The impact of photo-z on LSST science requirements

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With special thanks to
Andy Connolly

LSST Photo-z Workshop
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Outline

1) A couple of general points about the SRD
   - introduction: flow-down of science goals
   - cadence “conservation laws”
2) Photo-z and filter complement
   - basic characteristics
   - expected performance
3) Detailed filter design
   - tapered edges
4) Photo-z precision vs. time
   - photometric depth and precision vs. time
5) Systematic effects
   - dithering (emission lines, blue/red leaks)
6) How can you help the Project
What is LSST? A uniform sky survey.

- ~90% of time will be spent on a uniform survey: every 3-4 nights, the whole observable sky will be scanned twice per night.
- After 10 years, half of the sky will be imaged about 1000 times (in 6 bandpasses, ugrizy): a digital color movie of the sky.
- ~100 PB of data: about 2.5 million 3.2 Gpix images (visits), enabling measurements for 40 billion objects.

LSST in one sentence:
An optical/near-IR survey of half the sky in ugrizy bands to r~27.5 (36 nJy) based on 1000 visits over a 10-year period: deep wide fast.

Left: a 10-year simulation of LSST survey: the number of visits in the r band (Aitoff projection of eq. coordinates).
Flowdown of Science Goals to System Requirements

System

Atmosphere (transmission, refraction, seeing, sky background)

Telescope (collecting area, mirror reflectivity, slew and settle time, contribution to seeing, scattered light, FOV)

Camera (CCD QE curve, optical transmissions and reflections, charge diffusion, readout noise, crosstalk, filters)

Data processing (data throughput, algorithmic errors, speed, bugs)

Science

Dark matter, dark energy, cosmology (spatial distribution of galaxies, gravitational lensing, supernovae)

Time domain (cosmic explosions, variable stars)

The Solar System structure (asteroids)

The Milky Way structure (stars, ISM)

Any given science program drives numerous system parameters
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Data Properties

- Image Depth
- Delivered Seeing
- Number of images
- Distributions with respect to time, bandpass and observing conditions

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Key point: Science goals and technical parameters are connected through, and communicate via, data properties

SRD specifies data properties needed to achieve science goals
Science Requirements Document (SRD)

At the highest level, LSST objectives are:

1) Obtain about a billion 16 Megapixel images of the sky, with characteristics as specified in the SRD:

- ~90% of time will be spent on a uniform survey: every 3–4 nights, the whole observable sky will be scanned twice per night (one “visit” is two back-to-back 15-second exposures)

- after 10 years, half of the sky will be imaged about 800 times (in 6 bandpasses, ugrizy): a digital color movie of the sky

- ~24 PB of raw image data, enabling measurements for 37 billion objects

Baseline cadence is defined in terms of data properties, not photo-z, and window (sampling) functions (area on the sky, temporal sampling, bandpass sampling, etc.)

Simulated cadence output consists of ~2.5 million values for (mjd, ra, dec, filter, m5, seeing, sky brightness, etc)
Deployment optimization: cadence “conservation laws”

How can we optimize the main deployment parameters: exposure time and depth per visit, the mean revisit time, and the number of visits?

While each of these four parameters has its own drivers, they are not independent (scaled to nominal LSST):

\[
\begin{align*}
m_5 &= 24.7 + 1.25 \log(t_{vis} / 30 \text{ sec}) \\
N_{\text{revisit}} &= 3 \text{ days} \times (t_{vis} / 30 \text{ sec}) \\
N_{\text{vis}} &= 1000 \times (30 \text{ sec} / t_{\text{vis}}) \times (T / 10 \text{ years})
\end{align*}
\]

How to allocate the total observing time per position of ~8 hours to ugrizy, and how do we split allocations into individual visits?
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\]

\[
N_{\text{vis}} = 1000 \cdot (30 \text{ sec} / t_{\text{vis}}) \cdot (T / 10 \text{ years})
\]

Direct and indirect constraints on the shortest and longest acceptable exposure time per visit span a remarkably narrow range: \(20 \text{ sec} < t_{\text{vis}} < 40 \text{ sec}\) for the main survey \(t_{\text{vis}} = 30 \text{ sec}\) as default

(see section 2.2.2 in “overview” paper, arXiv:0805.2366)
Deployment optimization: cadence “conservation laws”

While each of these four parameters has its own drivers, they are not independent (scaled to nominal LSST):

\[ m_5 = 24.7 + 1.25 \times \log(t_{vis} / 30 \text{ sec}) \]

\[ n_{revisit} = 3 \text{ days} \times (t_{vis} / 30 \text{ sec}) \]

\[ N_{vis} = 1000 \times (30 \text{ sec} / t_{vis}) \times (T / 10 \text{ years}) \]

How to allocate the total observing time per position of ~8 hours to ugrizy, and how do we split allocations into individual visits?

The co-added depth is driven by photo-z:

\[ m_5^{\text{Coadded}} = 24.7 + 1.25 \times \log(f_{\text{band}} \times N_{vis}) \]

\[ m_5^{\text{Coadded}} = (26.1, 27.4, 27.5, 26.8, 26.1, 24.9) \]

in (ugrizy)
Combining these probes, LSST will measure the comoving distance as a function of redshift in the redshift range 0.3–3.0 with an accuracy of 1-2%, and separately the growth of cosmic mass structure. A sample of about four billion galaxies with sufficiently accurate photometric redshifts is required. In order to achieve this comoving distance accuracy, the photometric redshifts requirements for this $i < 25$ flux-limited galaxy sample are i) the rms ($\sigma$) for error in $(1 + z)$ must be smaller than 0.02, ii) the fraction of “catastrophic” outliers (defined as those with errors exceeding the larger of 0.06 and $3\sigma$) must be below 10%, and iii) the bias must be below 0.003. These requirements are primary drivers for the photometric depth of the main LSST survey. In addition, methods for rejecting the majority of those outliers, and for characterizing their effects on the sample, must be developed. The calibration of photometric redshifts and their errors can be a combination of correlation with bright spectroscopic samples and spot-checks with many-band photometric redshifts.

1) Assumes 4 billion galaxies with $i < 25.3$
2) Rms $< 0.02 \times (1+z)$
3) Bias $< 0.003$
4) “3-sigma” outlier fraction $< 10\%$
The adopted values come from iterative optimization: studies and analysis by Andy Connolly, Lynne Jones, Kirk Gilmore, Tony Tyson, Sam Schmidt, Jeff Newman, and many others. The science metrics (e.g. see Dark Energy Task Force report) scale with the number of galaxies, for assumed photo-z precision. Photo-z precision is in turn driven by photometric accuracy. LSST Project does not guarantee this photo-z performance, only the photometric accuracy that can enable such performance!

1) Assumes 4 billion galaxies with $i < 25.3$
2) $\text{Rms} < 0.02 \times (1+z)$
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Science Requirements Document (SRD)
At the highest level, LSST objectives are:

1) Obtain about a billion 16 Megapixel images of the sky, with characteristics as specified in the SRD:

Specification: The sky area uniformly covered by the main survey will include Asky square degrees (Table 22).

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Design Spec</th>
<th>Minimum Spec</th>
<th>Stretch Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asky (deg²)</td>
<td>18,000</td>
<td>15,000</td>
<td>20,000</td>
</tr>
</tbody>
</table>

Table 22: The sky area uniformly covered by the main survey.

Specification: The sum of the median number of visits in each band, Nv1, across the sky area specified in Table 22, will not be smaller than Nv1 (Table 23).

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Design Spec</th>
<th>Minimum Spec</th>
<th>Stretch Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nv1</td>
<td>825</td>
<td>750</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 23: The sum of the median number of visits in each band across the sky area specified in Table 22.
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At the highest level, LSST objectives are:

1) Obtain about a billion 16 Megapixel images of the sky, with characteristics as specified in the SRD:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>u</th>
<th>g</th>
<th>r</th>
<th>i</th>
<th>z</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nv1 (design spec.)</td>
<td>56</td>
<td>80</td>
<td>184</td>
<td>184</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>Idealized Depth</td>
<td>26.1</td>
<td>27.4</td>
<td>27.5</td>
<td>26.8</td>
<td>26.1</td>
<td>24.9</td>
</tr>
</tbody>
</table>

Table 24: An *illustration* of the distribution of the number of visits as a function of band-pass, obtained by detailed simulations of LSST operations that include realistic weather, seeing and sky brightness distributions, as well as allocation of about 10% of the total observing time to special programs. The median number of visits per field for all bands is 824. For convenience, the numbers in parentheses show the corresponding gain in depth (magnitudes), assuming $\sqrt{N}$ scaling. The last row shows the total *idealized* coadded depth for the design specification median depth of a single image (assuming 5σ depths at $X = 1$ of $u = 23.9$, $g = 25.0$, $r = 24.7$, $i = 24.0$, $z = 23.3$ and $y = 22.1$, from Table 6), and the above design specification for the total number of visits. The coadded image depth losses due to airmass greater than unity are not taken into account. For a large suite of simulated main survey cadences, they are about 0.2-0.3 mag, with the median airmass in the range 1.2-1.3.

Note: 824 visits with two 15-sec exposures is 6.9 hours (~1 night/field).
Photometric redshifts: random errors smaller than 0.02, bias below 0.003, fewer than 10% $>3\sigma$ outliers. These photo-z requirements are one of the primary drivers for the photometric depth and accuracy of the main LSST survey (and the definition of filter complement).

Photo-z requirements correspond to $r \sim 27.5$ with the following per band time allocations:

- $u$: 8%
- $g$: 10%
- $r$: 22%
- $i$: 22%
- $z$: 19%
- $y$: 19%

Consistent with other science themes (stars)
6 bands are needed!

Both $u$ and $y$ bands are needed for photo-$z$.

Both are also required by stellar science.
Photo-z:
From Sam Schmidt

Assuming that the SRD specs for photometry are met, all 3 photo-z specs will be met too.

But: need to train photo-z methodology.
Filters are specified to vendors individually. Filters represent substantial procurement. We wanted to build robustness into filter specifications - we cannot write acceptance criteria for a filter based on what happens with its adjacent filter(s). At least in principle, we might end up going with different vendors and this is the main reason for per filter specifications.

Photo-z is an important science driver, and it is very sensitive to gaps. Because filters have to be specified individually, we couldn't say "we don't want gaps", and because vendors could not guarantee exact placement of bandpass edges, Connolly et al. developed trapezoidal specs that were given to vendors.
Final specification
Requirements to be met over integrated incident cone for the central 100mm aperture

Linear Edge envelope:
- 25 nm taper
- 40% < Cross over < 60%
  (Except for u/g and z/y)

Integrated < 0.05% total transmission
QE curve can be combined above 1050nm

Mean in 10nm interval < 0.01% Peak
QE curve can be combined above 1050nm

Transmission first goes below 0.1% of Peak

Central wavelength

FWHM
Progress towards the survey goals

Main performance metrics as functions of time:
Co-added survey depth:

\[ m_5(t) = m_5^{\text{Final}} + 1.25 \times \log(t / 10 \text{ yr}) \]

Photometric errors at i=25 (4 billion galaxy sample):

\[ \sigma_{\text{ph}}(t) = 0.04 \text{ mag} \times (t / 10 \text{ yr})^{(-1/2)} \]

Trigonometric parallax errors at r=24:

\[ \sigma_{\pi}(t) = 3.0 \text{ mas} \times (t / 10 \text{ yr})^{(-1/2)} \]

Proper motion errors at r=24:

\[ \sigma_{\mu}(t) = 1.0 \text{ mas/yr} \times (t / 10 \text{ yr})^{(-3/2)} \]

DETF FOM (FOMFinal ~750):

\[ \text{FOM}(t) = \text{FOM}^{\text{Final}} \times (t / 10 \text{ yr}) \]

NEO (140m) completeness (t_{\text{NEO}}\sim4 \text{ yrs}; C_{\text{NEO}}\sim0.9):

\[ C(t) = C_{\text{NEO}} \times (1 - \exp[-(t / t_{\text{NEO}})\sim(-3/4)]) \]

And many other (e.g., the faint limit for period recovery of short-period variables, KBO and main-belt asteroid completeness )...

LSST design and performance analysis is based on sophisticated simulations but these scaling laws and resulting trade-offs offer basis for quick and robust multi-dimensional trade analysis of various “what if” scenarios.
Performance as a function of survey duration

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Year 1</th>
<th>Y3</th>
<th>Y5</th>
<th>Y8</th>
<th>Year 10</th>
<th>Y12</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_5$ coadd</td>
<td>26.3</td>
<td>26.8</td>
<td>27.1</td>
<td>27.4</td>
<td>27.5</td>
<td>27.6</td>
</tr>
<tr>
<td>$\sigma_{i=25}$</td>
<td>0.12</td>
<td>0.07</td>
<td>0.06</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Color vol.</td>
<td>316</td>
<td>20</td>
<td>6</td>
<td>1.7</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td># of visits</td>
<td>83</td>
<td>248</td>
<td>412</td>
<td>660</td>
<td>825</td>
<td>990</td>
</tr>
<tr>
<td>$\sigma_{r=24}$</td>
<td>9.5</td>
<td>5.5</td>
<td>4.2</td>
<td>3.3</td>
<td>3.0</td>
<td>2.7</td>
</tr>
<tr>
<td>$\sigma_{\mu}$</td>
<td>32</td>
<td>6.1</td>
<td>2.8</td>
<td>1.4</td>
<td>1.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Between years 1 and 10: 1.2 mag deeper, 30x better proper motions

While unprecedented science outcome will definitely be possible even with a first few years of LSST data, the complete planned and designed for science deliverables will require 10–years of data, with a tolerance of at most about 1–2 years.

Photo-z precision improvement between years 1 and 10: about a factor 2-3, depending on systematic effects (evolution etc).
Performance as a function of survey duration

Photo-z precision improvement between years 1 and 10: about a factor of 2.

NB 7 years for OK outliers!
Baseline cadence (OpSim3.61)

Median 5-sigma depth (for all visits)

OpSim gives variation around the mean depth due to seeing, sky brightness, and airmass variations. The mean value is inserted as input to OpSim (best Cm estimates).
MAF examples
- coadded depth
- sky plots, histograms, power spectrum etc.
- dithered vs. not
- user friendly
- @ cadence workshop
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New MAF functionality

Figure 4: The angular power spectrum of the coadded 5σ limiting magnitude, with and without dithering (blue and green lines, respectively).
How can you help the Project

1) Input for photo-z tools
   - template SEDs and other inputs
   - new photo-z methods

2) Sophisticated analysis
   - emission lines
   - the impact of varying atmosphere
   - complex joint modeling
     (e.g. stars vs. galaxies vs. quasars in color–flux–size–motion space)

3) Survey optimization
   - depth per band

4) pdf description (see “photoZ” in ls.st/dpdd)
   - e.g. parametric vs. non-parametric
The impact of varying atmosphere

Intrinsically different galaxies at different redshifts can have similar colors and thus hard to distinguish photo-z. But they can have different photometric corrections to standard photometric bandpass, which if measured with sufficient precision, can provide additional information to constrain their intrinsic SEDs and thus the true redshifts.
The impact of varying atmosphere

From LSE-180

4.1. Bandpasses and Associated Magnitudes

This then leads us to introduce a ‘normalized bandpass response function’, $\phi_b^{obs}(\lambda, t)$, that represents the true bandpass response shape for each observation,

$$
\phi_b^{obs}(\lambda, t) = \frac{S_{atm}(\lambda, alt, az, t) S_{sys}^{sys}(\lambda, x, y, t) \lambda^{-1}}{\int_0^\infty S_{atm}(\lambda, alt, az, t) S_{sys}^{sys}(\lambda, x, y, t) \lambda^{-1} d\lambda}.
$$

(5)

Note that $\phi_b$ only represents shape information about the bandpass, as by definition

$$
\int_0^\infty \phi_b(\lambda) d\lambda = 1.
$$

(6)

Using $\phi_b^{obs}(\lambda, t)$ we can represent the in-band flux at the top of the atmosphere for each observation as

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

(7)

where the normalization of $F_b(t)$ corresponds to the top of the atmosphere. Unless $F_\nu(\lambda, t)$ is a flat ($F_\nu(\lambda) = \text{constant}$) SED, $F_b^{obs}$ will vary with changes in $\phi_b^{obs}(\lambda, t)$ due simply to
The impact of varying atmosphere

\[ F_{b}^{\text{std}}(t) = \int_{0}^{\infty} F_{\nu}(\lambda, t) \phi_{b}^{\text{std}}(\lambda) \, d\lambda, \quad (8) \]

is a constant value for non-variable sources.

We define a ‘natural magnitude’

\[ m_{b}^{\text{nat}} = -2.5 \log_{10} \left( \frac{F_{b}^{\text{obs}}}{F_{AB}} \right) \quad (9) \]

where \( F_{AB} = 3631 \) Jy. The natural magnitude will vary from observation to observation as \( \phi_{b}^{\text{obs}}(\lambda, t) \) changes, even if the source itself is non-variable. The natural magnitude can be transformed to a ‘standard magnitude’, \( m_{b}^{\text{std}} \), as follows:

\[ m_{b}^{\text{nat}} = -2.5 \log_{10} \left( \frac{F_{b}^{\text{obs}}}{F_{AB}} \right) \quad (10) \]
\[ = -2.5 \log_{10} \left( \frac{\int_{0}^{\infty} F_{\nu}(\lambda, t) \phi_{b}^{\text{obs}}(\lambda, t) \, d\lambda}{F_{AB}} \right) \quad (11) \]
\[ = -2.5 \log_{10} \left( \left( \frac{\int_{0}^{\infty} F_{\nu}(\lambda, t) \phi_{b}^{\text{obs}}(\lambda, t) \, d\lambda}{\int_{0}^{\infty} F_{\nu}(\lambda, t) \phi_{b}^{\text{std}}(\lambda, t) \, d\lambda} \right) \left( \frac{\int_{0}^{\infty} F_{\nu}(\lambda, t) \phi_{b}^{\text{std}}(\lambda, t) \, d\lambda}{F_{AB}} \right) \right) \quad (12) \]

\[ m_{b}^{\text{obs}} = \Delta m_{b}^{\text{obs}} + m_{b}^{\text{std}} \quad (13) \]
\[ \Delta m_{b}^{\text{obs}} = -2.5 \log_{10} \left( \frac{\int_{0}^{\infty} F_{\nu}(\lambda, t) \phi_{b}^{\text{obs}}(\lambda, t) \, d\lambda}{\int_{0}^{\infty} F_{\nu}(\lambda, t) \phi_{b}^{\text{std}}(\lambda, t) \, d\lambda} \right) \quad (14) \]

where \( \Delta m_{b}^{\text{obs}} \) varies with the shape of the source spectrum, \( F_{\nu}(\lambda, t) \) and the shape of the bandpass \( \phi_{b}^{\text{obs}}(\lambda, t) \) in each observation. Note that \( \Delta m_{b}^{\text{obs}} = 0 \) for flat (constant) SEDs, as the integral of \( \phi_{b}(\lambda) \) is always one.
The impact of varying atmosphere

Intrinsically different galaxies at different redshifts can have similar colors and thus hard to distinguish photo-z. But they can have different photometric corrections to standard photometric bandpass, which if measured with sufficient precision, can provide additional information to constrain their intrinsic SEDs and thus the true redshifts.

The strength of this effect (change of magnitude with airmass, or more generally, with atmospheric throughput) is up to about 0.03 mag/airmass.

It’s not immediately obvious how useful this effect would be – we need detailed modeling and (5+6)-dimensional photo-z! (5 colors and 6 per-band gradients; n.b. the effect is much stronger in blue than in red bands)

(ZI’s seat-of-the-pants estimate: more than a few % and fewer than 50% of outliers could be mitigated using this method)
Photometric redshifts: random errors smaller than 0.02, bias below 0.003, fewer than 10% >3σ outliers.

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Photo-z requirements correspond to r~27.5 with the following per band time allocations:

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- i: 22%
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- y: 19%

Instead of Conclusions