D1.2.1 Science Requirements Document (Mar '20)

LSST:UK Phase B WP 1.2. Maintenance of the Science Requirements Document

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LSST:UK Science Requirements Document

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Document History

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1.2	19/MAY/16	Produced by Sarah Bridle for May 2016 Consortium Board meeting
2.0	07/DEC/18	Produced by Stephen Smartt, Bob Mann in advance of STFC PPRP meeting.
2.1	14/Feb/19	Final full version for release, after input from WP leads.
2.2	28/AUG/19	Project Delivery Group made updates in preparation for Phase B kick-off meeting.
2.3	21/APR/20	Revised in light of the LSST:UK Phase B review of Deliverable D.1.2.1

Reference Documents

LSST Project Documents

- LSST Science Requirements Document (SRD; LPM-17)
- LSST Data Products Definition Document (DPDD; LSE-163)
- LSST Data Management System Requirements (DMSR; LSE-61)

LSST Science Collaboration Documents

- LSST DESC Science Requirements Document https://arxiv.org/pdf/1809.01669.pdf

LSST:UK Documents

- LSST:UK Long-Term Plan
- LUSC Phase A Proposal
- LUSC Phase B Proposal
- Technical reports and related documentation
  - LUSC DAC Technical Reports for Transients
  - LUSC Science Working Group pages
- Comment page from the LSST:UK PoCs to give their views and feedback initial deadline 28th Feb, with deadline 28th March 2019. This will be reviewed at the planned LSST:UK All hands meeting in May 2019.

Introduction

This document captures the requirements on the LSST:UK Science Centre (LUSC) from the LSST:UK science programme, including indirect requirements on other organisations that are met through collaborative relationships with the LUSC: examples of such external organisations would be the LSST Project, the IRIS computing infrastructure initiative and the CC-IN2P3 computing centre in France. It may include requirements that exceed the capabilities of the currently-funded LUSC programme, but that are recorded here for completeness and to highlight that they need support for the full LSST:UK science programme to be realised.

The document is structured according to the different LSST data products, as defined in the DPDD, and, where appropriate, it references and inherits from LSST project requirements.

Summary Science Case for UK Involvement in LSST

LSST's temporal resolution, unprecedented depth and uniform photometry over an entire hemisphere combine to produce a compelling science case, and the LSST:UK Consortium possesses the expertise to secure leadership positions across a broad range of astrophysics. The UK's strengths and heritage in leading astronomical surveys, data processing and analysis combined with our access to ESO facilities provides an exciting platform for scientific leadership and impact in the 2020s. The UK community is now embedded within the LSST Science Collaborations, thanks to the Phase A funding, and we are already shaping our own direction and designing the tools and data products required to ensure we are at the forefront of LSST data analysis. The LSST:UK Executive Group solicited proposals for STFC funding to deliver science tools, software and data products to meet the requirements of the UK's science cases. Whole not all of these could go forward in the final Phase B, we present the full science cases below covering much of the LSST:UK's interests.

Cosmology

Cosmology is one of the main LSST science drivers. The STFC Science Priorities identify the major science goals for cosmology as discovering the nature of the dark Universe, and improving our understanding of the earliest moments of time (STFC Science Challenges A1, A3, C4, C5). The AAP Report for the STFC Programmatic Review outlines a multi-probe approach to test the underlying fundamental assumptions of General Relativity, using weak gravitational lensing, galaxy clustering, Type Ia supernovae, and galaxy clusters, as well as cross-correlation with the Cosmic Microwave Background. The AAP report highlights the step-change from DES to LSST and Euclid due to the order of magnitude increase in galaxy numbers, as well as the importance of LSST for finding large numbers of SNe because of its time domain capability.

The Dark Energy Science Collaboration (DESC) is the most organised and developed of the LSST Science Collaborations and the UK is now in key leadership roles within DESC. We envisage that the high profile cosmological results will come through analysis pipelines developed by DESC. LSST will measure the equation of state of dark energy to unprecedented percent-level accuracy, and will make similarly powerful measurements of the laws of gravity and the evolution of dark matter and cosmic structure. This accuracy will come from the combination of multiple probes tracing different aspects of the behaviour of light and matter (see the DESC Science Requirements). Weak lensing, the coherent distortion of galaxy shapes over wide fields caused by intervening gravitational fields, causes galaxy images to align around dark matter structure. Measuring it probes dark matter structure, dark energy's history, and the behaviour of relativistic objects under gravity. Galaxy number density measurements trace dark matter with a precise but biased relation, and in combination with lensing have provided the most powerful low-redshift measurements of cosmic structure to date (DES Collaboration et al 2017; van Uitert et al. 2018). Counting galaxy clusters probes the high-density tail of the dark matter distribution, while supernovae trace the relationship between redshift and distance out to large distances, again letting us probe dark energy dynamics, and, finally, strongly lensed quasars (and supernovae) and double source-plane lenses probe ratios of distances with complementary sensitivity to dark energy (Bonvin et al. 2017). When rigorously tested and combined, these measurements will provide the most powerful ever constraints on the cosmological density parameters and equation of state of dark energy, as well as new tests of the LCDM cosmology itself. Our next major step forward in understanding the dark universe relies on control of systematic errors through the combination of data from LSST, plus Euclid and the Square Kilometre Array, both already significant UK projects.

The UK has international leadership in these areas, and we are already making a major impact to ensure LSST realises its potential in cosmology. This task is so demanding that it requires the full power of the large DESC collaboration and the Phase B proposal directly addresses these challenges with UK leadership in the DESC simulations and operations, combining LSST with our near-infrared legacy data, providing photometric redshifts and error models, and discovering and classifying type Ia supernovae. and strongly lensed galaxies.

Transients and variables

LSST will provide an unprecedented sampling of the time-domain universe. No other time-domain experiment can compete with its Wide-Fast-Deep survey for science. The survey will deliver about 10 million transient and variable object alerts per night. This rich photometric data, with exquisite calibration and control of systematics, will be further enhanced by spectroscopic follow-up of ~100,000 selected objects. Spectra will reveal the energetics, distances, luminosities and nuclear physics of explosive transients, and, ultimately, the physical nature of the transient Universe. A combination of selecting the extra-galactic transients and exploiting the UK's strengths in massive spectroscopic follow-up will ensure our leadership in this field. The 4MOST project at ESO will place a multi-object spectrometer on the VISTA 4m telescope and our UK collaboration have secured a leadership role. The future of the ESO NTT is secured and it will be a full-time transient follow-up telescope with a new spectrometer (SOXS, with UK involvement), while, ESO's VLT and, ultimately, ELT are perfectly matched to LSST follow-up of faint and exotic transient or variable sources, as well as faint and distant sources in the early Universe.

Deep colour information will reveal exotic super-luminous supernovae out to redshift z~6 and potentially beyond, while there are immense opportunities to link with the SKA radio surveys, GRB and high energy missions such as Swift and SVOM. Multi-messenger astronomy has finally arrived with the LIGO-Virgo detection of its first neutron star–neutron star merger and the spectacular confirmation of a kilonova powered by the radioactive decay of heavy r-process elements (Abbott et al 2017, Smartt et al. 2017, Tanvir et al. 2017). LSST will be the optimal survey to target the uncharted parameter space of faint, fast extragalactic transients – i.e. gravitational wave sources, failed supernovae, orphan afterglows, and mysterious fast radio bursts.

Galactic plane coverage opens up a huge range of science. Episodic accretion in young stellar objects on timescales of years will dominate the Galactic population of high amplitude variables in the red optical bands (Contreras Pena et al. 2017, Lucas et al. 2017). Thousands of multi-colour light-curves will enable study of the poorly-understood processes in protoplanetary discs from the stellar surface out to 5 au. Accretion bursts in X-ray binaries will also be a major application, thanks to the availability of pre-outburst light curves. At lower amplitudes, the precision and duration of LSST is ideally suited to the study of recently discovered classes of variables such as brown dwarfs (probing cloud stratification and auroral activity), the very numerous OSARGs (OGLE Small Amplitude Red Giants, a new type of standard candle; Soszynski et al. 2004) and, of course, the decadal magnetic cycles of normal main sequence stars. The size of the dataset will lead to detection of rarely-seen variables that trace brief but important events, e.g. giant ring systems around young planets that reveal the formation of satellite systems (Kenworthy et al. 2015), the irregular circumstellar matter distributions around sun-like stars that may trace planet engulfment (Boyajian's star; Boyajian et al. 2016) and the new class of stars known as BLAPs (blue large amplitude pulsators; Pietrukowicz et a. 2017). The survey depth allows monitoring of optical counterparts of ultra-luminous x-ray sources in nearby galaxies. The precision, sampling and depth combination for supernova cosmology will define the field in the next decade and, undoubtedly, LSST will make serendipitous discoveries by pushing the time domain to new sensitivities and unprecedented survey volume. The UK has substantial heritage and leadership in this science and this is further underpinned by the proposed UK work on cross-matching of sources across multi-wavelength data sets.

Solar System

LSST will directly address STFC's SSAP goals of understanding the dynamical and physical evolution of bodies, and the transport of volatile ices throughout the solar system. While the primary LSST goal to find >90% of Potentially Hazardous Asteroids 140m across will be led by US funding, the survey will also record all solar system objects via MOPS (moving object pipeline system). LSST will discover, and obtain precise photometry of, inner belt asteroids >100m to TNOs >70km in the Kuiper belt. It will be the first comprehensive survey to cover the transition from rubble-pile to coherent asteroids in the main belt, and characterise non-hydrostatic equilibrium bodies in the Kuiper Belt. Sparse light-curve observations will increase known spin periods and pole positions in all populations by a factor of 10 over those from Pan-STARRS/PTF, allowing investigation into dynamical and physical evolution throughout the asteroid and Kuiper belts. LSST will provide high- cadence nuclear and coma magnitudes for comets on a systematic basis, similar to the exceptional major campaigns previously performed on a handful of individual objects such as comets 67P (Rosetta target) and ISON. LSST will also provide the first realistic chance of the systematic detection and observation of rare events, exemplified by the discovery of the first Interstellar Object in 2017. It should detect interstellar objects at the rate of ~1 per year, see pre-collision impactors at Jupiter and Mars, collisions in the Kuiper belt, and probe the rate of out-bursting of distant comets and Centaurs.

The UK has expertise in the follow-up of solar-system targets using ESO and other facilities (e.g. Fitzsimmons et al. 2018), and leadership in LSST will follow from our co-leadership of the Pan-STARRS Solar System survey, plus leadership of the ESO Large Programmes on Near Earth Object rotations and Rosetta.

Galaxies and the early Universe

LSST will identify billions of galaxies and hundreds of thousands of galaxy groups and clusters out to z=2, and beyond, thanks to the unprecedented solid angle, depth, and uniformity of its survey. It will revolutionise our view of the extragalactic universe, a topic in which the UK has a broad, deep, and rich track record of leadership. Recent highlights include: roadmap studies using simulations and small, deep surveys (e.g. the Stripe 82) of the low-surface-brightness Universe, UK leadership of infrared surveys, including the UKIDSS and VISTA public surveys, high-redshift galaxy-evolution and morphological studies using the HST (e.g. via CANDELS, GOODS), studies of intra-cluster light at z> 1 (XCS), characterisation of low-redshift galaxy clusters as cosmological probes (LoCuSS), optical/IR/mm studies of strongly-lensed high-redshift galaxies, exploration of the fossil record of galaxy formation at low-redshift (e.g. via SAURON, ATLAS-3D) and UK leadership in the Herschel Key Programmes. The long-term scope for UK exploration of the extragalactic Universe using LSST is vast and directly relevant to a large fraction of the UK community but our proposed Phase B work packages are focused on areas of specific UK strength, where we can add significant value to the Level 2 LSST data products to the benefit of the whole UK galaxy community.

To fully exploit the deep-wide galaxy images that LSST is capable of producing will require solutions to the coupled problem of detecting low-surface-brightness structures surrounding/between galaxies (e.g. tidal features and intra-cluster light) via accurate background modelling and subtraction and robust de-blended photometry of galaxies along crowded lines of sight. Overcoming this challenge will unlock the merger history of galaxies (Kaviraj et al. 2010, 2014) offering unprecedented constraints on the hierarchical paradigm, and create exciting synergies with future SKA diffuse HI detections. Overcoming this challenge at z > 0.5 is critical for secure identification, and mass calibration, of intermediate and high-redshift galaxy clusters that will deliver the strongest constraints on cosmology through measurements of the growth of large-scale structure (Kelvin et al. 2012, Williams et al. 2016). Low-surface-brightness science using deep images, and background subtraction techniques that can preserve low-surface-brightness features, are UK areas of focus and strength and the basis for WP 3.7.

LSST's impact will be greatly enhanced by the addition of information at other wavelengths to its optical data. In particular, by adding infrared (IR) wavelengths to the photometry in the six LSST optical bands , the UK will create a unique, legacy dataset that extend the parameter space of stars, galaxies and quasars explored by LSST, enabling a broad range of science.

The most distant galaxies and quasars, at redshifts z>7, corresponding to the Epoch of Reionization and beyond, can only be discovered by combining information from LSST (where the galaxies are “drop-outs”) and IR surveys (where the galaxies are robustly detected). Identification of large numbers of z~7 galaxies and quasars (e.g. Mortlock et al. 2011, Bowler et al. 2015, Reed et al. 2017) is an important goal for both the LSST AGN and Galaxies Science Collaborations (Robertson et al. 2017). It is an area where LSST will have early impact: e.g. we expect about 10 new z~7 quasars and thousands of the most luminous z~7 galaxies in the LSST Commissioning and Science Verification data alone. At redshifts of z~1-3, corresponding to the main epoch of galaxy formation, IR photometry is essential to obtain robust stellar masses and star-formation histories for galaxies (e.g. Muzzin et al. 2013) and, therefore, to produce a complete picture of the mass build-up of galaxies over cosmic time. The addition of IR photometry to optical surveys can significantly improve photo-z performance, reducing the scatter and catastrophic outlier fraction, as key spectral indicators for old and evolved stellar populations shift into the IR at redshifts above 1 (e.g. Banerji et al. 2008, 2015, Jarvis et al. 2013, Bezanson et al. 2016). More accurate photo-zs will, in turn, enhance LSST's ability to use photometric samples to constrain the dark energy equation of state (e.g. Rhodes et al. 2017).

Strong gravitational lensing directly traces the total mass distributions of lensing galaxies, groups and clusters. It probes new regimes of sensitivity and resolution in high-redshift lensed galaxies, tests detailed predictions of CDM on sub-galaxy scales, and can deliver competitive constraints on cosmological parameters (Suyu et al. 2013). A large number of strong lenses could be used as accurate probes of background shear, thereby providing significant support for weak lensing (Birrer et al. 2017). LSST's sensitivity, image quality, survey volume and time-resolved measurements will transform our use of strong gravitational lenses as astrophysical and cosmological probes, enlarging samples of galaxy-scale lenses from $<10^3$ to 10^5 (comparable with, and complementary to, Euclid), discovering 10^4 strongly lensed quasars and 500 lensed type Ia SN (Goldstein & Nugent 2017); time delays can be determined for hundreds of these, plus thousands of group- and cluster-scale lenses.

The two problems of galaxy morphological classification and finding strong gravitational lenses in Big Data surveys are linked through the common technique of machine-learning image analysis techniques (particularly unsupervised techniques which are ideal for processing the unprecedented data volumes expected from surveys like LSST). We now have significant machine learning and AI-assisted tools across the UK astronomy community, and we will aim to link this expertise and initiate a hub for code swapping, expertise sharing and novel development. Machine learning components are now of great interest and this growing area is set to dominate and influence LSST and other UK Big Data projects, with the STFC-funded CDTs providing a forum for sharing large-scale data analysis techniques and algorithms. Indeed, WP3.7 will utilise unsupervised machine-learning algorithms developed within the UK community to solve the problem of shredding of galaxies and their low-surface-brightness components.

AGN and supermassive black holes

LSST will provide a step-change in determining the host properties - e.g. star formation, stellar populations - of active galaxies identified at gamma, X-ray and radio wavelengths as well as opening new parameter space to chart newly-triggered black hole activity in real time. The ubiquity of supermassive black holes in all bulge-dominated galaxies and their driving role in the formation and evolution of galaxies throughout cosmic time are now well accepted. Spending around 10% of their lives actively accreting matter, they are the most energetic radiation sources in the Universe. Consequently, the physics of accretion and black hole growth, the nature of galaxy-black-hole coevolution, and the relation to the host galaxy environment are forefront research questions. Accretion is a genuinely dynamic process with the underlying physics working on time scales of minutes to decades and with amplitudes of variability of up to three orders of magnitude. However, our current understanding of AGN originates predominantly from static data, limiting the ability to put the various phenomena and incarnations of AGN activities into a coherent picture. Only recently have we begun to glimpse the diagnostic and discovery power of the time-domain window, e.g. with the discovery of changing-look quasars/AGN or switch-off accretion.

LSST will be transformational for AGN. Its revolutionary combination of wide-area coverage with redshift depth, temporal sampling and a long time baseline will provide the first census of black hole accretion from quiescence to major outburst. LSST will allow real-time follow-up of accreting and quiescent black holes, specifically probing the triggering of black hole activity and jet formation via detection and multi-wavelength follow-up of gamma-ray, X-ray and optical flares produced by tidal disruption events around quiescent black holes. The UK has a uniquely strong international research pedigree in the study of Active Galactic Nuclei (AGN) across the electromagnetic spectrum and their role in galaxy formation and evolution, with leadership of major AGN programmes on eMERLIN, ALMA, JVLA+VLBA, Liverpool Telescope, VLT, Chandra, Swift, & Fermi, ELT, VISTA and DES.

Definition of Terms

This document uses the terminology used by the LSST Project in the DMSR (v5.0), namely:

- "A **requirement** refers to a declaration of a specified function or quantitative performance that the delivered system or subsystem must meet."
- "Statements of...requirements...are written using one of the three verbs that have a specific meaning with respect to verification:
    - **Will** - A statement of fact. *Will* statements document something that will occur through the course of normal design practice, project process, etc. The statements do not get formally verified.
    - **Should** - A goal. *Should* statements document a stretch goal. A *should* statement is typically partnered with a *shall* statement. *S hould* statements do not get formally verified.
    - **Shall** - A requirement that gets formally verified. *Shall* statements document critical requirements that must be verified through inspection, demonstration, analysis of test...to ensure objectively that the as-built design meet the requirement."

Requirements

The requirements are numbered and labelled according to the DEV Work Package numbers in the initial LSST:UK Phase B proposal which contained 11 workpackages (WP1 to WP11) and are therefore labelled R1 to R11.

R1 : Requirements for Solar System Science Server (S^4)   (Work Package 3.1)

Funding status : selected by the LSST:UK panel and proposed to STFC. This WP was not funded due to budgetary cuts

Contact : Alan Fitzsimmons

LSST will detect and track ~10^7 objects in the Solar System including comets, asteroids, Trans- Neptunian Objects and Interstellar Objects. LSST Moving Object Pipeline System (LSST-MOPS) guaranteed data products include Level 1 products such as photometry and astrometry, and Level 2 products such as heliocentric orbits. Development of Level 3 data products are not yet funded anywhere within the LSST Solar System Science Consortium. There are specific science areas that are of significant importance to UK Solar System scientists, including but not restricted to Main-Belt Comets, asteroid collisions, cometary nuclei, Centaurs, and properties of Near-Earth Objects.

Funding is not currently secured for this WP. If funding is secured, then WP3.1 would build on the Phase A development to create Level 3 software and database tools for use in the UK-DAC and the US-based Solar System server, providing a subset of Level 3 products for the UK and wider LSST community.

The DAC **should provide**:

R1.01: Single epoch detections of known (linked) moving objects, and detections of unknown moving objects, from the LSST alert stream.

R1.02: Linked identifications of known and unknown objects from the daytime LSST-MOPS runs.

S^4 **should** provide **:**

R1.03: Independent phase curve fits in the (H,G) and (H,G12) systems.

R1.04: Comparison between measured and predicted magnitudes of known objects.

R1.05: Alerts for objects with significant (1) magnitude brightness enhancements.

R1.06: Approximate rotation periods for the majority of asteroids following the phasecurve fits; estimation of the maximum lightcurve amplitude when a period cannot be found.

R1.07: Nightly stacked postage stamps for known and unknown moving objects, with metrics indicating presence of coma/ejecta, linked to **R9.03.**

R1.08: Stacked postage stamps for known comets.

R1.09: Measurements of Afp (dust production) for cometary objects with known orbits.

R2 : Requirements for LASAIR - the UK transient broker for LSST (Work Package 3.2)

Funding status : selected by the LSST:UK panel and proposed to STFC. This WP was funded.

Contacts : Roy Williams, Ken Smith, Stephen Smartt,

The LSST Project will provide a stream of 10^7 transient or variable sources (total volume 400-600 GB per night). This stream would overwhelm individual scientists. In the UK DAC, we will build, maintain and run LASAIR, which will ingest the Prompt Products that LSST will produce on a nightly basis and serve them to the UK community. We will provide a critical and essential service specifically focused specifically on the science requirements of the UK community (see User-generated Products). The rate of alerts is given in this document : ***"LSST Alerts: Key Numbers (DMTN 102, Graham et al. 2019)".***

LASAIR will manage the transient data stream and provide users with a database, web pages, visualisation tools, classification and search queries that will enable LSST transient science to be done by UK and international scientists. We expect LASAIR to be one of the official LSST brokers, receiving the full transient stream.

LASAIR is a massive database project, assimilating all transient sources together with the all-sky catalogues with Edinburgh (DAC) and Cambridge (WP3.5) and providing users with easy access through user selected web-pages. Users will be able to login to the database and run either *SQL* queries or upload code (through *Jupyter* Notebooks) to run on the whole database. The QUB team now have more than 8 years' experience running this with the Pan-STARRS and ATLAS surveys in real time in Belfast. The combination of this and the UK:DAC expertise in Edinburgh is essential to build a robust and larger scale version for LSST. We will be focused on the UK science requirements, but LASAIR shall be open to anyone from the LSST community (which is a requirement for official LSST broker status). It will provide the platform for the light-curve fitting and spectroscopic classification work-package. We plan to link with further developments in machine learning, and our development of catalogue cross-matching shall use the state-of-the-art algorithms.

This is a close collaboration between the UK DAC and QUB. For every alert, we will provide an answer to the question *"what has been detected (resolved in time) at this position in the sky, at every wavelength from x-ray to radio?".* This means the following requirements.

LASAIR **shall** provide **:**

R2.01 A searchable database containing all the LSST alerts : with time latency to match the detailed science requirements specified in the document "LSST Transients and Variables Science requirements; Lawrence et al."

R2.02 Light-curves: assimilate all *diaSource* alerts in *diaObjects*: providing interactive webpages (linked to database), plots, ability to select ranges, submit user added points.

R2.03 Postage stamps: all LSST detections and most recent non-detections. Plus multi-colour images from LSST, near infra-red (VISTA/UKIDSS), H-alpha (VPHAS) and EUCLID, or HST/JWST if space based imaging is available. Size of postage stamps should be selectable (number of different, fixed sizes).

R2.04 Massive catalogue cross-match: with star, galaxy, AGN, x-ray, radio catalogues, galaxy cluster catalogues, strong lens catalogues, and provide classification through boosted decision trees through our already working code "*Sherlock*" (Young et al. 2018).

R2.05 Cross match to all *previously* known transients: supernovae, transients, gamma ray-bursts, x-ray and radio burst sources (e.g. searching for currently unknown physical links over time)

R2.06 A database query platform and user-owned storage : for users to query the database and return their own objects and selections in various useful formats. This should be both a SQL query form and Jupyter platform. Users should have access to their own storage where they can store lists of their own objects (more details in the detailed user requirements R2.13)

R2.07 In real-time, cross-match to all other wavelength time-domain surveys: gamma-ray, x-ray and radio (e.g. MEERKat/Thunderkat through 4pisky.org , Swift, SVOM, eRosita)

R2.08 Spectroscopic and/or photometric redshift : locate catalogued redshifts of the likely host galaxy and hence absolute mag (we will link to WPs 3.2 and 3.4 for redshifts)

R2.09 Combine all of the above information: including the first 24hr-48hr lightcurve trend (e.g. rapid rise/decline) to probabilistically classify all transients as : supernova – kilonova – GRB – Tidal Disruption Event – AGN – XRB – CV – eruption star – microlens – orphan

R2.10 Multi-messenger cross-matching: *GW coincidence tag* based on their 4 dimensional position in space and time compared to LIGO-Virgo gravitational wave events (sky position, distance, and time). All transients will also be *Neutrino coincidence tagged* based on their 3D space time location (sky position and time) with IceCube high energy neutrinos.

R2.11 Provide a stream of transients to 4MOST and SOXS spectroscopic programmes and ingest the classifications and data from those facilities in return (linked to WP 3.3)

R2.12 Provide users with a means to upload a "Watchlist" : up to 10^6 objects and provide means to triggering on magnitude variations, and allow an adjustable search radius.

R2.13 Collect a detailed list of user requests and implement them : for additions, enhancements, suggestions, alterations, we will engage with the UK community to maintain a wish list of enhancements and additions and work with the Transient and Variable star PoCs to prioritise this list (maintained here)

LASAIR **should** provide **:**

R2.13 Previous history from Pan-STARRS, DES, Skymapper, ATLAS, CRTS, PTF/ZTF

R2.14 Test, and if successful, Implement machine learning : within the Sherlock classification algorithm

R2.15 Machine learning algorithms for real-bogus classification: as a final check on real-bogus objects, we will run our own trained ML code to weed out spurious objects (Wright et al. 2016, 2017, Smartt et al. 2016).

R3: Requirements for Transient Classification and Spectroscopic Follow-up (Work Package 3.3)

Funding status : selected by the LSST:UK panel and proposed to STFC. This WP was not funded due to budgetary cuts. It has been proposed again to STFC and LSST for funding as part of the UK's in kind contribution and is under view.

Contacts: Mark Sullivan, Isobel Hook

Follow-up spectroscopy of photometric detections from LSST is critical to extracting the full astrophysical detail of the objects discovered: their classifications, chemistry, distances (redshifts), luminosities, energetics – and ultimately their physical natures. As the leaders of the TiDES survey within the ESO 4MOST consortium, we will address this spectroscopic challenge with 250,000 fibre-hours of spectroscopy of transients, their host galaxies, and AGN. We will exploit the fact that wherever 4MOST points in the extragalactic sky, there will be known time-variable sources: both recently discovered transients, and older, now faded events. Around 30 low-resolution spectrograph (LRS) 4MOST fibres (2% of the total) in every pointing will be allocated to extragalactic transients, their host galaxies, and AGN.

We will build the infrastructure for rapid transient follow-up and classification, including interaction with the 4MOST spectroscopic engine, as well as other spectroscopic programs. We will develop the steps required to move from initial photometric prioritisation in LASAIR to spectral observations of ~30,000 transients and their subsequent classification release, together with spectroscopy of ~50,000 transient host galaxies. This will release spectral classifications back to the LSST:UK community via LASAIR, which we will test during commissioning, allowing the community to do high dimensional searches in photometric and spectroscopic phase space on a massive scale. Beyond Phase B, this will enable us to combine data from the 4MOST multi-object spectroscopic instrument and LSST to produce spectra during LSST operations.

We ***shall*** provide:

R3.01 A TiDES survey plan This shall be optimised for revisions to the LSST observing strategies. This will optimise TiDES for the evolving LSST field choice, cadence, filters and depth based on the latest LSST OpSim.

R3.02 An LSST:UK spectroscopic targeting algorithm This shall provide the overall framework to convert targets selected in LASAIR into the format required for 4MOST Observing Blocks (OBs). This should include the ability to provide OBs (or equivalent) for other facilities.

R3.03 A prioritisation algorithm This algorithm shall prioritise such targets for 4MOST observation according to science case, and shall include light-curve information and contextual data. This should include the ability to adjust the prioritisation for observation at other facilities.

R3.04 The 4MOST ingestion procedure This shall ingest our prioritised and formatted 4MOST OBs into the 4MOST observing system. This will combine as required with other 4MOST (static) targets.

R3.05 Spectral Success Criteria (SSC) We shall define SSC for 4MOST observations of LSST transients based on our simulations of LSST transients and the 4MOST Exposure Time Calculator

R3.06 Pseudo-automated (machine) classification We shall implement classification of the quick-look 4MOST spectra that will be produced at Paranal following observation by 4MOST. We will determine the level of required human oversight to produce error-free classifications. We should implement this algorithm on LASAIR.

R3.07 Handshake software We shall develop software to ‘handshake’ with LASAIR to return all transient classifications to the UK community.

R3.08 Testing programs during commissioning We shall test our algorithms on available data taken during LSST commissioning. This will include data from facilities such as the AAT/2dF spectrograph. This will ensure that our fibre allocation algorithms are optimal and our classification routines are working. We shall return any classifications to the UK community via LASAIR.

We ***should*** provide:

R3.09 Updated prioritisation algorithms We should update our spectroscopic prioritisation algorithms based on commissioning data, once SSC are confirmed and measured on real data as a function of observing variables.

R3.10 Updated classification algorithms We should test and update our machine classification algorithms based on commissioning data.

R4: Requirements for The UK variability broker for LSST (Work Package 3.4)

Funding status : selected by the LSST:UK panel and proposed to STFC. This WP was not funded due to budgetary cuts

Contacts : Phil Lucas, Seb Hoenig, Andy Lawrence

If funds will become available, we will develop a critical software package, the UK variability broker, for variable stars and active galactic nuclei (AGN) to be hosted at the UK DAC. This broker targets a large audience in the Galactic and extragalactic community, cutting across at least three LSST Science Consortia. It will establish firm leadership of the UK in variability science beyond the explosive transients covered by LASAIR (WP3.2 and requirements R2).

The work package ***shall*** deliver:

R4.1 base catalogue of variable candidate stars and galactic centres from on commissioning data
R4.2 rolling update of light curves for candidate variable sources in base catalogue via forced photometry (“preliminary lightcurves”)
R4.3 rolling update of variability indicators based on panchromatic LSST data
R4.4 monitoring of LASAIR data stream for fast variability of new sources to be included in base catalogue
R4.5 classification of variable sources into sub-classes of stars and AGN
R4.6 a time-domain software toolbox for variability analysis on the DAC by the users, including
(1) pre-whitening tool
(2) analysis tools for periodicity and aperiodic events
(3) classification tool for non-transient light curves based on templates

The work package ***should*** deliver:

R4.7 monitoring long-term imaging data for slow variability in previously un-flagged sources
R4.8 multi-filter cross-correlation analysis tools
R4.9 alert system for slow variability, similar to transients in LASAIR

R5: Requirements for LSST and Near-IR Data Fusion (Work Package 3.5)

Funding status : selected by the LSST:UK panel and proposed to STFC. This WP was funded.

Contacts : Manda Banerji, Richard McMahon

While LSST will undoubtedly revolutionize ground-based wide-field astronomy, its scientific return will be greatly enhanced by the addition of information at other wavelengths to the LSST optical data. In particular, by adding data at infrared (IR) wavelengths to the photometry in the six LSST optical bands, there is the opportunity to create a unique, legacy dataset that will open up the parameter space of galaxies explored by LSST. IR photometry for LSST stars, galaxies and quasars (and vice versa) will facilitate a very broad range of science including the study of galaxies in the Epoch of Reionisation, a better understanding of galaxy formation, improved photometric redshift performance for cosmology and the study of the obscured and cool Universe.

WP 3.5 requires ingestion of the key datasets that will be processed as part of this DEV work package within the UK DAC. The requirements on the DAC for the DEV WP 3.5 are therefore as follows:

The DAC **shall** make available to WP 3.5:

R5.01: Single epoch and coadd images together with associated weight-maps and catalogues for the following surveys: DES, HSC, UKIDSS imaging surveys, ESO VISTA imaging surveys.

R5.02: Postage stamp server with web-based access infrastructure to visualise images from above surveys

R5.03: Queryable database into which the data products from WP3.5 can be ingested and made accessible to the UK community.

The DAC **should** make available to WP 3.5:

R5.04: Single epoch and coadd images from other multi-wavelength surveys such as Spitzer, WISE, PanSTARRS.

WP 3.5 **shall** provide:

R5.05: A joint pixel-level analysis pipeline for the combined processing of optical and ground-based near infra-red imaging surveys of comparable seeing together with comprehensive documentation detailing the full pipeline implementation.

R5.06: Optical+near infra-red (NIR) catalogues produced by joint pixel-level analysis of LSST pre-cursor surveys (DES, HSC) and ground-based near infra-red imaging surveys (UKIDSS-LAS, VHS, VIKING, VIDEO, VEILS). Catalogue delivery **will** include source-level metadata, detection and measurement image provenance information and workflow provenance information (e.g. configuration files).

R5.07: Optical+near infra-red (NIR) catalogues produced by joint pixel-level analysis of LSST commissioning and science verification data and ground-based near infra-red imaging surveys (UKIDSS-LAS, VHS, VIKING, VIDEO, VEILS). Catalogue delivery **will** include source-level metadata, detection and measurement image provenance information and workflow provenance information (e.g. configuration files).

WP 3.5 **will** provide:

R5.08: Results of running benchmarking tests on the pipeline in order to scope out future computational requirements.

R5.09: Reports on scientific validation of catalogues produced by the pipeline in the form of scientific presentations and/or publications.

WP 3.5 **should** provide:

R5.10: An analysis pipeline that is easily reconfigured to process future datasets e.g. *Euclid*

R5.11: A modular pipeline structure such that new algorithms for joint pixel-level processing of LSST data and other multi-wavelength datasets (e.g. *Spitzer, WISE*) can be easily implemented within it.

R6: Requirements for 3D LSST : Photometric Redshifts (Work Package 3.6)

Funding status : selected by the LSST:UK panel and proposed to STFC. This WP was not funded due to budgetary cuts. It has been proposed again to STFC and LSST for funding as part of the UK's in kind contribution and is under view.

Contact : B. Joachimi

R7: Requirements for infrastructure for low-surface-brightness science using LSST (Work Package 3.7)

Funding status : selected by the LSST:UK panel and proposed to STFC. This WP was funded.

Contacts: S. Kaviraj, C. Collins

With its unique combination of depth and area, statistical low-surface-brightness (LSB) astronomy is one of LSST's niches. LSST will revolutionise galaxy-evolution studies, by revealing LSB objects and structures that are effectively invisible in past wide-area surveys, e.g. LSB galaxies, LSB tidal features and intra-cluster light (ICL). LSB tidal features encode galaxy assembly histories, making them essential tracers of hierarchical structure formation. ICL dominates the baryonic content of clusters, which are unique probes of our cosmological model. For stellar masses down to 10^7 $M_{¤}$ LSB galaxies are thought to dominate the local galaxy number density. In addition to enabling statistical studies of LSB structures, LSST will reveal the LSB components of all astrophysical objects, which will impact the measurements of their properties (e.g. photometry, sizes etc.). As such, LSST's LSB capabilities are fundamental to fulfilling the science requirements of several Science Collaborations (e.g. Galaxies, AGN, Strong Lensing, DESC).

The faint/diffuse nature of LSB structures makes them susceptible to two, serious data-processing issues: sky over-subtraction and shredding of galaxies and their tidal features by de-blenders. Since the default sky subtraction and de-blending pipelines from the LSST Project are optimised for accurate photometry in deep/crowded fields (i.e. typically smaller spatial scales than LSB structures), they are known to fail in both data-processing issues described above. Preparatory work is, therefore, essential for *any* LSB science to be possible using LSST.

WP 3.7 will provide the necessary mitigation of these issues by delivering (1) optimised sky-subtraction to preserve LSB structures on any spatial scale and (2) algorithms to mitigate shredding by de-blenders. This development work has been identified as a priority for the community (see LSST Galaxies Roadmap; Robertson et al. 2017) – without it a significant fraction of LSST's discovery space will remain untapped. They are also unique UK contributions, with no LSST Project work in this area.

WP 3.7 **will** provide:

R7.01: New sky-estimation algorithms: The work-package **will** result in the development of new sky-estimation algorithms, tailored for LSST LSB science on a wide range of spatial scales.

R7.02: LSB structural catalogues: The principal requirements for the sky-estimation algorithms are to preserve LSB structures (e.g. tidal features and ICL) in LSST images, so that they can be measured and used for science.

R7.03: A community-deliverable sky-estimation software package: The sky-estimation algorithms **will** be available as software packages within the LSST software stack that will implement them on LSST images.

R7.04: User manuals for our sky-estimation software packages: The sky-estimation software packages **will** be documented via user manuals, available to the LSST community, and the algorithms **should** be published as a refereed paper.

R7.05: A new de-shredding algorithm: The work-package **will** result in the development of an algorithm that mitigates the shredding of galaxies and their LSB tidal features.

R7.06: A community-deliverable de-shredding software package: The de-shredding algorithm **will** be available as a software package in the LSST software stack that will implement it on LSST images.

R7.07: User manuals for our de-shredding algorithm: The de-shredding algorithm **will** be documented via user manuals available to the LSST community and the algorithm **should** be published as a refereed paper.

WP 3.7 **should** provide:

R7.08: Mock images: As a useful by-product of this sky-estimation algorithm development, the work-package **should** produce mock images from hydro-dynamical cosmological simulations that are generically useful for the LSST community.

R8 : Requirements for Image recognition and machine learning: building LSST's strong lens discovery system (Work Package 3.8)

Funding status : selected by the LSST:UK panel and proposed to STFC. This WP was not funded due to budgetary cuts

Contacts : Aprajita Verma

LSST will be the first wide field survey of sufficient depth to discover $>10^5$ strongly lensed (SL) systems beginning a new era of statistical analysis. The rarity, varied morphologies and high rates of false positives in automated selection, makes SL discovery from the billion galaxies in the LSST surveys non-trivial and requires development of sophisticated discovery algorithms and methods, infrastructure, as well interfaces to the LSST data archive (both data release and prompt products) and delivery of user generated products. Our challenge is to find 1 SL in 10^6 galaxies, harder than typical machine learning problems; the neural net must be highly trained and work almost perfectly to produce samples of manageable purity. For this reliable, large and realistic training sets are required.

The main science requirements pertain to the annual Data Release Products from which we will create user generated products for strong lensing discovery and science. However, timely identification (for follow-up and analysis) of strongly-lensed variable sources will be enhanced by knowing where LSST's strong lenses are in advance. By cross-matching our increasing catalogue of LSST strong lens candidates (with value added information such as modelling, photometry and photo-z) with the 10^7 alerts per night brokered by LASAIR (R1.04), or other LSST transient broker outputs, will allow rapid identification of the even rarer strongly lensed transients.

Over the 10 year full depth we anticipate strong lensing samples of several 10^5 reliable lensed galaxies, however this implies image generation and inspection, by citizens or with machine learning, of $>10^{8\text{-to-}9}$ sources with multi-band imaging. Furthermore, strong lens detection, particularly for the more numerous systems with low Einstein radii, is improved when using 'best seeing' and/or lens-subtracted images. These require processing beyond the data release products.

WP 3.8 is focussed on development of software, infrastructure and user-generated products in preparation for operations at the end of phase B and beyond.

Funding is not currently secured for this WP. If funding is secured, then **WP8 should provide**:

Inputs

- **R8.01** large sets of high quality, realistic simulations of strong lenses within the LSST data framework
- **R8.02** DAC compatible software/Jupyter notebooks to query data release catalogue based lens candidate identification
- **R8.03** DAC compatible scripts to extract multi-colour imaging data (fits files) for strong lens candidates
- **R8.04** *user generated* 'best seeing' multi-filter image stacks
- **R8.05** *user generated* 'lens subtracted' multi-filter images
- **R8.06** *user generated* lens candidate colour composites

Discovery tools and infrastructure

- **R8.07** at least one deep learning neural network (NN) for lens discovery optimized for LSST data
- **R8.08** development of the interface and analysis software for the LSST Citizen Science platform
- **R8.09** infrastructure to deliver the user generated products to the LSST Citizen Science platform and machine learning codes

Data and modelling challenges

- **R8.10** run lens discovery challenge (platform, test data and ability to report results) for machine learning and inspection methods

R8.11 run a lens modelling challenge (platform, test data and ability to report results

LSST's Strong Lens Candidate Server

R8.12 infrastructure to host standard, best seeing/subtracted cutouts, colour composites for each lens candidate with additional value added data

R8.13 ingest citizen science and machine learning code scores

R8.14 ability to run lens modelling software and log the output to the server

R8.15 perform accurate (deblended) lens+source photometry and photometric redshifts for all lens candidates and lensed source images

R8.16 ability to send LASAIR (or other transient brokers) strong lens candidate catalogues to identify strongly lensed transients

R8.17 ability to curate strong lens candidate samples for imaging and spectroscopic follow-up

To enable the WP 3.8 Strong Lensing to progress, the DAC ***should*** *provide*

R8.18 capability to query data release images and catalogues for 10^9 lens candidates/fields

R8.19 capability to extract fits stamps for all lens candidates/fields for CS or ML inspection, run 'best-seeing', lens subtraction, colour composite software and store the outputs

R8.20 capability to run lens modelling, deblending and photo-z software on user generated products

R8.21 host & serve strong lens *user generated products* and value added data

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R9: Science Requirements specification for WP 3.9 "LSST Point Spread Function, sensor characterisation and modelling". *(Work Package 3.9)*

Funding status : selected by the LSST:UK panel and proposed to STFC. This WP was funded.

Contacts : Ian Shipsey, Lance Millar

WP3.9 ***will*** provide laboratory characterisation of the LSST detectors, and a model for propagating the laboratory measurements into the system PSF, with an accuracy suitable for weak lensing survey measurements. Tests of model accuracy will be made on Comcam data. Specific requirements follow:

R9.1 The WP shall use laboratory measurements to optimise the detector clocking and bias parameters.

R9.2 The WP shall provide a parameterised model of the wavelength dependent detector charge diffusion kernel from laboratory measurements.

R9.3 The WP shall provide a parameterised model for the intensity-dependent and wavelength-dependent detector brighter-fatter effect, from laboratory measurements.

R9.4 The accuracy of the models of the detector PSF components should be tested against commissioning data and compared with the DESC lensing survey accuracy requirements, as stated in the DESC Science Requirements Document https://arxiv.org/pdf/1809.01669.pdf to be updated following DESC Data Challenge 2 (DC2).

R10: Requirements for the UK's Contribution to DESC Operations (Work Package 3.10)

Funding status : selected by the LSST:UK panel and proposed to STFC. This WP was funded.

Contact : Joe Zuntz

The WP 3.10 represents contributions to a larger package of work being done within the Dark Energy Science Collaboration (DESC). Requirements 2-6 below summarize only the contributions of Zuntz and Perry towards these tools and operations.

Requirements for Ceci

Ceci is a wrapper around the workflow management system "Parsl" designed to provide tools to scientific software developers to run pipelines in parallel and at scale.

DESC pipelines are particularly challenging given the quantity of data involved (a single double precision column for a complete LSST catalogue will occupy ~ 50GB of memory) and the fact that multiple different analyses must be run on it for different science cases. For more complicated pipelines workflow management systems offer a host of features

Ceci is a thin wrapper around a particular workflow manager, Parsl, designed to make it easy for scientists/developers new to the system to use it, to hide the implementation details of pipelines, and to provide a standard way to

A prototype of ceci using an older version of Parsl and running on interactive nodes at NERSC is currently in use.

Ceci ***will*** provide:

R10.1 A connection between the Parsl workflow management framework (or another WMF) and DESC pipelines

R10.2 An abstract base class providing all the necessary tools for scientist-developers

Ceci ***shall*** provide:

R10.3 Automatic running of pipelines under the SLURM batch system.

R10.4 Automatic re-running or partially successful pipelines.

Ceci *should* provide:

R10.5 An interface to run on Grid computing systems using data transfer tools as well as NERSC.

R10.6 Use of spark as an alternative parallelization methodology to MPI.

Requirements for TXPipe

The TXPipe project is the two-point analysis pipeline for weak lensing and large-scale structure observables, starting from catalogues provided by data management and ending with summary statistcs.

Each stage is implemented as a Ceci python subclass, and most (at time of writing) have been prototyped, though not debugged and not optimal. The development of these stages and extension of them to existing science cases is the bulk of the task for Zuntz in WP 3.10.1.2. In some cases external code exists for these stages, and the task is to wrap them in an appropriate form for LSST scale. In others a method exists already but no specific code, and certainly not code that will function at the LSST scale. The remainder of the time is to extend this baseline analysis to include other UK science areas as noted in the original proposal.

TXPipe will provide:

R10.7 the structure for a pipeline from catalogues to summary statistics.

TXPipe should provide the following pipeline elements operating at the LSST scale and meeting the LSST DESC Science Requirements Document targets:

R10.8 TXSelector - selection of objects into tomographic bins for sources and lenses with shear selection biases computed with fractional accuracy 5e-2.

R10.9 TXMaps - generation of shear, depth, systematic, and mask maps with map-level calibration biases m<1e-3.

R10.10 TXTwopoint - estimation of real space two-point functions with multiplicative accuracy m<1e-3

R10.11 TXTwopointFourier - estimation of Fourier space power spectra with multiplicative accuracy m<1e-3.

R10.12 TXCovAnalytic - estimation of covariances using analytic methods (no accuracy requirement since this is an ingredient to a hybrid method).

TXPipe should provide, with the same requirements:

R10.13 TXMocks - generation of mock catalogues from cosmology simulations.

R10.14 TXRandoms TXMocks - generation of random catalogues matching tomographic bins.

R10.15 TXCovMocks - estimation of covariances from mocks.

Requirements for FireCrown

FireCrown is the designated parameter estimation code for DESC, which will analyze summary statistics to generate parameter constraints.

It connects the DESC Core Cosmology Library to MCMC engines in the CosmoSIS package, and implements systematic error modelling specific to LSST and its catalogues.

Zuntz's contribution to this is largely via CosmoSIS, which provides the various sampling algorithms to the system. The Data & Simulations Wrangler will manage simulation data generation, storage, and analysis as a key part of the data challenge simulation process (see below).

There will also be no UK expertise in running the LSST Data Management software stack at scale.

FireCrown will provide

- **R10.16** A parameter estimation system suitable for DESC.

FireCrown shall provide:

- **R10.17** a connection to the output of the TXPipe pipelines.
- **R10.18** CosmoSIS samplers work at LSST scale.

FireCrown should provide:

- **R10.19** a new forecasting sampler to simulate then analyze a new problem.

Requirements for ImSim

ImSim will provide:

- **R10.20** an image simulation tool suitable for DESC.

ImSim shall provide:

- **R10.21** improved optimization when running on Knight's Landing architectures and future NERSC architectures
- **R10.22** an optimized interface on the UK Archer system
- **R10.23** a suite of images generated for the DC3 simulations run and managed partly in the UK

ImSim should provide:

- **R10.24** Documentation for use on UK systems and elsewhere aimed at users studying variations from baseline image quality and content scenarios.

Requirements for DM Tools

The tools built by the Data Wrangler shall provide:

- **R10.25** a build of the Data Management Stack running on and optimized for UK grid and/or cloud systems.
- **R10.26** an interface to run the shape measurement or other related operations on the stack on image simulations.
- **R10.27** an analysis of the best job management system to use on the Grid for this case.

R11 : Requirements for Cross matching and astrometry at LSST depths *(Work Package 3.11)*

Funding status : selected by the LSST:UK panel and proposed to STFC. This WP was funded.

Contact : Tim Naylor

Cross-matching the LSST catalogues to other datasets is fundamental to much of the science the UK aims to carry out. There is both galactic and extra-galactic science which relies on identifying LSST objects with detections in UK legacy IR surveys. Reliable cross-matching is also important to identify the progenitors of transients events. Finally much of the UK science programme also relies on reliable proper motions and parallaxes for faint objects. However, LSST catalogues will be so crowded (even far from the Galactic Plane) that standard algorithms for cross-matching with other surveys will fail. In addition crowding will also affect the astrometry of faint objects. Hence we will provide (through the DAC) a service that uses cross-matching algorithms which include the effects of crowding, and partially mitigates them. Achieving this relies on understanding crowded field astrometry, so we will also provide algorithms which calculate the effects of crowding on proper motions and parallaxes.

R11.1 This workpackage **will** result in the creation a model for the LSST astrometric uncertainties which includes the effects of crowding.

R11.2 This **shall** be documented and **should** be published as a refereed paper.

R11.3 The workpackage **will** provide (either as tables or a software service) cross-matches of sources in the LSST catalogues with sources in the VISTA, VPHAS, WISE and Spitzer catalogues, with the ability to extend to EUCLID catalogues.

R11.4 It **should** provide cross-matches with other catalogues the LSST:UK community deem to be useful.

Each set of cross-matches must meet the following **requirements**.

R11.5 If appropriate, there **will** be an adjustment for crowding to the astrometric uncertainties of the catalogue LSST is matched to.

R11.6 For each cross-match pair there

R11.6.1 **shall** be the probability that the cross-matched pair are detections of the same object;

R11.6.2 **shall** be the probability that the cross-matched pair are detections of the same object based only on the astrometric information and

R11.6.3 **shall** be the probability that the cross-matched pair are detections of the same object based only on the photometric information.

R11.6.4 There **should** be one or more measures of the likely contaminating flux for the object in the catalogue LSST is matched to.

R11.7 The above information for each cross-match pair **will** be available through the UK DAC, and **shall** be documented in a form which **should** be a refereed paper.

Appendix: Summary of Requirements

The LSST project has defined three levels of data product and we adopt those definitions here. They refer to the type of data product and when it is produced. Here are the LSST definitions

Prompt Products : products generated from the nightly alert stream (labelled Prompt in the Summary Table). Data products will include images, difference images, catalogs of sources and objects detected in difference images, and catalogs of Solar System objects. Formerly known as Level 1.

Data Release : data products will include well calibrated single-epoch images, deep coadds, and catalogs of objects, sources, and forced sources, enabling static sky and precision time-domain science. Formerly known as Level 2.

User Generated : data products and will enable science cases that greatly benefit from co-location of user processing and/or data within the LSST Archive Center. Formerly known as Level 3.

Requirement ID	Title	Level	Priority	Owner	Relevant WP Objective and Deliverable
R1.01	Single epoch detections of moving objects	Prompt		Fitzsimmons	
R1.02	Link single epoch detections of moving objects	Prompt		Fitzsimmons	
R1.03	Independent phase curve fits	User		Fitzsimmons	
R1.04	Measured and predicted mags of objects	User		Fitzsimmons	
R1.05	Alerts for magnitude brightness changes	Prompt		Fitzsimmons	
R1.06	Rotation periods and phasecurve fits	User		Fitzsimmons	
R1.07	Nightly stacked postage stamps for all movers	Prompt		Fitzsimmons	
R1.08	Stacked postage stamps for known comets	Prompt		Fitzsimmons	
R1.09	Measurements of dust production for comets	User		Fitzsimmons	
R2.01	Lasair searchable database of all LSST alerts	User		Smartt	WP 3.2 O1
R2.02	Lightcurves - visual and data access	Prompt		Smartt	WP 3.2 O1
R2.03	Postage stamps for all *diaObjects*	Prompt		Smartt	WP 2.3 O1
R2.04	Massive catalogue cross-match	Prompt		Smartt	WP 3.2 O3
R2.05	Cross-match with previously known transients	Prompt		Smartt	WP 3.2 O3, O4
R2.06	A database query platform in SQL and Jupyter	User		Smartt	WP 3.2 O2
R2.07	Realtime cross-match to all other surveys	Prompt		Smartt	WP 3.2 O3, O4

R2.08	Spectroscopic and photometric redshift of hosts	User		Smartt	WP 3.2 O3
R2.09	Combine all catalogue information and classify probabilistically	User		Smartt	WP 3.2 O3, O4
R2.10	Multi-messenger cross-match	User		Smartt	WP 3.2 O3
R2.11	Provide stream of transients to 4MOST and SOXS	User		Smartt	WP 3.2 O3
R2.12	Provide watchlist capability	User		Smartt	WP 2.3 O3
R2.13	Detailed list of user requested enhancements	User		Smartt	WP 3.2 O4
R2.14	Previous history from transients surveys	User		Smartt	WP 3.2 O4
R2.15	Machine learning Sherlock classifications	User		Smartt	WP 3.2 O3
R2.16	Machine learning for real-bogus classification	User		Smartt	WP 3.2 O3
R3.01	TiDES Survey Plan	User		Sullivan	
R3.02	TiDES Spectroscopic targeting Algorithm	User		Sullivan	
R3.03	TiDES Prioritisation Algorithm	User		Sullivan	
R3.04	TIDES 4MOST Ingestion Procedure	User		Sullivan	
R3.05	TIDES Spectral Success Criteria	User		Sullivan	
R3.06	TiDES Machine Learning Classification for spectra	User		Sullivan	
R3.07	LSST-TiDES Handshake Software	User		Sullivan	
R3.08	TiDES Commissioning Programmes	User		Sullivan	
R3.09	TiDES Prioritisation Algorithm - enhanced after commissioning	User		Sullivan	
R3.10	TiDES Machine Learning - - enhanced after commissioning	User		Sullivan	
R4.01	Catalogue of Variable stars and variable galactic centres	User		Hoenig	
R4.02	Rolling update of light curves	User		Hoenig	
R4.03	Rolling update of variability indicators	User		Hoenig	
R4.04	Monitoring of LASAIR data stream for fast variability	User		Hoenig	
R4.05	Classification of variable sources from lightcurves	User		Hoenig	
R4.06	Time-domain software toolbox	User		Hoenig	
R4.07	Monitoring long-term imaging data for slow variability	User		Hoenig	
R4.08	Multi-filter cross-correlation analysis tools	User		Hoenig	
R4.09	Alert system for slow variability	User		Hoenig	
R5.01	Image and pixel data from DES, HSC, UKIDSS, VISTA, PanSTARRS surveys	User		Banerji	WP 3.5 O1
R5.02	Postage stamp server to visualise the above data	User		Banerji	
R5.03	Database containing data product catalogues from above	User		Banerji	WP 3.5 O2
R5.04	Image and pixel data from multi-wavelgenth : Spitzer, WISE	User		Banerji	
R5.05	Joint pixel-level analysis pipeline for LSST +pre-cursor surveys	User		Banerji	WP 3.5 O1
R5.06	Catalogues produced by joint pixel-level analysis of LSST pre-cursor surveys (DES, HSC) + NIR data	User		Banerji	WP 3.5 O2
R5.07	Catalogues produced by joint pixel-level analysis of LSST commissioning + NIR data	User		Banerji	WP 3.5 O2
R5.08	Benchmarking tests on pipeline and future requirements	User		Banerji	WP 3.5 O1
R5.09	Reports on scientific validation of catalogues	User		Banerji	WP 3.5 O2
R5.10	An analysis pipeline that is easily reconfigured to process future datasets e.g. *Euclid*	User		Banerji	WP 3.5 O1
R5.11	A modular pipeline structure such that new algorithms for joint pixel-level processing	User		Banerji	WP 3.5 O1

R7.01	New sky-estimation algorithms	User		Kaviraj	WP 3.7 O1
R7.02	LSB structural catalogues	User		Kaviraj	WP 3.7 O1
R7.03	A community-deliverable sky-estimation software package	User		Kaviraj	WP 3.7 O2
R7.04	User manuals for our sky-estimation software packages	User		Kaviraj	WP 3.7 O3
R7.05	A new de-shredding algorithm	User		Kaviraj	WP 3.7 O3
R7.06	A community-deliverable de-shredding software package	User		Kaviraj	WP 3.7 O3
R7.07	User manuals for our de-shredding algorithm	User		Kaviraj	WP 3.7 O3
R7.08	Mock images	User		Kaviraj	
R7.09	A de-shredded source catalogue	User		Kaviraj	
R7.10	Morphological classifications	User		Kaviraj	
R8.01	Simulations of strong lenses within the LSST data framework	User		Verma	
R8.02	Jupyter notebooks to query catalogue based lens candidate identification	User		Verma	
R8.03	Scripts to extract multi-colour imaging data (fits files) for strong lens candidates	User		Verma	
R8.04	*User generated* 'best seeing' multi-filter image stacks	User		Verma	
R8.05	*User generated* 'lens subtracted' multi-filter images	User		Verma	
R8.06	*User generated* lens candidate colour composites	User		Verma	
R8.07	Deep learning neural network (NN) for lens discovery	User		Verma	
R8.08	Software for the LSST Citizen Science platform	User		Verma	
R8.09	User generated products to the LSST Citizen Science platform and machine learning codes	User		Verma	
R8.10	Run lens discovery challenge	User		Verma	
R8.11	Run a lens modelling challenge	User		Verma	
R8.12	Best seeing/subtracted cutouts, colour composites for each lens candidate	User		Verma	
R8.13	Ingest citizen science and machine learning code scores	User		Verma	
R8.14	Lens modelling software	User		Verma	
R8.15	Lens+source photometry and photometric redshifts for all lens candidates	User		Verma	
R8.16	Send LASAIR (or other transient brokers) strong lens candidate catalogues	User		Verma	
R8.17	Curate strong lens candidate samples	User		Verma	
R8.18	Capability to query data release images and catalogues for 10^9 lens candidates/fields	User		Verma	
R8.19	Capability to extract fits stamps for all lens candidates/fields	User		Verma	
R8.20	Run lens modelling, deblending and photo-z software	User		Verma	
R8.21	Host & serve strong lens *user generated products*	User		Verma	
R9.01	Use laboratory measurements to optimise the detector clocking and bias parameters	Data		Miller	WP 3.9 O1, O2
R9.02	Model of the wavelength dependent detector charge diffusion kernel from laboratory measurements.	Data		Miller	WP 3.9 O2
R9.03	Model for the intensity-dependent and wavelength-dependent detector brighter-fatter effect, from laboratory measurements.	Data		Miller	WP 3.9 O2, O3
R9.04	Test accuracy of the models of the detector PSF components against DESC requirements	Data		Miller	WP 3.9 O4
R10.01	Ceci: Connection between the Parsl workflow and DESC pipelines	User		Zuntz	WP 3.10 O1

R10.02	Ceci: An abstract base class providing all the necessary tools for scientist-developers	User		Zuntz	WP 3.10 O1
R10.03	Ceci : Automatic running of pipelines under SLURM	User		Zuntz	WP 3.10 O1
R10.04	Ceci: Automatic re-running or partially successful pipelines.	User		Zuntz	WP 3.10 O1
R10.05	Ceci: interface to run on Grid computing systems	User		Zuntz	WP 3.10 O1
R10.06	Ceci: Use of spark	User		Zuntz	WP 3.10 O1
R10.07	TXPipe: the structure for a pipeline from catalogues to summary statistics.	User		Zuntz	WP 3.10 O1
R10.08	TXPipe: TXSelector	User		Zuntz	WP 3.10 O1
R10.09	TXPipe: TXMaps	User		Zuntz	WP 3.10 O1
R10.10	TXPipe: TXTwopoint	User		Zuntz	WP 3.10 O1
R10.11	TXPipe: TXTwopointFourier	User		Zuntz	WP 3.10 O1
R10.12	TXPipe: TXCovAnalytic	User		Zuntz	WP 3.10 O1
R10.13	TXPipe: TXMocks	User		Zuntz	
R10.14	TXPipe: TXRandoms	User		Zuntz	
R10.15	TXPipe: TXCovMocks	User		Zuntz	
R10.16	FireCrown: parameter estimation system suitable for DESC.	User		Zuntz	WP 3.10 O1
R10.17	FireCrown: connection to the output of the TXPipe pipelines.	User		Zuntz	WP 3.10 O1
R10.18	FireCrown: CosmoSIS samplers work at LSST scale.	User		Zuntz	WP 3.10 O1
R10.19	FireCrown: a new forecasting sampler to simulate then analyze a new problem.	User		Zuntz	WP 3.10 O1
R10.20	ImSim: an image simulation tool suitable for DESC.	User		Zuntz	WP 3.10 O2
R10.21	ImSim: improved optimization when running on Knight's Landing	User		Zuntz	WP 3.10 O2
R10.22	ImSim: an optimized interface on the UK Archer system	User		Zuntz	WP 3.10 O2
R10.23	ImSim: suite of images generated for the DC3 simulations run and managed partly in the UK	User		Zuntz	WP 3.10 O2
R10.24	ImSim: Documentation for use on UK systems and elsewhere	Data		Zuntz	WP 3.10 O2
R10.25	DM Tools : a build of the Data Management Stack on UK grid	User		Zuntz	WP 3.10 O2
R10.26	DM Tools : an interface to run operations on the stack on image simulations.	User		Zuntz	WP 3.10 O2
R10.27	DM Tools : an analysis of the best job management system	User		Zuntz	WP 3.10 O2
R11.01	A model for the LSST astrometric uncertainties which includes the effects of crowding.	User		Naylor	WP3.11 O2, D3.11.1
R11.02	Documentation and refereed paper	User		Naylor	WP3.11 O1, D3.11.1
R11.03	Cross-matches of LSST catalogues with NIR and MIR catalogues	User		Naylor	WP3.11 O3, D3.11.2, D3.11.3, D3.11.4
R11.04	Cross-matches with other catalogues the LSST:UK community deem to be useful.	User		Naylor	WP3.11 O3, D3.11.2, D3.11.3, D3.11.4
R11.05	Crowding and astrometric uncertainties	User		Naylor	WP3.11 O3, D3.11.2, D3.11.3, D3.11.4
R11.06	Set of probabilities of matching pairs	User		Naylor	WP3.11 O3, D3.11.2, D3.11.3, D3.11.4
R11.07	All information for cross-matching pairs available in UK DAC and documented	User		Naylor	WP3.11 O3, D3.11.2, D3.11.3, D3.11.4