The LSST Data Management System

Mario Juric,[1] Jeffrey Kantor,[2] K-T Lim,[3] Tim Jenness,[2] Frossie Economou,[2] Joshua Hoblitt,[2] Jonathan Sick,[2] J. Matt Peterson,[2] Angelo Fausti,[2] Fabio Hernandez,[4] Željko Ivezić,[1] R. Lynne Jones,[1] Peter Yoachim,[1] Darko Jevremović,[5] Veljko Vujčić,[5] Jovan Aleksić,[5] Richard A. Shaw,[6] Robert Armstrong,[7] James Bosch,[7] Merlin Fisher-Levine,[8] Vishal P. Kasliwal,[7,9] Robert H. Lupton,[7] Nate B. Lust,[7] Lauren A. MacArthur,[7] Paul A. Price,[7] Michael A. Strauss,[7] John D. Swinbank,[7] Jacek Becla,[3] Fabrice Jammes,[10] Matias Carrasco Kind,[11] Hsin-Fang Chiang,[11] Donald Petravick,[11] Stephen R. Pietrowicz[11]

[1]*University of Washington, Seattle, WA, U.S.A;* `mjuric@astro.washington.edu`

[2]*LSST Project Management Office, Tucson, AZ, U.S.A.*

[3]*SLAC National Laboratory, Menlo Park, CA, U.S.A.*

[4]*IN2P3 Computing Center, CNRS, Lyon-Villeurbanne, France*

[5]*Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia*

[6]*NOAO, Tucson, AZ, U.S.A.*

[7]*Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, U.S.A.*

[8]*Department of Physics, Brookhaven National Laboratory, Bldg. 510, Upton, NY, 11793, U.S.A.*

[9]*Department of Physics and Astronomy, Center for Particle Cosmology, University of Pennsylvania, 209 S. 33rd St., Philadelphia, PA 19104, U.S.A.*

[10]*LPC, IN2P3, Clermont-Ferrand, France*

[11]*National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign, Urbana IL, U.S.A.*

Abstract.

The Large Synoptic Survey Telescope (LSST; `http://lsst.org`) is a planned, large-aperture, wide-field, ground-based telescope that will survey half the sky every few nights in six optical bands from 320 to 1050 nm. It will explore a wide range of astrophysical questions, ranging from discovering "killer" asteroids, to examining the nature of Dark Energy.

The LSST will produce on average 15 terabytes of data per night, yielding an (uncompressed) data set of over 100 petabytes at the end of its 10-year mission. To enable the wide variety of planned science, the LSST Project is leading the construction of 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 Supreme-Cam (HSC) Survey data reduction pipeline. In the 2020-ies, running on dedicated HPC facilities, this system will enable us to process the LSST data stream in near real time, with full-dataset reprocessings on annual scale.

In this paper, we review the science goals and the technical design of the LSST, focusing on the data management system. We describe its software stack and the data products it will generate. Finally, we discuss the exciting opportunities this new code-base represents both for LSST, and the astronomical software community as a whole.

1. The Large Synoptic Survey Telescope

The Large Synoptic Survey Telescope (LSST; `http://lsst.org`) is an automated astronomical survey system that will survey half the sky every few nights in six optical bands from 320 to 1050 nm (Ivezic et al. 2008). It will explore a wide range of astrophysical questions, ranging from discovering "killer" asteroids, to examining the nature of Dark Energy.

The LSST consists of a large-aperture, wide-field, ground-based telescope currently being constructed on El Penon peak of Cerro Pachón in the Chilean Andes, a 3.2 gigapixel camera, presently being constructed by a collaboration of institutions lead by the SLAC National Laboratory, and a data management system, also currently in construction.

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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, 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 images by the LSST Data Management (DM) system.

The principal functions of the LSST Data Management system are to:

- Process, in real time, the incoming stream of images generated by the camera system during observing by archiving raw images, generating alerts to new sources or sources whose properties have changed, and updating the relevant catalogs ("Level 1" data products; § 3.1).

[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.

- Periodically process the accumulated survey data to provide a uniform photometric and astrometric calibration, 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; § 3.1). All data releases will be archived for the entire operational life of the LSST archive.

- Facilitate the creation of added-value (“Level 3”; § 3.1) data products, by providing suitable software, application programming interfaces (APIs), and computing infrastructure at the LSST data access centers.

- Make all LSST data available 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 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.

The data management system is conceptually divided into three layers: an infrastructure layer consisting of the computing, storage, and networking hardware and system software; a middleware layer, which handles distributed processing, data access, user interface, and system operations services; and an applications layer, 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 Nucleaire 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 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. (see Fig. 2). Although the data processing center will have substantial computing power (e.g., the central facility will peak at $\sim$ 1.6 petaflops of compute power), the continuation of current trends suggests that the center will not qualify for the top 500 list by the time of first light. Hence, while LSST is making a novel use of advances in information technology, it is not taking the risk of pushing the expected technology to the limit, reducing the overall risk to the project.

A novel aspect of the LSST DM system will be its “Level 3" capabilities, allowing the end-users to create, store, and share custom data products not created by standard LSST processing. These could be new catalogs created by simple post-processing of

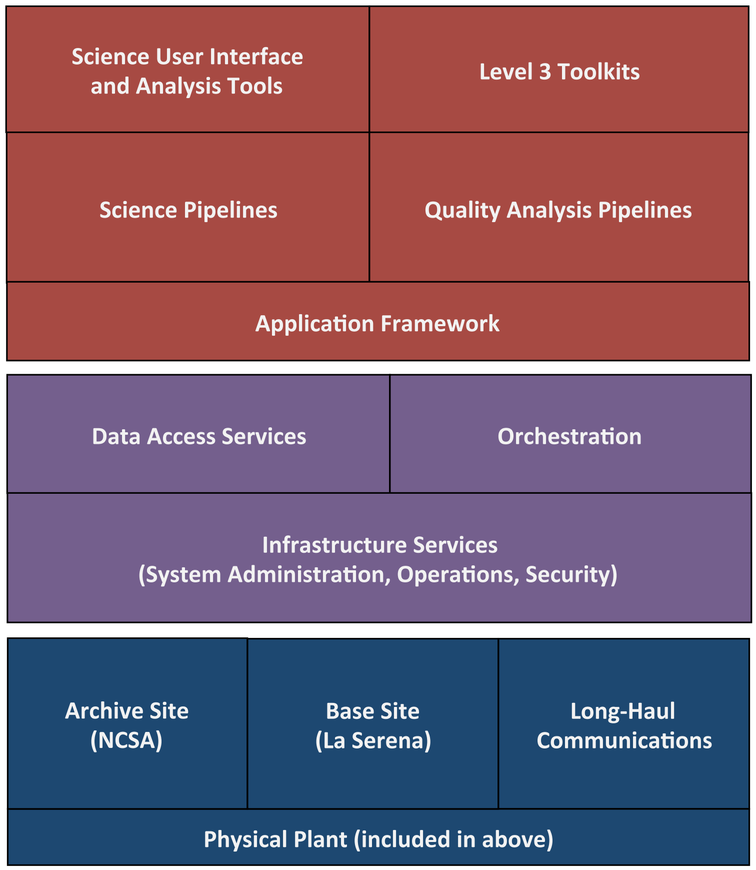

Figure 1. The three-layered architecture of the data management system (application [red, top], middleware [purple, middle], and infrastructure [blue, bottom] layers) enables scalability, reliability, and evolutionary capability.

the LSST data release catalogs, or entirely new data products generated by running custom code on raw LSST data. The LSST software stack (described below) will be made available to LSST end-users, as a basis on which to quickly build such code. Approximately 10% of the total budget for the LSST Archive Center compute and storage capacity has been reserved for end-user, Level 3, processing support infrastructure[2].

3. The LSST software stack

The *LSST Software Stack* is a well documented, state-of-the-art, high-performance, scalable, multi-camera, open source, O/IR survey data processing and analysis system,

[2]Furthermore, the data management system architecture will enable Level 3 tasks to "piggyback" onto annual Level 2 reprocessings, leveraging considerable I/O and computing resources employed in the production of a data release.

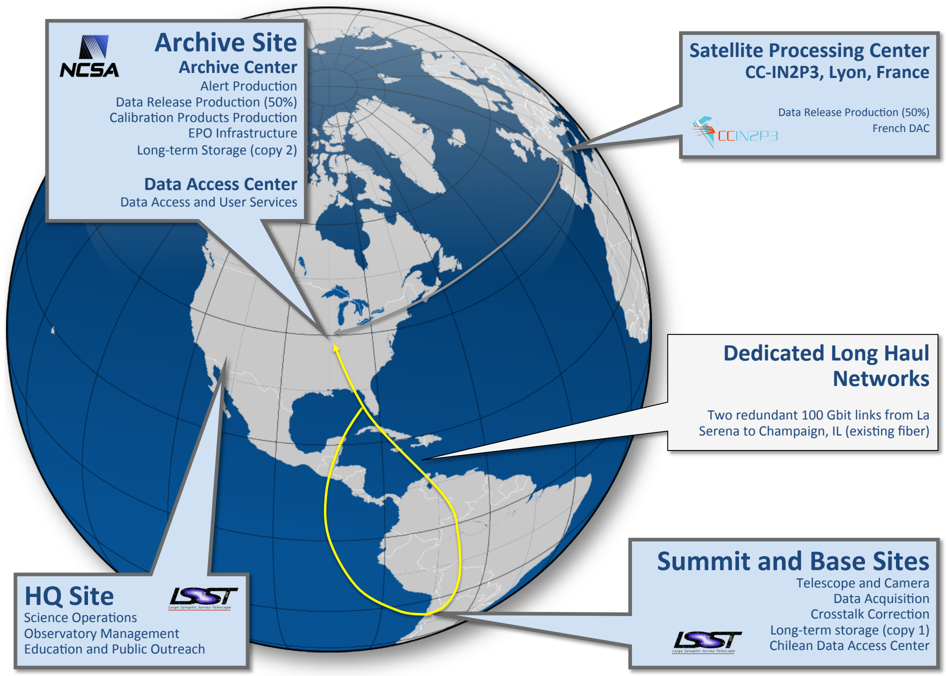

Figure 2. The LSST data flow from the mountain summit/base facility in Chile to the data access center and archive centers in the U.S. and France.

built to enable LSST survey data reduction and the writing of custom, user-driven, code for Level 3 processing. It comprises all science pipelines needed to accomplish LSST data processing tasks (e.g., calibration, single frame processing, co-addition, image differencing, multi-epoch measurement, asteroid orbit determination, etc.), the necessary data access and orchestration middleware, as well as the database and user interface components.

Algorithm development for the LSST software builds on the expertize and experience of prior large astronomical surveys (including SDSS, Pan-STARRS, DES, SuperMACHO, ESSENCE, DLS, CFHTLS, and UKIDSS). 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. All LSST codes have been designed and implemented 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, and others. The primary implementation language is Python and, where necessary for performance reasons, C++[3]. See the

[3]All components implemented in C++ have been wrapped and exposed as Python modules to the rest of the system. Python truly is the "native language of LSST".

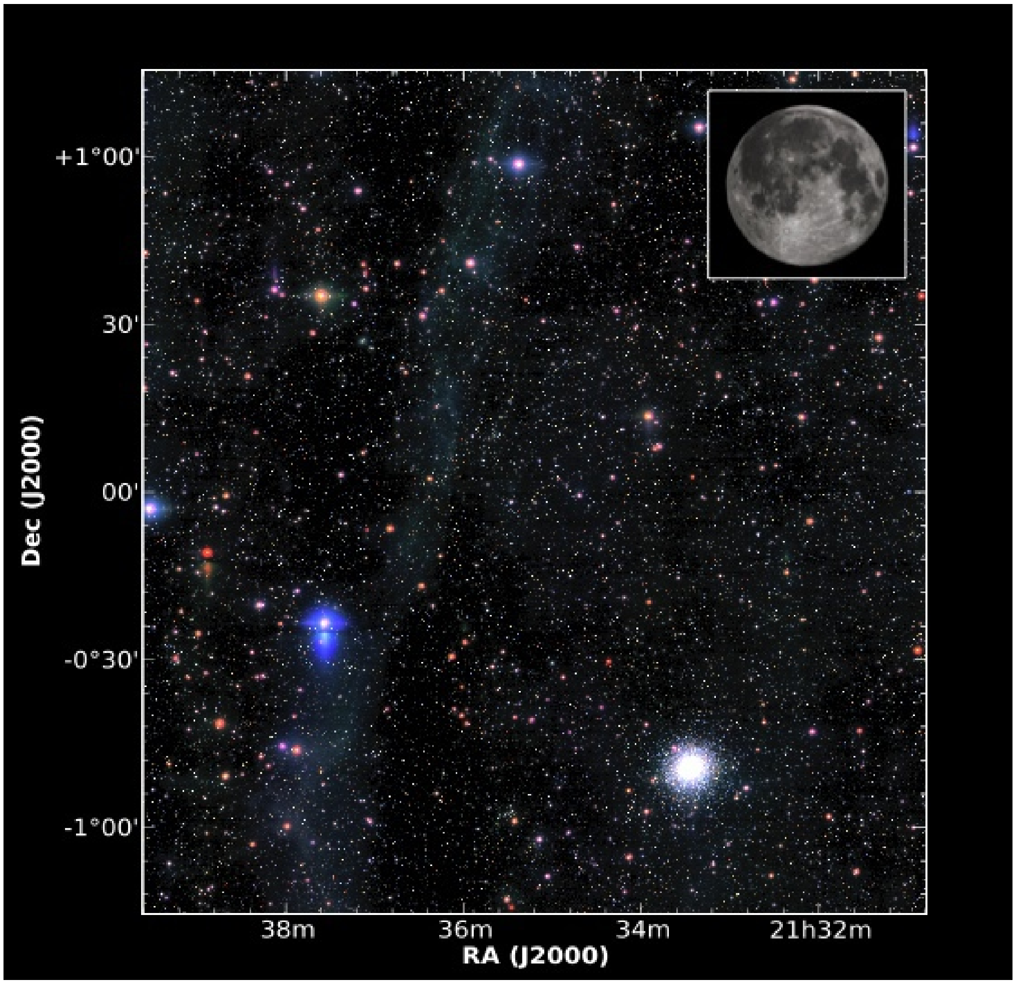

Figure 3. A small region in the vicinity of globular cluster M2, taken from a co-add of SDSS Stripe 82 data produced with LSST software stack prototypes. The co-addition employs a novel "background matching" technique that improves background estimation and preserves the diffuse structures in the resulting co-add. The full co-add can be browsed at `http://moe.astro.washington.edu/sdss`.

contribution by Jenness (2016) 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, with increasing degrees of complexity. Besides processing simulated LSST data (§ **??**), it has been used to process images from CFHTLS and SDSS (Abazajian et al. 2009). 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.

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://ls.st/ug`. Its open source nature, an open development process, attention to software engineering, a long-term project commitment and a modular design that can be modified for use with other cameras may make it useful for the processing of imaging data beyond LSST.

3.1. Data Products

Data collected by the LSST telescope and camera 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 (Juric et al. 2013).

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

- **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.

  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 ((**?**)).

- **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 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[4].

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.

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 has been explicitly architected with reusability and extendability in mind, and will be made available to the LSST user community (§ 3). 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.

We have described that approximately 10% of the observing time will be devoted to mini-surveys that do not follow the LSST baseline cadence (§ **??**). The data products for these programs will be generated using the same processing system and exhibit the same general characteristics of Level 1 and 2 data products, but these data may be reduced on a somewhat different timescale.

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

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