Photometric Correction with Forward Global Calibration Model in the context of DM Rubin-LSST science pipeline

matter of discussion for the LSST France parallel session

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Motivations

- Sources/Object standard magnitude estimation from instrumental magnitude $\rightarrow$ allowing coaddition of sigle epoch measurements
- use of time dependent epoch transmissions (instrument + atmosphere)
- photometric correction depending on poorly known objects SED
- to be implemented inside DM Rubin-LSST science pipelines
- participation of DESC technical groups (SAWG,PCWG,PSF), namely during commissioning phase,
- need participation of Science groups (PhotoZ, and objects groups like SN, and other astrophysical groups),

Outline

1. Key formula, definitions and notations
   - Instrumental Flux
   - Observed Magnitude
   - Standard Magnitude
   - Approximation for SED shape
   - Summary of definitions on interpretable standard magnitude
   - SED shape correction
   - Bias on Magnitude for SED shape correction
   - What is FGCM in DES&LSST ?
2. LSST Rubin science pipelines
3. Simulation of the photometric corrections
   - Atmospheric simulation and S_b^{obs}
   - The zero's order of the photometric correction
   - The 1st and 2nd orders Integral differences

Instrumental Flux

Photometric flux of a source

$$ADU_b = \frac{A\Delta T}{gh} \int_0^\infty F_\nu(\lambda) \times S_b^{obs}(\lambda, x, y, az, alt, t) \frac{d\lambda}{\lambda} \quad (1)$$

- ADU_b : ADU count of a source measured by photometry in band b
- F_ν : SED in $\mathrm{erg/cm^2/Hz/s}$
- S_b^{obs} : Observation transmission in band b(atmosphere + instrument)
- A : Collection efficiency in $\mathrm{cm^2}$
- g : Electronic gain in $\mathrm{e^-/ADU}$
- ΔT : Exposure time
- h : Planck constant

Observed Magnitude

Observed Magnitude of a source

$$m_b^{obs} = -2.5 \log_{10} \left(\frac{\int_0^\infty F_\nu(\lambda) \times S_b^{obs}(\lambda, x, y, az, alt, t) \frac{d\lambda}{\lambda}}{\int_0^\infty F^{AB} \times S_b^{obs}(\lambda, x, y, az, alt, t) \frac{d\lambda}{\lambda}} \right) \quad (2)$$

- m_b^{obs} : observed magnitude in band b
- F_ν : SED in $\mathrm{erg/cm^2/Hz/s}$
- $F^{AB} = 3631 Jy$: Flat SED with $1 Jy = 10^{-23} \mathrm{erg/cm^2/Hz/s}$
- S_b^{obs} : Observation transmission in band b (atmosphere + instrument)

In the above formula gives how the physics provides m_b^{obs}. However usually the $F_\nu(\lambda)$ of an object is unknown. Note m_b^{obs} is defined independently of any reference to a standard magnitude.

Natural magnitude in Rubin-LSST

Rubin-LSST usually use the concept of normalized passband

normalized bandpass response function

$$\phi_b^{obs}(\lambda, t) = \frac{S_b^{obs}(\lambda, t)\frac{1}{\lambda}}{\int_0^\infty S_b^{obs}(\lambda, t)\frac{d\lambda}{\lambda}} \quad (3)$$

Observed flux

$$F_b^{obs} = \int_0^\infty F_\nu(\lambda)\phi_b^{obs}(\lambda)d\lambda \quad (4)$$

Natural magnitude

$$m_b^{nat} = -2.5\log_{10}\left(\frac{F_b^{obs}}{F^{AB}}\right) \quad (5)$$

The natural magnitude m_b^{nat} is similar to the observed magnitude m_b^{obs}

Decomposition of observed Magnitude

The observed magnitude is estimated from the measured ADU counts rate $C_b = ADU_b/\Delta T$ in filter b

$$m_b^{obs} = -2.5\log_{10}(C_b) + 2.5\log_{10}\left(\mathbb{I}_0^{obs}(b)\right) + ZPT^{AB} \quad (6)$$

However the two following quantities which depend on atmospheric + detectors conditions must be estimated by calibration.

Calibration quantities:

$$\mathbb{I}_0^{obs}(b) \equiv \int_0^\infty S_b^{obs}(\lambda)\frac{d\lambda}{\lambda} \quad (7)$$

$$ZPT^{AB} \equiv 2.5\log_{10}\left(\frac{AF^{AB}}{gh}\right) \quad (8)$$

Zero point

Note sometimes one defines the zero point as the magnitude m_b^{obs}, such $ADU_b/\Delta T = 1$ count per sec, then

$$m_b^{obs}(ZP) \equiv 2.5 \log_{10}\left(\mathbb{I}_0^{obs}(b)\right) + ZPT^{AB} \tag{9}$$

- the zero point is common to all sources whatever their color is
- it has a time dependent and passband b dependent component : $2.5 \log_{10}\left(\mathbb{I}_0^{obs}(b)\right)$
- it has a detector (CCD) dependent component : ZPT^{AB} through the relative electronic gain g, (independent of the passband b ?, long time-scale dependence (night) ?)

Standard magnitude is the magnitude to be published with the standard passband. It must be calculated from the observed magnitude.

Standard magnitude in standard passband

$$m_b^{std} = -2.5 \log_{10} \left(\frac{\int_0^\infty F_\nu(\lambda) \times S_b^{std}(\lambda) \frac{d\lambda}{\lambda}}{\int_0^\infty F^{AB} \times S_b^{std}(\lambda) \frac{d\lambda}{\lambda}} \right) \quad (10)$$

$$\delta_b^{std} \equiv m_b^{std} - m_b^{obs} \quad (11)$$

$$\equiv 2.5 \log_{10} \left(\frac{\mathbb{I}_0^{std}(b)}{\mathbb{I}_0^{obs}(b)} \right) + 2.5 \log_{10} \left(\frac{\int_0^\infty F_\nu(\lambda) \times S_b^{obs}(\lambda) \frac{d\lambda}{\lambda}}{\int_0^\infty F_\nu(\lambda) \times S_b^{std}(\lambda) \frac{d\lambda}{\lambda}} \right) \quad (12)$$

standard magnitude

$$m_b^{std} = m_b^{nat} + \Delta m_b^{obs} \quad (13)$$

$$\Delta m_b^{obs} = 2.5 \log_{10} \frac{\int_0^\infty F_\nu(\lambda)\phi_b^{obs}(\lambda)d\lambda}{\int_0^\infty F_\nu(\lambda)\phi_b^{std}(\lambda)d\lambda} \quad (14)$$

$$\Delta m_b^{obs} = \delta_b^{std} = 2.5 \log_{10} \left(\frac{\mathbb{I}_0^{std}(b)}{\mathbb{I}_0^{obs}(b)} \right) + 2.5 \log_{10} \left(\frac{\int_0^\infty F_\nu(\lambda) \times S_b^{obs}(\lambda)\frac{d\lambda}{\lambda}}{\int_0^\infty F_\nu(\lambda) \times S_b^{std}(\lambda)\frac{d\lambda}{\lambda}} \right)$$

$$= 2.5 \log_{10} \left(\frac{\int_0^\infty F_\nu(\lambda) \times \phi_b^{obs}(\lambda)d\lambda}{\int_0^\infty F_\nu(\lambda) \times \phi_b^{std}(\lambda)d\lambda} \right)$$

Zero Point in Rubin-LSST

Zero point definition

$$m_b^{std} = -2.5\log_{10}(C_b^{obs}) + \Delta m_b^{obs} + Z_b^{obs} \quad (15)$$

with $C_b^{obs} = ADU_b/\Delta T$

Correspondence of Zero point in Rubin-DES

$$Z_b^{obs} = 2.5\log_{10}\left(\mathbb{I}_0^{obs}(b)\right) + ZPT^{AB} \quad (16)$$

option A : with zero point as unit counting rate

$$m_b^{std} = -2.5\log_{10}(C_b^{obs}) + 2.5\log_{10}\left(\frac{\mathbb{I}_0^{std}(b)}{\mathbb{I}_0^{obs}}\right) + m_b^{obs}(ZPT)$$
$$+2.5\log_{10}\left(\frac{\int_0^\infty F_\nu(\lambda)\times S_b^{obs}(\lambda)\frac{d\lambda}{\lambda}}{\int_0^\infty F_\nu(\lambda)\times S_b^{std}(\lambda)\frac{d\lambda}{\lambda}}\right) \quad (17)$$

- $-2.5\log_{10}(C_b^{obs})$: measured instrumnetal aperture photometric term (ADU rate)
- $2.5\log_{10}\left(\frac{\mathbb{I}_0^{std}(b)}{\mathbb{I}_0^{obs}}\right)$: SED color free correction term for atmospheric transparency standard/observed
- $m_b^{obs}(ZPT)$: SED color free observed magnitude Zero Point correction term at CCD level,
- $2.5\log_{10}\left(\frac{\int_0^\infty F_\nu(\lambda)\times S_b^{obs}(\lambda)\frac{d\lambda}{\lambda}}{\int_0^\infty F_\nu(\lambda)\times S_b^{std}(\lambda)\frac{d\lambda}{\lambda}}\right)$: SED color dependent term correction

Interpretable standard magnitude expression

option B : with zero point as constants

$$\begin{aligned} m_b^{std} &= -2.5\log_{10}(C_b^{obs}) + 2.5\log_{10}\left(\mathbb{I}_0^{std}(b)\right) + ZPT^{AB} \\ &+2.5\log_{10}\left(\frac{\int_0^\infty F_\nu(\lambda)\times S_b^{obs}(\lambda)\frac{d\lambda}{\lambda}}{\int_0^\infty F_\nu(\lambda)\times S_b^{std}(\lambda)\frac{d\lambda}{\lambda}}\right) \end{aligned} \quad (18)$$

- $-2.5\log_{10}(C_b^{obs})$: measured instrumental aperture photometric term (ADU rate)
- $2.5\log_{10}\left(\mathbb{I}_0^{std}(b)\right)$: Calculable constant
- $ZPT^{AB} = \frac{AF^{AB}}{gh}$: SED color free observed magnitude Zero Point correction term at CCD level (electronic gain),
- $2.5\log_{10}\left(\frac{\int_0^\infty F_\nu(\lambda)\times S_b^{obs}(\lambda)\frac{d\lambda}{\lambda}}{\int_0^\infty F_\nu(\lambda)\times S_b^{std}(\lambda)\frac{d\lambda}{\lambda}}\right)$: SED color dependent term correction

Interpretable standard magnitude expression

option C : using normalized passband

$$m_b^{std} = -2.5\log_{10}(C_b^{obs}) + 2.5\log_{10}\left(\mathbb{I}_0^{obs}(b)\right) + ZPT^{AB} + 2.5\log_{10}\left(\frac{\int_0^\infty F_\nu(\lambda)\times\phi_b^{obs}(\lambda)d\lambda}{\int_0^\infty F_\nu(\lambda)\times\phi_b^{std}(\lambda)d\lambda}\right) \quad (19)$$

- $-2.5\log_{10}(C_b^{obs})$: measured instrumental aperture photometric term (ADU rate)
- $2.5\log_{10}\left(\mathbb{I}_0^{obs}(b)\right)$: order 0 correction : measured variable absorption in the band b (compensate C_b^{obs})
- $ZPT^{AB} = \frac{AF^{AB}}{gh}$: SED color free observed magnitude Zero Point correction term at CCD level (electronic gain),
- $2.5\log_{10}\left(\frac{\int_0^\infty F_\nu(\lambda)\times\phi_b^{obs}(\lambda)d\lambda}{\int_0^\infty F_\nu(\lambda)\times\phi_b^{std}(\lambda)d\lambda}\right)$: SED color dependent term correction

SED approximation as Taylor expansion

$$F_\nu(\lambda) = F_\nu(\lambda_b)\left(1 + f'(\lambda_b)(\lambda-\lambda_b) + \frac{f''(\lambda_b)}{2}(\lambda-\lambda_b)^2 + \cdots\right) \quad (20)$$

$$f'_\nu(\lambda) \equiv \frac{1}{F_\nu(\lambda)}\frac{dF_\nu(\lambda)}{d\lambda} \qquad f''_\nu(\lambda) \equiv \frac{1}{F_\nu(\lambda)}\frac{d^2F_\nu(\lambda)}{d\lambda^2}$$

$$\lambda_b \equiv \frac{\int_0^\infty \lambda \times S_b^{inst}(\lambda)\frac{d\lambda}{\lambda}}{\int_0^\infty S_b^{inst}(\lambda)\frac{d\lambda}{\lambda}} \quad (21)$$

- $S_b^{obs}(\lambda) = S_b^{inst}(\lambda, t, x, y) \times S^{atm}(\lambda, t, alt, az)$

Decomposition of standard magnitude

$$
\begin{aligned}
m_b^{std} \quad = \quad & -2.5 \log_{10}(C_b) \\
& +2.5 \log_{10}(\mathbb{I}_0^{obs}(b)) + ZPT^{AB} \\
& +2.5 \log_{10} \left(\frac{1 + f_\nu'(\lambda_b)\mathbb{I}_{10}^{obs}(b) + \frac{f_\nu''(\lambda_b)}{2}\mathbb{I}_{20}^{obs}(b)}{1 + f_\nu'(\lambda_b)\mathbb{I}_{10}^{std}(b) + \frac{f_\nu''(\lambda_b)}{2}\mathbb{I}_{20}^{std}(b)} \right)
\end{aligned}
\tag{22}
$$

Transmission moments definitions

$$\mathbb{I}_0^i(b) = \int_0^\infty S_b^i(\lambda) \frac{d\lambda}{\lambda} \quad (23)$$

$$\mathbb{I}_1^i(b) = \int_0^\infty (\lambda - \lambda_b) S_b^i(\lambda) \frac{d\lambda}{\lambda} \quad (24)$$

$$\mathbb{I}_2^i(b) = \int_0^\infty (\lambda - \lambda_b)^2 S_b^i(\lambda) \frac{d\lambda}{\lambda} \quad (25)$$

$$\mathbb{I}_{10}^i(b) = \frac{\mathbb{I}_1^i(b)}{\mathbb{I}_0^i(b)} \quad (26)$$

$$\mathbb{I}_{20}^i(b) = \frac{\mathbb{I}_2^i(b)}{\mathbb{I}_0^i(b)} \quad (27)$$

with $i = obs$ or $i = std$

SED shape (f'_ν, f''_ν) color correction

$$
\begin{aligned}
m_b^{std} = & -2.5\log_{10}(C_b) \\
& +2.5\log_{10}(\mathbb{I}_0^{obs}(b)) + ZPT^{AB} \\
& +1.087\left(f'_\nu(\lambda_b)\Delta\mathbb{I}_{10}(b) + \frac{f''_\nu(\lambda_b)}{2}\Delta\mathbb{I}_{20}(b) \right. \\
& \left. - \frac{1}{2}\left(f'_\nu(\lambda_b)\Delta\mathbb{I}_{10}(b)\right)^2 \right) \qquad (28)
\end{aligned}
$$

Moments difference definition

$$\Delta\mathbb{I}_{10}(b) = \mathbb{I}_{10}^{obs}(b) - \mathbb{I}_{10}^{std}(b) \qquad (29)$$

$$\Delta\mathbb{I}_{20}(b) = \mathbb{I}_{20}^{obs}(b) - \mathbb{I}_{20}^{std}(b) \qquad (30)$$

Error on Magnitude for SED-shape correction

$$\begin{aligned}\Delta m &= \Bigg| 2.5 \log_{10}\left(\frac{\mathbb{I}_0^{std}(b)}{\mathbb{I}_0^{obs}(b)}\right) + 2.5 \log_{10}\left(\frac{\int_0^\infty F_\nu(\lambda) \times S_b^{obs}(\lambda)\frac{d\lambda}{\lambda}}{\int_0^\infty F_\nu(\lambda) \times S_b^{std}(\lambda)\frac{d\lambda}{\lambda}}\right) \\ &\quad -1.087\left(f'_\nu(\lambda_b)\Delta\mathbb{I}_{10}(b) + \frac{f''_\nu(\lambda_b)}{2}\Delta\mathbb{I}_{20}(b) - \frac{1}{2}\left(f'_\nu(\lambda_b)\Delta\mathbb{I}_{10}(b)\right)^2\right) \\ \Delta m &= \Bigg| 2.5 \log_{10}\left(\frac{\int_0^\infty F_\nu(\lambda) \times \phi_b^{obs}(\lambda)d\lambda}{\int_0^\infty F_\nu(\lambda) \times \phi_b^{std}(\lambda)d\lambda}\right) \\ &\quad -1.087\left(f'_\nu(\lambda_b)\Delta\mathbb{I}_{10}(b) + \frac{f''_\nu(\lambda_b)}{2}\Delta\mathbb{I}_{20}(b) - \frac{1}{2}\left(f'_\nu(\lambda_b)\Delta\mathbb{I}_{10}(b)\right)^2\right)\end{aligned}$$

Bias on Magnitude for SED shape correction

Error on Magnitude for SED-shape correction

$$\begin{aligned}
\Delta\mathbb{I}_{i0}(b) &= \mathbb{I}_{i0}^{obs}(b, z_{obs}, aer_{obs}, pwv_{obs}) - \mathbb{I}_{i0}^{std}(b, z_{std}, aer_{std}, pwv_{std}) \\
&= \left(\mathbb{I}_{i0}^{obs}(b, z_{obs}, aer_{obs}, pwv_{obs}) - \mathbb{I}_{i0}^{std}(b, z_{obs}, aer_{std}, pwv_{std})\right) + \\
&\quad \left(\mathbb{I}_{i0}^{std}(b, z_{obs}, aer_{std}, pwv_{std}) - \mathbb{I}_{i0}^{std}(b, z_{std}, aer_{std}, pwv_{std})\right)
\end{aligned}$$

Linearity of corrections - standard atmosphere at different airmass

$$\Delta\mathbb{I}_{i0}(b) = \left(\mathbb{I}_{i0}^{obs}(b, z_{obs}) - \mathbb{I}_{i0}^{std}(b, z_{obs})\right) + \frac{\partial}{\partial z}\mathbb{I}_{i0}^{std}(b, z_{std})(z_{obs} - z_{std}) + \cdot$$

- $\mathbb{I}_{i0}^{obs}(b, z_{obs})$: measured
- $\mathbb{I}_{i0}^{std}(b, z_{obs})$ and $\frac{\partial}{\partial z}\mathbb{I}_{i0}^{std}(b, z_{std})$: from standard atmospheric model

- From a reference catalog of calibration stars j wih known $\overline{m_b^{std}(j)}$
- Optimize the following χ^2 in band b (i exposure, j star-object, $\sigma_{phot}(i,j)$, photometric error):

$$\chi_b^2 = \sum_{(i,j)} \frac{\left(m_b^{std}(i,j) - \overline{m_b^{std}(j)}\right)^2}{\sigma_{phot}^2(i,j)} \quad (31)$$

- With the measured magnitude in LSST is :

$$\begin{aligned} m_b^{std}(i,j) &= -2.5\log_{10}(C_b^{i,j}) + 2.5\log_{10}(\mathbb{I}_0^{obs,i}(b)) + ZPT^{AB}(i) \\ &+ 2.5\log_{10}\left(\frac{1 + f_\nu'(\lambda_b)(b)\mathbb{I}_{10}^{obs,i}(b)}{1 + f_\nu'(\lambda_b)(b)\mathbb{I}_{10}^{std}(b)}\right) \end{aligned} \quad (32)$$

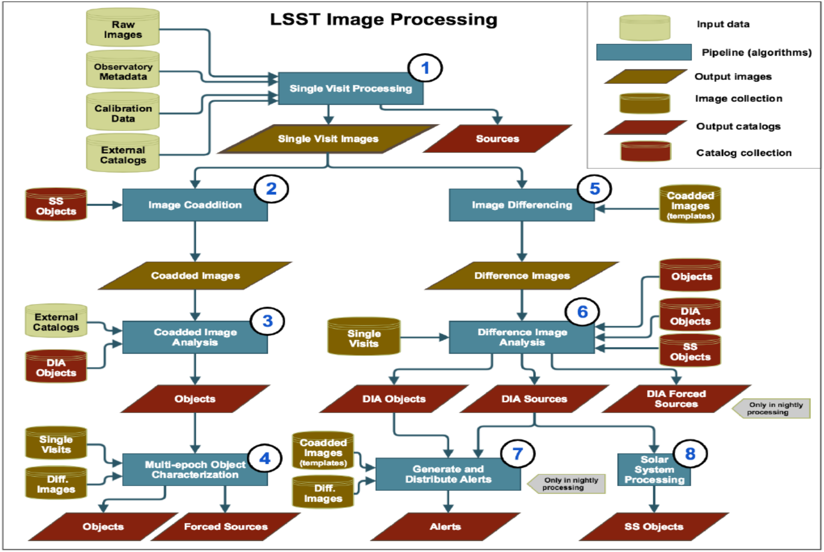


FIGURE 2: Illustration of the conceptual design of LSST science pipelines for imaging processing.

Rubin-LSST science pipeline

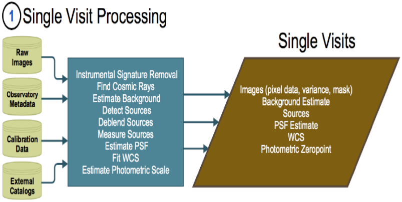


FIGURE 3: Illustration of the conceptual algorithm design for Single Visit Processing pipeline.

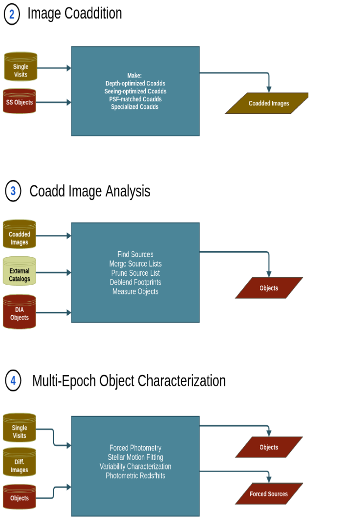
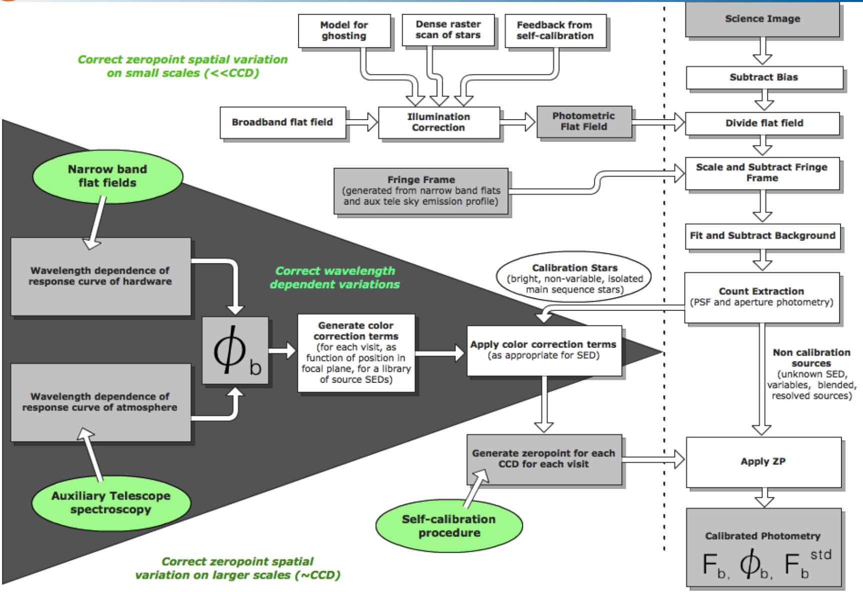
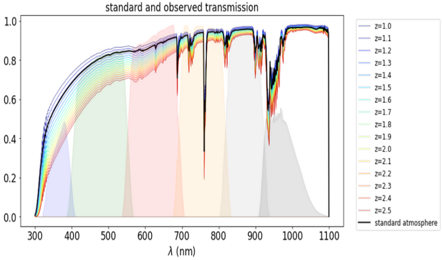


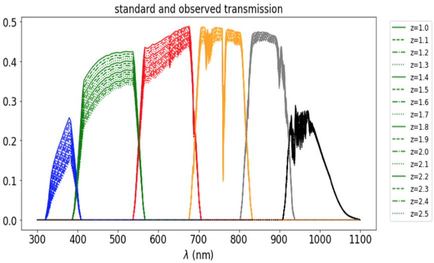
FIGURE 4: Illustration of the conceptual algorithm design for Image Coaddition, Coadded Image Analysis, and Multi-epoch Object Characterization pipelines.

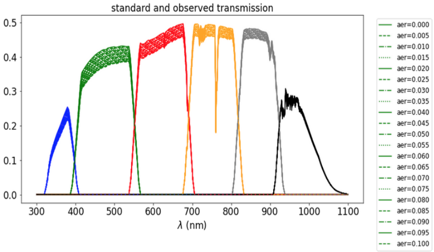
Rubin-LSST calibration plan

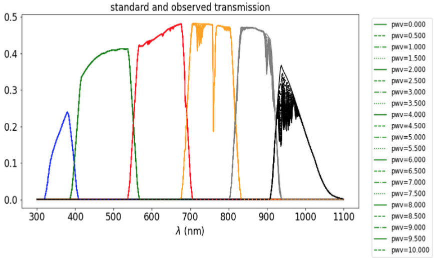


Atmospheric simulation and S_b^{obs}



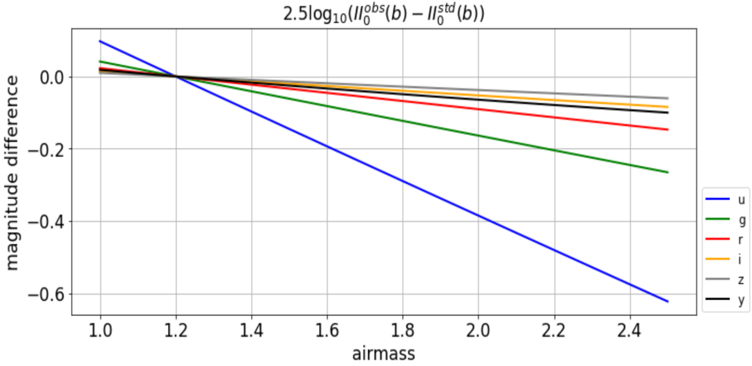






vs airmass, relative to the standard transmission

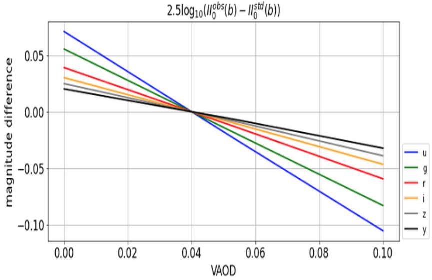
$$\mathbb{I}_0^{obs}(b, z) - \mathbb{I}_0^{std}(b, z_{std}) \tag{33}$$

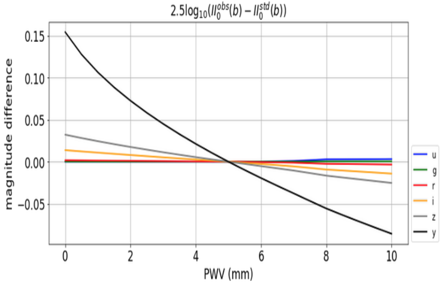


The 0^{th} order of the photometric correction

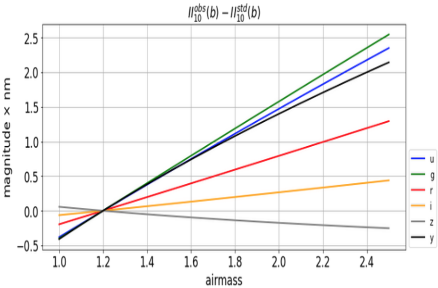
vs aeorols or PWV, relative to the standard transmission

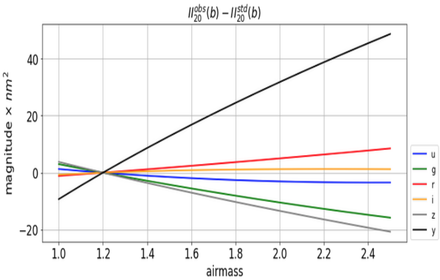
$$\mathbb{I}_0^{obs}(b, z_{std}) - \mathbb{I}_0^{std}(b, z_{std}) \quad (34)$$





The $1^{st}\&2^{nd}$ orders Integral differences





End of part 1