The LSST Data Management System

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Abstract.
The Large Synoptic Survey Telescope (LSST; Ivezić et al. 2008) is a large-aperture, wide-field, ground-based survey system that will image the sky in six optical bands from 320 to 1050 nm, uniformly covering approximately $18,000$ deg^2 of the sky over

800 times. The LSST is currently under construction on Cerro Pachón in Chile, and expected to enter operations in 2022. Once operational, the LSST will explore a wide range of astrophysical questions, from discovering "killer" asteroids to examining the nature of Dark Energy.

The LSST will generate on average 15 TB of data per night, and will require a comprehensive Data Management system to reduce the raw data to scientifically useful catalogs and images with minimum human intervention. This processing will result in a real-time alert stream, and eleven data releases over the 10-year duration of LSST operations.

To enable this processing, the LSST project is developing a new, general-purpose, high-performance, scalable, well documented, open source data processing software stack for O/IR surveys. Prototypes of this stack are already capable of processing data from existing cameras (e.g., SDSS, DECam, MegaCam), and form the basis of the Hyper-Suprime Cam (HSC) Survey data reduction pipeline.

1. The Large Synoptic Survey Telescope

The Large Synoptic Survey Telescope (LSST; `http://lsst.org`) will be an automated astronomical survey system that will survey approximately $10,000$ deg^2 of the sky every few nights in six optical bands from 320 to 1050 nm (Ivezić et al. 2008). Over the planned 10-year baseline survey, it will uniformly and repeatedly image about $18,000$ deg^2 of the sky over 800 times. These data will be used to explore a wide range of astrophysical questions, ranging from discovering "killer" asteroids to examining the nature of Dark Energy (e.g., see LSST Science Collaboration 2009).

The LSST survey system consists of a large-aperture, wide-field, ground-based telescope (Gressler et al. 2014) currently being constructed on the El Peñón peak of Cerro Pachón in the Chilean Andes, a 3.2 gigapixel camera (Kahn et al. 2010), and a data management system, also currently under construction.

In this paper, we review the science goals and technical design of the LSST Data Management system (LSST DM; described previously in Kantor et al. (2007) and Kantor & Axelrod (2010)). We begin by describing the overall architecture of the system in Section 2, followed by a discussion of the planned data products in Section 3. In Section 4, we discuss the software stack being developed for processing and serving of LSST data. We conclude by pointing out opportunities that this new codebase represents both for LSST and the astronomical software community as a whole, in Section 5.

2. The LSST Data Management System

The rapid cadence and scale of the LSST observing program will produce approximately 15 TB per night of raw imaging data[1]. The large data volume, the real-time aspects (to be explained below), and the complexity of processing involved makes it impractical to defer the data reduction to the LSST end-users. Instead, the data collected by the LSST system will be automatically reduced to scientifically useful catalogs and

[1]For comparison, the volume of all imaging data collected over a decade and published in SDSS Data Release 7 (Abazajian et al. 2009) is approximately 16 TB.

images by the LSST Data Management system.

The principal functions of the LSST Data Management system (Ivezić & the LSST Science Collaboration 2013) are to:

- Within 60 seconds of observation, process the incoming stream of exposures by archiving raw images, generating alerts to new sources or sources whose properties have changed significantly, and updating the relevant catalogs ("Level 1" data products).
- Periodically reprocess the accumulated survey data to provide a uniform photometric and astrometric calibration (e.g., Jones et al. 2013a), measure the properties of all detected objects, and characterize objects based on their time-dependent behavior. The results of such a processing run form a *Data Release* (DR), which is a static, self-consistent data set suitable for use in performing scientific analyses of LSST data and publication of the results (the "Level 2" data products). All data releases will be archived for the entire operational life of the LSST archive, with the two most recent releases available in a queryable database.
- Facilitate the creation of added-value ("Level 3") data products, by providing suitable software, application programming interfaces (APIs), and computing infrastructure at the LSST data access centers.
- Make all LSST data available to the community through an interface that utilizes community-based standards to the maximum possible extent. Provide enough processing, storage, and network bandwidth to enable user analyses of the data without the need for petabyte-scale data transfers.

Over the ten years of LSST survey operations and 11 data releases, this processing will result in a cumulative *processed* data size approaching 500 petabytes (PB) for imaging, and over 50 PB for the catalog databases. The final data release catalog database alone is expected to be approximately 15 PB in size. A more detailed overview of the data products will be given in Section 3.

The Data Management system is conceptually divided into three layers (Kantor et al. 2013): an infrastructure layer (Freemon et al. 2013) consisting of the computing, storage, and networking hardware and system software; a middleware layer (Lim et al. 2013), which handles distributed processing, data access, user interface, and system operations services; and an applications layer (Jurić et al. 2013b; Becla et al. 2013; Dyk & Levine 2013), which includes the data pipelines and products and the science data archives (see Fig. 1).

Physically, the DM system components will span four key facilities on three continents: the Summit Facility at Cerro Pachón (where the initial detector cross-talk correction will be performed), the Base Facility in La Serena (which will serve as a retransmission hub for data uploads to North America, as well as the data access center for the Chilean community), the central Archive Facility at the National Center for Supercomputing Applications (NCSA) in Champaign, Illinois, and a satellite data processing center at Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (CC-IN2P3) in Lyon, France. All Level 1 (nightly) and 50% of Level 2 (data release) processing will take place at the Archive Facility, which will also serve

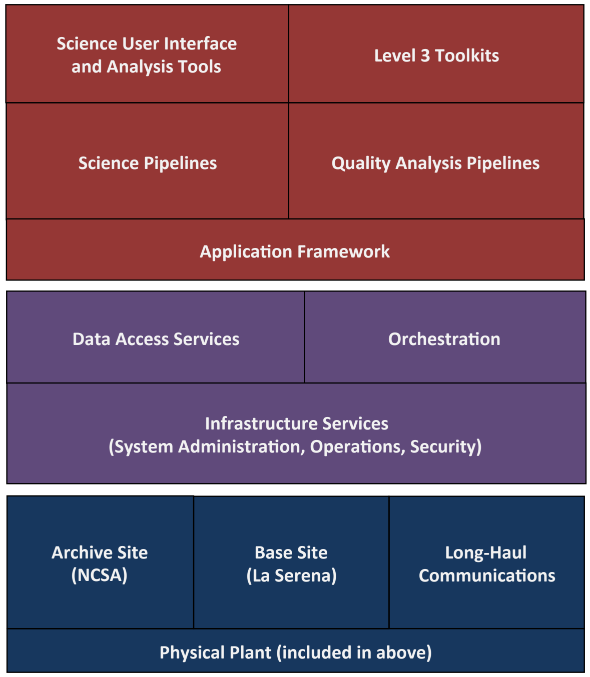

Figure 1. The three-layered architecture of the data management system (application [red, top], middleware [purple, middle], and infrastructure [blue, bottom] layers) enables scalability, reliability, and evolutionary capability.

as a data access center for the US community. The remaining 50% of data processing will be performed at the satellite center in Lyon.

The data will be transported between the centers over existing and new high-speed optical fiber links from South America to the U.S., and from the U.S. to France (see Fig. 2). The data processing centers will have substantial computing power (e.g., the central facility will peak at ~ 1.6 petaflops of compute power).

3. LSST Data Products

Data collected by the LSST camera and telescope will be automatically processed to *data products* – catalogs, alerts, and reduced images – by the LSST Data Management system (§ 2). These products are designed to be sufficient to enable a large majority of LSST science cases, without the need to work directly with the raw pixels. We give a high-level overview of the LSST data products here; further details may be found in the LSST Data Products Definition Document (Jurić et al. 2013a).

Two major categories of data products will be produced and delivered by the DM system:

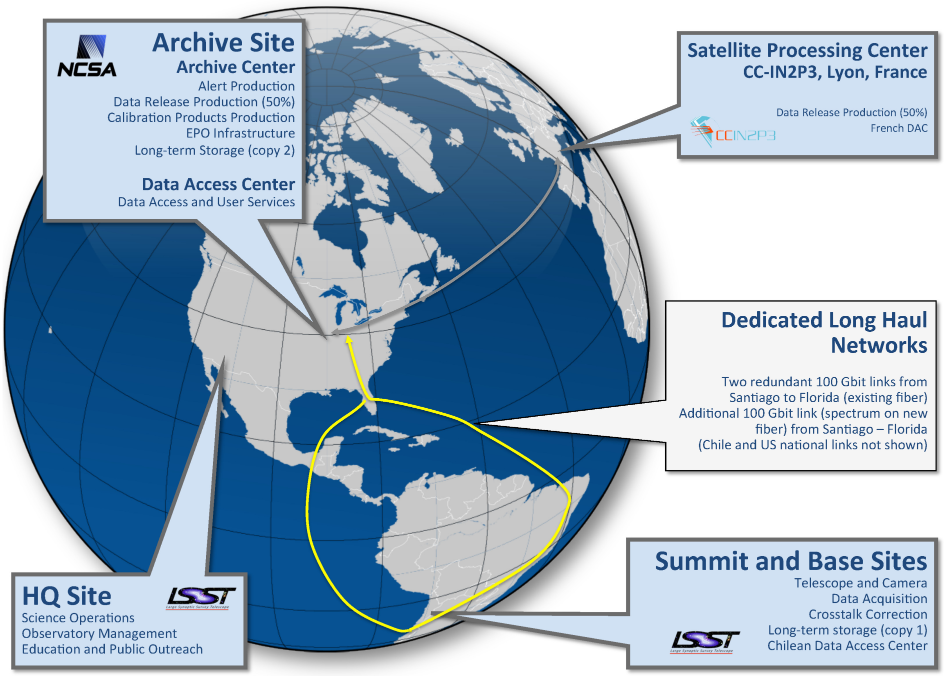

Figure 2. The LSST data flow from the mountain summit/base facility in Chile to the data access center and archive centers in the U.S. and France. The data will be transported, in real time, over two (redundant) 100 Gbit links from La Serena, Chile to Champaign, IL.

- **Level 1 data products**, designed to support the discovery, characterization, and rapid follow-up of time-dependent phenomena (“transient science”). These will be generated continuously every observing night, by detecting and characterizing sources in images differenced against deep templates. They will include alerts to objects that were newly discovered, or have changed brightness or position at a statistically significant level. The alerts to such events will be published within 60 seconds of observation (see e.g. Kantor 2014, for details).

  In addition to transient science, Level 1 data products will support discovery and follow-up of objects in the Solar System. Objects with motions sufficient to cause trailing in a single exposure will be identified and flagged as such when the alerts are broadcast. Those that are not trailed will be identified and linked based on their motion from observation to observation, over a period of a few days. Their orbits will be published within 24 hours of identification. The efficiency of linking (and thus the completeness of the resulting orbit catalog) will depend on the final observing cadence chosen for LSST, as well as the performance of the linking algorithm (Jones et al. 2013b; Jones et al. 2015).

- **Level 2 data products** are designed to enable systematics- and flux-limited science, and will be made available in annual Data Releases. These will include the (reduced and raw) single-epoch images, deep co-adds of the observed sky, catalogs of objects detected in LSST data, catalogs of sources (the detections and measurements of objects on individual visits), and catalogs of "forced sources" (measurements of flux on individual visits at locations where objects were detected by LSST or other surveys). LSST data releases will also include fully reprocessed Level 1 data products, as well as all metadata and software necessary for the end-user to reproduce any aspect of LSST data release processing.

A noteworthy aspect of LSST Level 2 processing is that it will largely rely on **multi-epoch model fitting**, or ***MultiFit***, to perform near-optimal characterization of object properties. That is, while the co-adds will be used to perform object *detection*, the *measurement* of their properties will be performed by simultaneously fitting (PSF-convolved) models to sets of single-epoch observations. An extended source model – a constrained linear combination of two Sérsic profiles – and a point source model with proper motion – will generally be fitted to each detected object[2].

Secondly, for the extended source model fits, the LSST will characterize and store the shape of the associated likelihood surface (and the posterior), and not just the maximum likelihood values and covariances. The characterization will be accomplished by sampling, with up to ~200 independent likelihood samples retained for each object. For storage cost reasons, these samples may be retained only for those bands of greatest interest for weak lensing studies.

The quality of all Level 1 and Level 2 data products will be extensively assessed, both automatically as well as manually, using the Science Data Quality Assurance (SDQA) pipelines (Tyson et al. 2011).

While a large majority of science cases will be adequately served by Level 1 and 2 data products, a limited number of highly specialized investigations may require custom, user-driven, processing of LSST data. This processing will be most efficiently performed at the LSST Archive Center, given the size of the LSST data set and the associated storage and computational challenges. To enable such use cases, the LSST DM system will devote the equivalent of 10% of its processing and storage capabilities to creation, use, and federation of **Level 3** (user-created) data products. It will also allow the science teams to use the LSST database infrastructure to store and share their results.

To further enable user-driven Level 3 processing, the *LSST Software Stack*, described in Section 4, has been explicitly designed with reusability and extendability in mind, and will be made available to the LSST user community. This will allow the LSST users to more rapidly develop custom Level 3 processing codes, leveraging 15+ years of investment and experience put into LSST codes. In addition to executing such customized codes at the LSST data centers, LSST users will be able to run it on their own computational resources as well.

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[2]For performance reasons, it is likely that only the point source model will be fitted in the most crowded regions of the Galactic plane.

4. The LSST Software Stack

The LSST Software Stack[3] aspires to be a well documented, state-of-the-art, high-performance, scalable, multi-camera, open source, O/IR survey data processing and analysis system, built to enable LSST survey data reduction and the writing of custom, user-driven, code for Level 3 processing. Its design and implementation are led by a team distributed across six institutions (the LSST Project Management Office, IPAC, NCSA, Princeton University, SLAC National Laboratory and the University of Washington) but also includes contributions from external contributors. Once completed, it will comprise of all science pipelines (Jurić et al. 2013b; Jones et al. 2013b) needed to accomplish LSST data processing tasks (e.g., calibration, single frame processing, co-addition, image differencing, multi-epoch measurement, asteroid orbit determination, etc.), quality assessment pipelines, the necessary data access and orchestration middleware (Lim et al. 2013), the image store and catalog database (Becla et al. 2013; Wang et al. 2011) as well as the science user interface components (SUI; Dyk & Levine 2013). The SUI components are planned to be based on IPAC's Firefly toolkit, described by Wu et al. (2016) later in this volume.

Algorithm development for the LSST software builds on the expertise and experience of prior large astronomical surveys such as SDSS (York et al. 2000), Pan-STARRS (Magnier 2006; Kaiser et al. 2010), DES (Sevilla et al. 2011), SuperMACHO (Becker et al. 2005), ESSENCE (Miknaitis et al. 2007), DLS (Wittman et al. 2002), CFHT-LS (Heymans et al. 2012; Miller et al. 2013; Gwyn 2012), and UKIDSS (Lawrence et al. 2007) to name a few, as well as software tools (e.g., SExtractor, Bertin & Arnouts 1996, ascl:1010.064). The pipelines written for these surveys have demonstrated that it is possible to carry out largely autonomous data reduction of large data sets, automated detection of sources and objects, and the extraction of scientifically useful characteristics of those objects.

While firmly footed in this prior history, the LSST software stack has largely been written anew, for reasons of performance, extendability, and maintainability as well as stringent science and system quality requirements. All LSST codes are being developed with the intent of following software engineering best practices, including modularity, clear definition of interfaces, continuous integration, utilization of unit testing, a single set of documentation and coding standards. The primary user-facing implementation language is Python and, where necessary for performance reasons or when the algorithms require access to complex data structures, we use C++ with SWIG wrappers (Beazley 1996). See the contribution by Jenness (2016) in this conference for more discussion on the architecture of the LSST software stack.

The LSST data management software has been prototyped for over eight years. It has been exercised in eight data challenges (see e.g. Kantor 2010), with increasing degrees of complexity. Advanced prototypes of the distributed, shared-nothing, database being written for LSST – Qserv – have been tested on a 150-node cluster using 55 billion rows and 30 terabytes of simulated data (Wang et al. 2011; Becla et al. 2015). Besides processing simulated LSST data (Connolly et al. 2014; Peterson et al. 2015), LSST science pipelines have also been used to process images from CFHTLS

[3]Source code and development versions are available at `http://dm.lsst.org`.

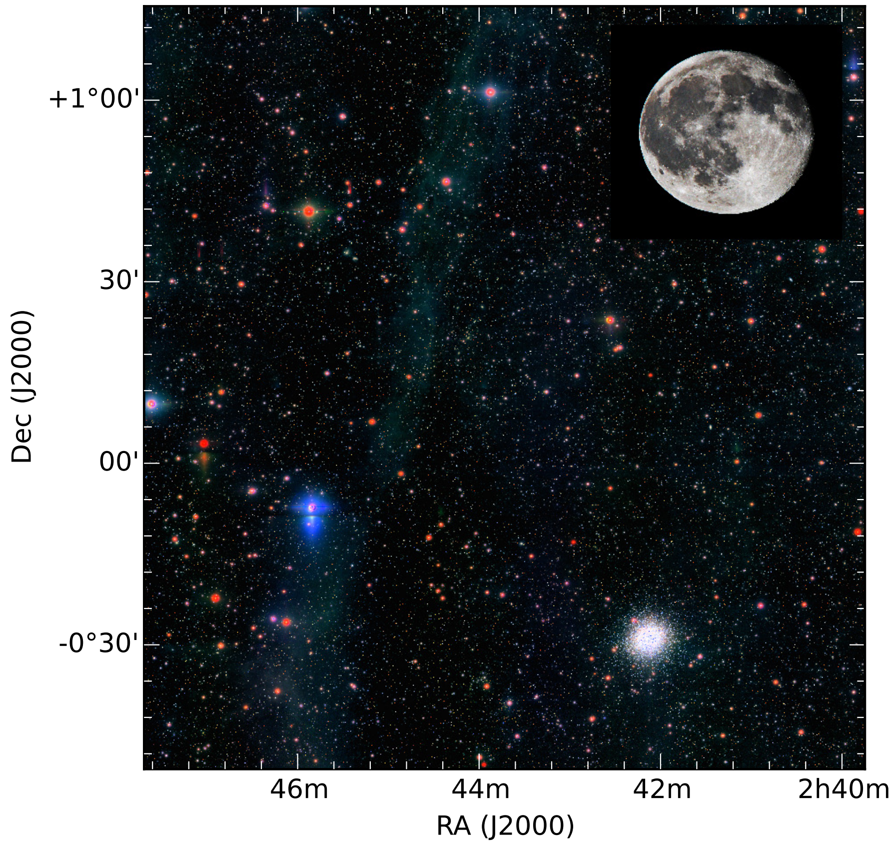

Figure 3. A *gri* color composite of a small region in the vicinity of globular cluster M2, taken from a co-add of SDSS Stripe 82 data produced with LSST software stack prototypes. The co-addition employs a novel "background matching" technique (Huff et al. 2014) that improves background estimation and preserves the diffuse structures in the resulting co-add. The image of the Moon has been inserted for scale. The full co-add can be browsed at `http://moe.astro.washington.edu/sdss`.

and SDSS (Ahn et al. 2012). As an example, Figure 3 shows a small region in the vicinity of M2 taken from a large co-addition of SDSS Stripe 82 data, generated with LSST software stack prototypes. Furthermore, the current development version of the LSST software stack forms the basis for the data processing pipelines of the Subaru Hyper-Suprime Cam Survey (Miyazaki et al. 2012) and has been used successfully to produce two data releases of HSC Survey data.

5. Summary

The LSST is envisioned to be a highly automated survey system designed to enable investigations of phenomena on timescales ranging from minutes to years, and covering approximately half of the sky (LSST Science Collaboration 2009). A comprehensive data management system, such as the one described in this paper, is necessary to make possible the research expected of such a facility.

Though built to enable LSST science, we are hopeful that the individual components of LSST data management system – and especially the software stack – will be of broader utility. The LSST software stack is free software, licensed under the terms of the GNU General Public License, Version 3. The stack prototype code and documentation are available via `http://dm.lsst.org`. Its open source nature, an open development process, a long-term project commitment and a design that can be modified for use with other cameras may make it useful for the processing of imaging data beyond LSST.

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