New calibration methods

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LPNHE
Outline

- Why calibration?
- Calibration requirements
  - For a 4th generation survey (e.g. LSST)
  - For a third generation survey (e.g. Subaru)
- Primary flux references
  - CALSPEC & NIST
- Survey flux metrology chain
  - Survey uniformity, GAIA
- Characterization of the survey telescope
  - Bench & in-situ throughput measurements
- Conclusion
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Why calibration?

- Cosmological signal from comparison of
  - Nearby SNe (g,r)
  - Distant SNe (i,z)
- SNe measured at different locations of the sky
  - Far away from each other
  - Far away from primary flux references
  - In different observing conditions (IQ, atm. transparency)
- Indirect measurement
  - Need instrument model to interpret fluxes
  - Need SN model + instrument model to infer rest frame fluxes
Distances to low-z SNe rely on blue bands \((g,r)\)
Distances to high-z SNe rely on red band \((i,z)\)

**Critical calibration ingredients:**
- relative (band-to-band) flux calibration
- positions of filter cut-on/cut-off

**Calibration errors affect**
- SN magnitudes
- SN empirical model
- \(\rightarrow\) SN distances \((\times2)\)
- Relative flux calibration
  - Primary flux reference
  - Flux metrology chain

\[
\varphi_{SN,b}[\gamma/s] = \frac{\varphi_{SN,b}[ADU/s]}{\varphi_{WD,b}[ADU/s]} \times \varphi_{WD,b}[\gamma/s]
\]
Survey uniformity

CALSPEC primary standards

CALSPEC stars

DDF

WFD
Instrument model & SN model

SN fluxes interpreted as:

\[ \phi \propto \int S \left( \frac{\lambda}{1+z}, p | \theta_{SN} \right) T(\lambda) \frac{\lambda}{hc} d\lambda \]

- Spectrophotometric model (SALT2, SALT3, SNEMO...)
- Trained from real data
- **Carries calibration uncertainties!**

Constraints on SN models:
- Need a way to propagate calibration uncertainties
- Should be trained primarily on the cosmo sample (to benefit from its calibration)

- Instrument transmission
- Shape measured (bench / in-situ)
- Throughput at a given time obtained from star observations
- Filter metrology
  - On bench
  - In situ (e.g. with stable monochromatic light source)
- Relative flux calibration
  - Primary flux reference
  - Flux metrology chain

\[ \varphi_{SN,b}[\gamma/s] = \frac{\varphi_{SN,b}[ADU/s]}{\varphi_{WD,b}[ADU/s]} \times \varphi_{WD,b}[\gamma/s] \]
Calibration ingredients

Primary flux reference → Survey flux metrology chain

Instrument model

SN distances

SN model
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Calibration requirements

- **For a given dataset**, what is the impact of calibration on the cosmological parameters (e.g. the DETF FoM)
- **To answer this question**, need to build a fast emulator of the SN analysis, including the training

\[ m_b = 2.5 \log_{10}(1 + z) + \mu(z, \theta_{\text{cosmo}}) + M_X + P\left(\frac{\bar{\lambda}_b + \delta\lambda_b}{1 + z}\right) + cQ\left(\frac{\bar{\lambda}_b + \delta\lambda_b}{1 + z}\right) + c\beta + zp_b + \delta zp_b \]

Work led by F. Hazenberg (LPNHE)
Calibration requirements

- **Model**
  - Compress light curves into amplitudes
  - Reduce SALT2 to 2 polynomials (mean “surface” + color law)
  - Keep color standardization (large penalty associated to beta)
  - Fisher analysis taking all all parameters taken into account simultaneously
  - Marginalize over nuisance parameters and yield a FoM

- ~ 20 minutes to simulate light curves,
- ~ 1 second to obtain the FoM from light curve amplitudes

Work led by F. Hazenberg (LPNHE)
Calibration requirements for LSST

20000 SNe from WFD + 15000 from DDF

F. Hazenberg
Calibration requirements for LSST

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Calibration requirements for LSST

20000 SNe from WFD + 15000 from DDF
Calibration requirements for LSST

- JLA: 15
- $5 \, \text{mmag}$

20000 SNe from WFD + 15000 from DDF

F. Hazenberg
Calibration requirements for LSST

$5 \text{ mmag} \sigma(\delta \lambda_{b}) \sim 1 \text{ nm}$

LSST: 55
JLA: 15

20000 SNe from WFD + 15000 from DDF

F. Hazenberg
Calibration requirements for LSST

20000 SNe from WFD + 15000 from DDF
Calibration requirements for LSST

\[ \sigma_{\delta\lambda} = 1 \text{Å} \]
\[ \sigma_{\delta\lambda} = 0.7 \text{Å} \]
\[ \sigma_{\delta\lambda} = 1 \text{nm} \]

20000 SNe from WFD + 15000 from DDF
Calibration requirements in ~ 2020?

JLA + SSP(2 years) + 800 additional nearby SNe
Impact of training

![Graph showing the impact of training on DETF FoM]
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CALSPEC

- Primary flux references based on *DA white dwarf models*
- Bohlin, Gordon, Tremblay, 2014
  - 3 DA WD (G191B2B, GD153, GD71)
  - NLTE atmosphere models from (Rauch et al, 2013)
- The average defines the *HST/STIS flux calibration*
  - Residuals ~ 1% (visible)
- Extended to a larger network with *HST/STIS*
CALSPEC : model uncertainties ?

- 2 models, same physics
  - ~ 4 mmag \( 400 < \lambda < 1000 \) nm
- What about physics unaccounted for ?
  - Metal lines found in high-resolution spectra of G191B2B
  - Lyman / Balmer line problem
  - Convection / turbulence
  - ...
- Need for alternate primary references with different systematics

(Bohlin, 2014)
Comparing CALSPEC and NIST

- Uncertainties on WD flux scale (~0.5%, Bohlin 2014)
- However,
  - It is easier, for large survey telescopes, to keep stars as flux references (real point sources, same calibration beam)
  - Producing a good calibration source for a large survey telescope (same beam as science beam) is very difficult
- Strategy
  - Keep using stars as calibration transfer tools
  - Keep CALSPEC as flux references (high quality spectrophotometric standards)
  - **Use a NIST-calibrated artificial source and a dedicated telescope to intercalibrate NIST and CALSPEC**
Projects

- **First attempts by Stubbs & Tonry**
  - e.g. Stubbs et al, 2010 ([2010ApJS..191..376S](https://doi.org/10.1088/0067-0049/191/1/376)) ~ 5% precision

- **NIST stars**
  - Use NIST calibrated spectrometer + additional hardware to monitor line of sight
  - Target bright standards (Vega)

- **SCALA**
  - See talk by G. Aldering (~ 1%)
  - Target all SNfactory calibration stars (include CALSPEC)

- **starDICE**
  - Use stable LED-based, NIST calibrated artificial source
  - dedicated, small focal length telescope
  - Target mainly CALSPEC stars
New metrology chain

**sources**

- NIST POWR
- NIST Photodiodes
- Small aperture telescope

**detectors**

- NIST SCF
- Narrow spectrum LEDs with stable drive elec
- Spectrophotometric standard stars

**Intensity Levels**

- $10^{-13} \text{ W/cm}^2/\text{nm}$
- $10^{-17} \text{ W/cm}^2/\text{nm}$
- $10^{-19} \text{ W/cm}^2/\text{nm}$
Telescope
small aperture

Calibrated light source

few 100's m

CALSPEC stars
(artist’s view)

variations controlled at 0.1%

variations controlled at 0.1%

Telescope
small aperture

Calibrated light source

few 100's m

F. Hazenberg
Telescope small aperture

variations controlled at 0.1%

CALSPEC stars (artist’s view)

Calibrated light source

variations controlled at 0.1%

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Source seen by the telescope

Telescope seen by the source
starDICE

- Output of starDICE
  - a smooth recalibration function $\kappa(\lambda)$
  - Based on photometric measurements of LEDs & CALSPEC
starDICE

- **Observations** at Observatoire de Haute-Provence (south of France)
- **Phase I completed**
  - Bench measurements
    - Spectrophotometric characterization of the source
    - Assessment of source stability
    - Characterization of telescope & camera throughput
  - Measurements on site
    - ~ O(20) nights
    - O(4000) stellar observations (6 different CALSPEC stars)
    - O(3000) observations of LEDs
- **Phase II starting**
  - New telescope, new fainter source, monitoring hardware
  - O(100) nights
Bench measurements

LED flux vs. temperature

LED spectrophotometric characterization

Telescope & detector throughput

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Accuracy of bench measurements

- 12 LEDs with \( S(\lambda,T) \)
- Bench noise and LED noise lower than 0.1%
- Model uncertainty < 0.5%
- Still ongoing
  - LED spectra at low flux

\[36\]
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Data taking
LED imaging
Uncertainties

- Low current LED spectra (5.7%)
- Gray atmospheric variations (1.7%)
- Atmosphere models (1.5%)
- LED temperature dependent flux (0.4%)
- Flux solid angle (0.4%)

- New spectroscopic bench
- Cloud monitoring
- OHP monitoring + models
- New standardization technique (LED rev voltage monitoring)
- New LED maps + laser alignment
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Uniformity: DES and Gaia DR2

- Test uniformity of DES r-band with Gaia DR2 G-band
- 2.2 mmag uniformity at low Galactic latitude
  - MW Galaxy contamination because Gaia G-band is very broad, making comparison strongly dependent on SED

[Rykoff]
Uniformity: Gaia as a Reference

- Testing internal Gaia uniformity (Blue channel “BP”; red channel “RP”; broad “G” band)
- Map Gaia “flux excess” == (f\_BP + f\_RP) / f\_G
- To be able to use Gaia for mmag precision will require more work
- Additional challenge of using spectrophotometry
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Re-characterization of the MegaCam filters

- MegaCam filters decommissioned in Feb 2016
- Sent to LMA (Lyon) in Dec 2016 for a complete re-characterization
- Two setups
  - Fast spectroscopic scan (1cm beam, normal incidence)
  - Slow spectrophotometric scan (variable incidence)
- Measurements described in (sassolas et al, 2018, 2018SPIE10706E..4ES)
- Filters sent back to CFHT in June 2018
Filter measurements

- Model fitted simultaneously on data from both setups
- Stray light within the bench taken into account (normal incidence)

(Betoule et al, in prep)
Consistency

- Filter model fitted simultaneously on both sets of measurements
- The model describes measurements with a precision better than 0.5-nm

(Betoule et al, in prep)
Filter uniformity maps

(Betoule et al, in prep)
Radially averaged residuals

- Comparing relative color terms
  - Synthetic (B13, LMA)
  - Measured
- Re-measurement solves spatial issues observed in B13
- Agreement better than 4mmag/mag everywhere
In-situ measurements of filters

- LSST plans to use a Collimated Beam Projector (CoBP)
- No bench re-measurements of filters planned (so far)
- Tests of CBP precursors (aka "Harvard CBP") have been done on PanSTARRS and at CTIO
- CBP currently used to characterize and monitor starDICE telescopes
  - In the lab
  - In situ (at OHP)
- Will allow to assess accuracy and to gain experience
Conclusion

- Calibration requirements for 4th generation surveys will be very hard to meet
- Challenging goal
  - Relative flux calibration @ 0.1%
  - Characterization of filter wavelength positions @ 1A
  - Flux metrology chain controlled at better than 0.1%
- State of the art
  - Relative flux calibration :
    - ~0.5% (CALSPEC)
    - ~ 1% (NIST-CALSPEC)
  - Filter metrology : ~ 5A
  - Flux metrology chain < 0.5% (FGCM)
- **Lots of instrumental work ahead**
  - (starDICE, SCALA, filter metrology)