StarDICE : Concept test results and perspectives

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LSST/DESC calibration workshop
LPNHE, July 2019

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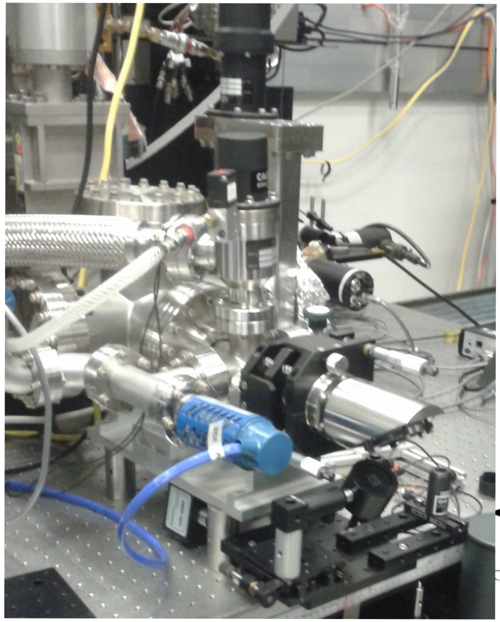
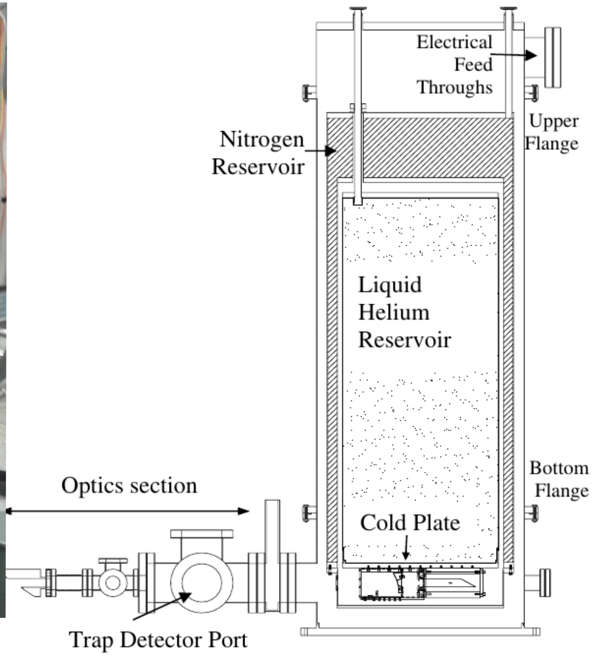
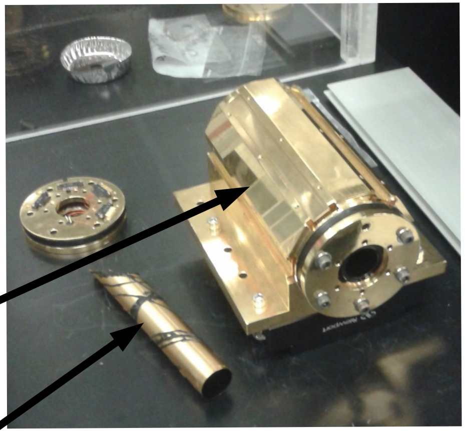
OHP : Pierre-Eric Blanc, Auguste Le Van Suu

The alternative standard

POWR: the Primary Optical Watt Radiometer (Brown et al. 2006, Houston et al. 2006) high-accuracy electrical substitution cryogenic radiometer

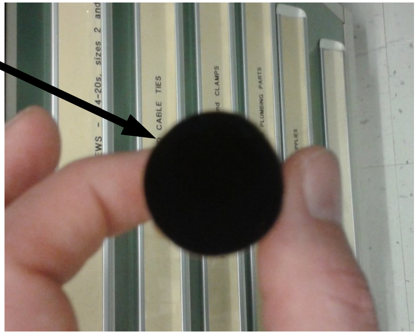




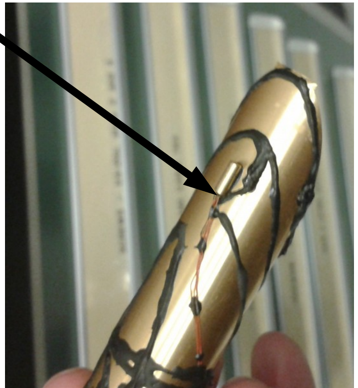


Cryogenic shelter

Black absorbing cavity

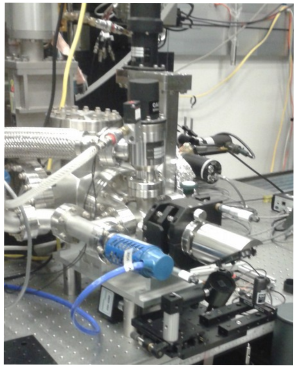


Germanium resistance thermometer



Claimed accuracy at the 10^{-4} level

Linking instrumental and Stellar calibration



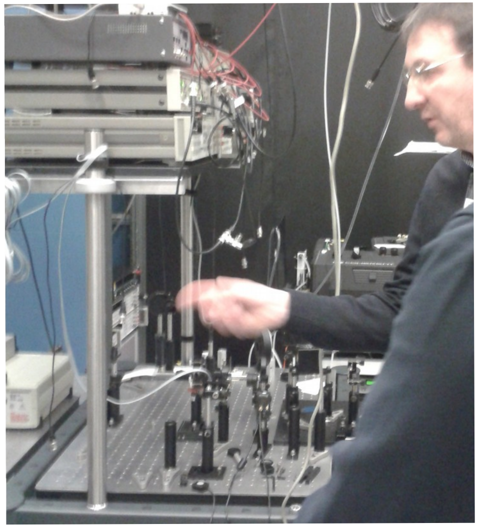
NIST POWR

10^{-3}W

NIST SCF

10^{-6}W

NIST calibrated Photodiodes

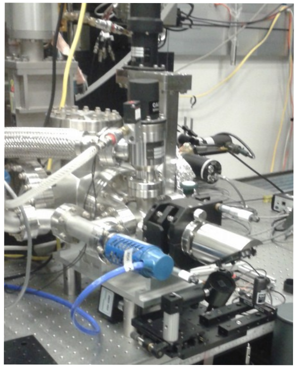


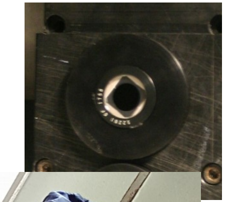
A bridge between 13 order of magnitudes is needed

10^{-19}W/cm^2/nm
(1γ/s/cm^2/nm)

Mag 13 Spectrophotometric standard stars

The last arch of the bridge known : Telescope + CCD

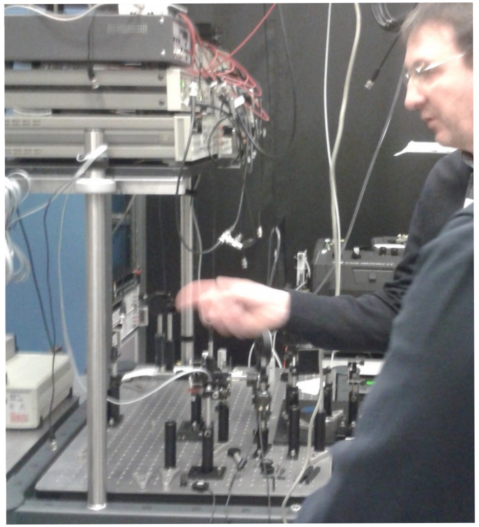




NIST POWR

10^{-3}W

NIST SCF



10^{-6}W

NIST calibrated Photodiodes

Integrating over 500cm^2 and 100nm gives ~10^5γ/s
Integration time can be varied but practical bounds:

- Mechanical repeatability: > 1s
- Airmass follow-up: < 100s

Telescope + CCD

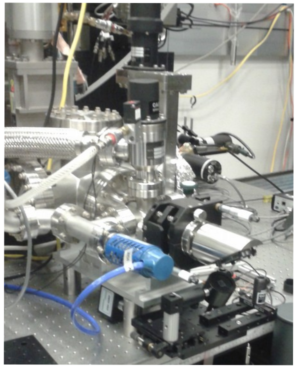
10^{-19}W/cm^2/nm
(1γ/s/cm^2/nm)

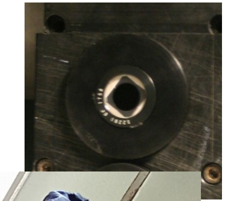
Mag 13 Spectrophotometric standard stars

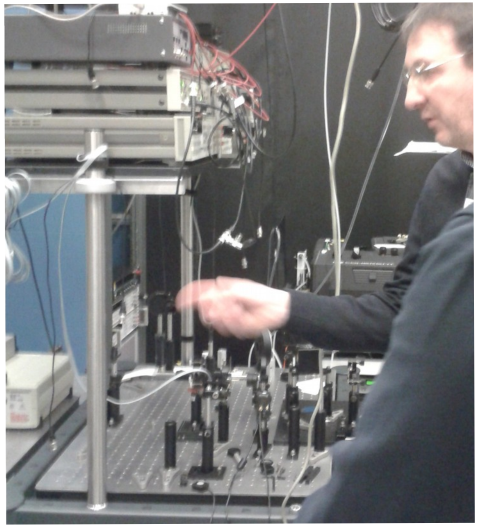
Measuring the transmission of the optical gain is tricky

- Because it depends on the beam shape. The PSF receives chromatic contributions from
  - Pupil diffraction
  - Scattering by surface defects
  - Reflections
- In principle, everything gets mixed up in flatfield illumination, so that you measure the total light in each pixel.
- This is not accessible on stars, where what you get depends on the photometry method but is always a (chromatic) fraction of the total.

The last arch of the bridge known : Telescope + CCD







NIST POWR

10^{-3}W

NIST SCF

10^{-6}W

NIST calibrated Photodiodes

A point source delivering at most 10^{-17} W/cm²/nm is required if you accept 10^2 differences in exposure time but no other differences in the beam

Telescope + CCD

10^{-19}W/cm²/nm
(1γ/s/cm²/nm)

Mag 13 Spectrophotometric standard stars

Only two ways to get a standard source that faint

1

Make one

2

Use a random brigther source

That you can monitor with a stable detector

And dim it in a stable way
(By stable I mean at least chromatically stable)

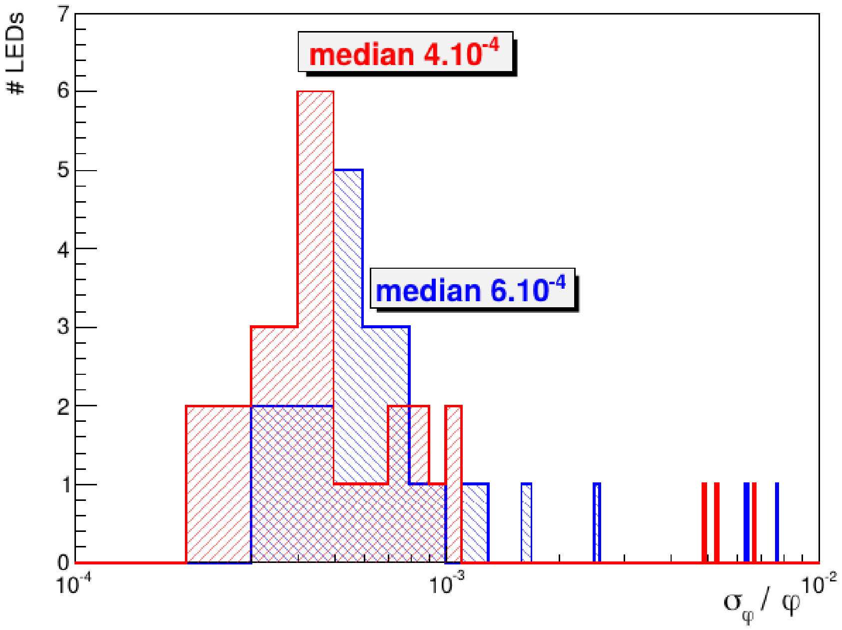
Due to the availability of stable quantum detectors, route 2 is followed by most experiments

StarDICE has been experimenting route 1

The idea of using narrow spectrum LEDs comes from SnDICE results

- LEDs are the emitting equivalent of silicon detectors

Stability of 24 LEDs measured over 30 days



In Regnault et al. 2015, 24 narrow spectrum LEDs to cover 300-1000nm were tested with 2 standardization technique

- Temperature monitoring (in blue)
- Control photodiode (in red)

Temperature monitoring performs nearly as well as photodiode standardization and meets the 10^{-3} goal.

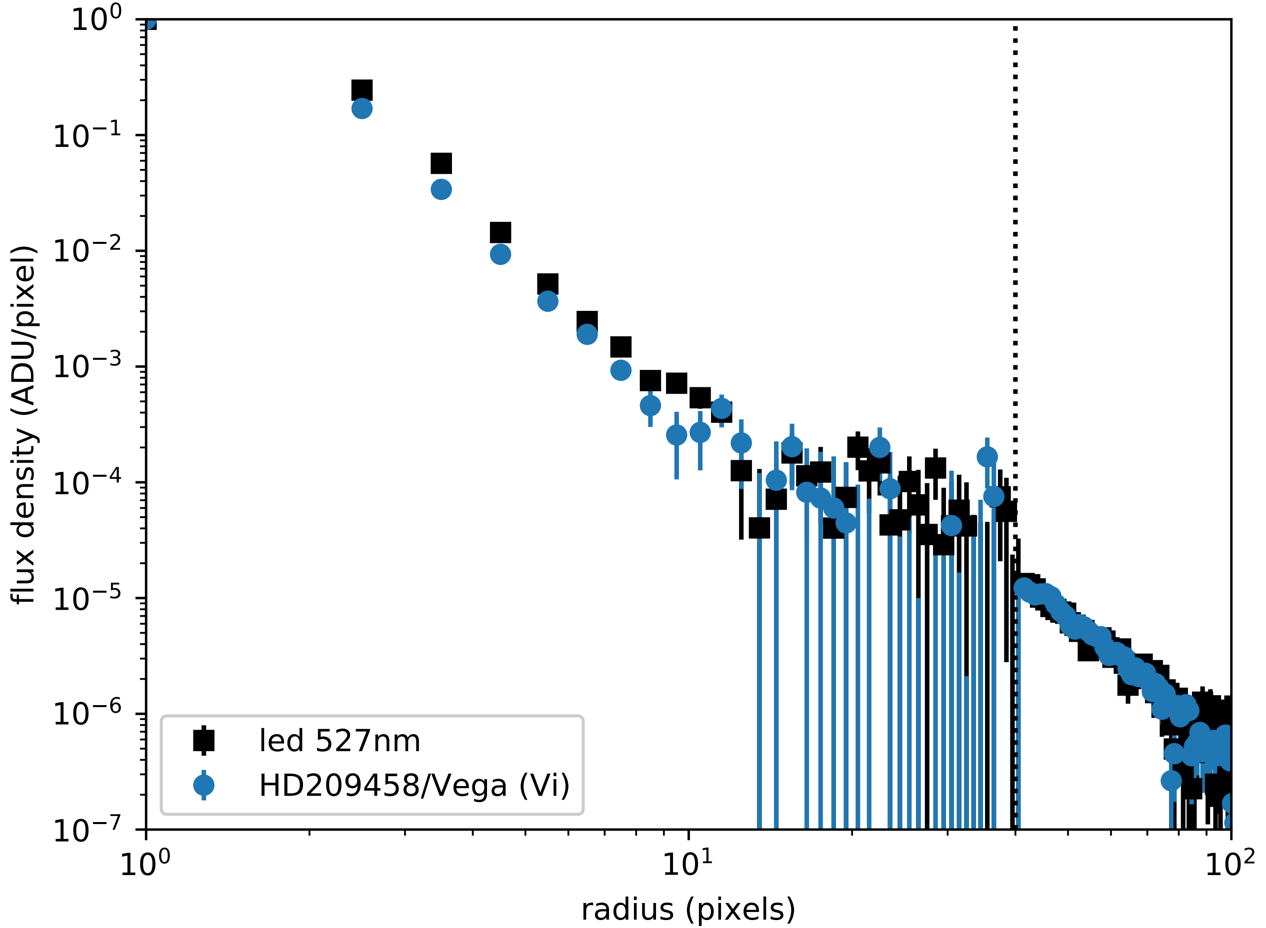
StarDICE is 3 things

1) Stable (stabilized) point source delivering 100γ/s/msr
2) Ability to calibrate a light source this faint
3) Ability to transfer this calibration across the atmosphere

Outline of the talk:

- PSF and aperture systematics
- Integrated flux measurements and stability
- Hardware developments for spectra and beam maps measurements
- Atmospheric transfer

Star and LED flux density profile

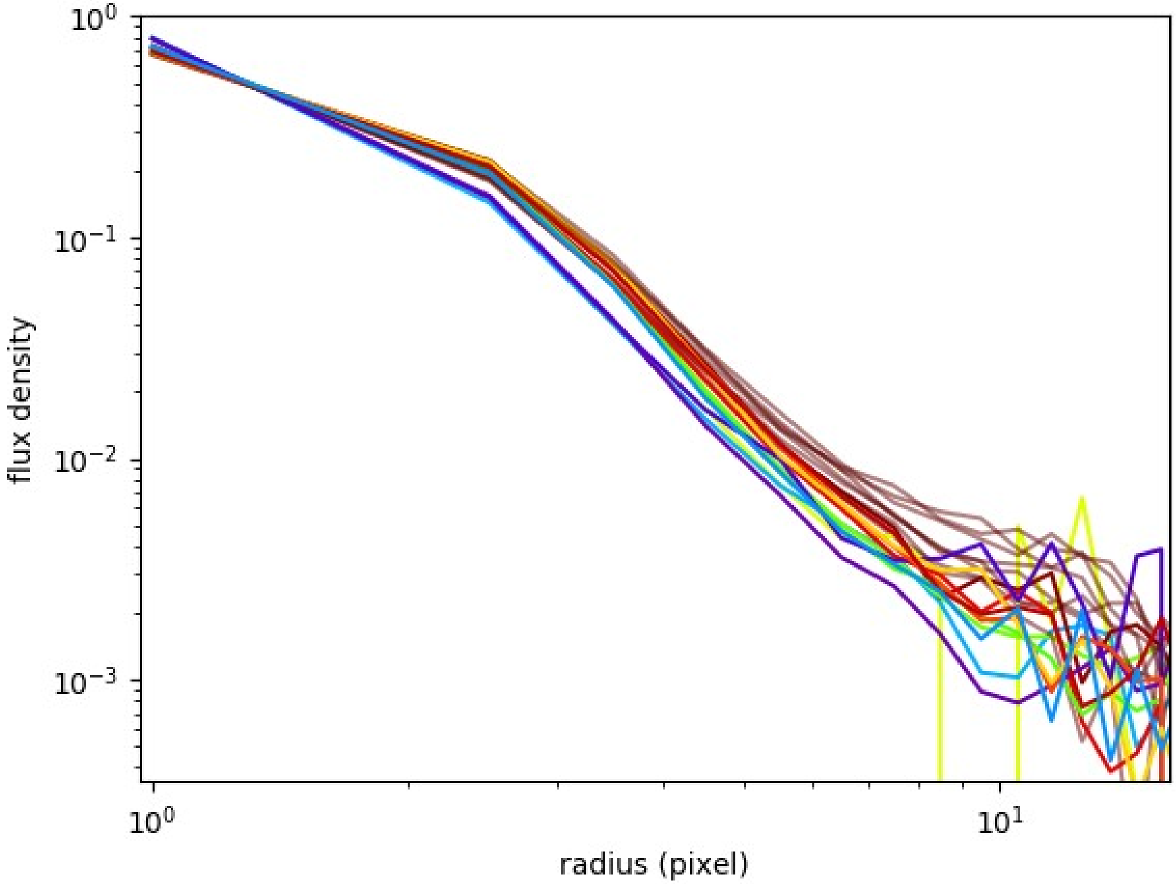


Composite flux profile reconstruction

- First part (r<40) obtained on a stack of 10 unsaturated images
- Second part (r>40) obtained on a stack of saturated images (normalized so that the flux in the 40-50 annulus matches the unsaturated measurement)

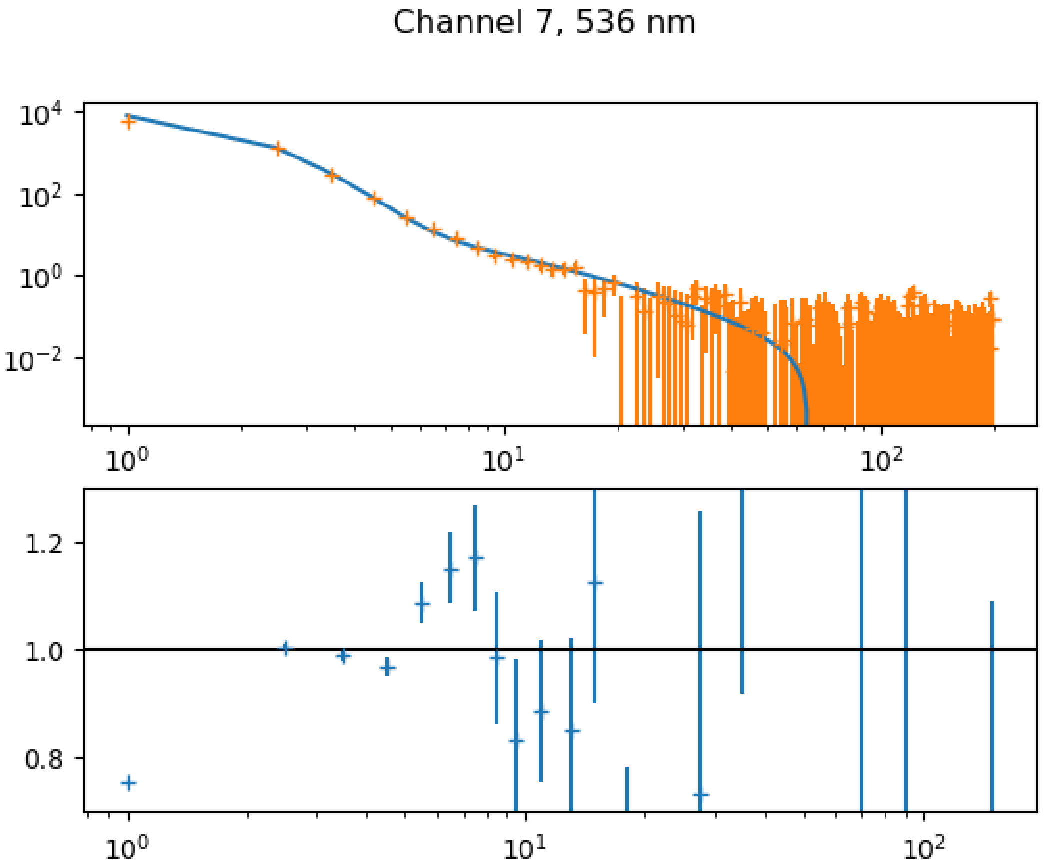
- Tails are similar
- And steep with a power law index of -4. If one extrapolates the slope, only 0.5% of the total flux is missing from this plot

PSF chromaticity ?



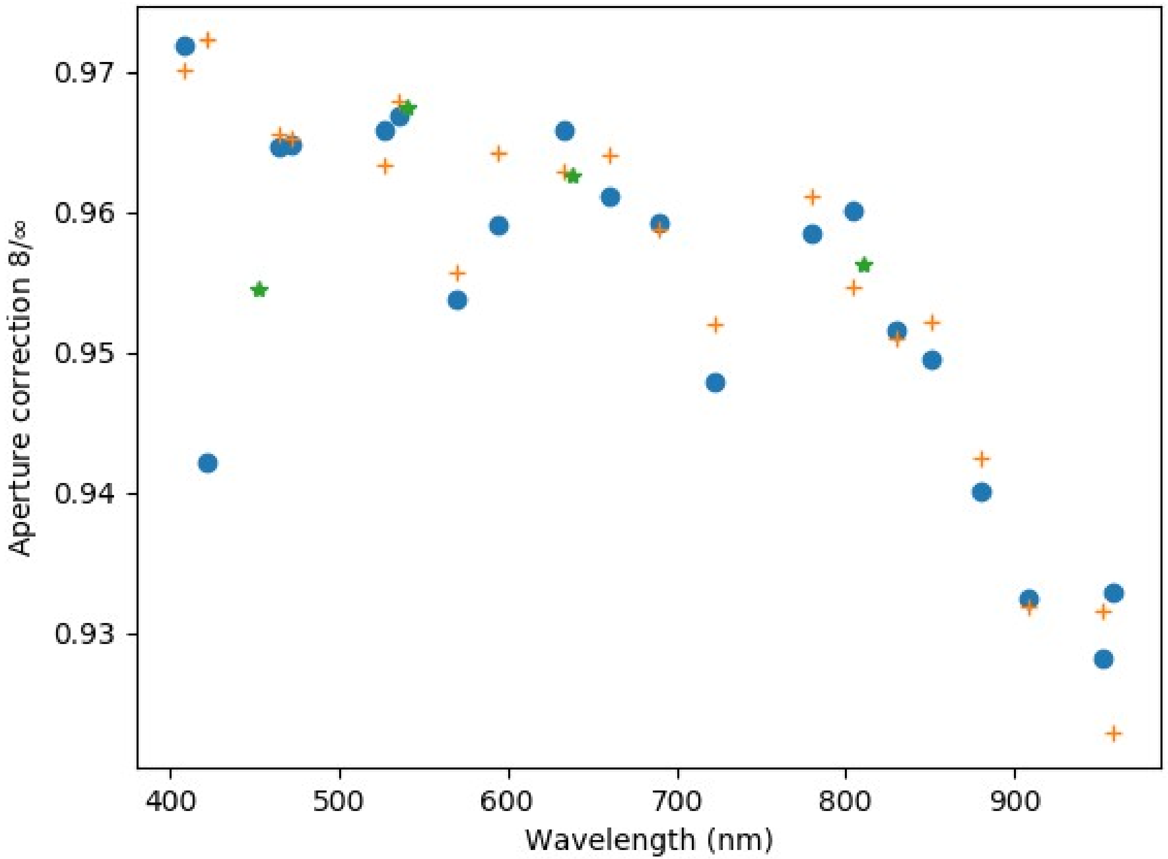
- We integrate star and LED fluxes within 8 pixels
- Profiles looks ordered by wavelengths
- Regular data do not tell much about aperture corrections, background subtraction especially problematic for stars.
- Going further requires modeling
- And specific data

Attempt to model the flux profile



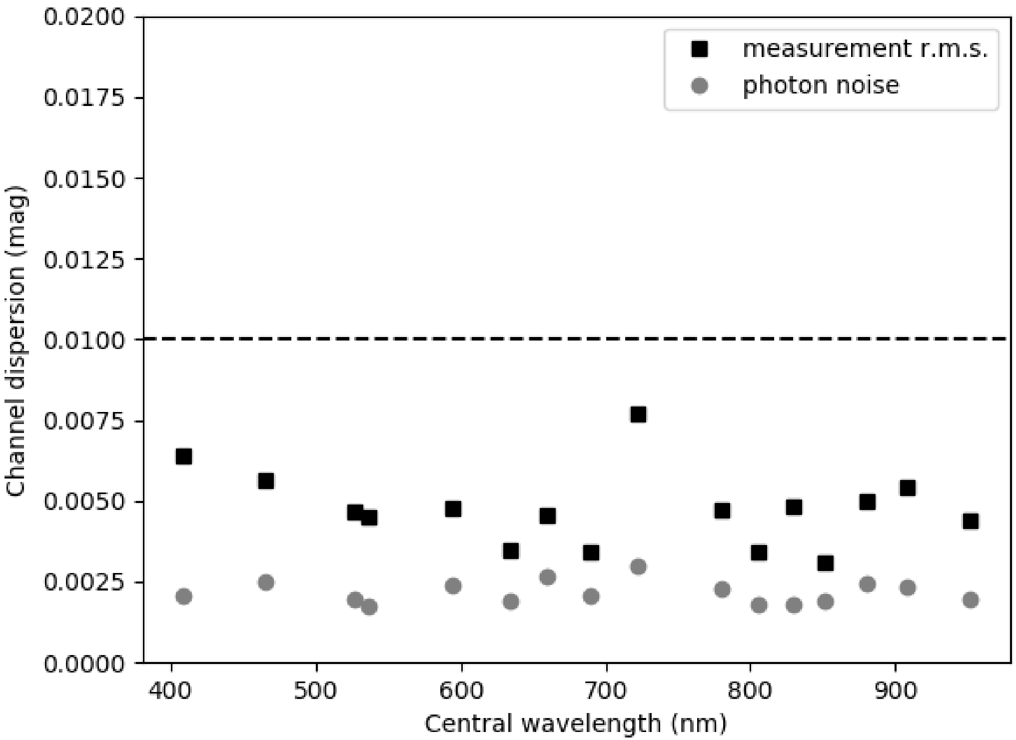
- Profile more or less adequately defined as moffat+aureole+bckg residual
- Fitted to the standard data
- A dedicated dataset is required
- Still the exercise seems to tell something on aperture corrections

Predicted aperture corrections from the fit flux profile model



- For stars in each filters (green stars)
- For each LEDs (blue and orange corresponds to 2 different datasets)
- Consistent picture for star and LEDs so far
- Hints for chromatic effects at the few percent level
- Care obviously required to reach the mmag

Relative stability over 3 monthes on site



Which one is responsible for the extra-scatter ?
Does it average out ?

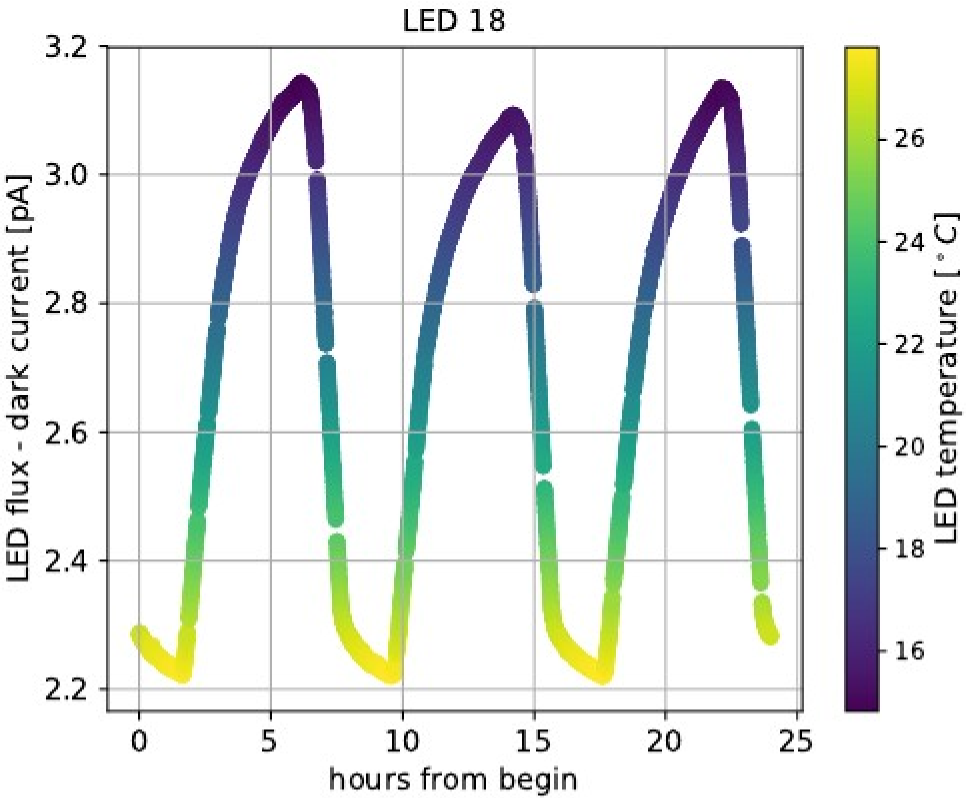
Measured flux / predicted LED flux gives an absolute zero point per channel

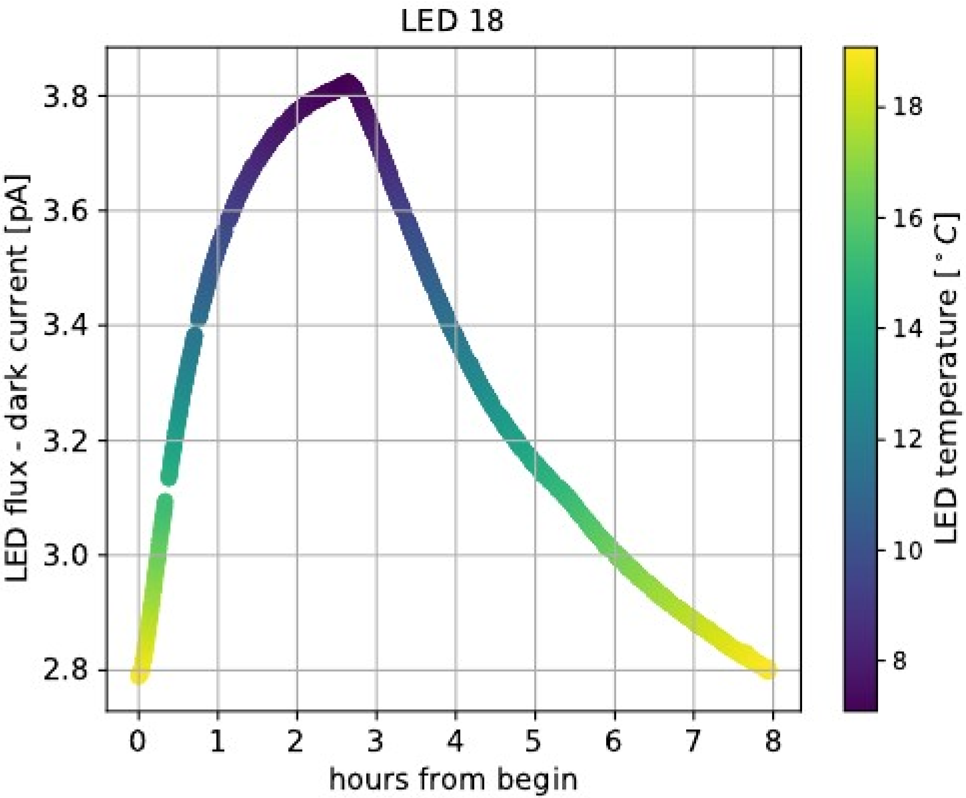
RMS of zero point measurement by LED channel after:
- standardization by temperature
- fit of a global instrument zero point per night

Mean dispersion is 4.8 mmag
Best channel ~ 2.8mmag

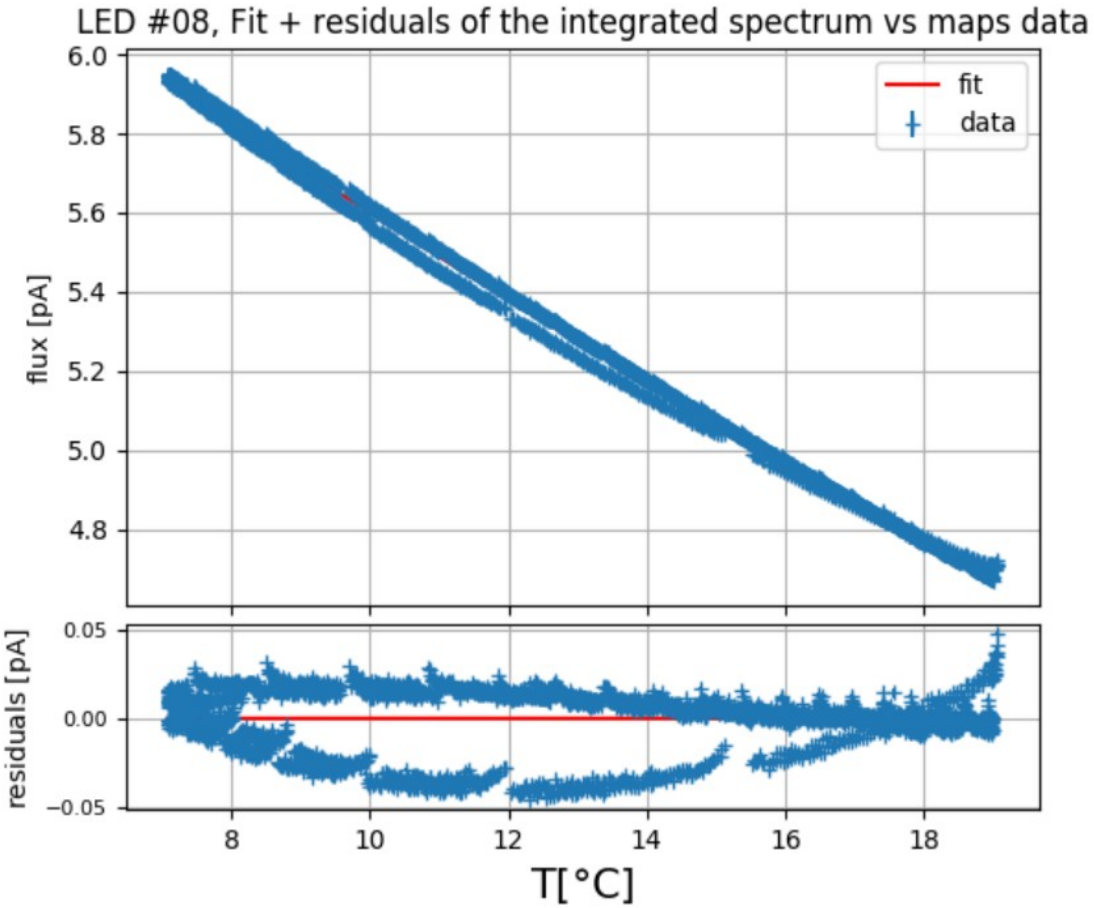
This encompass everything:
- Measurement noise
- Potential variations of the instrument
- Line of sight transparency variations
- relative led variations

Measurement of integrated fluxes as a function of temperature



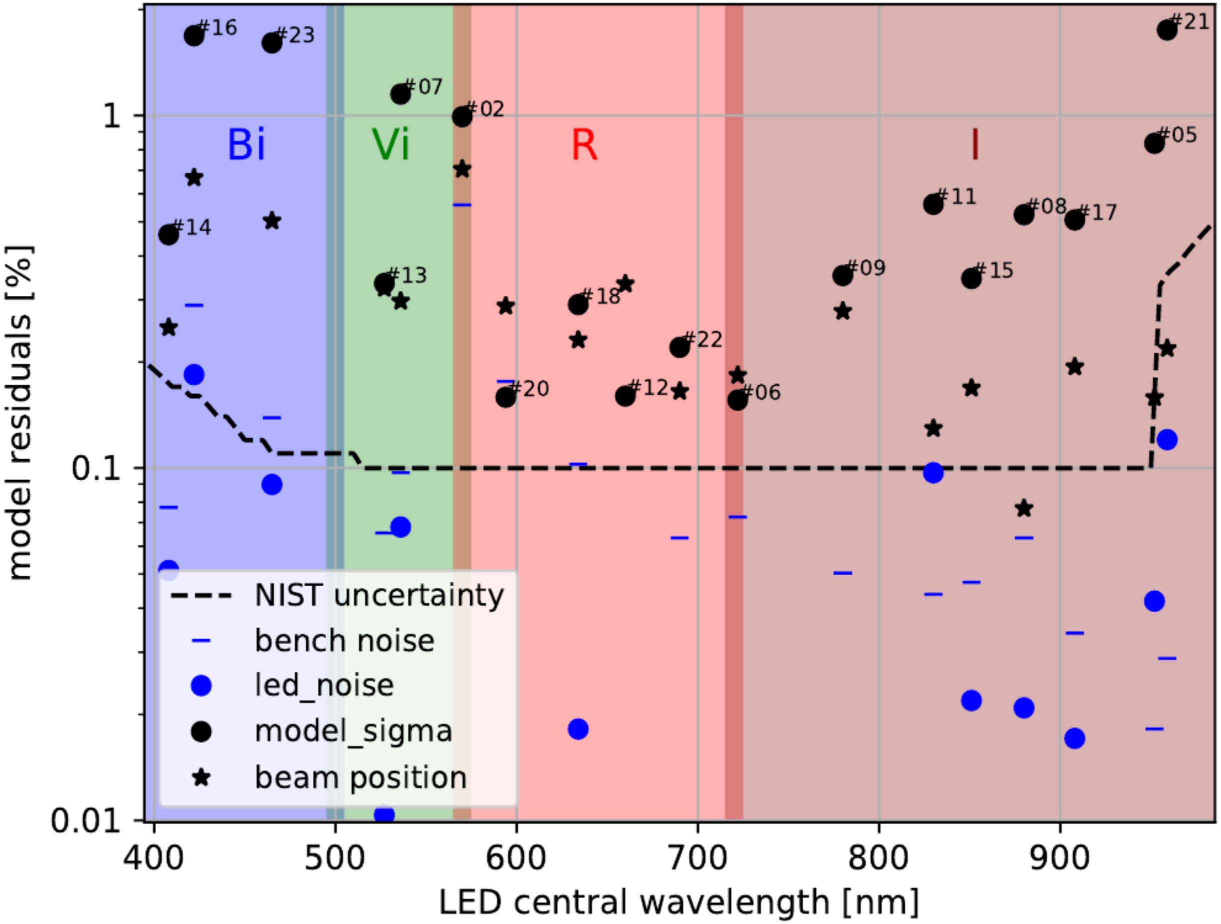


Model of the flux-temperature relation



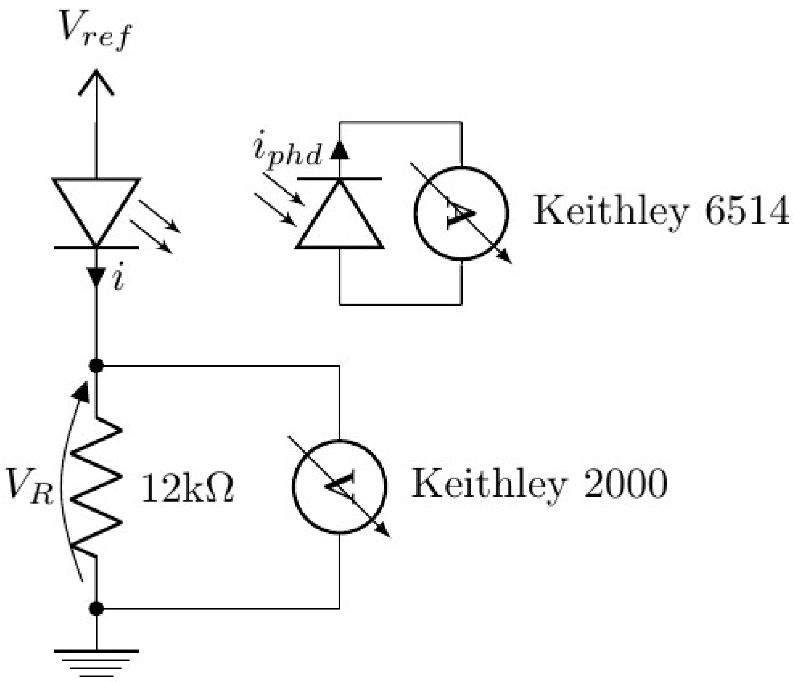
- Bench noise always subdominant (<0.1%)
- 2 kind of model residuals:
  - Short transitory at turn on
  - Hysteresis figure
- Lag between junction temperature and proxy temperature expected
- However, attempts to build a thermal model describing all LEDs behavior were not successful at this stage

Summary of bench measurements



- Bench noise is the rms of dark measurement (<0.1% in general)
- Led noise is the extra high frequency scatter that is observed when the LED is turned on. Hardly significative in most case and lower than (<0.1%) in all cases.
- Model sigma is the rms of the structured residual to the temperature law. DOMINANT TERM in all case. >0.1% in all cases, >1% at some frequencies.
- Last systematic comes from the non-homogeneity of the beam in a 1 degree solid angle. Can be canceled with more precise alignment.

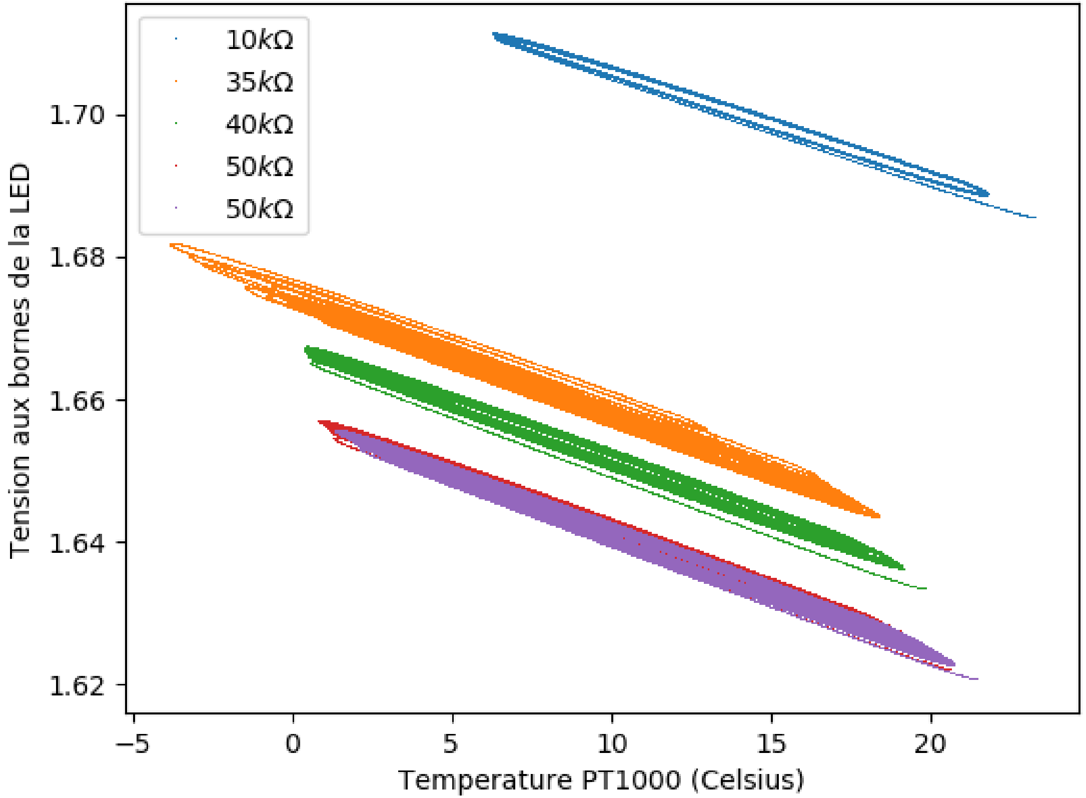
Is there a better way to standardize LEDs



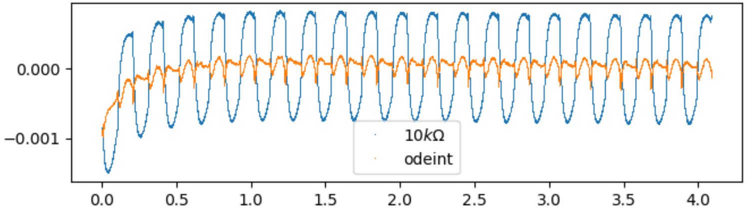
- Use the junction forward voltage as a direct probe of the junction temperature
- Imposing Vref (instead of i) links i, Vf, Vr and T altogether.
- Only a single independent variable left
- Measuring Vr is easy

- Éduardo made a prototype with a LED glued on top of a PT1000, itself glued to a peletier module

Forward voltage vs proxy temperature

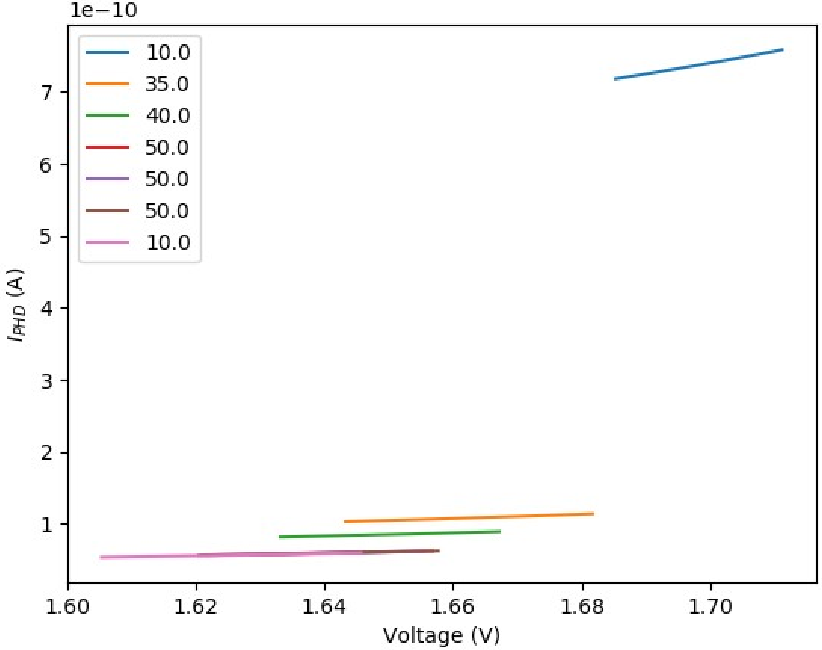


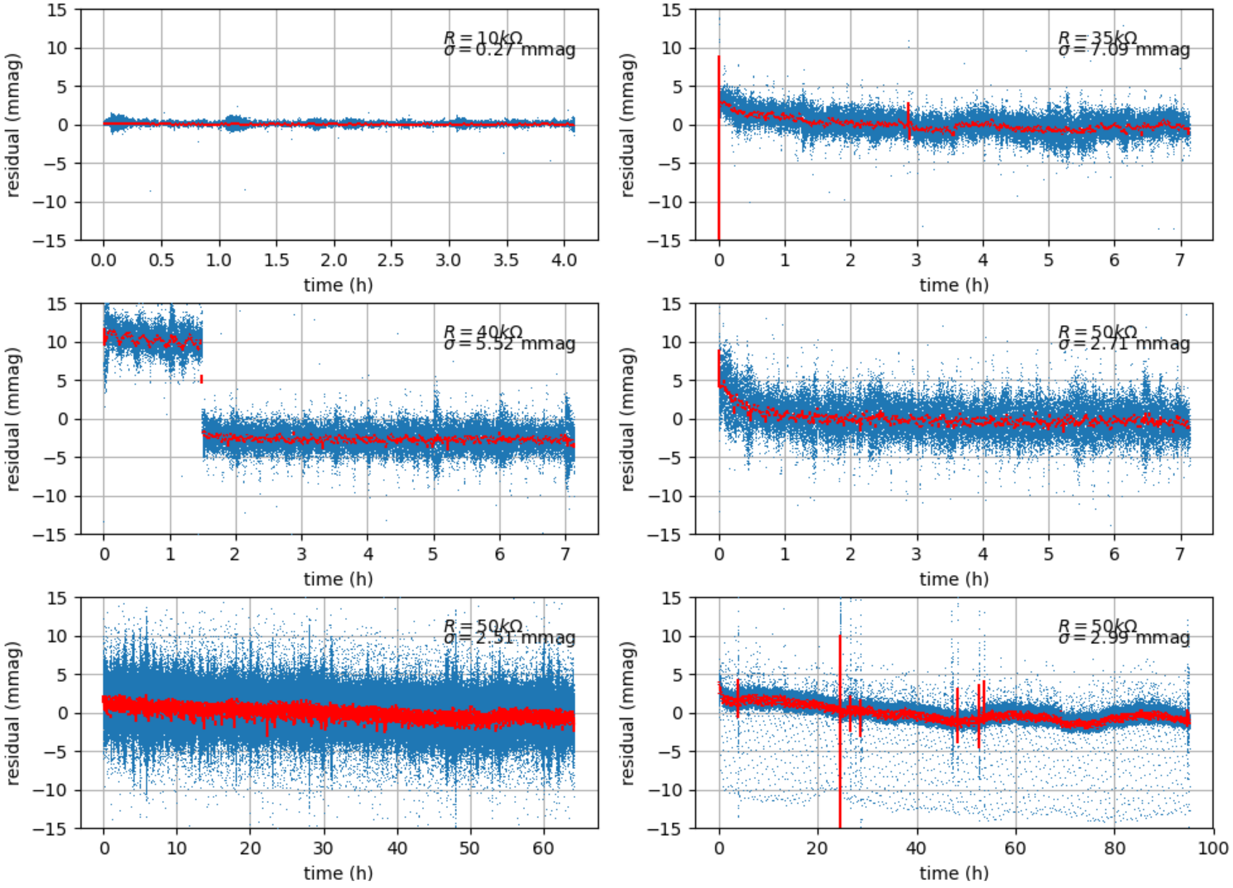
- The temperature is varied as fast as 20 degrees in 6 minutes.
- Clear lag between proxy temperature and forward voltage
- Simple thermal model explains most of it, but details are hard to get



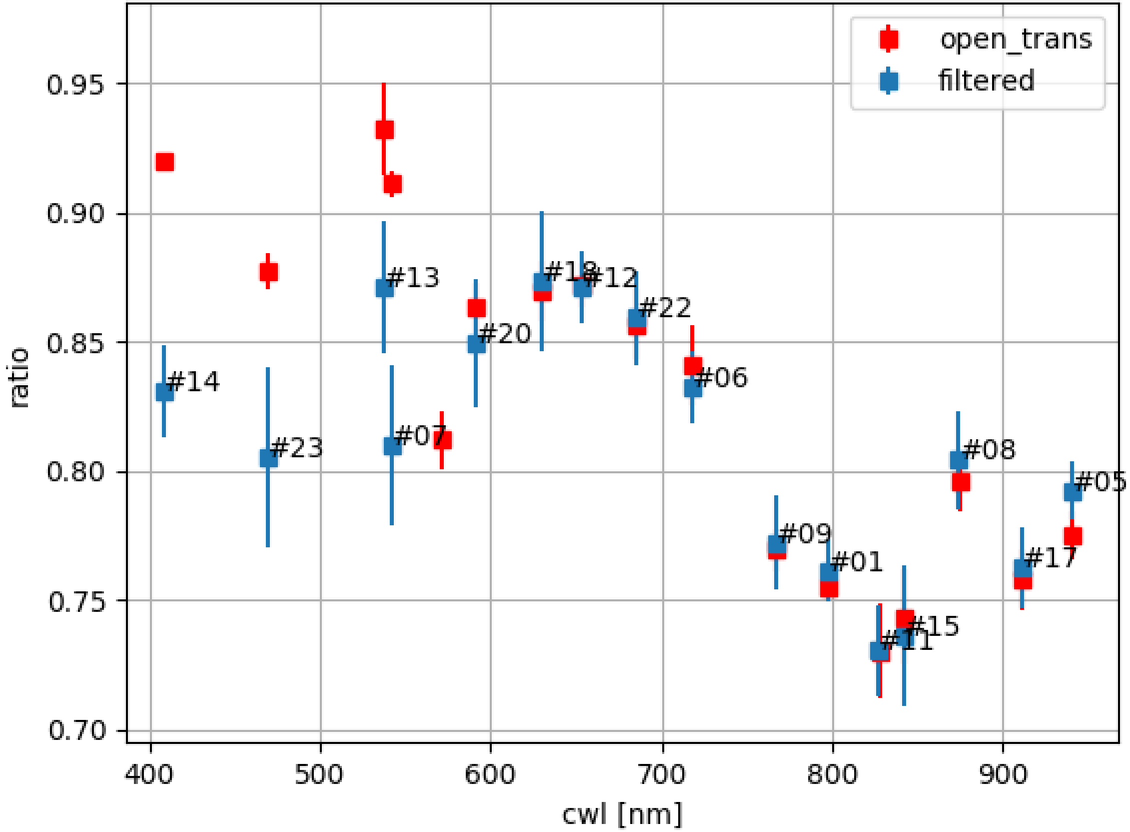
Standardization from voltage instead of proxy temperature

10^{-4} reached for 10kΩ





What does the instrument transmission look like ?



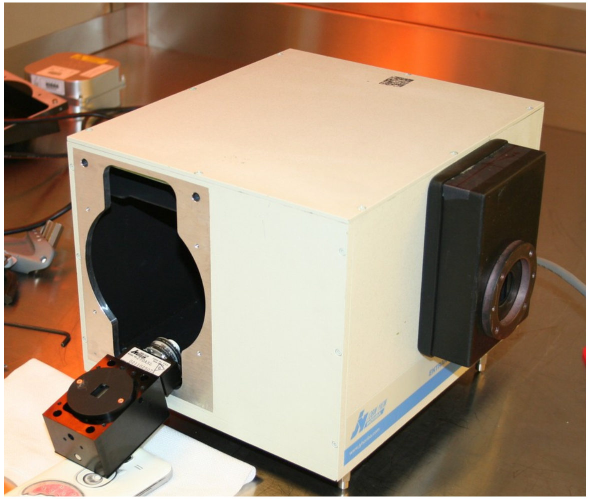
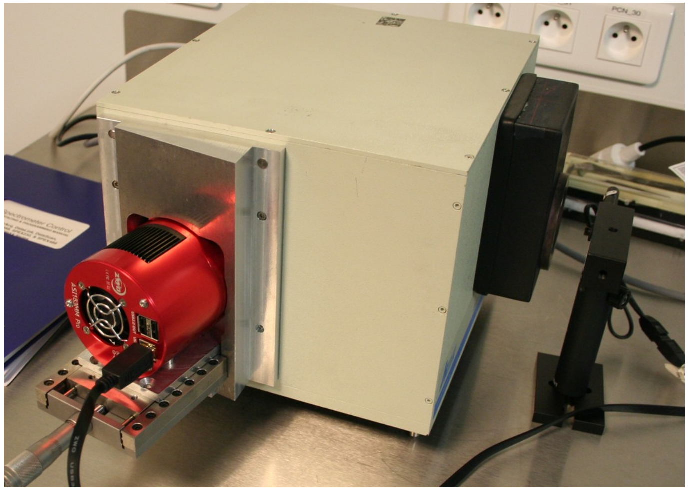
Required metrology developments

- Integrated flux measurement OK
- But spectra and beam maps require a move toward charge collecting devices with low dark current (either CMOS or CCDs)

2 Hardware developments

- A (adjustable) small wavelength range spectrograph to monitor LED flux during temperature changes
- A calibration transfer bench to transfer photodiode calibration to pixel detectors

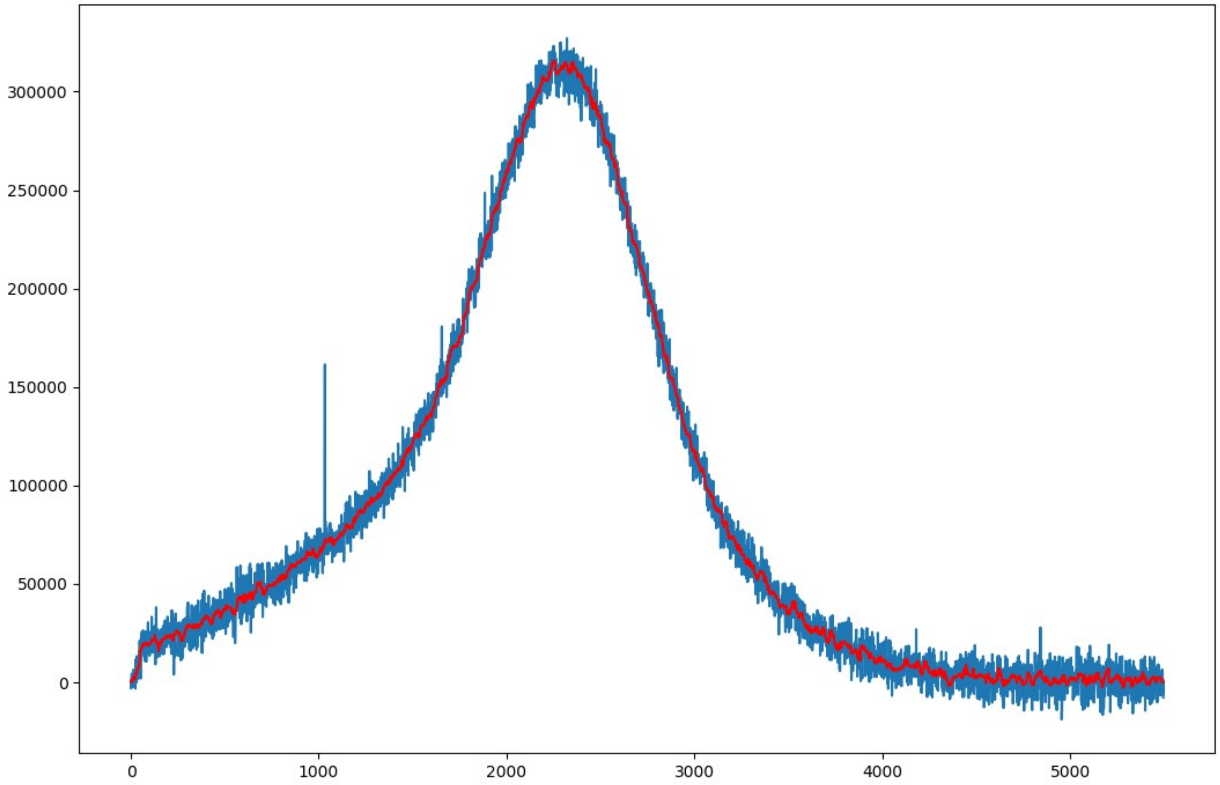
Turning a Czerny-Turner monochromator into a spectrograph

- Replacing the exit slit with a cooled CMOS camera covering an adjustable 50nm wavelength range

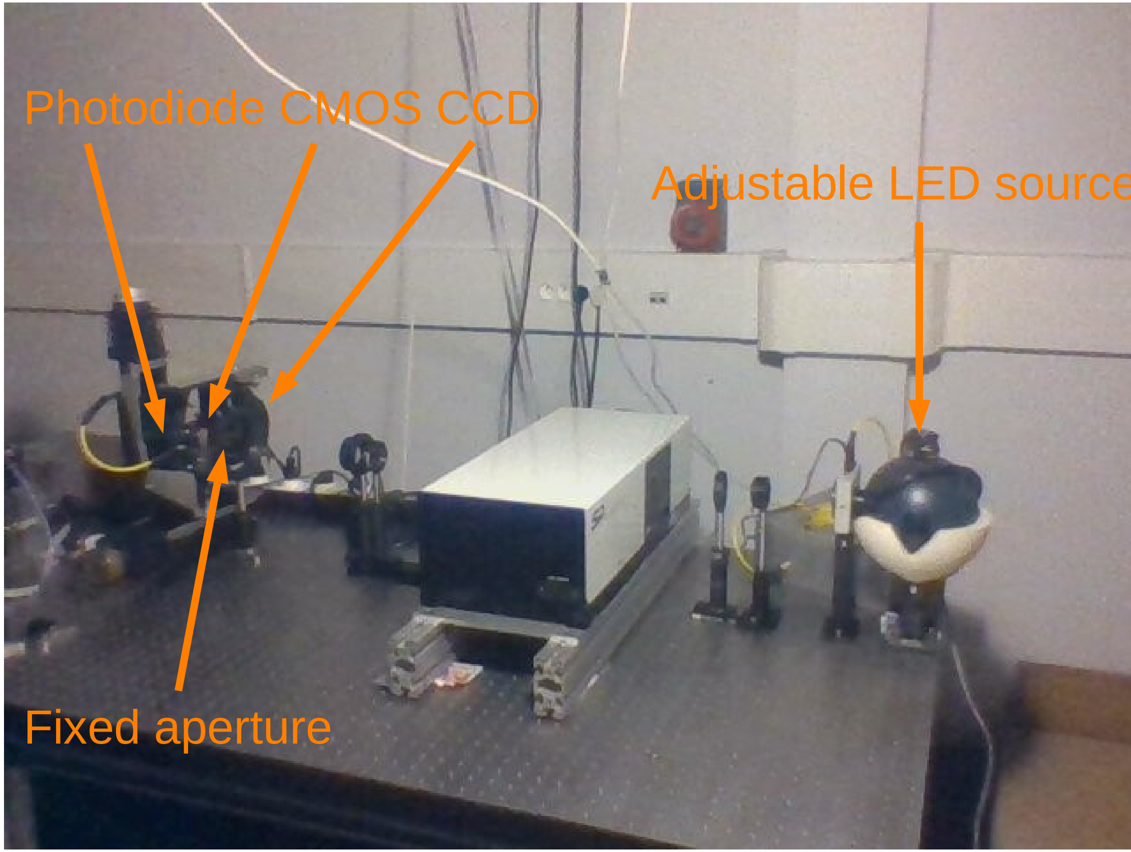
High resolution LED spectrum in 150s

- Bleue spectrum resolution: 0.01nm
- Red resolution: 0.2nm
- Forward model for calibrated spectrum extraction being written by Laurent and Nicolas

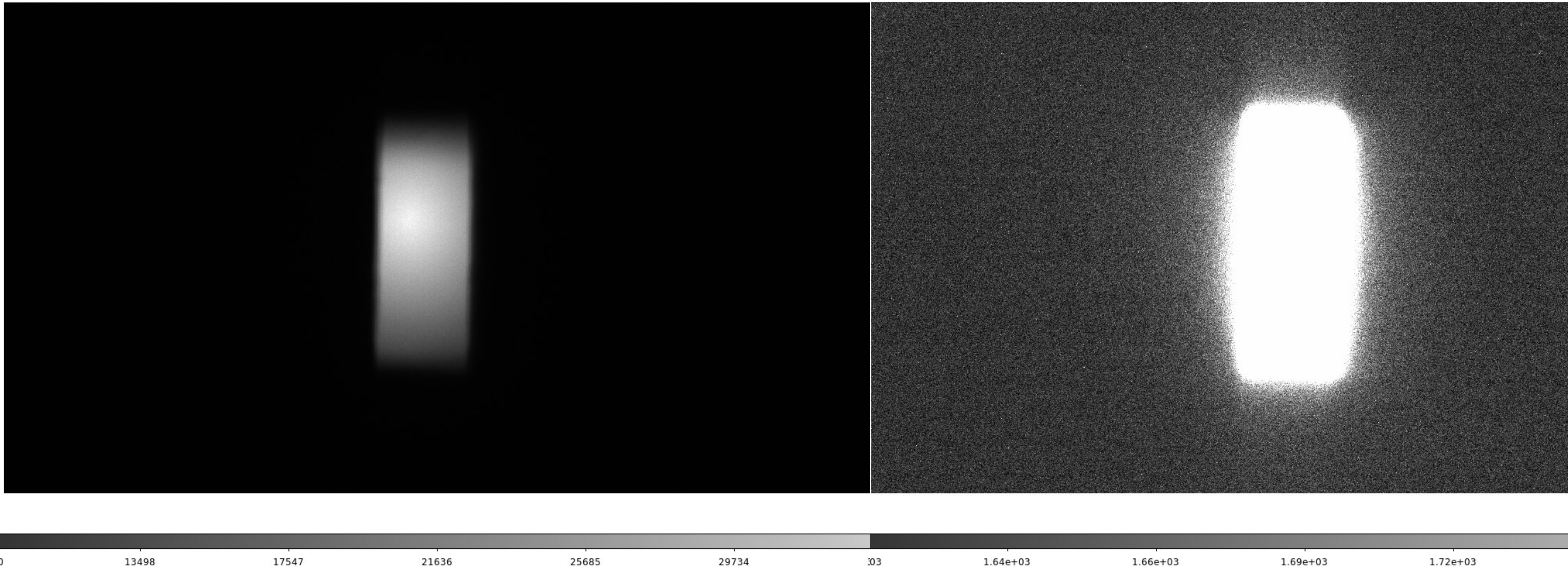


Calibration transfer bench

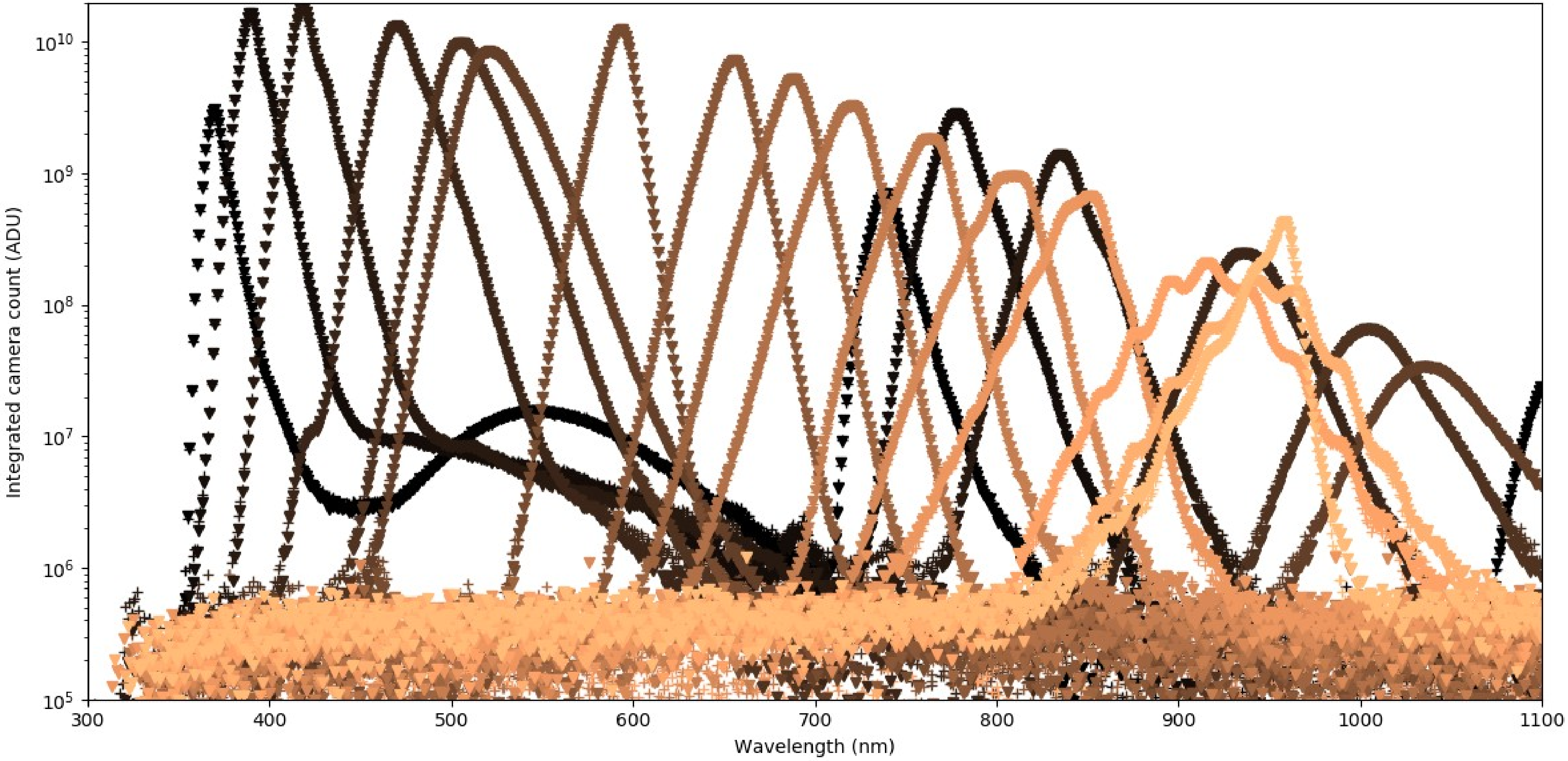
- Project an extended monochromatic image onto both detectors
- Image to pixel area (~mm²/µm²) ratio provides a large dimming factor allowing to operate the photodiode at flux as large as 100pA (6.10^8 e^-/s), well above their dark current (of the order of .4pA) while keeping the count rate in 10µm pixels as low as a few tens of ke^-/s
- This is our particular implementation
  - Narrow band, stable, adjustable illumination (LEDs)
  - Single monochromator
  - Movable sensor in front of fixed aperture



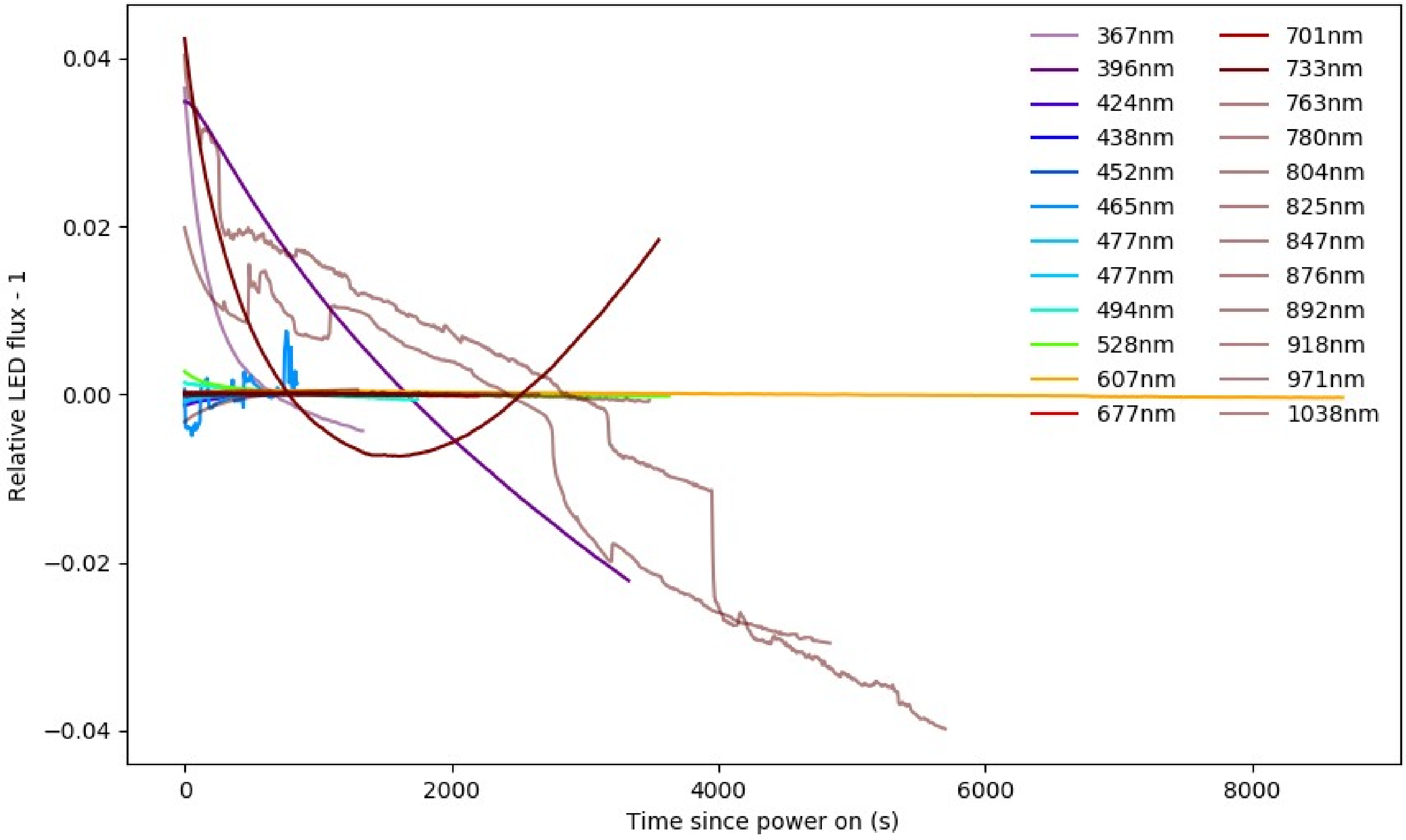
Sample image on the detector



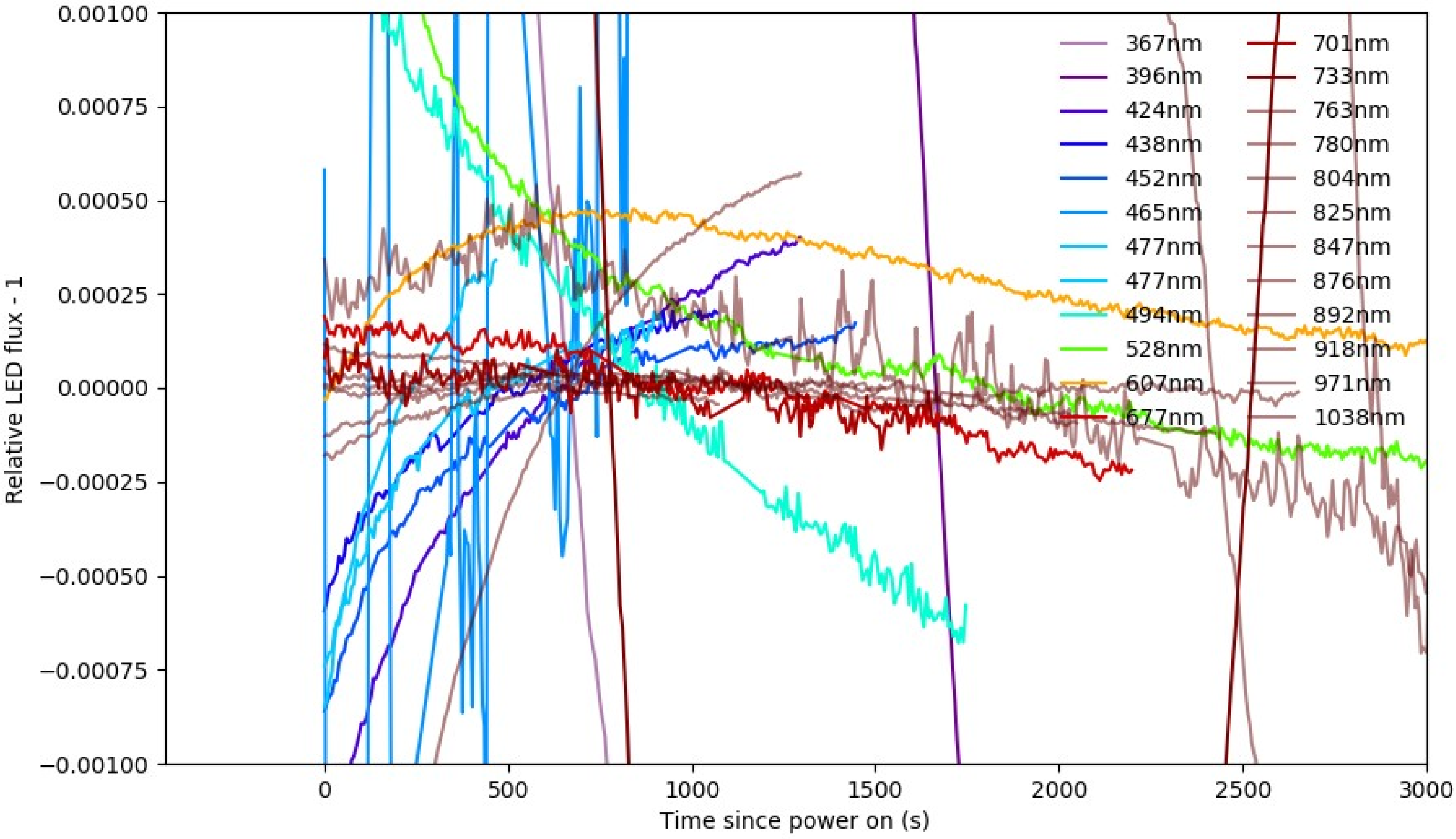
Looking for out of band emission



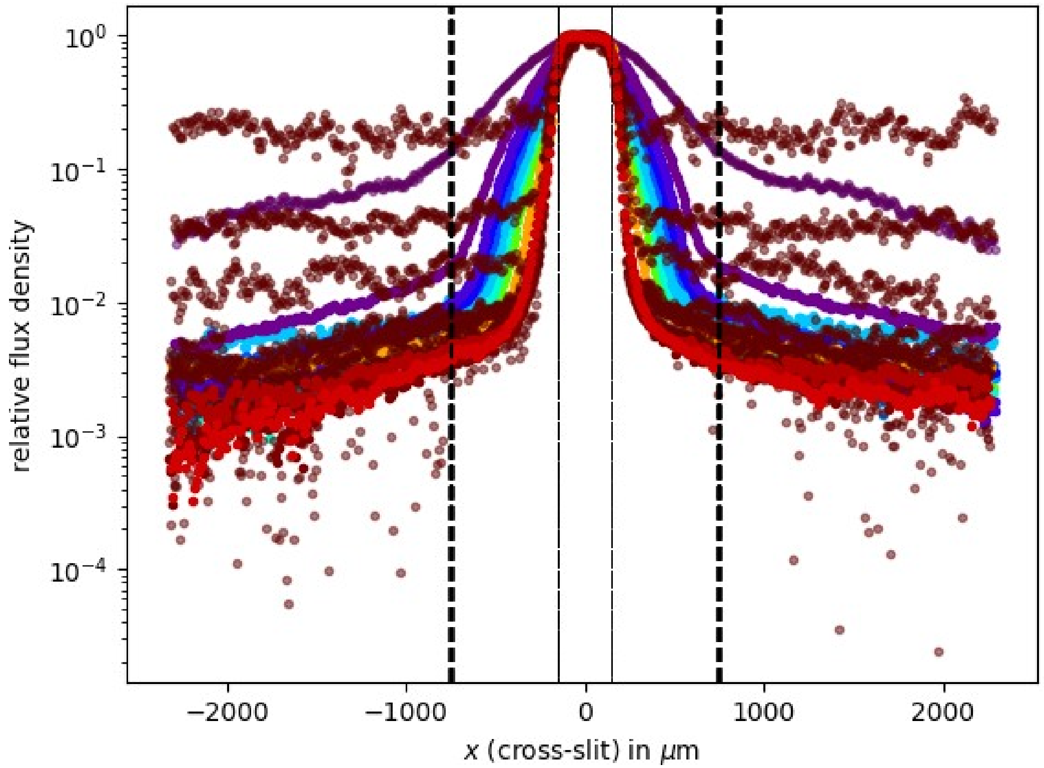
Raw illumination stability

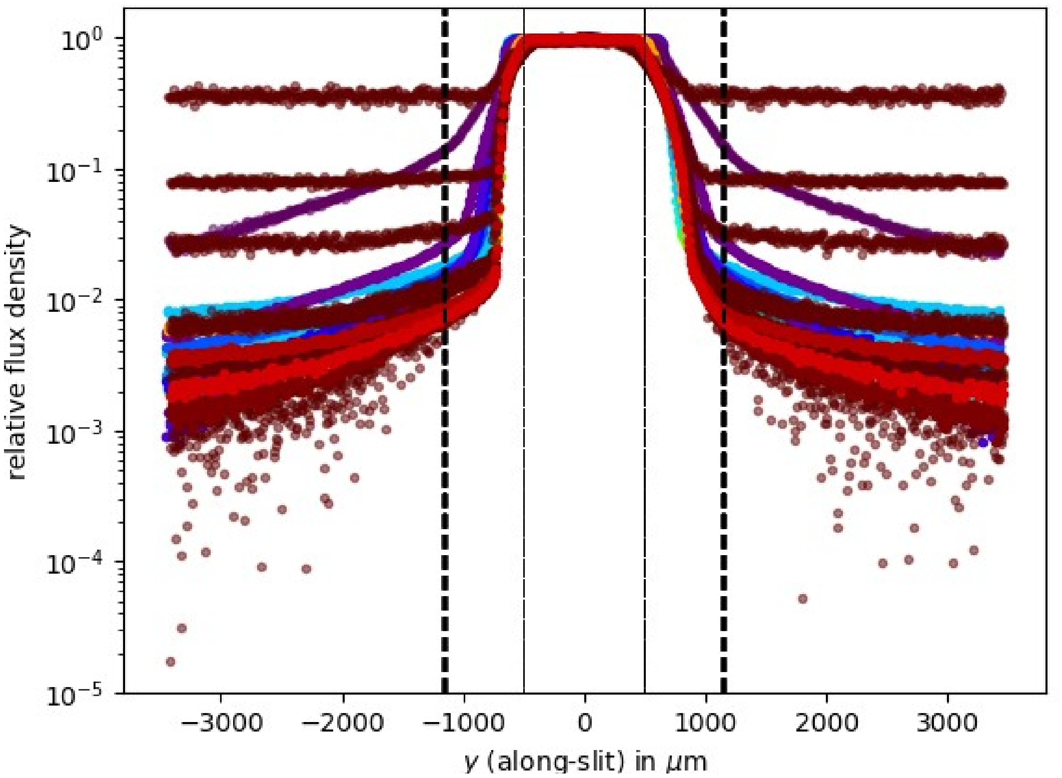


Raw illumination stability (zoom on stable LEDs)



Chromaticity in the image profile

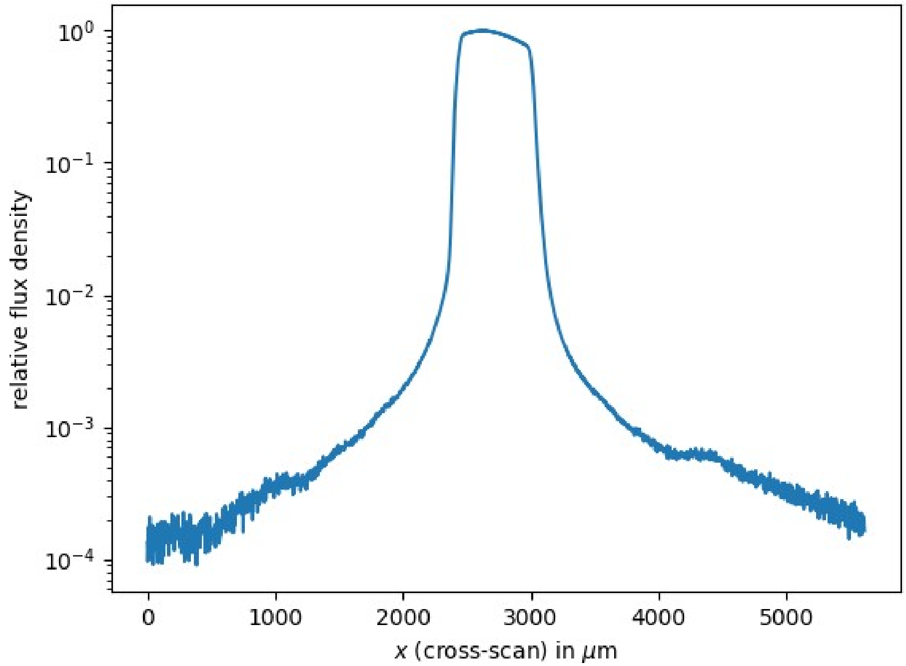


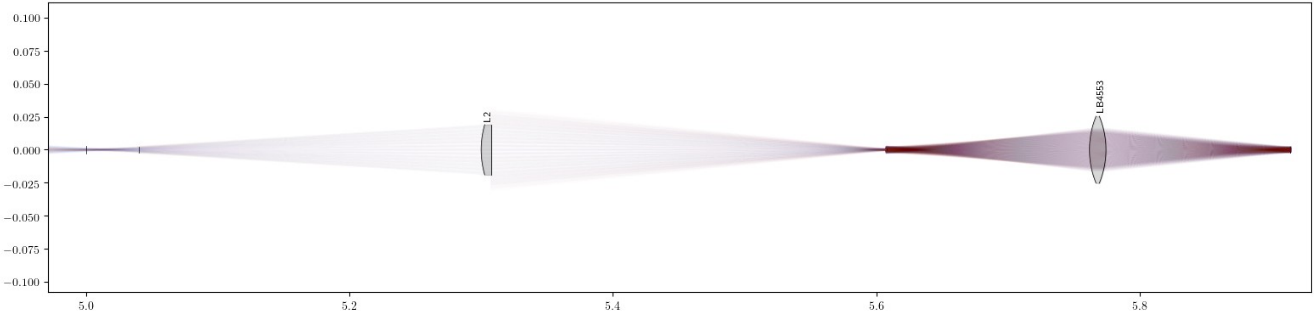


This results in unacceptable chromatic errors in the Photodiode/CCD ratio

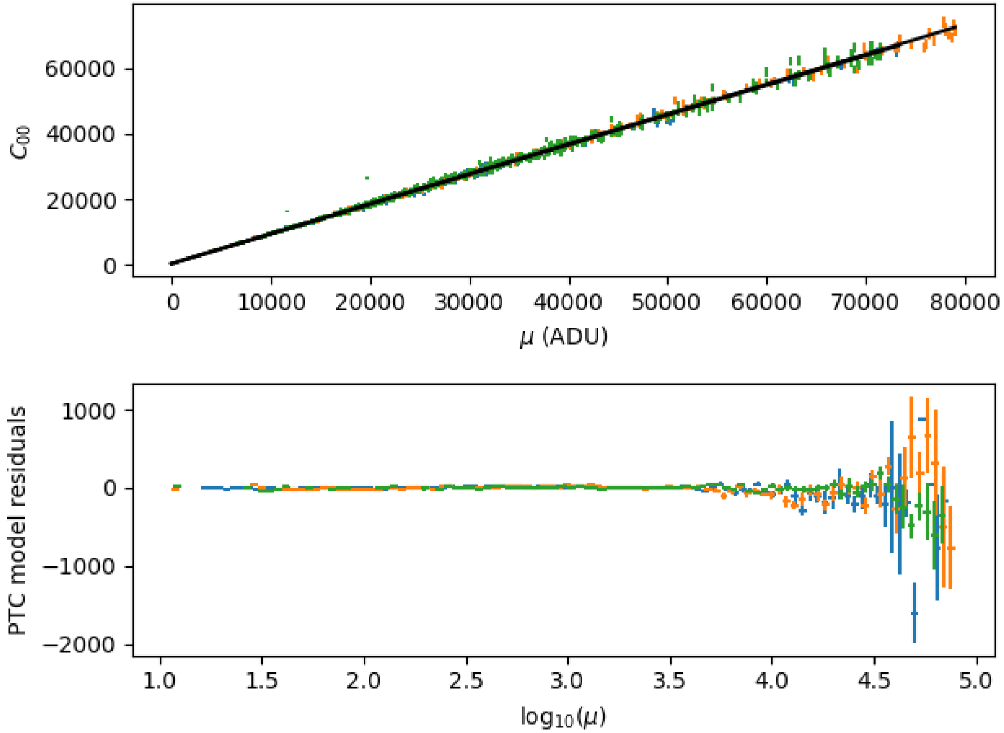
Decreasing the amount of scattered light

- Can be done at a given wavelength by tuning aperture stops and focus
- For the profile on the right, PHD/CCD aperture correction are brought down the mmag level
- An achromatic optics is required to have that at all wavelengths

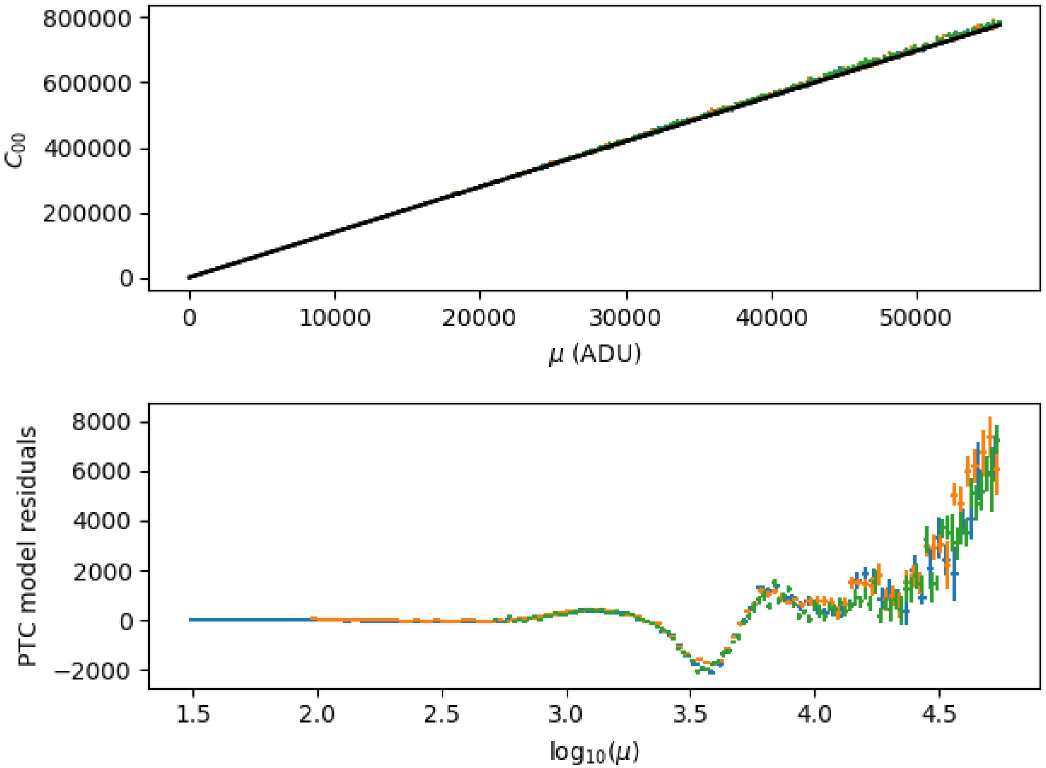




Camera characterization I
Gain and read noise from PTC



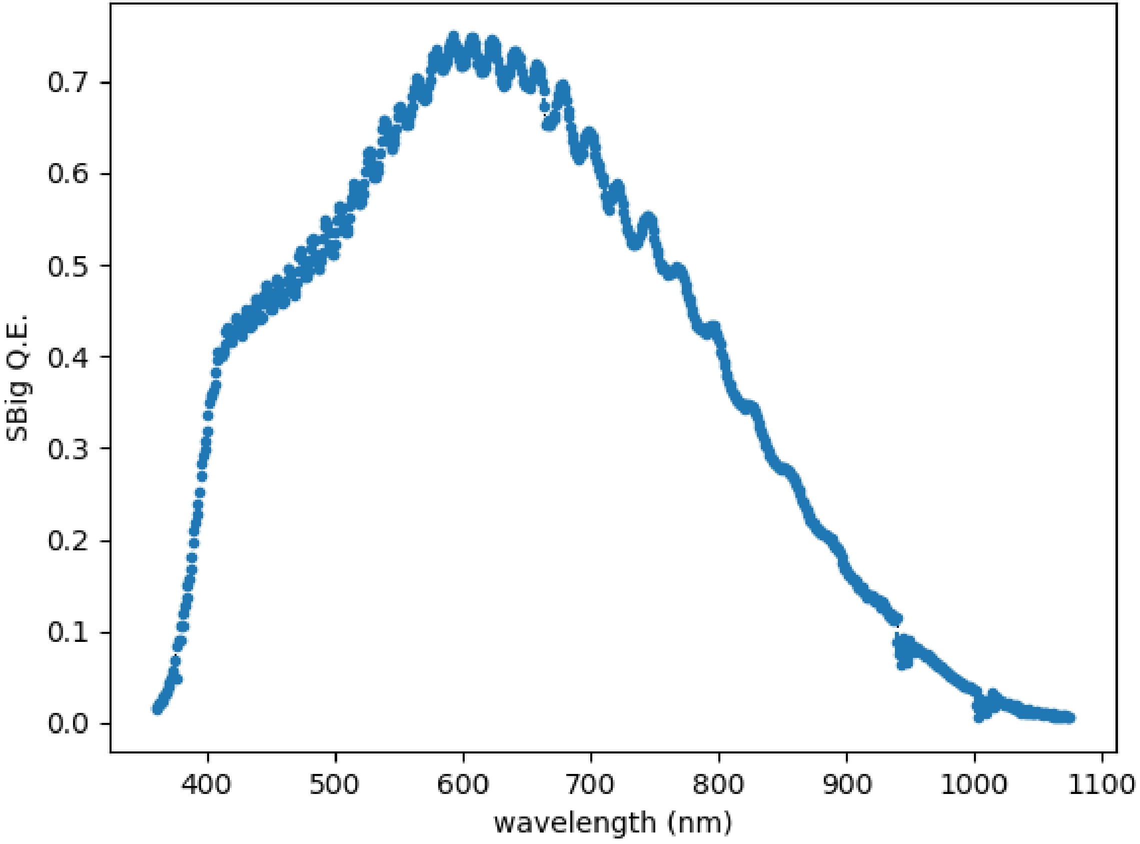
Sbig CCD camera



Zwo CMOS camera

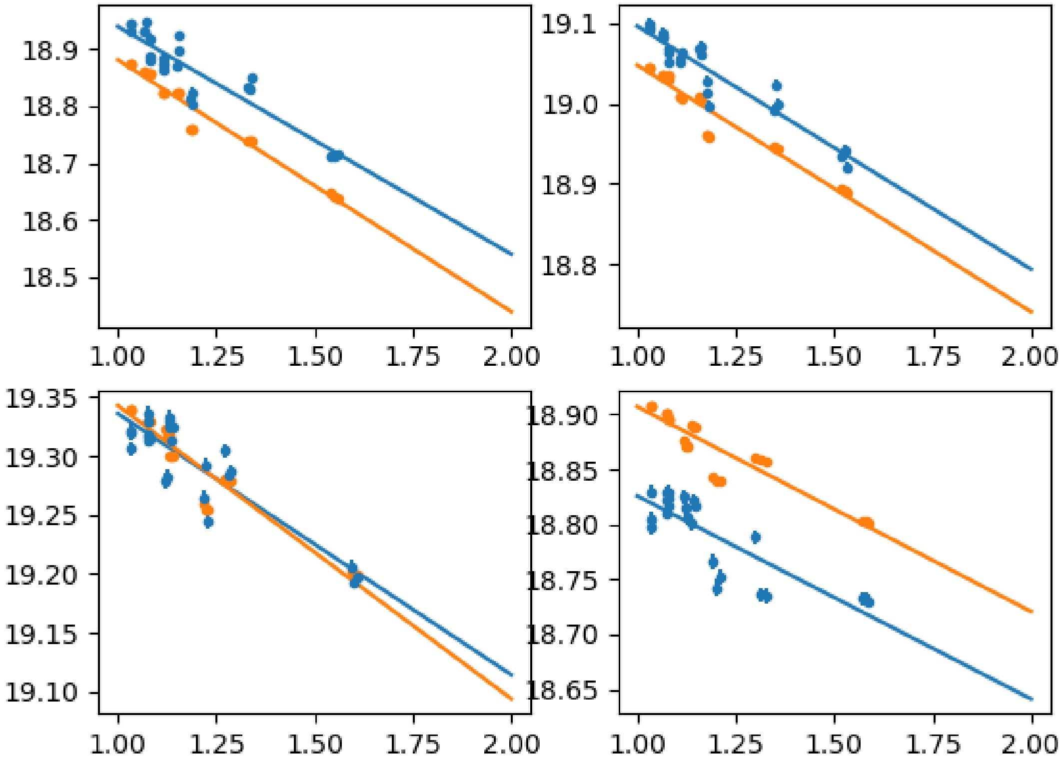
Camera characterization II
Quantum efficiency

- Missing a bit of flux at specific wavelength in the infrared (holes between LEDs)
- Accuracy limited by PHD/CCD aperture differences for the moment
- Mirrors ordered (for a while now)

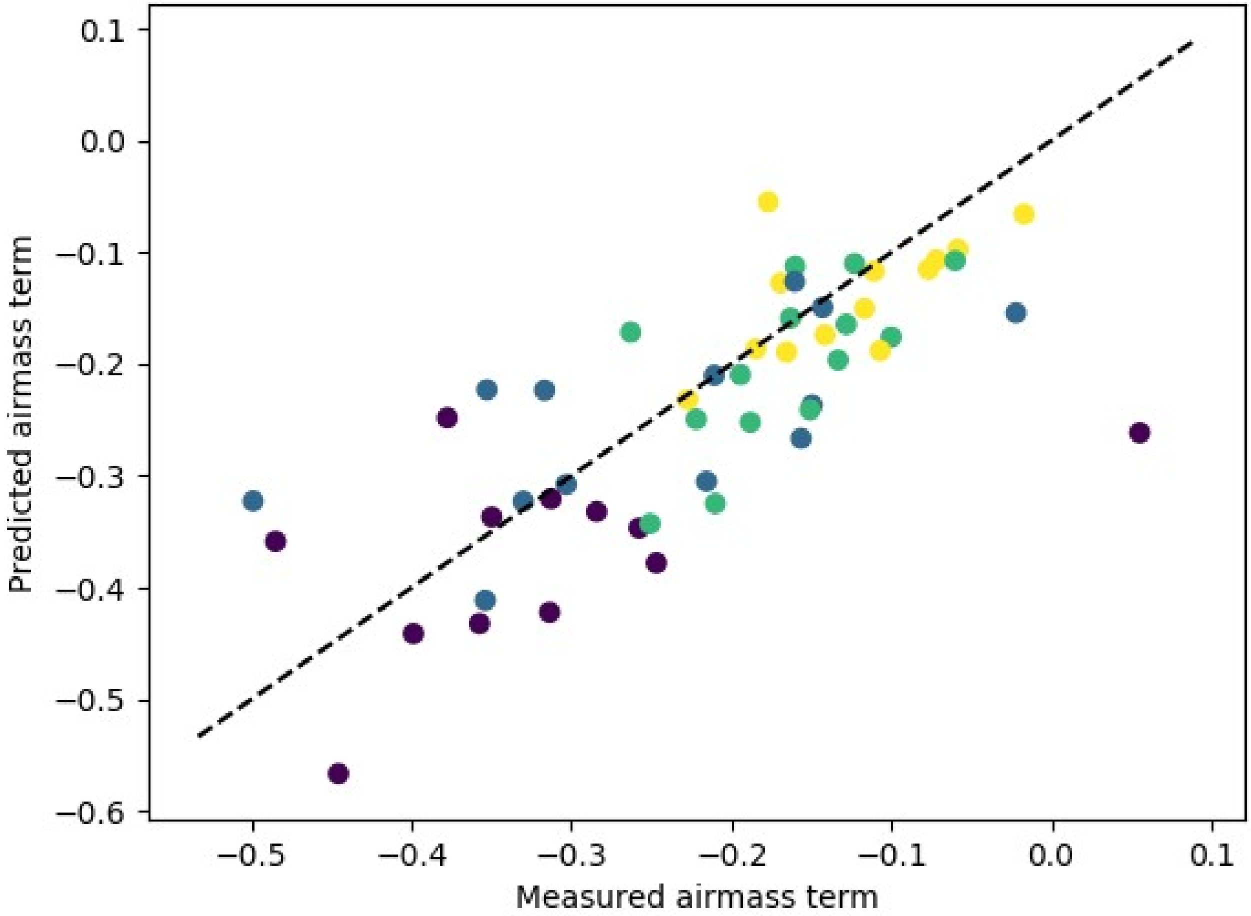


Atmospheric transmission

- Sylvie provides prediction of the atmospheric transmission for every single StarDICE observations from MERRA atmospheric parameters
- We achieve nightly determination of the airmass term (median accuracy 0.028, best night 0.013)
- We can compare the prediction to our data



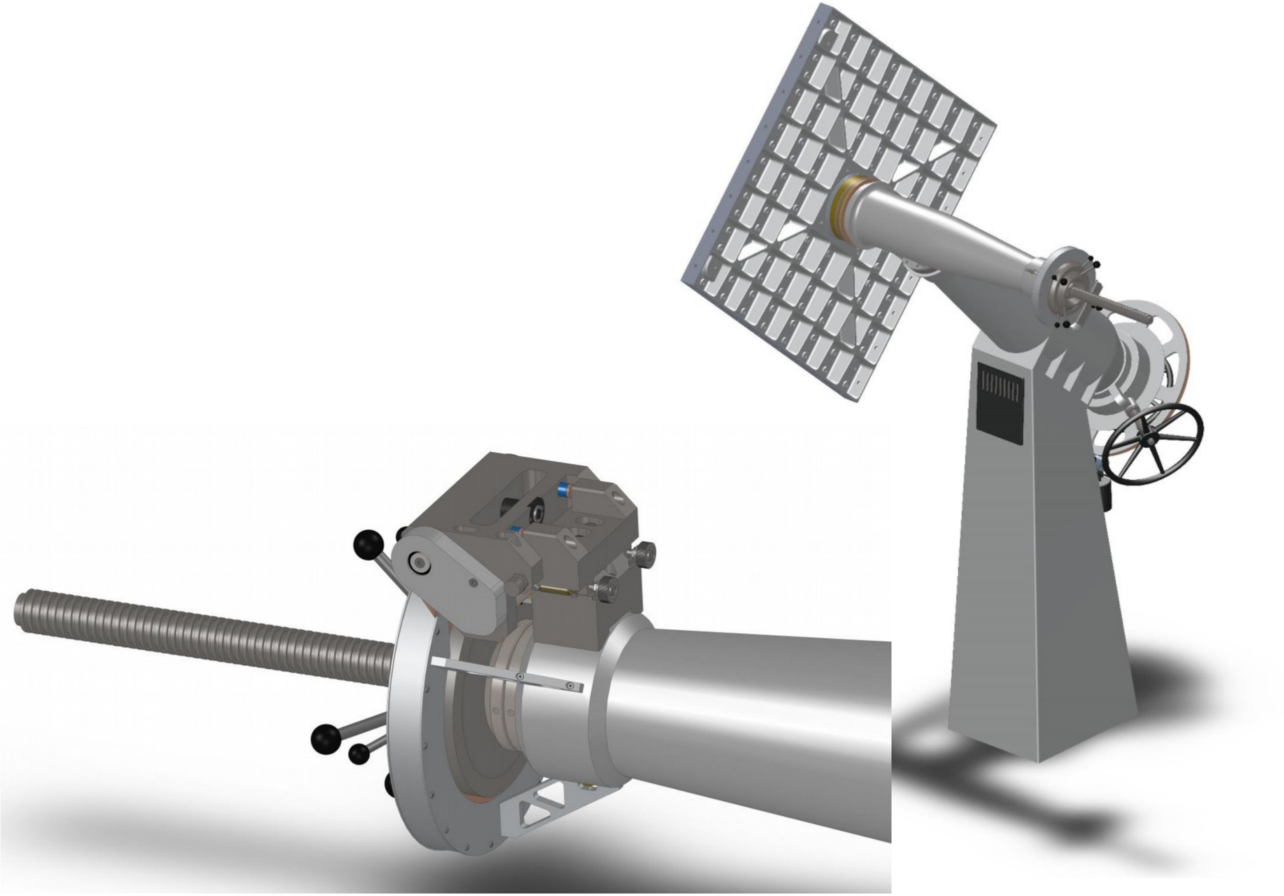
Atmospheric comparison

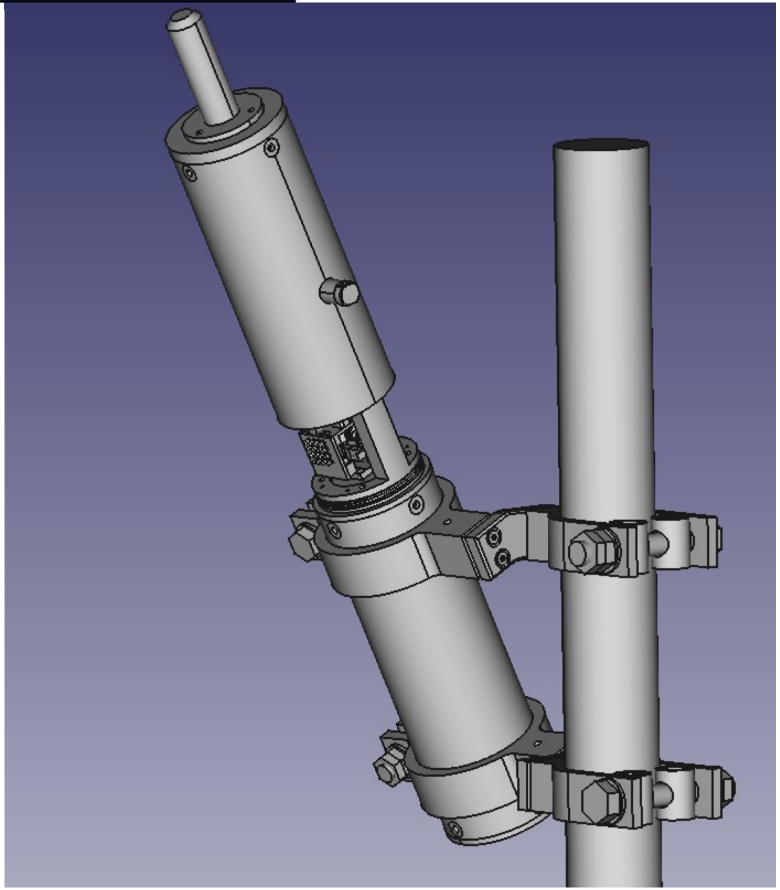


- There is a clear correlation !
- We are observing through quite a bunch of extinction

	Δk	σ(k)	Predicted σ(k)
B	0.048	0.1	0.09
V	0.002	0.14	0.08
R	0.042	0.05	0.09
I	0.033	0.07	0.07

A word on hardware upgrade





Conclusion

- Test completed
- Analysis ongoing with two hard points:
  - Low flux LED spectroscopy
  - Monochromatic instrument transmission
- Upgrade has started
  - Better telescope
  - Better source
  - Better metrology