Large Synoptic Survey Telescope
Data Products Definition Document
(*** DRAFT ***)

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with input from

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Abstract

This document describes the plans for contents of Level 1 and 2 LSST data products, and the rationale behind various choices that were made. This is an **internal draft** and a work in progress. **It should not be circulated widely until this notice is removed.**

Contents

1 Introduction

LSST will be a large, wide-field ground-based optical telescope system designed to obtain multiple images covering the sky that is visible from Cerro Pachón in Northern Chile. The current baseline design, with an 8.4m (6.7m effective) primary mirror, a 9.6 deg^2 field of view, and a 3.2 Gigapixel camera, will allow about 10,000 square degrees of sky to be covered using pairs of 15-second exposures twice per night every three nights on average, with typical 5σ depth for point sources of $r \sim 24.5$ (AB). The system is designed to yield high image quality as well as superb astrometric and photometric accuracy. The total survey area will include 30,000 deg^2 with $\delta < +34.5°$, and will be imaged multiple times in six bands, *ugrizy*, covering the wavelength range 320–1050 nm. The project is scheduled to begin the regular survey operations at the start of next decade. About 90% of the observing time will be devoted to a deep-wide-fast survey mode which will uniformly observe a 18,000 deg^2 region about 1000 times (summed over all six bands) during the anticipated 10 years of operations, and yield a coadded map to $r \sim 27.5$. These data will result in databases including 10 billion galaxies and a similar number of stars, and will serve the majority of the primary science programs. The remaining 10% of the observing time will be allocated to special projects such as a Very Deep and Fast time domain survey.

The LSST will be operated in fully automated survey mode. The images acquired by the LSST Camera will be processed by LSST Data Management software to a) detect and characterize imaged astrophysical sources and b) detect and characterize changes in time in LSST-observed universe. The results of that processing will be reduced images, catalogs of detected objects and the measurements of their properties, and prompt alerts to "events" – changes in astrophysical scenery discovered by differencing incoming images against older, deeper, images of the sky in the same direction (*templates*, see §2.4.3).

The *broad*, *high-level*, requirements for LSST Data Products are given by the LSST Science Requirements Document. This document lays out the *specifics* of what the data products will comprise of, how those data will be generated, and when. It serves to inform the flow-down from the *LSST Science Requirements Document* and the *LSST Observatory System Specifications*, to the *LSST Data Management System Requirements* document, the UML model, and the database schema.

1.1 Level 1 and 2 Data Products

LSST Data Management will perform two, somewhat overlapping in scientific intent, types of image analyses:

1. Analysis of difference images, with the goal of detecting and characterizing astrophysical phenomena revealed by their time-dependent nature. The detection of supernovae superimposed on bright extended galaxies is an example of this analysis. The processing is done on a nightly or daily basis and produces **Level 1** data products. They include the difference images, the sources detected in difference images (`DIASources`), astrophysical objects[1] these are associated to (`DIAObjects`), and Solar System objects (`SSObjects`[2]). These are added to the **Level 1 database** and made available in real time. Notifications ("alerts") about new `DIASources` will be issued using community-accepted standards within 60 seconds of observation.

2. Analysis of direct images, with the goal of detecting and characterizing astrophysical objects. Detection of faint galaxies on deep co-adds and their subsequent characterization is an example of this analysis. The results are **Level 2** data products. These products, released annually[3], will include the single-epoch images, deep co-adds, catalogs of `Objects` (detections on deep co-adds) and `Sources`[4] (measurements on individual direct images), as well as fully reprocessed Level 1 data products (see §2.3.7). In contrast to the Level 1 database, which is updated in real-time, the Level 2 databases are static and will not change after release.

The two types of analyses have different requirements on timeliness. Changes in flux or position of objects may need to be immediately followed

[1]The LSST has adopted the nomenclature by which single-epoch detections of astrophysical *objects* are called *sources*. This nomenclature is not universal: some surveys call *detections* what we call *sources*, and use the term *sources* for what we call *objects*.

[2]`SSObjects` used to be called call "Moving Objects" in previous versions of the Data Products baseline. The name is potentially confusing as high-proper motion stars are moving objects as well. A more accurate distinction is the one between objects inside and outside of the Solar System.

[3]Except for the first two data releases, which will be created six months apart.

[4]When written in bold monospace type, `Objects` and `Sources` refer to objects and sources detected and measured as a part of Level 2 processing.

up, lest interesting information be lost. Thus the primary results of analysis of difference images – discovered and characterized `DIASources` – generally need to be broadcast as *event alerts* within 60 seconds of end of visit[5] acquisition. The analysis of science (direct) images is less time sensitive, and will be done as a part of annual data release process.

2 Level 1 Data Products

2.1 Overview

Level 1 data products are a result of difference image analysis (DIA; §2.2.1). They include the sources detected in difference images (`DIASources`), astrophysical objects that these are associated to (`DIAObjects`), identified Solar System objects[6] (`SSObject`), and related, broadly defined, metadata (including eg., cut-outs[7]).

`DIASources` are sources detected on difference images (those above $S/N = 5$ after correlation with an appropriate PSF profile). They represent changes in flux with respect to a deep template. Physically, a `DIASource` may be an observation of new astrophysical object that was not present at that position in the template image (for example, an asteroid), or an observation of flux change in an existing source (for example, a variable star). Their flux can be negative (eg., if a source present in the template image reduced its brightness, or moved away).

Groups of `DIASources` detected on visits taken at different times are associated with either a `DIAObject` or an `SSObject` to represent the underlying astrophysical phenomenon. The association can be made in two different ways: by assuming the underlying phenomenon is an object within the Solar System moving on an orbit around the Sun[8], or by assuming it to be distant

[5]The LSST takes two (nominally 15 second) exposures per pointing, called *snaps*. That pair of exposures is called a *visit*.

[6]The LSST SRD considers Solar System object orbit catalog to be a Level 2 data product (LSSTSRD, Sec 3.5). Nevertheless, to successfully differentiate between apparitions of known Solar System objects and other types `DIASources` we consider it functionally a part of Level 1.

[7]Small, 30×30, sub-images at the position of a detected source. Also known as *postage stamps*.

[8]We don't plan to fit for motion around other Solar System bodies; eg., identifying new satellites of Jupiter is left to the community.

enough to only exhibit small parallactic and proper motion[9]. The latter type of association is performed during difference image analysis right after the image has been acquired. The former is done at daytime by the Moving Objects Processing Software (`MOPS`), unless the `DIASource` is an apparition of an already known `SSObject`. In that case, it will be flagged as such during difference image analysis.

All `DIASources` will be alerted on at the end of the difference image analysis[10].

2.2 Level 1 Data Processing

2.2.1 Difference Image Analysis

The following is a high-level description of steps which will occur during regular difference image analysis:

1. A visit is acquired and reduced to a single *visit image* (cosmic ray rejection, instrumental signature removal[11], combining of snaps, etc.).

2. The visit image is differenced against the appropriate template and `DIASources` are detected.

3. The flux and shape[12] of the DIASource are measured on the difference image. The visit image is force-photometered at the position of the `DIASource` to obtain a measure of the absolute flux. No deblending will be attempted.

4. The Level 1 database (see §2.3) is searched for a `DIAObject` or `SSObject` with which to positionally associate the observed `DIASource`[13]. If

[9] Where 'small' is small enough to unambiguously positionally associate together individual apparitions of the object.

[10] For observations on the ecliptic near the opposition, Solar System objects will dominate the `DIASource` counts, and (until they're recognized as such) overwhelm the explosive transient signal. It will therefore be advantageous to quickly identify the majority of Solar System objects early in the survey.

[11] Eg., subtraction of bias and dark frames, flat fielding, bad pixel/column interpolation, etc.

[12] The "shape" in this context are weighted 2^{nd} moments, as well as a fit to a trailed source model.

[13] The association algorithm will guarantee that a `DIASource` is associated with not more than one `DIAObject` or `SSObject`. The algorithm will take into account the parallax and

no match is found, a new `DIAObject` is created and the observed `DIASource` is associated to it.

5. If the `DIASource` has been associated with an `SSObject` (a known Solar System object), it will be flagged as such and an alert will be issued. Further processing will occur in daytime (see section 2.2.2).

6. Otherwise, the associated `DIAObject` measurements will be updated with new data. All affected columns will be recomputed, including proper motions, centroids, light curves, etc.

7. The Level 2 database[14] is searched for one or more `Objects` positionally close to the `DIAObject`, out to some maximum radius[15]. The IDs of these `Objects` are recorded in the `DIAObject` record and provided in the event alert.

8. An alert is issued that includes: the name of the Level 1 database, the timestamp of when this database has been queried to issue this alert, the `DIASource` ID, the `DIAObject` ID[16], name of the Level 2 database and the IDs of nearby `Objects`, and the associated science content (centroid, fluxes, low-order lightcurve moments, periods, etc.), *including the full light curves*. See Section 2.5 for a more complete enumeration.

9. For all `DIAObjects` overlapping the field of view, to which a `DIASource` from this visit has not been associated, forced photometry will be performed (point source photometry only). Those measurements will be stored as appropriately flagged `DIASources`[17]. No alerts will be issued for these `DIASources`.

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proper or Keplerian motions, as well as the errors in estimated positions of `DIAObject`, `SSObject`, and `DIASource` to find the maximally likely match. Multiple `DIASources` in the same visit will not be matched to the same `DIAObject`.

[14] Level 2 database is a database resulting from annual data release processing.

[15] Eg., a few arcseconds.

[16] We guarantee that a receiver will always be able to regenerate the alert contents at any later date using the included timestamps and metadata (IDs and database names).

[17] For the purposes of this document, we're treating the `DIASources` generated by precovery measurements to be the same as `DIASources` detected in difference images (but flagged appropriately). In the logical schema, these may be divided into two separate tables.

10. Within 24 hours of discovery, *precovery* PSF forced photometry will be performed on any difference image overlapping the position of new `DIAObjects` taken within the past 30 days, and added to the database. Alerts will not be issued with precovery photometry information.

In addition to the processing described above, a smaller sample of sources detected on difference images *below* the nominal $S/N = 5$ threshold will be measured and stores, in order to enable monitoring of difference image analysis quality.

Also, the system will have the ability to measure and alert on a limited[18] number of sources detected below the nominal threshold for which additional criteria are satisfied. For example, a $S/N = 3$ source detection near a gravitational keyhole may be highly significant in assessing the danger posed by a potentially hazadous asteroid. The project will define the initial set of criteria by the start of Operations.

2.2.2 Solar System Object Processing

The following will occur during regular Solar System object processing (in daytime[19], after a night of observing):

1. The orbits/physical properties of `SSObjects` that were re-observed on the previous night are recomputed. Updated data are entered to the `SSObjects` table.
2. All `DIASources` detected on the previous night, that have not been matched with high probability to a known `Object`, `SSObject`, or an artifact, are analyzed for potential pairs, forming *tracklets.*
3. The collection of tracklets collected over the past 30 days is searched for subsets forming *tracks* consistent with being on the same Keplerian orbit around the Sun.

[18]It will be sized for no less than $\sim 10\%$ of average `DIASource` per visit rate.

[19]Note that there *is no guarantee on when daytime Solar System processing must finish*, just that, averaged over some reasonable timescale (eg., a month), a night's worth of observing is processed within 24 hours. Nights rich in moving objects may take longer to process, while nights with less will finish more quickly. In other words, the requirement is on *throughput*, not latency.

4. For those that are, an orbit is fitted and a new `SSObject` table entry created. `DIASource` records are updated to point to the new `SSObject` record. `DIAObjects` "orphaned" by this unlinking are deleted.[20].

5. Precovery linking is attempted for all `SSObjects` whose orbits were updated in this process. Where successful, `SSObjects` (orbits) are updated as needed.

2.3 The Level 1 database

The described alert processing design presupposes the existence of a Level 1 database that contains the objects and sources detected on difference images. At the very least[21], this database will have tables of `DIASources`, `DIAObjects`, and `SSObjects`, populated in the course of difference image and Solar System object processing[22]. As these get updated and added to, their updated contents becomes visible (queryable) immediately[23].

Note that *this database is only loosely coupled to the Level 2 database.* All of the coupling is through providing positional matches between the `DIAObjects` entries in the Level 1 database and the `Objects` in the Level 2 database database. There is no direct `DIASource`-to-`Object` match. The adopted data model emphasizes that *having a `DIASource` be positionally coincident with an `Object` does not imply it is physically related to it.* Absent other information, the least presumptuous data model relationship is one of *positional association*, not *physical identity*.

This may seem odd at first: for example, in a simple case of a variable star, matching individual `DIASources` to `Objects` is exactly what an astronomer would want. That approach, however, fails in the following scenarios:

- *A supernova in a galaxy.* The matched object in the `Object` table will be the galaxy, which is a distinct astrophysical object. We want to keep the information related to the supernova (eg., colors, the light curve) separate from those measurements for the galaxy.

[20]Some `DIAObjects` may only be left with forced photometry measurements at their location (since all `DIAObjects` are force-photometered on previous and subsequent visits); these will be kept but flagged as such.

[21]It will also contain exposure and visit metadata, MOPS-specific tables, etc. These are either standard/uncontroversial, or implementation-dependent, irrelevant for science, and therefore not discussed here.

[22]The latter is also colloquially known as *DayMOPS*.

[23]No later than the moment of issuance of any event alert that may refer to it.

- *An asteroid occulting a star.* If associated with the star on first apparition, the association would need to be dissolved when the source is recognized as an asteroid (perhaps even as early as a day later).

- *A supernova on top of a pair of blended galaxies.* It is not clear in general to which galaxy this `DIASource` would belong. That in itself is a research question.

`DIASource`-to-`Object` matches can still be emulated via a three-step link (`DIASource`-`DIAObject`-`Object`). For ease of use, views or pre-built table with these will be offered to end-users.

In the sections to follow, we present the *conceptual schemas* for the most important Level 1 database tables. These convey *what* data will be recorded in each table, rather than the details of *how*. For example, columns whose type is an array (eg., `radec`) may be expanded to one table column per element of the array (eg., `ra`, `decl`) once this schema is translated to SQL. Secondly, the tables to be presented are normalizes (i.e., contain no redundant information). For example, since the band of observation can be found by joining a `DIASource` table to the table with exposure metadata, there's no column for 'band' in the `DIASource` table. In the as-built database, the views presented to the users will be appropriately denormalized for ease of use.

2.3.1 `DIASource` Table

This is a table of sources detected at $SNR \geq 5$ on difference images (`DIASources`). On average, we expect ~ 2000 `DIASources` per visit ($\sim$ 2M per night; 20,000 per deg^2 per hour).

Some $SNR \geq 5$ sources will not be caused by observed astrophysical phenomena, but by artifacts (bad columns, diffraction spikes, etc.). The difference image analysis software will attempt to identify and flag these as such.

Unless noted otherwise, all `DIASource` quantities (fluxes, centroids, etc.) are measured on the difference image.

Table 1: `DIASource` Table

Name	Type	Unit	Description
diaSourceId	uint128		Unique source identifier
ccdVisitId	uint64		Id. of CCD and visit where this source was measured
diaObjectId	uint128		Id. of the `DIAObject` this source was associated with, if any.
ssObjectId	uint64		Id. of the `SSObject` this source has been linked to, if any.
midPointTai	double	time	Time of mid-exposure for this DIASource.
radec	double[2]	degrees	(α, δ)[24]
radecCov	float[3]	various	`radec` covariance matrix
xy	float[2]	pixels	Column and row of the centroid.
xyCov	float[3]	various	Centroid covariance matrix
SNR	float		The signal-to-noise ratio at which this source was detected in the difference image.[25]
psFlux	float	nmgy[26]	Calibrated flux for point source model. Note this actually measures the flux *difference* between the template and the visit image.
psFluxSigma	float	nmgy	Estimated uncertainty of `psFlux`.

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[24] The astrometric reference frame will be chosen closer to start of operations.

[25] This is not necessarily the same as psFlux/psFluxSigma, as the flux measurement algorithm may be more accurate than the detection algorithm.

[26] A "maggie", as introduced by SDSS, is a linear measure of flux; one maggie has an AB magnitude of 0. "nmgy" is short for a nanomaggie. Flux of 0.063 nmgy corresponds to a 24.5^{th} magnitude star. See §2.3.5 for details.

Table 1: `DIASource` Table

Name	Type	Unit	Description
psLnL	float		Natural *log* likelihood of the observed data given the point source model.
trailFlux	float	nmgy	Calibrated flux for a trailed source model[27,28]. Note this actually measures the flux *difference* between the template and the visit image.
trailLength	float	arcsec	Maximum likelihood fit of trail length[29,30].
trailAngle	float	degrees	Maximum likelihood fit of the angle between the meridian through the centroid and the trail direction (bearing).
trailLnL	float		Natural *log* likelihood of the observed data given the trailed source model.
trailCov	float[6]	various	Covariance matrix of trailed source model parameters.

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[27] A *Trailed Source Model* attempts to fit a (PSF-convolved) model of a point source that was trailed by a certain amount in some direction (taking into account the two-snap nature of the visit, which may lead to a dip in flux around the mid-point of the trail). Roughly, it's a fit to a PSF-convolved line. The primary use case is to characterize fast-moving Solar System objects.

[28] This model does not fit for the *direction* of motion; to recover it, we would need to fit the model to separately to individual snaps of a visit. This adds to system complexity, and is not clearly justified by increased MOPS performance given the added information.

[29] Note that we'll likely measure trailRow and trailCol, and transform to trailLength/trailAngle (or trailRa/trailDec) for storage in the database. A stretch goal is to retain both.

[30] TBD: Do we need a separate trailCentroid? It's unlikely that we do, but one may wish to prove it.

Table 1: `DIASource` Table

Name	Type	Unit	Description
fpFlux	float	nmgy	Calibrated flux for point source model measured on the visit image centered at the centroid measured on the difference image (forced photometry flux)
fpFluxSigma	float	nmgy	Estimated uncertainty of `fpFlux`.
fpSky	float	nmgy/asec^2	Estimated sky background at the position (centroid) of the object.
fpSkySigma	float	nmgy/asec^2	Estimated uncertainty of `fpSky`.
moments	float[5]	various	Adaptive first and second moments $(I_x, I_y, I_{xx}, I_{yy}, I_{xy})$, measured on the difference image.
momentsSigma	float[5]	various	Estimated uncertainty for each entry in `moments`.
extendedness	float		A measure of extendedness, computed using a combination of available moments and model fluxes or from a likelihood ratio of point/trailed source models (exact algorithm TBD). $extendedness = 1$ implies a high degree of confidence that the source is extended. $extendedness = 0$ implies a high degree of confidence that the source is point-like.
flags	bit[64]	bit	Flags

2.3.2 `DIAObject` Table

Table 2: `DIAObject` Table

Name	Type	Unit	Description
diaObjectId	uint128		Unique identifier
radec	double[2]	degrees	(α, δ) position of the object at time `radecTai`
radecCov	float[3]	various	`radec` covariance matrix
radecTai	double	time	Time at which the object was at a position `radec`.
pm	float[2]	mas/yr	Proper motion vector[31]
parallax	float	mas	Parallax
pmParallaxCov	float[6]	various	Proper motion - parallax covariances.
psFlux	float[ugrizy]	nmgy	Weighted mean point-source model magnitude.
psFluxErr	float[ugrizy]	nmgy	Standard error of `psFlux`
psFluxSigma	float[ugrizy]	nmgy	Standard deviation of the distribution of `psFlux`.
fpFlux	float[ugruzy]	nmgy	Weighted mean forced photometry flux.
fpFluxErr	float[ugrizy]	nmgy	Standard error of `fpFlux`
fpFluxSigma	float[ugrizy]	nmgy	Standard deviation of the distribution of `fpFlux`.
lsPeriod	float[ugrizy]	day	Period (the coordinate of the highest peak in Lomb-Scargle periodogram)
lsSigma	float[ugrizy]	day	Width of the peak at `lsPeriod`.
lsPower	float[ugrizy]		Power associated with `lsPeriod` peak.

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[31] High proper-motion or parallax objects will appear as "dipoles" in difference images. Great care will have to be taken not to misidentify these as subtraction artifacts.

Table 2: `DIAObject` Table

Name	Type	Unit	Description
lcChar	float[$6 \times M$]		Light-curve characterization summary statistics (eg., 2nd moments, etc.). The exact contents, and an appropriate value of M, are to be determined in consultation with time-domain experts.
nearbyObj	uint128[3]		Closest `Objects` in Level 2 database.
nearbyObjDist	float[3]	arcsec	Distances to `nearbyObj`.
flags	bit[64]	bit	Flags

2.3.3 `SSObject` Table

Table 3: `SSObject` Table

Name	Type	Unit	Description
ssObjectId	uint64		Unique identifier
oe	double[7]	various	Osculating orbital elements at epoch (q, e, i, Ω, ω, M_0, epoch)
oeCov	double[21]	various	Covariance matrix for `oe`
arc	float	days	Arc of observation.
orbFitLnL	float		Natural log of the likelihood of the orbital elements fit.
nOrbFit	int16		Number of observations used in the fit.
MOID	float[2]	AU	Minimum orbit intersection distances[32]

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[32] `http://www2.lowell.edu/users/elgb/moid.html`

Table 3: `SSObject` Table

Name	Type	Unit	Description
moidLon	double[2]	degrees	MOID longitudes.
H	float[6]	mag	Mean absolute magnitude, per band.
G	float[6]	mag	Fitted slope parameter, per band[33]
hErr	float[6]	mag	Uncertainty in estimate of H
gErr	float[6]	mag	Uncertainty in estimate of G
flags	bit[64]	bit	Flags

The LSST database will provide functions to compute the phase (Sun-Asteroid-Earth) angle α for every observation, as well as the reduced ($H(\alpha)$) and absolute (H) asteroid magnitudes.

2.3.4 Estimator and Naming Conventions

We employ a convention where estimates of standard errors have the suffix `Err`, while the estimates of inherent widths of distribution (or functions in general) have the suffix `Sigma`[34]. The latter are defined as the square roots of the second moment about the quoted value of the quantity at hand.

Unless noted otherwise, maximum likelihood values are be quoted for all fitted parameters (measurements). Together with covariances, these let the end-user apply whatever prior they deem appropriate when computing posteriors[35].

For fluxes, we recognize that a substantial fraction of astronomers will just want the posteriors marginalized over all other parameters, trusting the LSST

[33] The slope parameter for the large majority of asteroids will not be well constrained until later in the survey. We may decide not to fit for it at all over the first few DRs, and add it later in Operations. Alternatively, we may fit it with a strong prior.

[34] Given N measurements, standard errors scale as $N^{-1/2}$, while widths remain constant.

[35] There's a tacit assumption that a Gaussian is a reasonably good description of the likelihood surface around the ML peak.

experts to select an appropriate prior[36]. For example, this is nearly always the case when constructing color-color or color-magnitude diagrams. We will support these use cases by providing additional pre-computed columns, taking care to name them appropriately so as to minimize accidental incorrect usage. For example, a column named `gFlux` may be the expectation value of the g-band flux, while `gFluxML` may be the maximum likelihood value.

2.3.5 Fluxes and Magnitudes

Because flux measurements on difference images are performed against a template, the measured flux of a source on the difference image can be negative. The flux can also go negative for faint sources in the presence of noise. Negative fluxes cannot be stored as (Pogson) magnitudes; log of a negative number is undefined. We've therefore decided to store fluxes rather than magnitudes, in database tables[37].

We quote fluxes in units of "maggie". A maggie, as introduced by SDSS, is a linear measure of flux. An object with flux of one maggie (integrated over the bandpass) has an AB magnitude of zero:

$$m_{AB} = -2.5 \log_{10}(f/\mathrm{maggie}) \tag{1}$$

We chose to use maggies (as opposed to Jansky) to allow the user to differentiate between two separate sources of calibration error: the error in relative (internal) calibration of the survey, and the error in absolute calibration that depends on the knowledge of absolute flux of photometric standards.

We realize that the large majority of users will want to work with magnitudes. For convenience, we plan to provide columns with (Pogson) magnitudes[38], where values with negative flux will evaluate to `NULL`. Similarly, we will provide columns with flux expressed in Jy (and its error estimates).

2.3.6 Precovery Measurements

When a new `DIASource` is detected, it's useful to perform (PSF) forced photometry at the location of the new source on images taken prior to discovery.

[36]It's likely that most cases will require just the expectation value alone.

[37]This is a good idea in general. Eg. given multi-epoch observations, one should always be averaging fluxes, rather than magnitudes.

[38]These will most likely be implemented as "virtual" or "computed" columns

These are colloquially know as *precovery measurements*[39]. Performing precovery in real time over all previously acquired visits is too I/O intensive to be feasible. We therefore plan the following:

1. For all newly discovered objects, perform precovery PSF forced photometry on visits taken over the previous 30 days[40].

2. Make available a "precovery service" to request precovery for a limited number of `DIASources` across all previous visits, and make it available within 24 hours of the request. Web interface and machine-accessible APIs will be provided.

The former should satisfy the most common use cases (eg., SNe), while the latter will provide an opportunity for more extensive timely precovery of targets of special interest.

2.3.7 Annual Reprocessings

In what we've described so far, the Level 1 database is continually being added to as new images are taken and `DIASources` identified. Every time a new `DIASource` is associated to an existing `DIAObject`, the `DIAObject` record is updated to incorporate new information brought in by the `DIASource`. Once discovered and measured, the `DIASources` would never be re-discovered and re-measured at the pixel level.

This is not optimal. Newer versions of LSST pipelines will improve detection and measurements on older data. Also, PSF forced photometry should be performed on the position of the `DIAObject` on all pre-discovery images. This argues for periodic *reprocessing* of the Level 1 data set.

We plan to reprocess all image differencing-derived data (the Level 1 database), at the same time as we perform the annual Level 2 data release productions. This will include all images taken since the start of observation, to the time when the DR production begins. The images will be reprocessed using a single version of the image differencing and measurement software, resulting in a consistent data set.

[39] When Solar System objects are concerned, precovery has a slightly different meaning: predicting the position of a newly discovered `SSObject` on previously acquired visits, and associating with it `DIASources` consistent with its predicted position.

[40] We will be maintaining a cache of 30 days of processed images to support this feature.

As reprocessing is expected to take approximately ~ 9 months, more imaging will be acquired in the meantime. These data will be reprocessed as well, and added to the new Level 1 database generated by the data release processing. The reprocessed database will thus "catch up" with the Level 1 database currently in use, possibly in a few increments. Once it does, the existing Level 1 database will be replaced with the new one, and all future alerts will refer to the reprocessed Level 1 database. Alerts for new sources "discovered" during data release processing and/or the catch-up process will *not* be issued.

Note that Level 1 database reprocessing and switch will have *significant* side-effects on downstream users. For example, all `DIASource` and `DIAObject` IDs will change in general. Some `DIASources` and `DIAObjects` will disappear (eg., if they're image subtraction artifacts that the improved software was now able to recognize as such). New ones may appear. The `DIASource/DIAObject/Objects` associations will change as well.

While the annual database switches will undoubtedly cause technical inconvenience (eg., a `DIASource` detected at some position and associated to one `DIAObject` ID on day $T-1$, will now be associated to a different `DIAObject` ID on day $T+0$), the resulting database will be a more accurate description of the astrophysics that the survey is seeing (eg., the association on day $T+0$ is the correct one; the associations on $T-1$ and previous days were actually made to an artifact that skewed the `DIAObject` summary of measurements).

To ease the transition, third parties (event brokers) may choose to provide positional-crossmatching to older versions of the Level 1 database. A set of best practices will be developed to minimize the disruptions caused by the switches (eg., when writing event-broker queries, filter on position, not on `DIAObject` ID, if possible, etc.). A Level 1 database distribution service, allowing for bulk downloads of the reprocessed Level 1 database, will need to be established to support the brokers who will use it locally to perform more advanced brokering[41].

Older versions of the Level 1 database will be archived following the same rules as for the Level 2 databases. DR1, the most recent DR, and the penultimate data release will be kept on disk and loaded into the database.

[41] A "bulk-download" database distribution service will be provided for the Level 2 databases as well, to enable end-users to establish and run local mirrors (partial or full).

Others will be archived to tape and available as bulk downloads.

2.3.8 Repeatability of Queries

We require that queries executed at a known point in time against some version of the Level 1 database be repeatable at a later date. The exact implementation of this requirement is under consideration by the DM database team.

One possibility may be to make the key tables (nearly) append-only, with each row having two timestamps – createdTai and deletedTai, so that queries may be limited through a `WHERE` clause:

```
SELECT * FROM DIASource WHERE 'YYYY-MM-DD-HH-mm-SS' BETWEEN
createdTAI and deletedTAI
```

or, more generally:

```
SELECT * FROM DIASource WHERE ‘‘data is valid as of YYYY-MM-DD"
```

A perhaps less error-prone alternative, if technically feasible, may be to provide multiple virtual databases that the user would access as:

```
CONNECT lsst-dr5-yyyy-mm-dd
SELECT * FROM DIASource
```

The latter method would probably be limited to nightly granularity, unless there's a mechanism to create virtual databases/views on-demand.

2.3.9 Uniqueness of IDs across database versions

To reduce the likelihood for confusion, all `Source`, `Object`, `DIASource`, and `DIAObject` IDs shall be unique across database versions. For example, DR4 and DR5 reprocessings will share no identical IDs.

Note, however, that exposure and visit IDs will remain the same across releases.

2.4 Level 1 Image Products

2.4.1 Visit Images

Raw and processed visit images will be made available for download no later than 300 seconds from the end of visit acquisition.

The images will remain accessible with low-latency (seconds from request to start of download) for at least 30 days, with slower access afterwards (minutes to hours).

2.4.2 Difference Images

Complete difference images will be made available for download no later than 300 seconds from the end of visit acquisition.

The images will remain accessible with low-latency (seconds from request to start of download) for at least 30 days, with slower access afterwards (minutes to hours).

2.4.3 Image Differencing Templates

Templates for difference image analysis will be created by co-adding 6-months to a year long groups of visits. The co-addition process will take care to remove any transients or fast moving objects (eg., asteroids) from the templates.

The input images may be further grouped by airmass and/or seeing[42]. Therefore, at DR11, we will be creating 11 groups templates: two for the first year of the survey (DR1 and DR2), and then one using imaging from each subsequent year.

Difference image analysis will use the appropriate template given the time of observation, airmass, and seeing.

2.5 Alerts to `DIASources`

2.5.1 Information Contained in Each Alert

For each detected `DIASource`, LSST will emit an "Event Alert" within 60 seconds of the end of exposure. These alerts will be issued in `VOEvent` format[43], and should be readable by `VOEvent`-compliant clients.

Each alert (a `VOEvent` packet) will at least include the following:

[42] The number and optimal parameters for airmass/seeing bins will be determined in Commissioning.

[43] Or some other format that is broadly accepted and used by the community at the start of LSST commissioning.

- Level 1 database id (example: DR5-Level1)
- alertTimestamp (A timestamp that can be used to execute a query against the Level 1 database as it existed when this alert was issued)
- Science Data:
  - The `DIASource` record that triggered the alert
  - The entire `DIAObject` (or `SSObject`) record
  - All previous `DIASource` records
- 30×30 pixel cut-out of the difference image (10 bytes/pixel, FITS MEF)
- 30×30 pixel cut-out of the template image (10 bytes/pixel, FITS MEF)

2.5.2 Receiving and Filtering the Alerts

Alerts will be transmitted in `VOEvent` format, using standard IVOA protocols (eg., VOEvent Transport Protocol; VTP). As a very high rate of alerts is expected, approaching ~ 2 million per night, we plan for public VOEvent Event Brokers[44] to be the primary end-points of LSST's VTP streams. End-users will use these brokers to classify and filter events on the stream for those fitting their science goals. End-users will *not* be able to subscribe to full, unfiltered, alert streams coming directly from LSST[45].

For the end-users, LSST will provide a basic, limited capacity, alert filtering service. This service will run at the LSST archive center (at NCSA). It will let astronomers create simple filters that limit what alerts are ultimately forwarded to them[46]. These *user defined filters* will be possible to specify using an SQL-like declarative language, or short snippets of (likely Python) code. For example, here's what a filter may look like:

[44] These brokers are envisioned to be operated as a public service by third parties who will have signed MOUs with LSST. An example may be the VAO or its successors.

[45] This is due to finite network bandwidth available: for example, a 100 end-users subscribing to a ~ 100 Mbps stream (the peak full stream data rate at end of the first year of operations) would require 10Gbps WAN connection from the archive center, just to serve the alerts.

[46] More specifically, to their VTP clients. Typically, a user will use the Science User Interface (the web portal to LSST archive center) to set up the filters, and use their VTP client to receive the filtered `VOEvent` stream.

```
# Keep only never-before-seen events within two
# effective radii of a galaxy. This is for illustration
# only; the exact methods/members/APIs may change.

def filter(alert):
    if len(alert.sources) > 1:
        return False
    nn = alert.diaobject.nearest_neighbors[0]
    if not nn.flags.GALAXY:
        return False
    return nn.dist < 2. * nn.Re
```

We emphasize that this LSST-provided capability will be limited, and is *not* intended to satisfy the wide variety of use cases that a full-fledged public Event Broker could. For example, we do not plan to provide any classification (eg., "is the light curve consistent with an RR Lyra?", or "a Type Ia SN?"). No information beyond what is contained in the `VOEvent` packet will be available to user-defined filters (eg., cross-matches with other catalogs). The complexity and run time of user defined filters will be limited by available resources. Execution latency will not be guaranteed. The number of `VOEvents` transmitted to each user per user will be limited as well (eg., at least up to ~ 20 per visit per user, dynamically throttled depending on load). Finally, the total number of simultaneous subscribers is likely to be limited – in case of overwhelming interest, a TAC-like proposal process may be instituted.

2.6 Open Issues

What follows is a (non-exhaustive) list of issues, technical and scientific, that are still being discussed and where changes are likely. Input on any of these will be appreciated. These need to be resolved before this document is baselined.

- *What light-curve metric should we compute and provide with alerts?* We strive to compute general purpose metrics which will facilitate classification. We have not baselined any yet.

- *Should we measure on individual snaps (or their difference)?* Is there a demonstrable science case requiring immediate followup that would be triggered by the flux change over a ~15 second period? Is it technically feasible?

- *Should we choose* `nearbyObj`*s differently?* One proposal is to find the brightest `Object` within XX arcsec (with $XX \sim$ 10arcsec), and the total number of `Objects` within XX arcsec.

- *Should the postage stamps provided with the alerts be binned, and by what factor?*

- *When should we (if ever) stop performing forced photometry on positions of* ***`DIAObjects`****?* Depending on the rate of false positives, unidentified artifacts, or unrecognized Solar System objects, the number of forced measurements may dramatically grow over time.

- *Can we, should we, and how will we measure proper motions on difference images?* This is a non-trivial task (need to distinguish between dipoles that are artifacts, and those due to proper motions), without a clear science driver (since high proper motion stars will be discoverable using Level 2 catalogs).

- *Is Level 1 database required to be relational?.* A no-SQL solution may be more appropriate given the followup-driven use cases. Even if it is relational, the Level 1 database will *not* be sized or architected to perform well on large or complex queries (eg. complex joins, full table scans, etc.).

- *Can users query the Level 1 database for all* ***`DIASources`*** *next to an* ***`Object`****?* Is this technically feasible?

- *Do we have to, and can we, use 128 bit integers for IDs?.* If 64 bit integers are provably sufficient, they will take up less space and be better supported (technologically).

3 Level 2 Data Products

3.1 Overview

Level 2 data products result from direct image[47] analysis. They're designed to enable *static sky* science (eg., studies of galaxy evolution, or weak lensing), and time-domain science that is not time sensitive (eg. statistical investigations of variability). They include images products (reduced single-epoch exposures, called *calibrated exposures*, and co-adds), and catalog products (tables of objects, sources, and related metadata).

Similarly to Level 1 catalogs of `DIAObjects` and `DIASources`, `Objects` in the Level 2 catalog represent the astrophysical phenomena (stars, galaxies, quasars, etc.), while `Sources` represent their single-epoch observations. In contrast to Level 1, `Objects` in Level 2 are not generated by associating the `Sources` detected in individual frames. Instead, we first measure the position and number of `Objects` on special-purpose built *deep-coadds*, and then characterize their properties in individual epochs.

The co-adds used for `Object` detection are designed to be deeper and have better effective seeing than the median visit. At least one co-add per band will be built, a multi-color coadd, and possibly a series of shorter period (eg. yearly) co-adds[48]. The flux limit in deep co-adds will be fainter than on most visits, and detected sources will be easier to deblend.

The deblender will be run simultaneously on the catalog of peaks[49] detected in the deep co-adds, the `DIAObject` catalog from the Level 1 database, and one or more external catalogs. It will use the knowledge of peak positions, bands, time, time variability (from Level 1), Galactic longitude and latitude, and other available information to produce a master list of deblended `Objects`. Metadata on why and how a particular `Object` was deblended will be kept.

The properties of `Objects`, including their exact positions, motions, par-

[47]As opposed to *difference image*, in Level 1.

[48]The short-period co-adds are necessary to avoid missing faint objects showing long-term variability.

[49]The source detection algorithm we plan to employ returns the regions of connected of pixels above the nominal S/N threshold in the *PSF-likelihood image* of the visit. These regions are called *footprints*. Each footprint may have one or more *peaks*, and it is these peaks that the deblender will use to infer the number and positions of objects blended in each footprint.

allaxes, and shapes, will be characterized by MultiFit-type algorithms[50]. Using the measured position as a strong prior, their properties in individual visits (independent of any others) will be measured, forming the table of `Sources` (where $S/N \geq 5$) and `FaintSources` (where $S/N < 5$).

3.2 Level 2 Data Processing

Figure 1 presents a high-level view of the Level 2 data processing workflow[51]. Chronologically, the processing begins with co-add creation (top) and ends with single-epoch object characterization[52].

The following is a high-level description of steps which will occur during regular Level 2 data processing:

1. *Coadd creation*: Deep co-adds are created in *ugrizy* bands, as well as a deeper, multi-color, co-adds[53]. They will be optimized for a reasonable combination of depth (i.e., no PSF matching) and resolution (i.e., only above-average seeing visits may be used to construct them). Transient sources (including Solar System objects, explosive transients, etc), will be rejected from the co-adds. See § 3.4.2 for details.

2. *Co-add source detection and characterization.* Sources will be detected on all co-adds generated in the previous step. The source detection algorithm will detect regions of connected of pixels, known as *footprints*, above the nominal S/N threshold in the *PSF-likelihood image* of the visit. Each footprint may have one or more *peaks*, and the collection of these peaks (and their membership in the footprints) are the output of this stage.

3. *Association and deblending.* The next stage in the pipeline, which we will for simplicity just call *the deblender*, synthesizes a list of unique objects given the information about peaks and footprints detected in

[50] "MultiFit algorithms" are those that simultaneously fit PSF-convolved models to multi-epoch observations of an object. This is in contrast to measurement techniques where multi-epoch images are co-added first, and the properties are measured from the co-added pixels.

[51] Some LSST documents refer to *Data Release Processing*, which includes both Level 1 reprocessing (see § 2.3.7), and the Level 2 processing described here

[52] We're omitting global astrometric and photometric calibration steps, as well as quality assessment tasks, as they're beyond the current scope of this document.

[53] We'll denote the "band" of the multi-color co-add as 'M'.

all co-adds, the list of `DIAObjects` detected of difference images, and objects from external catalogs. It will make use of all information available at this stage, including the knowledge of peak positions, bands, time, time variability (from Level 1), Galactic longitude and latitude, etc. The output of this stage is a list of (uncharacterized) `Objects`[54].

4. *Multi-epoch object characterization.* A set of predefined model fits and measurements will be performed on each of the `Objects` identified in the previous step, taking all available multi-epoch data into account. Model fits will be performed using *MultiFit*-type algorithms. Rather than co-adding a set of images and measuring object characteristics off a co-add, MultiFit simultaneously fits PSF-convolved models to multi-epoch observations of an object. This reduces systematic errors, improves the overall S/N, and allows one to fit for some time-dependent quantities not easily recoverable from the co-adds (for example, the proper motion). The models we plan to fit will *not* allow for flux variability (see the next item).

5. *Single-epoch object characterization.* Once the position, motion, shape, and average flux have been characterized in the previous step, they will be used as priors and/or initial conditions for source measurements and model fits in individual epochs (on visits). The per-epoch measurements will generally have a lower S/N than the multi-epoch ones, and some will fall below the nominal detection $S/N = 5$ ratio. For these low SNR sources, we will only measure the PSF flux, and not the full suite of measurements presented in § 3.3.2. The results will be stored in `Source` and `FaintSource` tables.

3.2.1 Object Characterization Measures

Properties of detected objects will be measured as a part of the object characterization step described in the previous section. This section discusses at a high level which properties will be measured and how. For a more detailed list and description of quantities being fit/measured, see the table in § 3.3.1.

All measurements discussed in this section deal with properties of *objects*, and will be performed on multi-epoch co-adds or by simultaneously fitting

[54] Depending on the exact implementation of the deblender, this stage may also attach significant metadata (eg, deblended footprints and pixel-weight maps) to each deblended `Object` record.

to all epochs. Measurements of sources in individual visits, independent of all others, are described in § 3.2.2.

To characterize objects, we plan to measure the following:

- *Point source model fit.* The object is modeled as a point source with finite proper motion and parallax, and constant flux (in each band). There are a total of 11 free parameters, simultaneously constrained using information from all available epochs and bands. This model is a good description for stars and other unresolved sources.

- *Bulge-disk model fit.* The object is modeled as a sum of a de Vaucouleurs (Sersic $n = 4$) and an exponential (Sersic $n = 1$) component. This model is intended to be a reasonable description of galaxies. The object is assumed not to move. The components share the same ellipticity and center. One effective radius is fit for each component (i.e., the radius is not a function of band). The central surface brightness is allowed to vary from band to band. There are a total of 18 free parameters, which will be simultaneously constrained using information from all available epochs and bands. Where there's insufficient data to constrain the likelihood (eg., small, poorly resolved, galaxies, or very few epochs), priors will be adopted.

  In addition to the maximum likelihood values of fitted parameters and their covariances, a number (~ 200) of independent samples from the likelihood function will be provided. These will enable use-cases sensitive to departures of the likelihood function from Gaussian approximation.

- *Centroids.* Centroids will be computed independently in each band using an algorithm similar to that employed by SDSS. Information from all epochs will be used to perform the estimation. These centroids will be used for adaptive moment, Petrosian, Kron and aperture measurements.

- *Adaptive moments.* Adaptive moments will be computed using the information from all epochs, independently for each band. The moments of the PSF realized at the position of the object will be provided as well.

- *Petrosian and Kron fluxes.* Petrosian and Kron radii and fluxes will be measured using elliptical apertures computed from adaptive moments. The apertures will be PSF-corrected and convolved to a canonical circular PSF (*"PSF-homogenized"*[55]). The radii will be computed independently for each band. Fluxes will be computed in each band, by integrating the light within some multiple of *the radius measured in the canonical band*[56] (most likely the i band). Radii enclosing 50% and 100% of light will be provided.

- *Aperture fluxes.* Aperture fluxes will be computed in a variable number[57] of concentric, logarithmically spaced, PSF-homogenized, elliptical apertures.

3.2.2 Source Characterization Measures

3.3 The Level 2 Catalogs

3.3.1 `Object` Table

Table 4: Level 2 Catalog `Object` Table

Name	Type	Unit	Description
objectId	uint128		Unique object identifier
psRadec	double[2]	degrees	Point source model: (α, δ) position of the object at time `radecTai`.

Continued on next page

[55]This is an attempt to derive a definition of elliptical apertures that does not depend on seeing. For example, for a large galaxy, the correction to standard seeing will introduce little change to measured ellipticity. Apertures for small galaxies will tend to be circular (due to smearing by the PSF). But in the intermediate regime, this method results in derived apertures that are relatively seeing independent. Note that this is only the case for *apertures*; the measured flux will still be seeing dependent and it is up to the user to take this into account.

[56]The aperture in all bands will be set by the profile of the galaxy in the canonical band alone. This procedure ensures that the color measured by comparing the flux in different bands is measured through a consistent aperture. See `http://www.sdss.org/dr7/algorithms/photometry.html` for details.

[57]The number will depend on the size of the source.

Table 4: Level 2 Catalog `Object` Table

Name	Type	Unit	Description
psRadecTai	double	time	Point source model: Time at which the object was at position `radec`.
psPm	float[2]	mas/yr	Point source model: Proper motion vector.
psParallax	float	mas	Point source model: Parallax.
psFlux	float[ugrizy]	nmgy	Point source model fluxes[58].
psCov	float[66]	various	Point-source model covariance matrix[59].
psLnL	float		Natural *log* likelihood of the observed data given the point source model.
bdRadec	double[2]	degrees	B+D model[60]: (α, δ) position of the object at time `radecTai`, in each band.
bdEllip	float[2]		B+D model: Ellipticity (e_1, e_2) of the object.
bdI0B	float[ugrizy]	nmgy/as^2	B+D model: Central surface brightness of the de Vaucouleurs component.
bdI0D	float[ugrizy]	nmgy/as^2	B+D model: Central surface brightness of the exponential component.
bdReB	float	arcsec	B+D model: Effective radius of the de Vaucouleurs profile component.

Continued on next page

[58]Point source model assumes that fluxes are constant in each band. If the object is variable, `psFlux` will effectively be some estimate of the average flux.

[59]Not all elements of the covariance matrix will be stored with same precision. While the variances will be stored as 32 bit floats (∼ seven significant digits), the covariances may be stored to ∼ three significant digits (∼ 1%).

[60]Though we refer to this model as "Bulge plus Disk", we caution the reader that the decomposition, while physically motivated, should not be taken too literally.

Table 4: Level 2 Catalog `Object` Table

Name	Type	Unit	Description
bdReD	float	arcsec	B+D model: Effective radius of the exponential profile component.
bdCov	float[171]	various	B+D model covariance matrix[61].
bdLnL	float		Natural *log* likelihood of the observed data given the bulge+disk model.
bdSamples	float[18][200]		Independent samples of bulge+disk likelihood surface. All sampled quantities will be stored with at least $\sim$ 3 significant digits of precision. The number of samples will vary from object to object, depending on how well the object's likelihood function is approximated by a Gaussian.
radec	double[6][2]	arcsec	Position of the object (centroid), computed independently in each band. The centroid will be computed using an algorithm similar to that employed by SDSS.
radecSigma	double[6][2]	arcsec	Uncertainty of `radec`.
E1	float[ugrizy]		Adaptive e_1 shape measure. See Bernstein & Jarvis (2002) for detailed discussion of all adaptive-moment related quantities[62].
E2	float[ugrizy]		Adaptive e_2 shape measure.

Continued on next page

[61] See `psCov` for notes on precision of variances/covariances.
[62] Or `http://ls.st/5f4` for a brief summary.

Table 4: Level 2 Catalog `Object` Table

Name	Type	Unit	Description
E1E2cov	float[3]		`E1`, `E2` covariance matrix.
mSum	float[6]		Sum of the second adaptive moments.
mSumSigma	float[6]		Uncertainty in `mSum`
m4	float[6]		Fourth order adaptive moment.
petroRad	float[6]	arcsec	Petrosian radius computed using.
petroRadSigma	float[6]	arcsec	Uncertainty of `petroRad`
petroFlux	float[6]	nmgy	Petrosian flux within a defined multiple of `petroRad`
petroFluxSigma	float[6]	nmgy	Uncertainty in `petroFlux`
petroRad50	float[6]	arcsec	Radius containing 50% of Petrosian flux.
petroRad50Sigma	float[6]	arcsec	Uncertainty of `petroRad50`.
petroRad90	float[6]	arcsec	Radius containing 90% of Petrosian flux.
petroRad90Sigma	float[6]	arcsec	Uncertainty of `petroRad90`.
kronRad	float[6]	arcsec	Kron radius
kronRadSigma	float[6]	arcsec	Uncertainty of `kronRad`
kronFlux	float[6]	nmgy	Kron flux within a defined multiple of `kronRad`
kronFluxSigma	float[6]	nmgy	Uncertainty in `kronFlux`
kronRad50	float[6]	arcsec	Radius containing 50% of Kron flux.
kronRad50Sigma	float[6]	arcsec	Uncertainty of `kronRad50`.
kronRad90	float[6]	arcsec	Radius containing 90% of Kron flux.
kronRad90Sigma	float[6]	arcsec	Uncertainty of `kronRad90`.
apN	int8		Number of radial apertures.
apMeanFlux	float[6][`apN`]	nmgy	Mean flux within an aperture.
apMeanFluxSigma	float[6][`apN`]	nmgy	Standard deviation of `apMeanFlux`.

Continued on next page

Table 4: Level 2 Catalog `Object` Table

Name	Type	Unit	Description
flags	bit[128]	bit	Flags

3.3.2 `Source` Table

3.3.3 `FaintSource` Table

3.4 Level 2 Image Products

3.4.1 Visit Images

All raw and processed visit images will be available for download as FITS files. They will be downloadable both through the human-friendly Science User Interface, as well as machine-friendly APIs.

Sufficient metadata[63] and all necessary image processing software will be provided to enable the user to regenerate bitwise identical processed from raw images.

3.4.2 Coadded Images

To support Level 2 processing, LSST will create three classes of co-adds:

- One set of full depth[64] *deep co-adds*. One deep co-add will be created for each of the *ugrizy* bands, plus a seventh, deeper, multi-color co-add[65]. These co-adds will be optimized for a reasonable combination of depth (i.e., no PSF matching) and resolution (i.e., only above-average seeing visits may be used to construct them). Transient sources (including Solar System objects, explosive transients, etc), will be removed. These co-adds will be kept indefinitely and made available to the users.

- Multiple (ugrizyM) sets of yearly co-adds. Each of these sets will be created using only a year's worth of data, but be like the deep co-adds described above in all other respects. These are designed to enable

[63]Including the hardware and operating system specifications.
[64]Including all visits from the start of the survey
[65]In text to follow, we'll denote the "band" of the multi-color co-add as 'M'.

detection of long-term variable objects that would be "washed out" (or rejected) in full-depth co-adds. **We *do not plan to keep and make these co-adds available*.** We will retain and provide sufficient metadata for users to re-create them using Level 3 or other resources.

- One (ugrizyM) set of PSF-matched co-adds. These will be used to measure colors of objects at "standard" seeing. ***We do not plan to keep and make these co-adds available*.**. We will retain and provide sufficient metadata for users to re-create them using Level 3 or other resources.

To build the co-adds, we plan to subdivide the sky into 12 overlapping[66] *tracts*, spanning approximately 75×72 degrees. The sky will be stereographically projected onto the tracts[67], and be pixelized into (logical) images 2.0 x 1.9 megapixels in size (3.8 terapixels in all). Physically, these large images will be subdivided into smaller (e.g. $2k \times 2k$), non-overlapping, *patches*, though that will be transparent to the users. The users will be able to request arbitrarily chosen regions[68] in each tract, and receive them back as a FITS file.

We re-iterate that **not all co-adds will be kept and served to the public**[69], though sufficient metadata will be provided to users to recreate them on their own. Some co-adds may be entirely "virtual": for example, the PSF-matched co-adds could be implemented as ad-hoc convolutions of postage stamps when the colors are measured.

We **will** retain smaller sections of all generated co-adds, to support quality assessment and targeted science. For example, the retained sections may be positioned to cover areas of the sky of special interest such as overlaps with other surveys, nearby galaxies, large clusters, etc.

3.5 Data Availability

What's kept and for how long.

[66] We're planning for 3.5 degrees of overlap, roughly accommodating a full LSST focal plane.

[67] See `https://dev.lsstcorp.org/trac/wiki/DM/SAT/SkyMap` for details.

[68] Up to some reasonable upper size limit; i.e., we don't plan to expect to support creation of 2.8 Tpix FITS files.

[69] The co-adds are a major cost driver for storage. LSST Data Management system is currently sized to keep and serve seven co-adds.

3.6 Open Issues

- *Which co-adds to we keep and serve to the public?* Probably non-PSF matched co-adds with CoaddPSF (aka. StackFit PSF). PSF-matched co-adds are another option and may be easier for the community to work with.

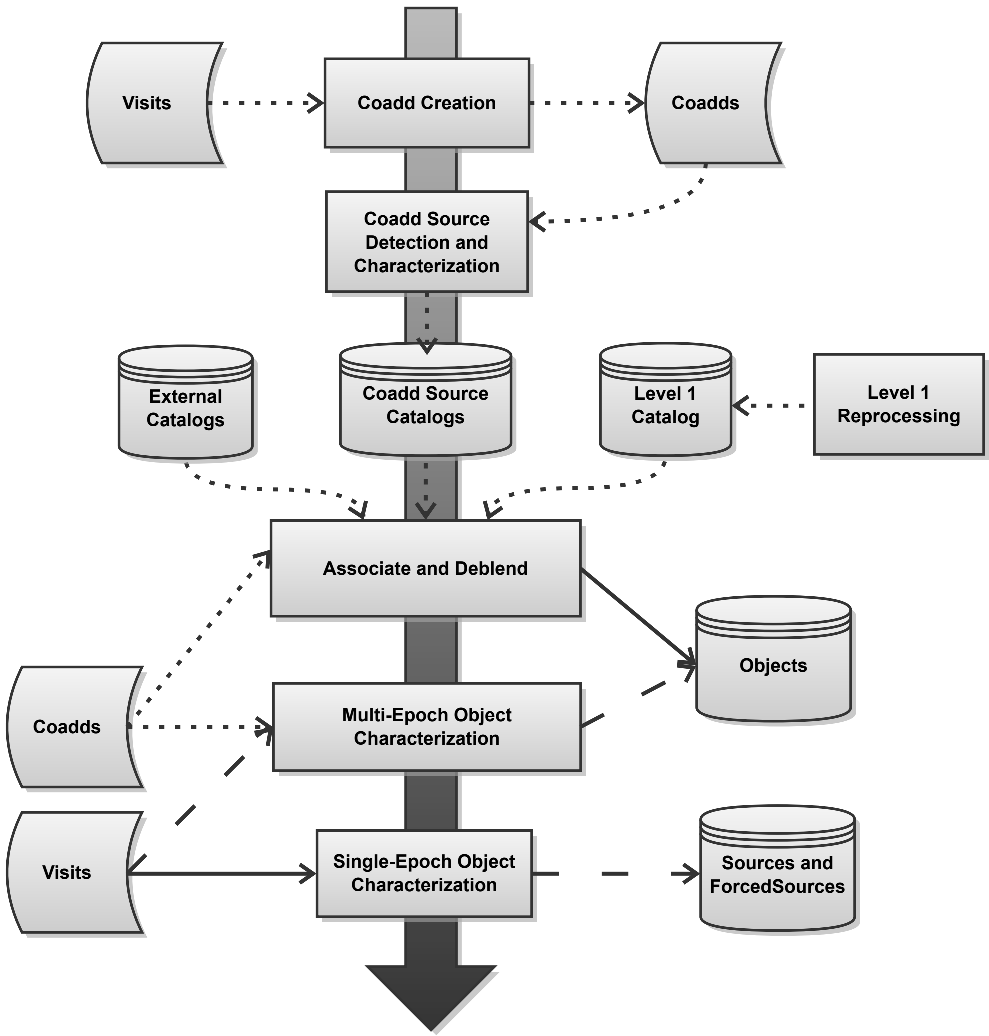

Figure 1: Level 2 Data Processing Overview