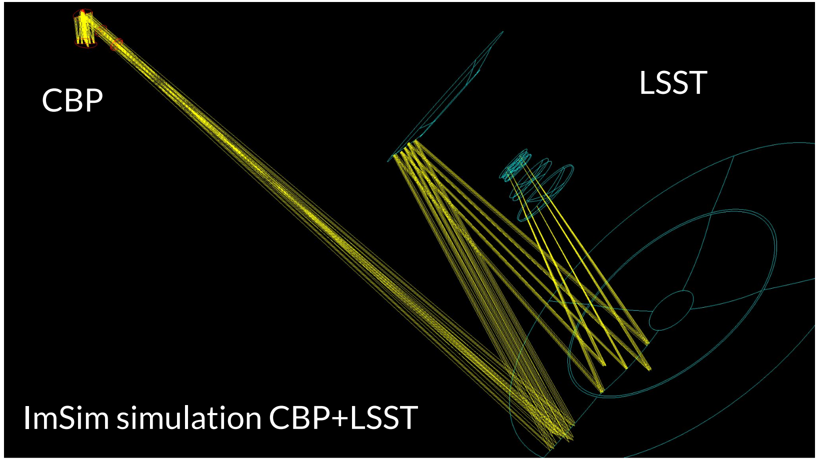
Ratio of charges : CBP response ! At least some numbers on a plot…



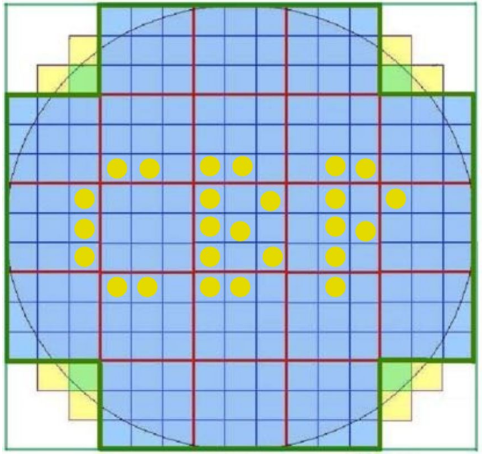
More than preliminary :
unreliable at this stage

Summary

- **Good things :**
  - Light in the instruments
  - Good portability of the StarDice CBP code to the Rubin CBP data
  - Team in place: LPNHE+Harvard+NoirLab



- **Things to do :**
  - Characterize the instruments (spectrograph, electrometers)
  - Design masks to map and characterize LSSTCam focal plane and filters
  - Ask DM to perform aperture photometry on CBP pinhole images
  - Ghost/distortion analysis with ImSim (LSST image simulator)



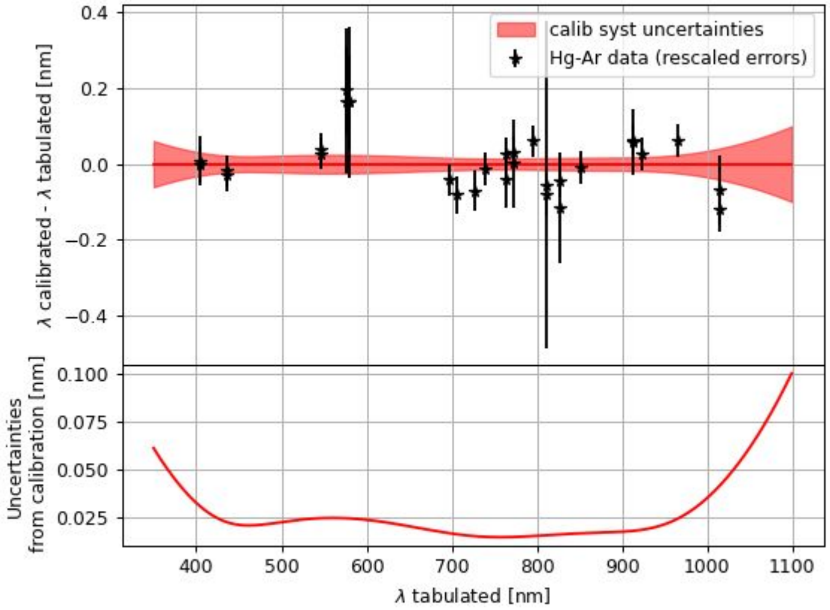
Thanks for your attention

IV. Major corrections

a. 532nm contamination correction

Spectrograph wavelength calibration

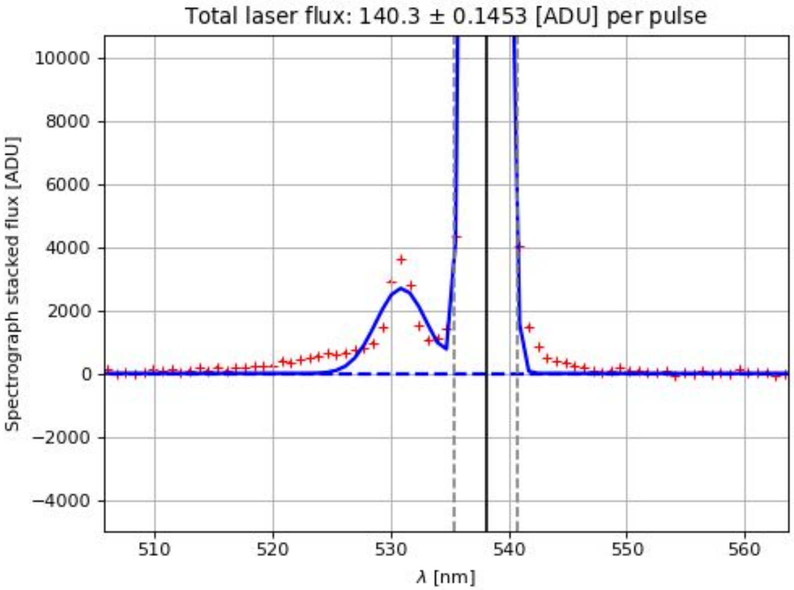
- Load the parameters, make the mapping and propagate detection uncertainties plus calibration uncertainties
  - contribution of 0.03nm systematic uncertainty from calibration in the visible range, more outside



532nm contribution : extraction

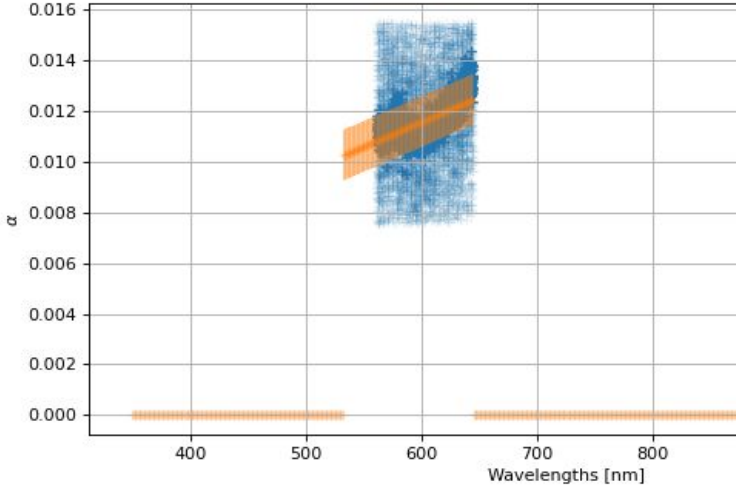
- $\alpha(\lambda) = Q_{SP,532}/Q_{SP}(\lambda)$ in the [532 - 644] nm range
- Within the [560 - 644] nm range, $Q_{SP,532}$ and $Q_{SP}(\lambda)$ are well separated so we can make a good estimation of α
- Below 560 nm, the shape of the psf in the spectrograph induces a superposition between the two peaks

⇒ We fit the values of $\alpha(\lambda)$ between [560-644] nm for all the runs at a given QSW and we extrapolate in the range of [532-560] nm



532nm contribution : extraction

- $\alpha(\lambda) = Q_{SP,532}/Q_{SP}(\lambda)$ in the [532 - 644] nm range
- Within the [560 - 644] nm range, $Q_{SP,532}$ and $Q_{SP}(\lambda)$ are well separated so we can make a good estimation of α
- Below 560 nm, the shape of the psf in the spectrograph induces a superposition between the two peaks



⇒ We fit the values of $\alpha(\lambda)$ between [560-644] nm for all the runs at a given QSW and we extrapolate in the range of [532-560] nm

532nm correction : application

$$\alpha(\lambda) = \frac{Q_{\text{spectro, } 532nm}}{Q_{\text{spectro}}(\lambda)}$$

$$Q_{\text{phot}}(\lambda) = \frac{Q_{\text{phot, mes}}(\lambda)}{1 + \alpha(\lambda)}$$

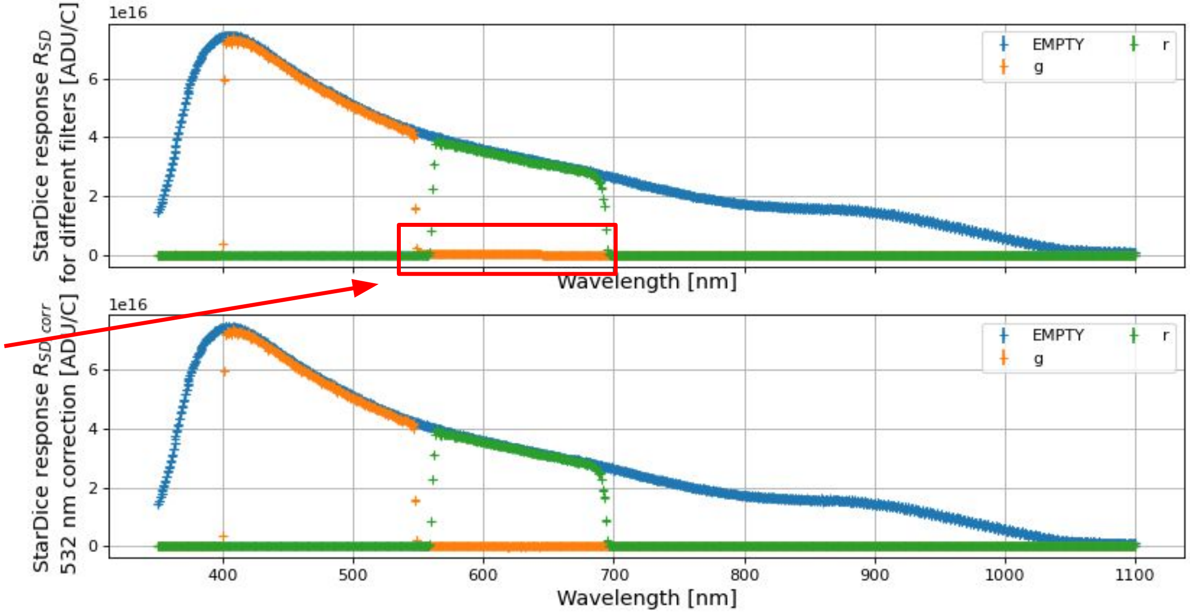
$$Q_{\text{solar}} = Q_{\text{solar, mes}} - R_{\text{solar, } 532nm} \times Q_{\text{phot}}(\lambda) \times \alpha(\lambda)$$

$$Q_{\text{telescope}} = Q_{\text{telescope, mes}} - R_{\text{telescope, } 532nm} \times Q_{\text{phot}}(\lambda) \times \alpha(\lambda)$$

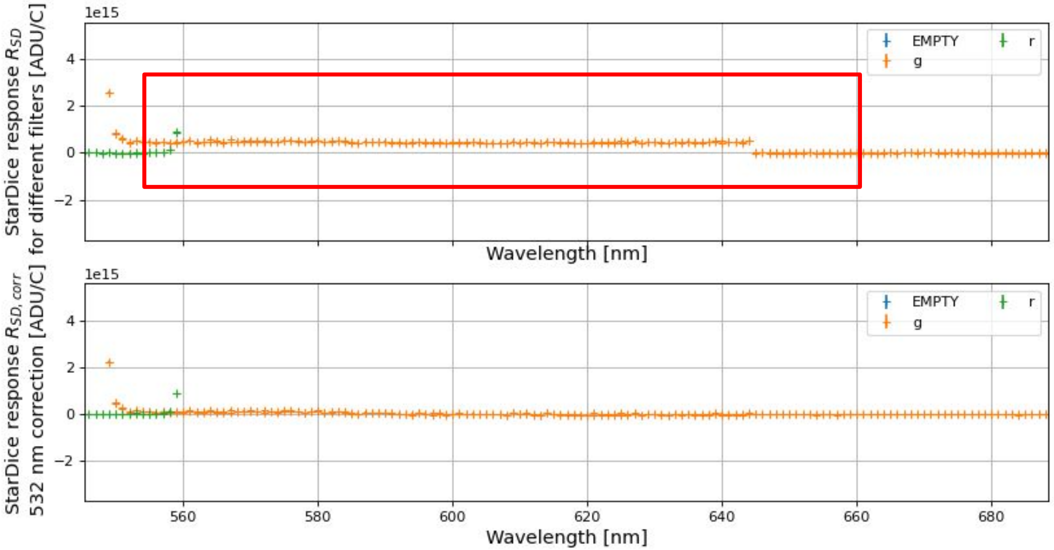
532nm contribution : g filter demonstration

g filter : cut after ~560nm

→ we don’t see the main wavelength light, but only the 532nm contribution

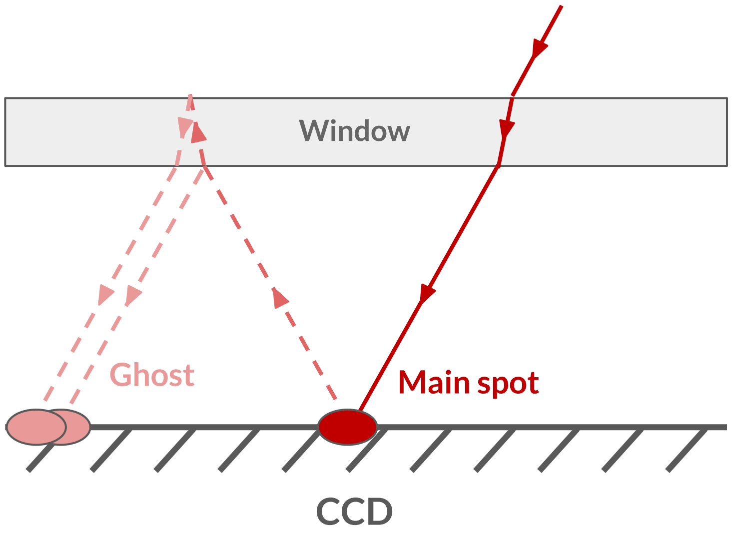


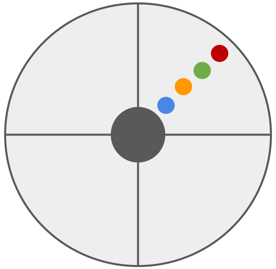
532nm contribution : g filter demonstration

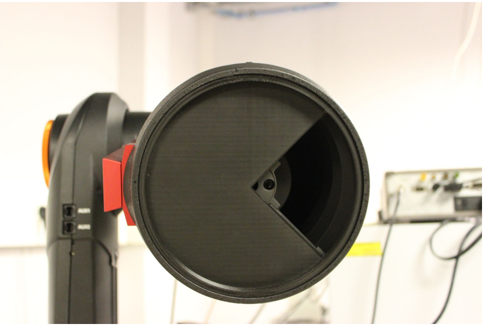


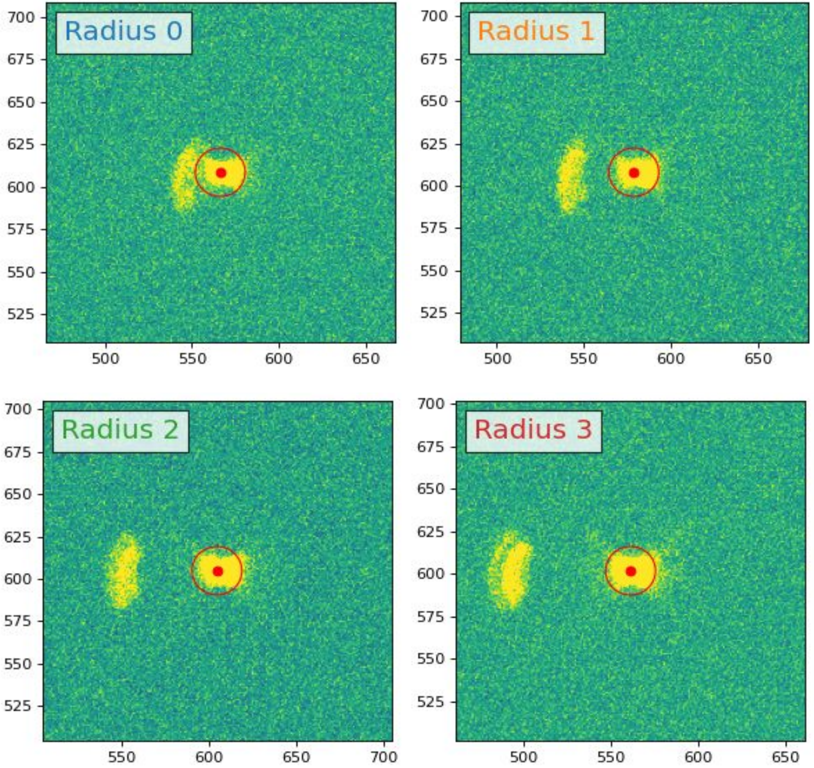
b. Ghost correction

Ghost photometry









Ghost correction

- Φ_0 : Main spot flux
- Φ_G : Ghost flux

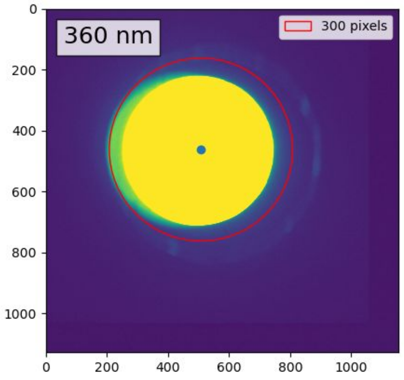
- 75µm photometry : $\Phi_{tot} = \Phi_0$
- 5mm photometry : $\Phi_{tot} = \Phi_0 + \Phi_G$

We consider that the contribution of the ghost is a function of lambda *f(λ)* :

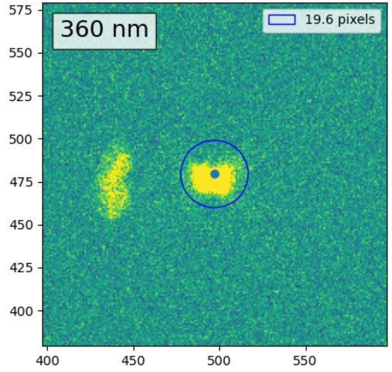
$$\Phi_G = f(\lambda) \times \Phi_0$$

We can deduce the main spot contribution for the 5mm pinhole :

$$\boxed{\Phi_0 = \Phi_{tot}/(1+f(\lambda))}$$



5mm pinhole

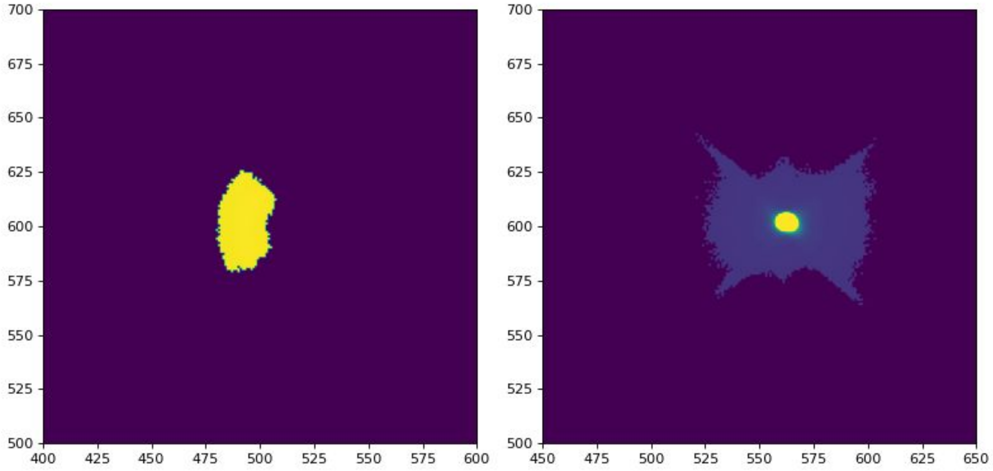


75µm pinhole

Ghost photometry : looking for the masks

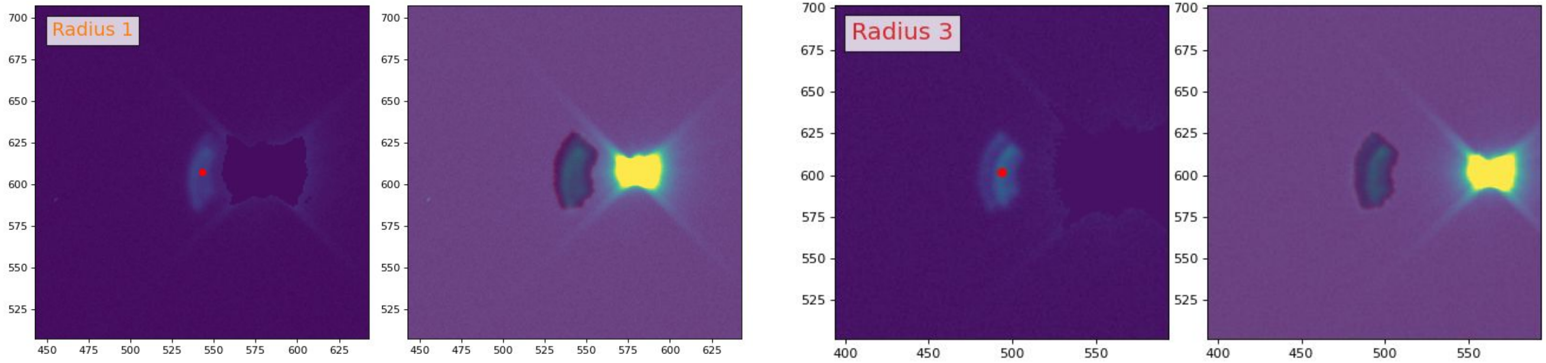
Produces a stack of all the similar datas

→ Create a mask for the main spot and the ghost



Ghost photometry : fitting positions

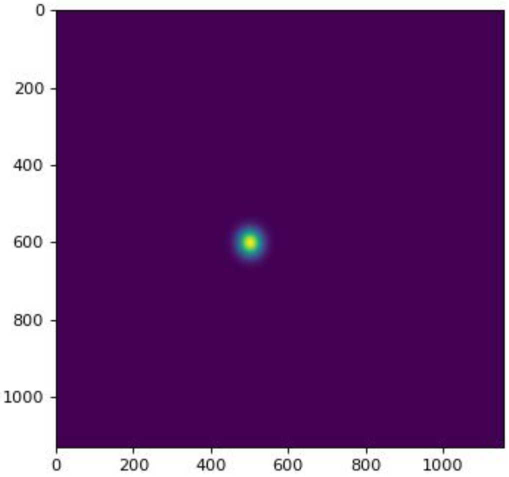
- Find the barycenter of the main spot and mask it
- Fit the best position for the ghost with a gaussian filter step by step



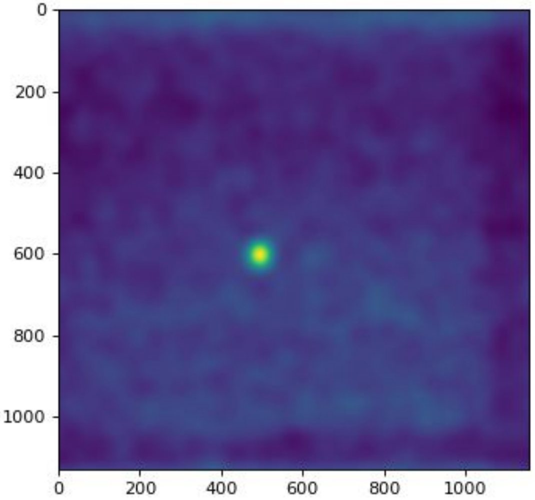
Ghost photometry : fitting positions

Fit with a high sigma → reduces the sigma and fit again → until sigma=1

Ghost mask



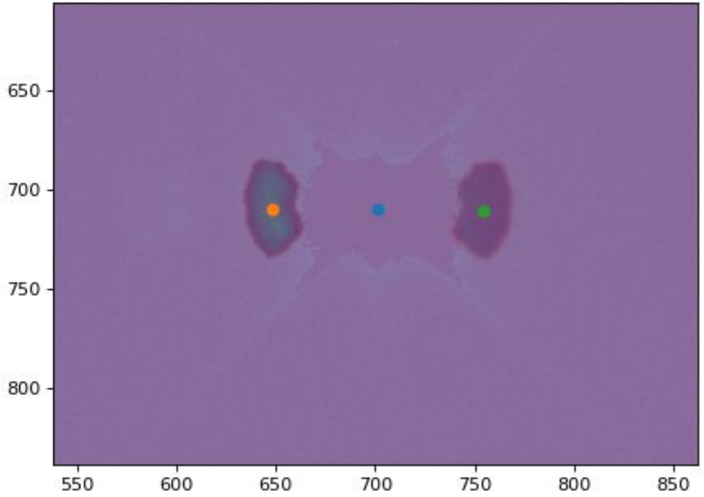
Data with main spot masked



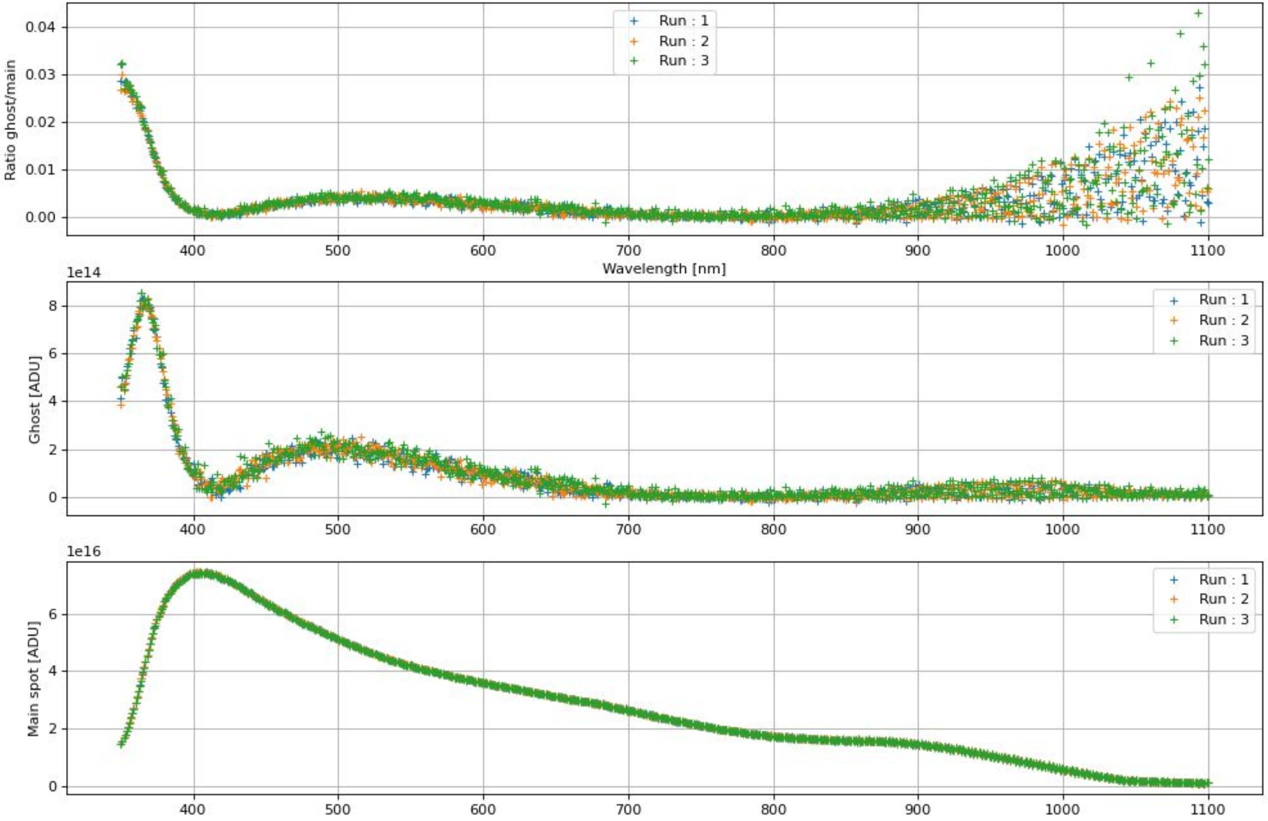
Ghost photometry : background subtraction

Find ghost position and draw the vertical symmetric according to the main spot position

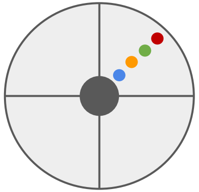
→ calculate the mean of the symmetric photometry and subtract it

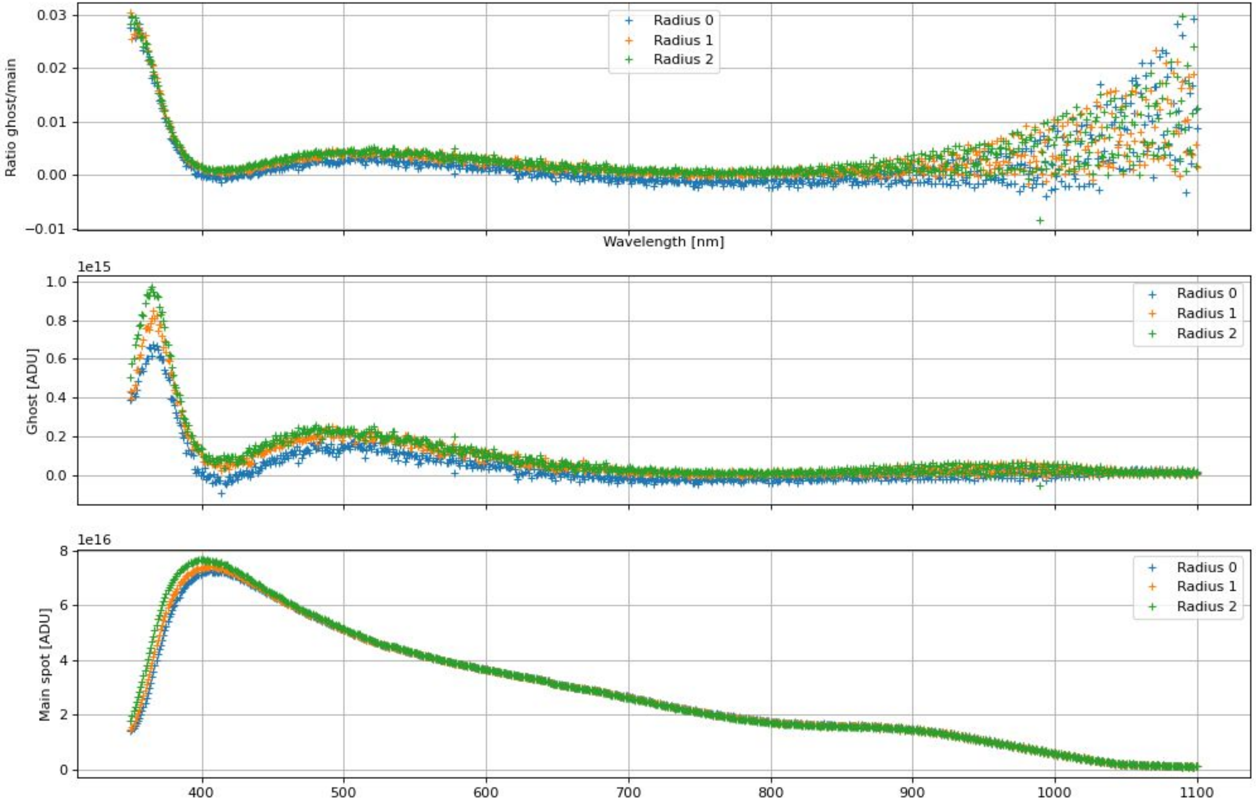


Ghost photometry : same mirror positions

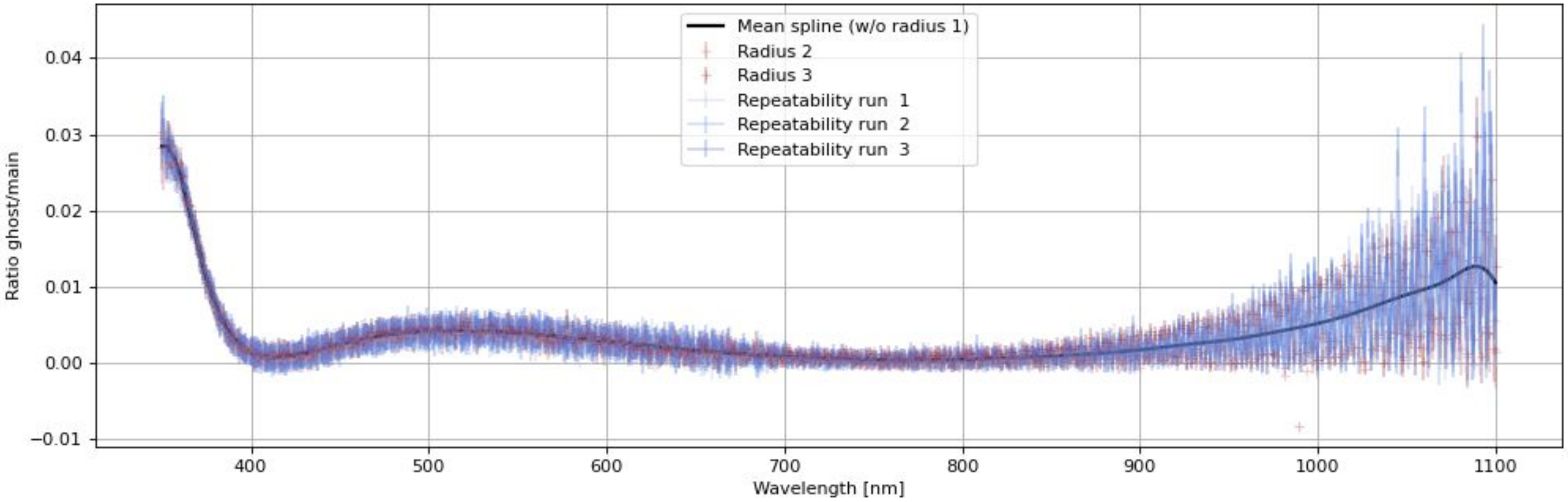


Ghost photometry : different radius positions

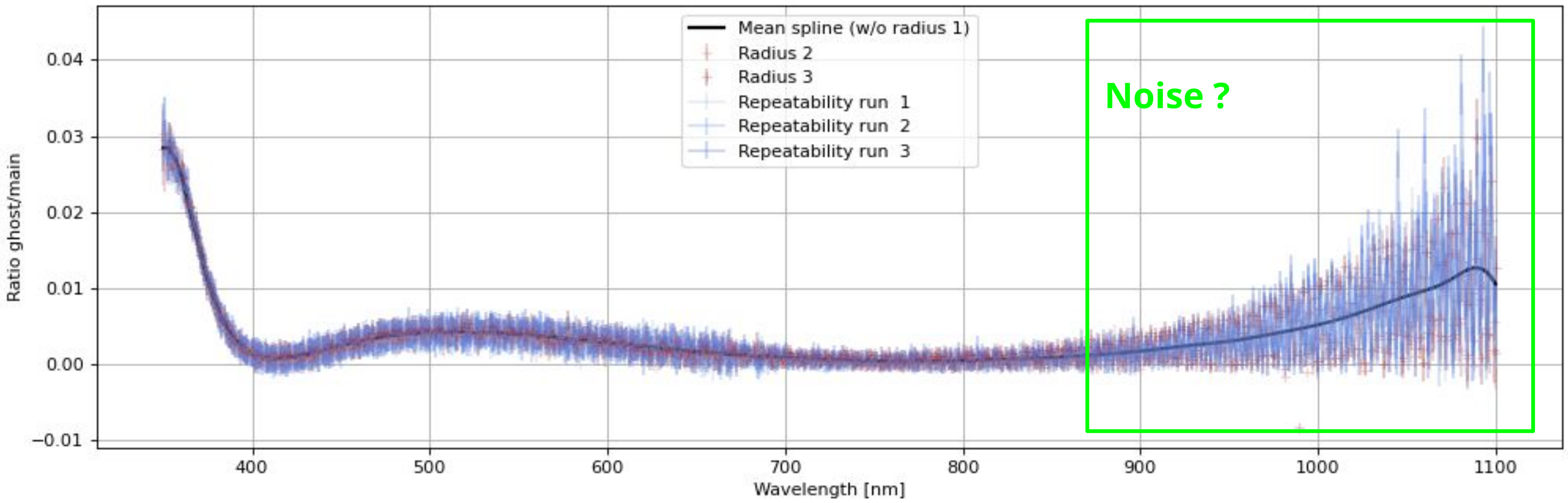




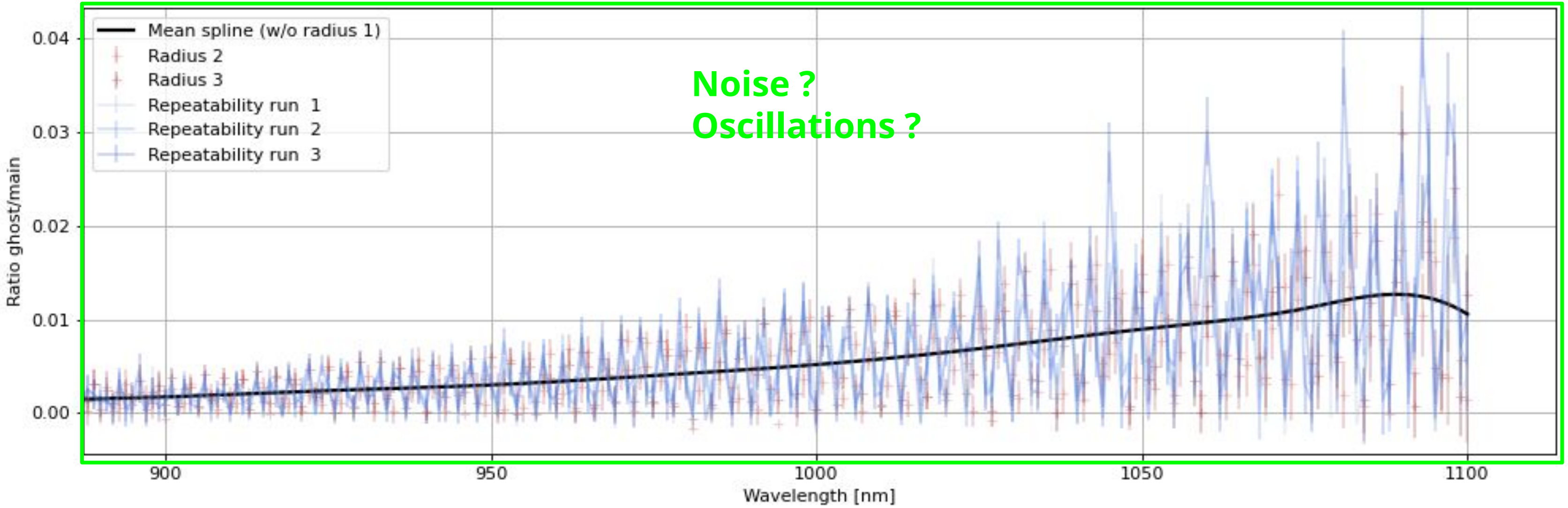
Ghost photometry : spline with all data (except radius 1)



Ghost photometry : spline with all data (except radius 1)

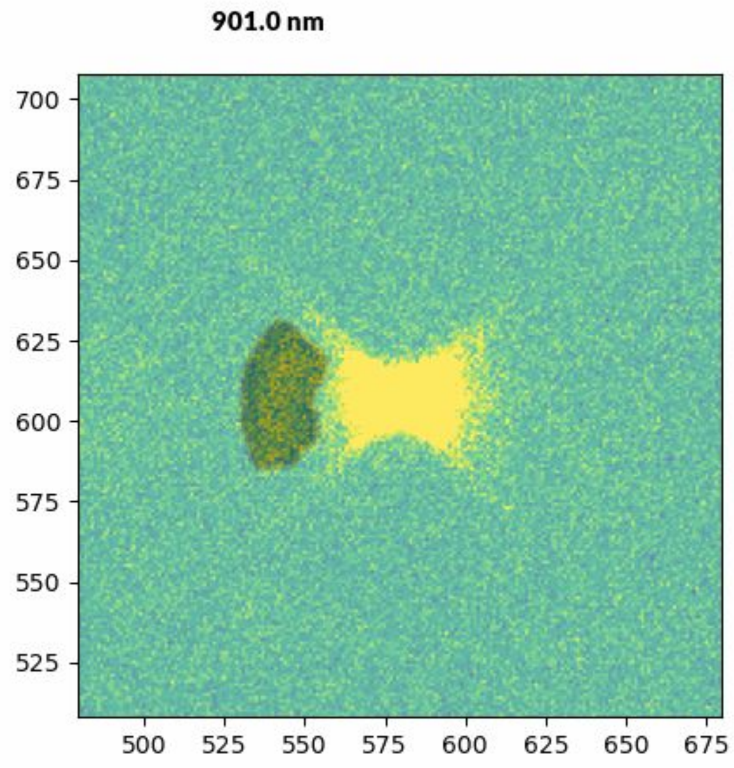


Ghost photometry : spline with all data (except radius 1)

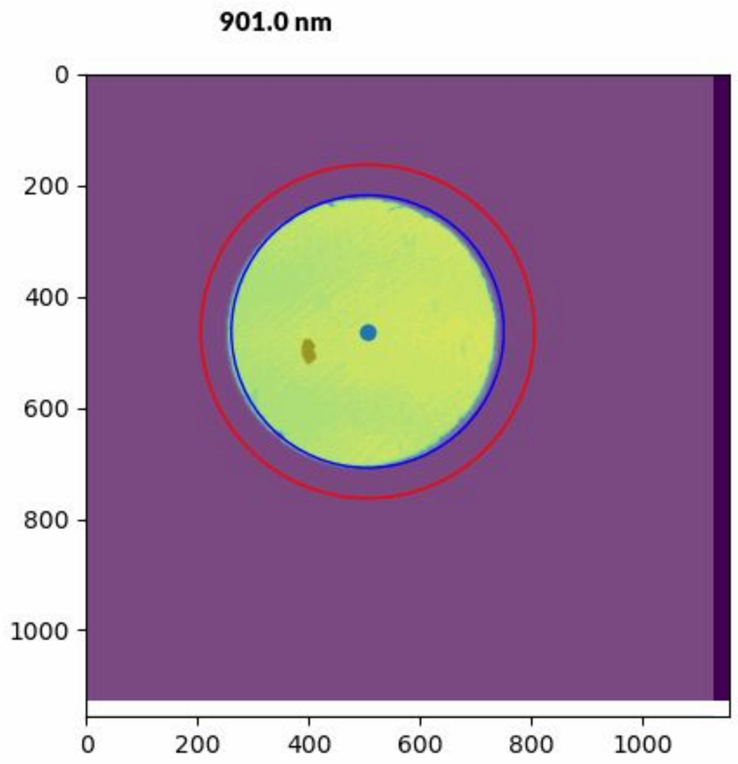


Noise ?
Oscillations ?

Ghost photometry : IR oscillations



Ghost photometry : IR oscillations

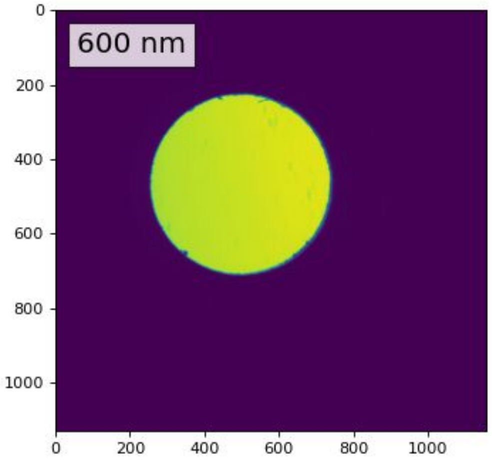


c. Intercalibration 5mm/75µm

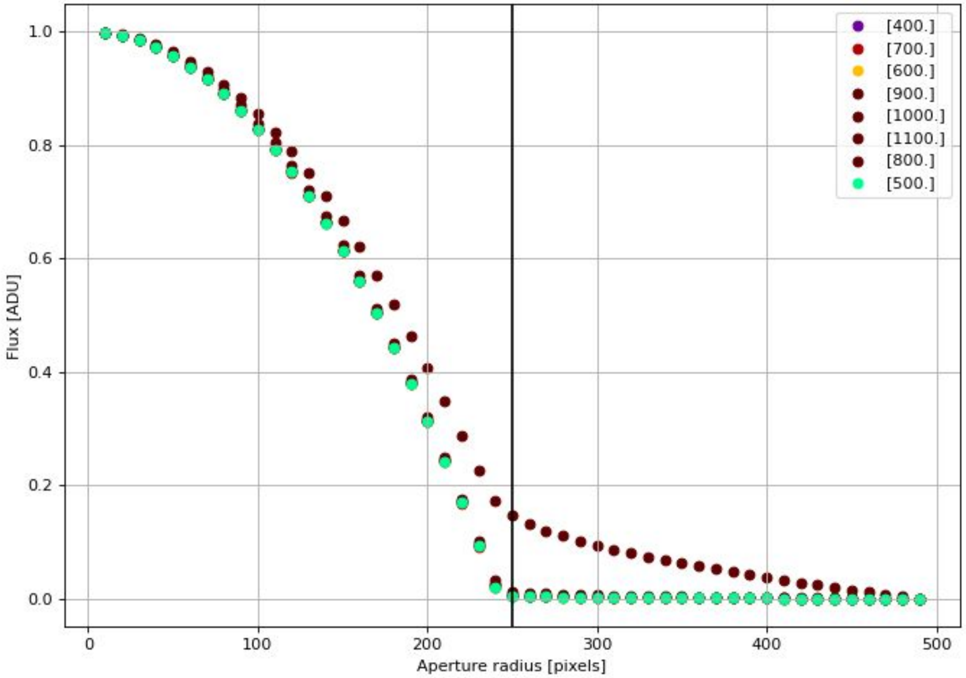
Intercalibration 5mm/75µm : goals

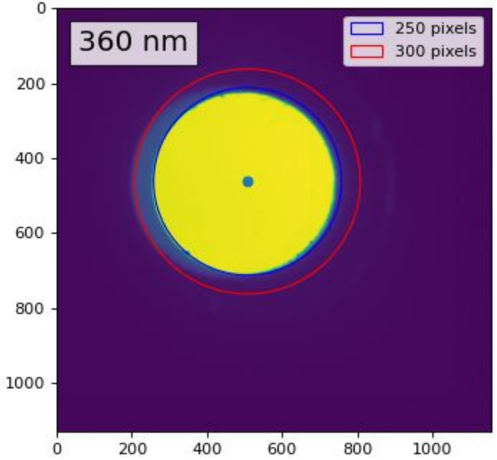
The pinholes are not the same when we shoot in the Solar Cell (5mm) or in the StarDice telescope (75µm)

- See if the ratio between the 5mm and 75µm pinhole is flat or not
- Understand the ghost contribution in the 5mm case
- Correct the ghost contribution thanks to the analysis with the 75µm



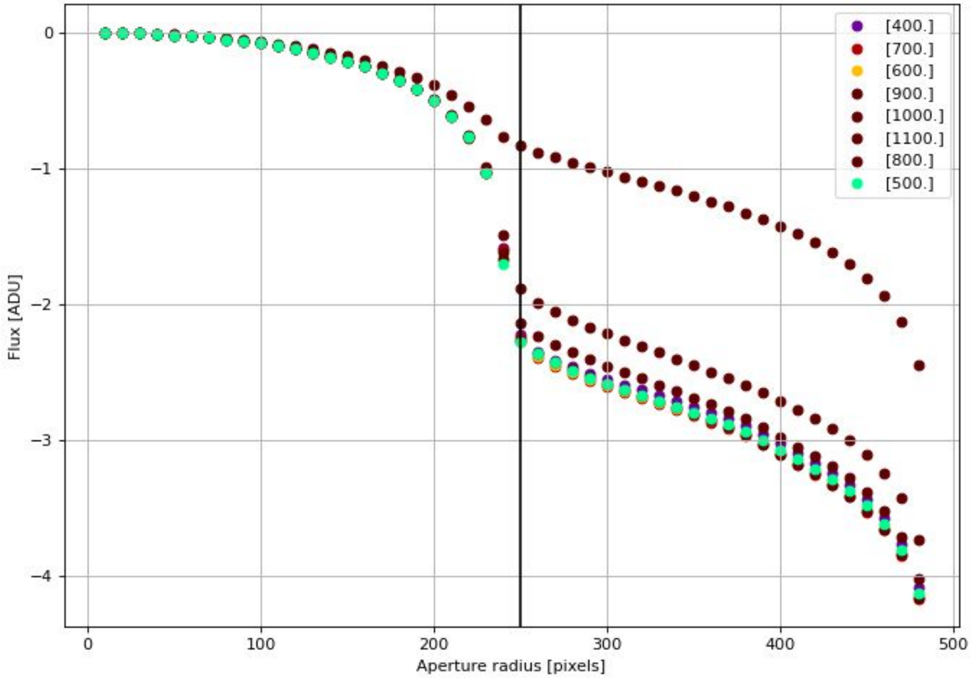
Growth curve

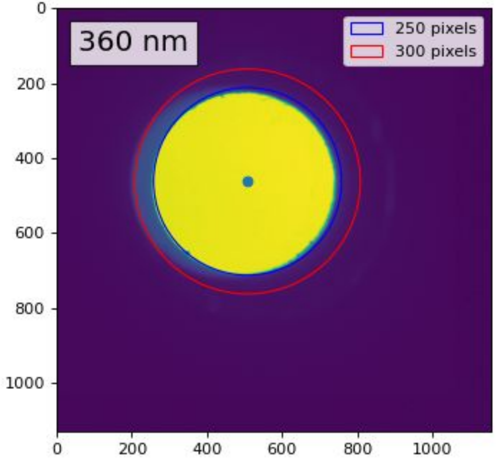




Why this growth after 250 pixels radius even when there is nearly no ghost ?

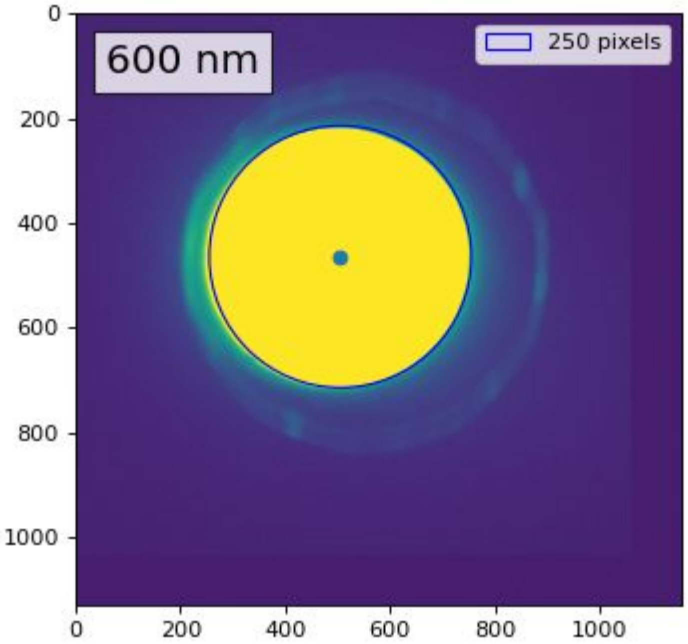
Growth curve : log scale





Why this growth after 250 pixels radius even when there is nearly no ghost ?

Growth curve : beyond 250 pixels radius



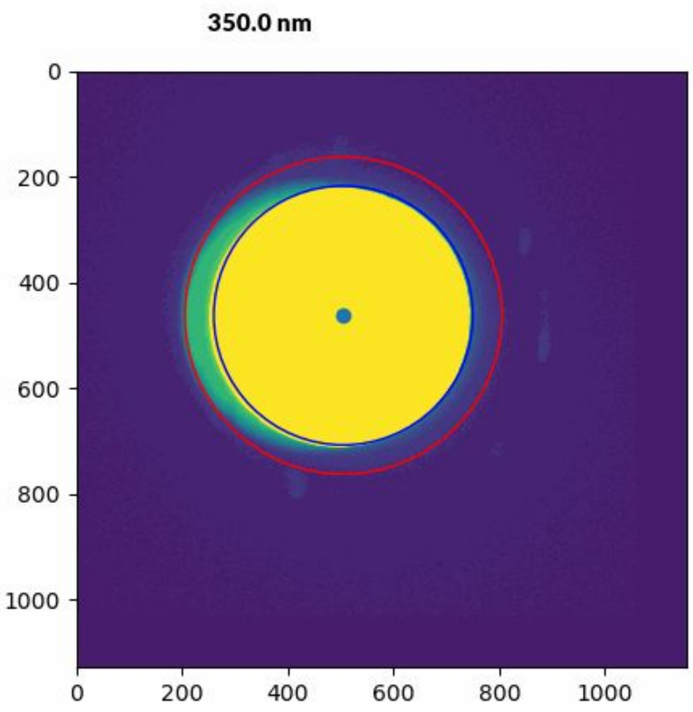
Same image but in logarithm and with a vmax value to see the contrast

3 visible elements :

- The border of the pinhole are faint
- The diffusion over the diaphragm
- The ghost in the left

⇒ Present at all wavelengths, so why is it higher in IR ?

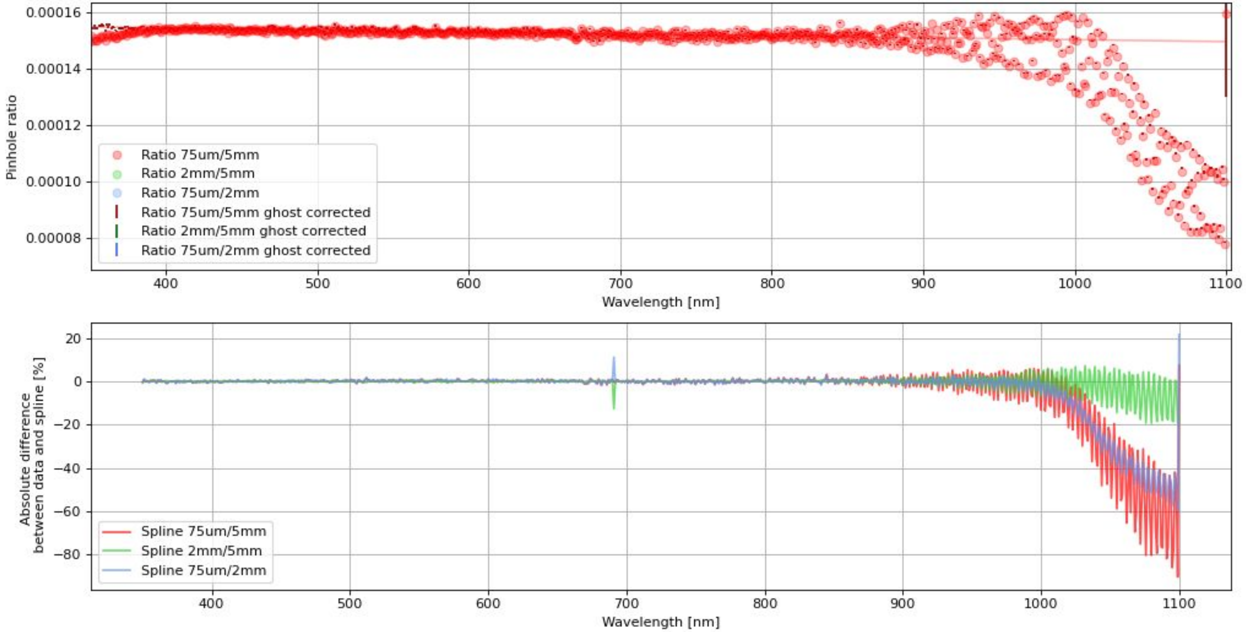
Growth curve : evolution of the 5mm hole



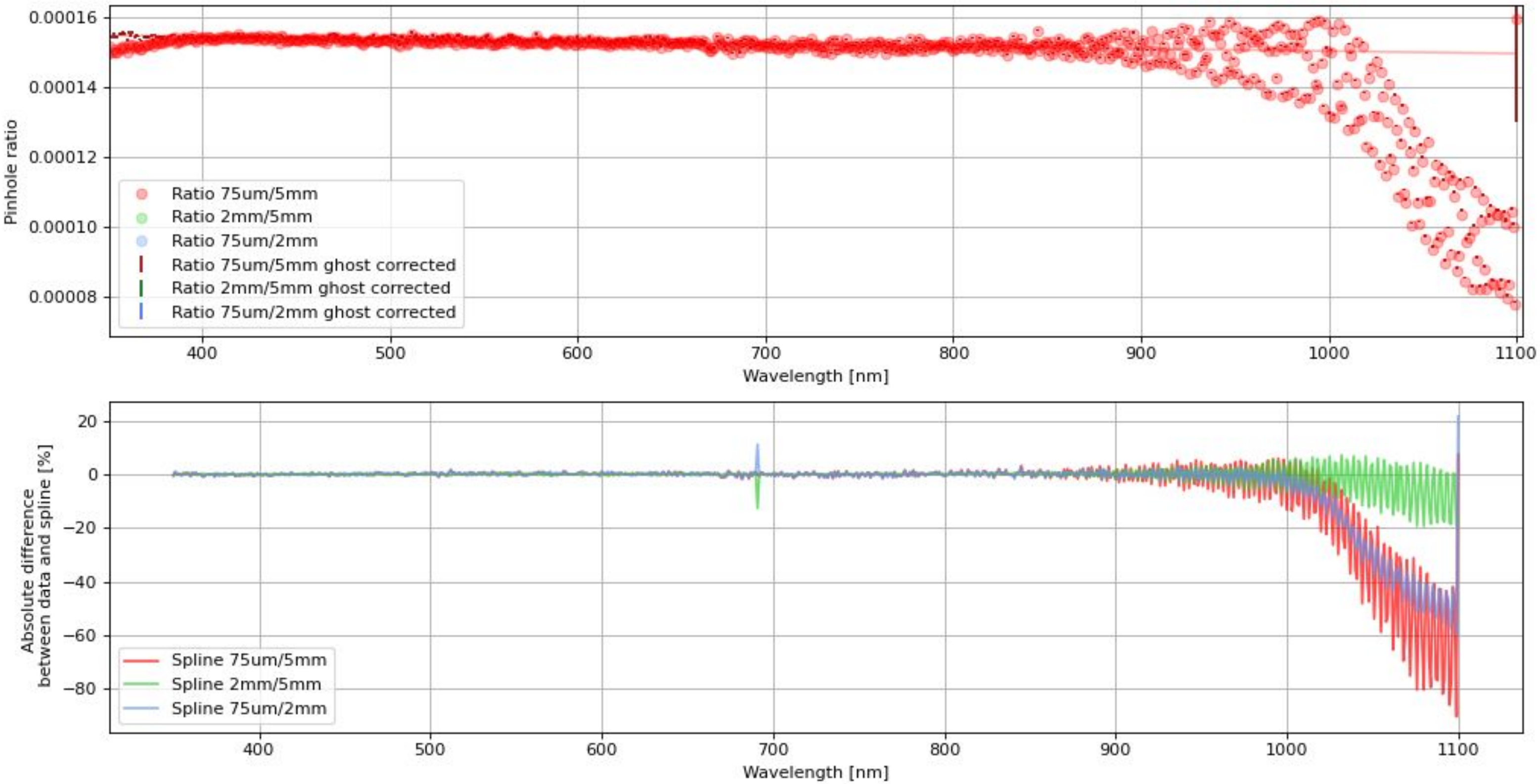
Ratio 75µm/5mm

Ratio 75µm/5mm decrease in the IR, it can be either :

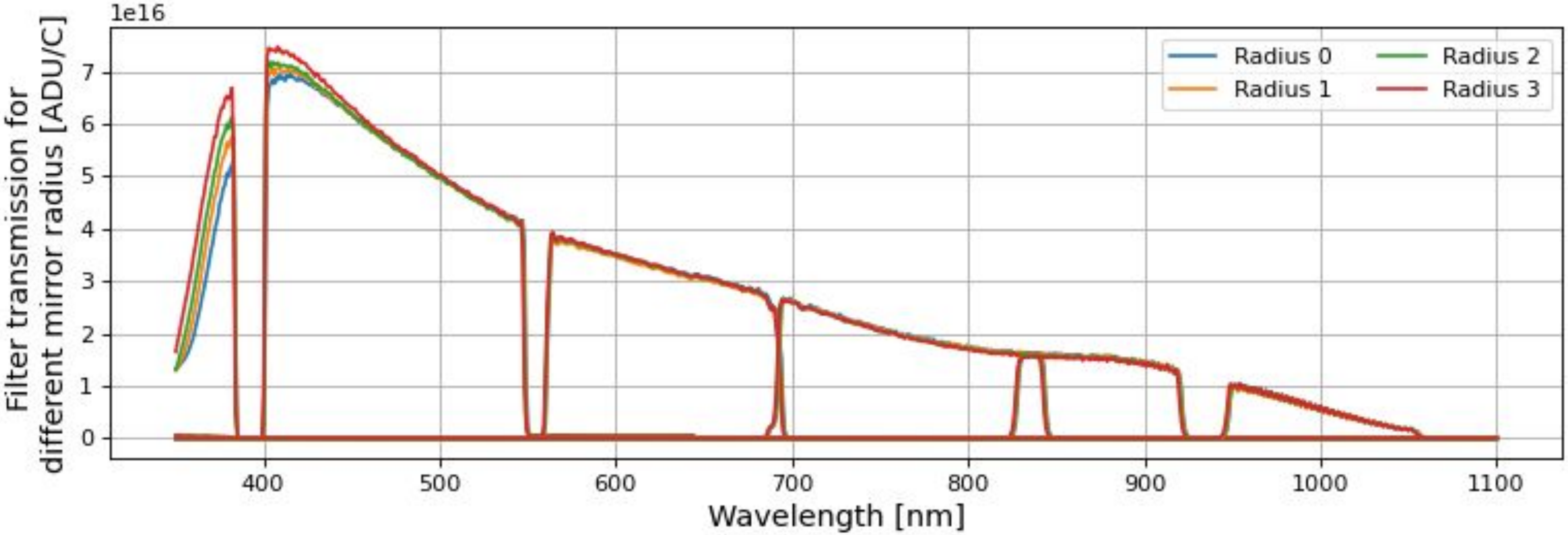
- 75µm decreases → not what we observe
- 5mm increases → what we observe



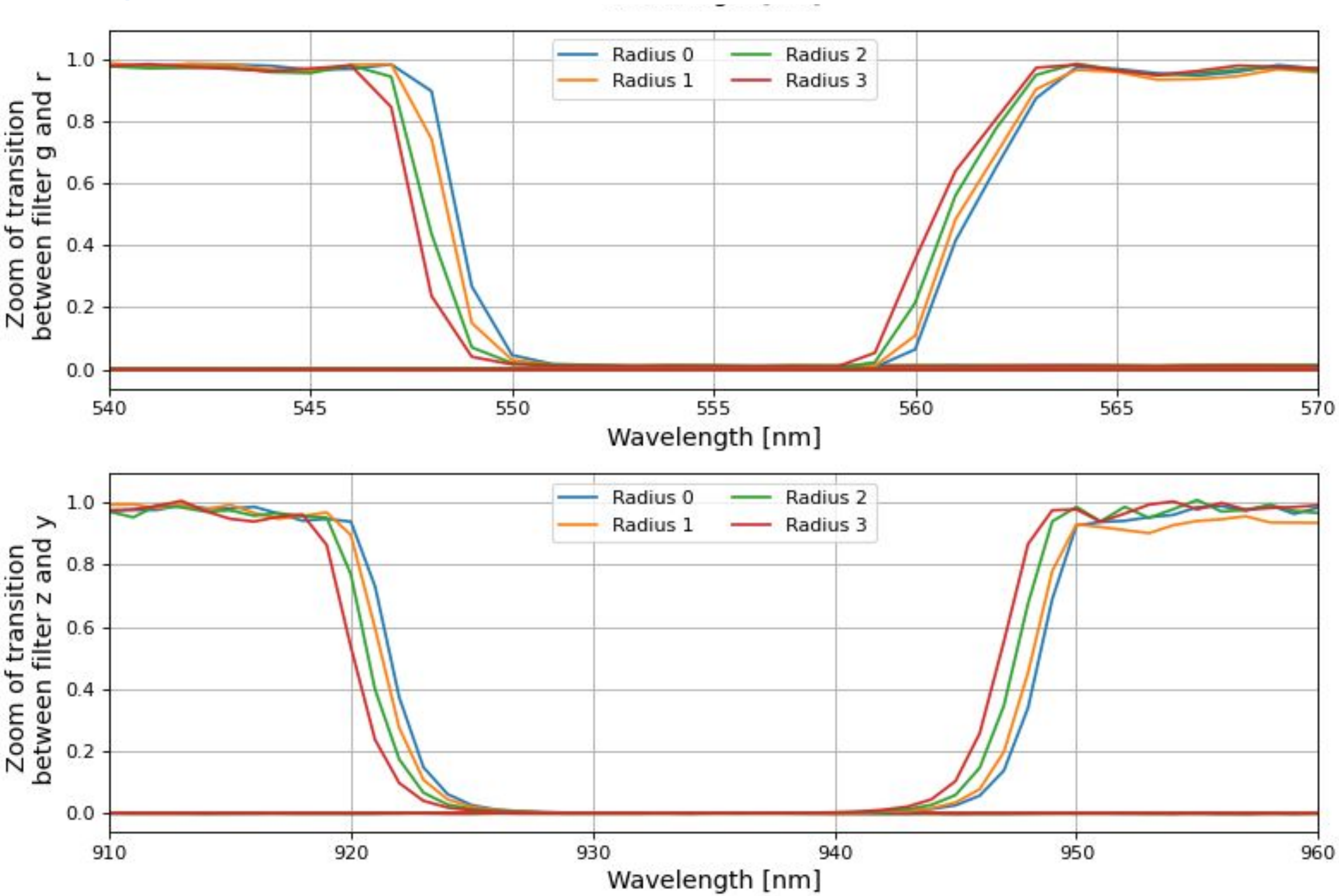
Ratio 75µm/5mm



Radius


1e16
Filter transmission for different mirror radius [ADU/C]
0
1
2
3
4
5
6
7
400
500
600
700
800
900
1000
1100
Wavelength [nm]
Radius 0
Radius 1
Radius 2
Radius 3

Filter edges



Rubin CBP masks

Numbers to have in mind:

- CBP focal length is 625mm, primary mirror diameter is 330mm
- LSST + CBP magnification factor is 16 (LSST focal is 8.4m x 1.2 = 10.1m):
  - 100um on mask = 1600um on LSSTCam = 160 pixels = ~⅓ amplifier
  - max size to have a spot that fit an amplifier + annulus to estimate dark is 150um
- mask holder inner part is 25.4mm wide
  - LSST full focal plane projected on mask is 600mm/16 = 38mm
- N_CCD = 189, N_amplifiers = 8 N_CCD = 1512 => constellation of N_pinholes = 1512 stars
- Effective pinhole diameter : D_eff = sqrt(N_pinholes) D_{1 pinhole}
  - 1 star per amplifier : D_eff = sqrt(1512)x150um = 5.8mm
  - 1 star per CCD : D_eff = sqrt(189)x150um = 2.1mm