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LIVERPOOL TELESCOPE AND LIVERPOOL TELESCOPE 2

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RESUMEN

El telescopio robótico Liverpool es un telescopio óptico e infrarrojo completamente robótico de 2m de diámetro, ubicado en el Observatorio del Roque de los Muchachos en la Isla de la Palma. El telescopio es propiedad de la Universidad John Moores de Liverpool, que también lo opera, contando con el apoyo financiero del Consejo de Infraestructuras Científicas y Tecnológicas del Reino Unido. El telescopio comenzó las operaciones científicas de forma rutinaria en 2004 y es una infraestructura de uso común cuyo tiempo está disponible a través de una serie de comités de asignación de tiempo por medio de un proceso abierto y arbitrado. Siete instrumentos montados simultáneamente apoyan un programa científico completo, priorizado en el seguimiento de fuentes transitorias y en otros objetivos típicos de estos observatorios. También se está desarrollando un telescopio de segunda generación que con el nombre de Telescopio Liverpool 2 con el que se podrá innovar en esta era de “Time-Domain Astronomy” cuando ya estén operativas infraestructuras como el LSST. El Telescopio Robótico Liverpool 2 tendrá un diámetro de 4m y una respuesta temporal más rápida. En este artćulo presentamos una visión completa de ambos desarrollos.

ABSTRACT

The Liverpool Telescope is a fully robotic optical/near-infrared telescope with a 2-metre clear aperture, located at the Observatorio del Roque de los Muchachos on the Canary Island of La Palma. The telescope is owned and operated by Liverpool John Moores University, with financial support from the UK’s Science and Technology Facilities Council. The telescope began routine science operations in 2004 and is a common-user facility with time available through a variety of committees via an open, peer reviewed process. Seven simultaneously mounted instruments support a broad science programme, with a focus on transient follow-up and other time domain topics well suited to the characteristics of robotic observing. Development has also begun on a successor facility, with the working title ‘Liverpool Telescope 2’, to capitalise on the new era of time domain astronomy which will be brought about by the next generation of survey facilities such as LSST. The fully robotic Liverpool Telescope 2 will have a 4-metre aperture and an improved response time. In this paper we provide an overview of the current status of both facilities.

Key Words: instrumentation: photometers — instrumentation: polarimeters — instrumentation: spectrographs — telescopes

1. INTRODUCTION

The Liverpool Telescope (LT: Steele et al. 2004) is a fully robotic optical/near-infrared telescope with a 2-metre clear aperture, located at the Observatorio del Roque de los Muchachos on the Canary Island of La Palma. The telescope is owned and operated by the Astrophysics Research Institute of Liverpool John Moores University (LJMU). It was designed and constructed on Merseyside in the UK by Telescope Technologies Limited, a spin-off company of the university. First light for the telescope was in July 2003, with routine robotic science operations beginning in 2004.

The telescope is a Ritchey-Chrétien Cassegrain design with a 2 metre clear aperture on an alt-azimuth mount. The basic specifications are listed in Table 1. Of note is the enclosure, which is a novel clamshell design, providing an unencumbered view of the sky to an optical horizon of 25° altitude which facilitates rapid follow-up of targets-of-opportunity.

2. SCIENCE

The LT is a common-user facility. Time is awarded through a variety of committees via an open, peer reviewed process. In the first semester of 2016, availability was as follows: 280 hours for applicants from LJMU, 280 hours for UK-based and international applicants via the Panel for the Allocation of Telescope Time (PATT), 150 hours for Spanish-based applicants via the *Comision de Asig-*

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TABLE 1

LT KEY PERFORMANCE SPECIFICATIONS

Item	Specification
Clear aperture	2.0 metres
Focal length	20.0 metres
Image quality (on axis)	0.4″ (80 per cent encircled energy)
Image quality (6″ off axis)	< 0.6″ (80 per cent encircled energy)
Pointing accuracy	< 10″ RMS
Open loop tracking	< 0.4″ in 10 min
Closed loop tracking	< 0.2″ in one hour
Slew speed	2°/s

nación de Tiempos (CAT), 50 hours via the CCI international time programme, and 50 hours were offered via the OPTICON programme. In addition, 90 hours were pre-purchased by individual projects, and 150 hours are allocated to educational outreach via the National Schools Observatory (NSO)[2]. Additionally, the LJMU, PATT and CAT panels also allocate some time each semester for 'reactive time': for which proposals for targets-of-opportunity can be submitted outside of the normal call deadlines.

In Figure 1 we show the distribution of science areas for proposals submitted in the most recent semester. The flexible scheduling and rapid response capabilities of robotic telescopes make them powerful tools for time domain astrophysics, and so it is no surprise that the proposals are dominated by such topics. A significant fraction of telescope time is spent on transients, such as supernovae, gamma-ray bursts and blazars. Variable stars are another popular topic, as are eclipsing binaries and transiting exoplanets. Solar system science, such as occultations and the characterisation of minor planets, is also a core part of the programme. The telescope is capable of rapid non-sidereal tracking for the study of near-Earth objects.

3. OPERATIONS

The LT is a fully robotic facility: the telescope operates autonomously throughout the night without remote control. Users upload observation requests into the telescope queue via a Java-based interface, and the robotic scheduler chooses what to observe and when based on target position, weather conditions and scientific priority.

[2]http://www.schoolsobservatory.org.uk

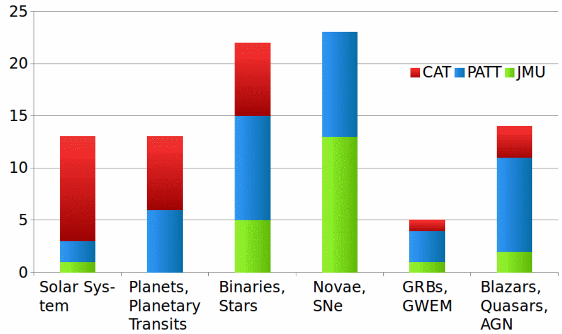

Fig. 1. LT Proposals by science area in the most recent semester.

A detailed overview of robotic operations and the scheduler is provided in Smith et al. (2011). From an observer-based perspective, users can select a variety of different observing modes depending on the nature of their target. *FLEXIBLE* observations are carried out at any time during the semester when the observing conditions are appropriate. *MONITOR* time is for observations of an object at a regular interval. *INTERVAL* time is where observations are taken as often as possible provided the interval between observations is never less than that specified. *PHASED* time allows the user to make an observation of a target (such as an eclipsing binary, for example) at a particular phase of its periodic cycle. Finally *FIXED* time mirrors observing at a classically scheduled telescope, in which observations are carried out at a specified time, or not at all. This is appropriate when observations are required to be simultaneous with another facility, for example. For users which require it, bespoke methods are offered to allow them to communicate directly with the software running on the telescope via an RTML-based submission process. This is appropriate for science programmes such as gamma-ray burst follow-up, which require an immediate override.

Outside of the science observations, routine calibrations are obtained and made available to all users. Twilight flats are obtained most mornings and evenings, and imaging standards are observed every ∼3 hours. Spectrophotometric standards for all three spectrographs are obtained on photometric nights. Raw data and a quick reduction of each exposure is available to science users via the LT website approximately five minutes after the exposure is complete. Fully reduced data products are provided to science users typically the morning after their data is obtained. The steps in the full reduction vary from instrument to instrument, but typically include bias subtraction, trimming of the overscan regions,

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flat fielding, bad pixel masking, sky subtraction and frame registration/stacking (for infrared IO:I data) and wavelength calibration (for spectra).

4. INSTRUMENTATION

All LT instruments are mounted at the Cassegrain focus. This focus provides a 40′ field-of-view with an image scale of 97μm/″. The Acquisition and Guidance box at this focus contains a deployable and rotatable science fold mirror, providing one straight-through port and a number of science fold ports. There are currently seven instruments simultaneously mounted and available for science use. The time overhead for instrument changes is 60 seconds.

4.1. *IO:O*

IO:O is the optical imaging component of the IO (Infrared-Optical) suite of instruments, and is the 'workhorse' optical imager for the telescope. The detector is a 4096 × 4112 px *e2v* CCD 231-84 deep depletion device, which provides a $10' \times 10'$ field of view with an unbinned 0.15″/px pixel scale. The read noise is < 8 electrons. 1×1 and 2×2 binning modes are offered, which provides a readout time of ∼37s and ∼13.5s. We are currently investigating offering either 4×4 binning or windowing modes in future semesters, for faster readout times.

IO:O uses a single, 12 position filter wheel. By default this wheel contains the Sloan $u'g'r'i'z'$ set, Bessell B and V, and a selection of $H\alpha$ filters (rest wavelength and four redshifted wavelengths).

4.2. *IO:I*

IO:I (Barnsley et al. 2014) is the infrared counterpart to IO:O. The detector in this instrument is a Teledyne 2048 × 2048px Hawaii-2RG HgCdTe array. The field of view is $6.27' \times 6.27'$ with an unbinned 0.184″/px pixel scale. Currently this instrument does not feature a filter wheel, and is deployed with a fixed H-band filter. However, two other filter options are available: a J-band filter, and a split J/H filter, in which a $\sim 3' \times 6'$ field is provided simultaneously in each band. For this last option quasi-simultaneous multiband data could be obtained by offsetting the target from one side of the chip to the other between exposures, at the price of a reduced field-of-view. These alternative fixed filter options could be deployed on a semester-by-semester basis given a clear science requirement, however the needs of existing multi-semester programmes would always be prioritised.

IO:I is always used with a sequence of short, dithered exposures that are coadded by the pipeline. The minimum exposure time of 6 s is defined by the hardware read time overheads. The maximum is limited by the background count rate and is dependent on the filter: the recommendation for H-band imaging is 60 seconds.

Upgrading the instrument with a filter wheel is a potential future improvement, but would be expensive and so would depend on demand from science users. In addition, the IO suite was designed to allow for simultaneous optical/infrared imaging. This has not been deployed, but is a possible upgrade given demand. Note however that such simultaneous observing is complicated by the usually very different exposure times required in the optical and infrared, and the need to dither.

4.3. *RISE*

The **R**apid **I**mager to **S**earch for **E**xoplanets (RISE, Steele et al. 2008) is a fast-readout camera developed in collaboration with Queens University Belfast for the precision measurement of transiting exoplanet timing. The detector is an E2V CCD 47-20 frame transfer device, which provides an effectively negligible readout overhead. The field of view is $9.2' \times 9.2'$ field of view with an unbinned 0.54″/px pixel scale. Typically this instrument is used with a 2×2 binning, which provides a read noise of 10 electrons and a minimum exposure time of 0.6 seconds.

The instrument uses a single fixed 'V+R' filter, constructed from a 2 mm Schott KG5 filter bonded to a 3 mm Schott OG515. The use of a fixed filter makes this a very simple and reliable instrument. However, we are currently considering replacing RISE with an upgraded 'RISE-3' instrument, which would contain three cameras and dichroics to enable simultaneous observations in multiple bands.

4.4. *RINGO3*

RINGO3 (Arnold et al. 2012) was commissioned in 2013 as the latest in the novel RINGO series of optical imaging polarimeters. The science driver for these instruments has been the need to make reliable polarisation measurements of fast-fading transients, such as gamma-ray burst afterglows (see, e.g., Mundell et al. 2013). RINGO3 uses a polaroid that rotates once per second to measure the polarisation of light entering the instrument. A pair of dichroic mirrors split the light into three beams for simultaneous polarised imaging in three wavebands using three separate Andor cameras. Each camera contains a 512 × 512 pixel electron multiplying CCD, with negligible dark current and effectively negligible read noise when the EMCCD gain is used.

The wavelength ranges of the three cameras are dictated by the dichroics in the optical layout. The approximate ranges are 350–640 nm, 650–760 nm and 770 – 1000 nm. Different camera lenses are used in different arms, providing slightly different plate scales and vignetting of the beam. The plate scales are in the range of 0.43 – 0.49″/px, and the 50 per cent vignetted field diameters are 4.1 – 5.9′, with the largest field diameter and plate scale in the red camera. The dichroics inevitably introduce some instrumental polarisation. When the instrument was commissioned in 2013 this was a serious problem, but in December 2013 a depolarising Lyot prism was inserted into the beam, after the rotating polaroid but before the beam reaches the first dichroic mirror. Note that downstream of the rotating polaroid all one needs to measure is the intensity of the light, not its polarisation state. Following this modification a polarisation accuracy of up to 0.3 per cent is achievable.

A new instrument currently under consideration is a **M**ultiwavelength **OPT**imized **O**ptical **P**olarimeter (MOPTOP). The conceptual design of this instrument contains a dual-camera configuration, with ‘s’ and ‘p’ polarization states on separate cameras to minimize systematic errors and provide the highest possible sensitivity. Dichroics would be used for simultaneous measurement in two colours, but these would be deployable so they could be removed from the beam if polarisation accuracy was prioritised over simultaneous multiwavelength observations.

4.5. *FRODOspec*

The **F**ibre-fed **RO**botic **D**ual-beam **O**ptical **Spec**trograph (FRODOspec, Morales-Rueda et al. 2004) was designed and built in collaboration with the University of Southampton. It is a multi-purpose integral-field input spectrograph, with a dual beam design in which the beam is split before the entrance to the individually optimized collimators. The integral field input module covers 9.84″ × 9.84″, and consists of 12 × 12 lenslets, each 0.82″ on sky. Two resolution options are offered. A low resolution grating provides $R \sim 2600/2200$ in the blue/red arms, with wavelength ranges of 3900–5700 Å and 5800–9400 Å. The high resolution option uses a VPH grism as the dispersing element, which provides $R \sim 5500/5300$ in the blue/red arms, with wavelength ranges of 3900–5100 Å and 5900–8000 Å. In October 2015 the red arm was upgraded with a deep depleted CCD, which significantly improved the throughput and reduced the fringing.

Robotic acquisition relies on an imager to fine tune the telescope pointing and place the target precisely in the focal plane so that it will lie on the FRODOspec IFU. This is performed either via a WCS fit carried out using USNO-B2 and 2MASS reference catalogues, or alternatively in situations where the WCS would fail due to catalogue incompleteness, the brightest target within the imager field-of-view can be selected.

4.6. *SPRAT*

In the year since the **SP**ectrograph for the **R**apid **A**cquisition of **T**ransients (SPRAT: Piascik et al. 2014) was commissioned on the LT, it has become the second most-used instrument, after IO:O. SPRAT was conceived as a simple, high-throughput, low-resolution spectrograph for the rapid follow-up and classification of supernovae and other transients. It is a long slit spectrograph (the slit having a width of 1.8″ and a length of 95″) and employs a VPH grism assembly to give a straight-optical path. An Andor iDus 420 Series camera is used, which contains a 1024 × 255 pixel CCD giving a 0.44″/px spatial pixel scale. The wavelength range of SPRAT is 4000–8000 Å, with a resolving power of $R = 350$ at the centre of the spectrum. The grating is adjustable and may be set to two different configurations which are optimized for throughput at the blue or red end of the wavelength range.

As with FRODOspec, acquisition via a WCS fit or selection of the brightest target are offered. The grism and slit in SPRAT are deployable, so can be removed from the beam to allow direct acquisition on the SPRAT CCD, eliminating a source of positional error in changing instruments. However, the field of view of the SPRAT CCD is rather limited at 7.5′ × 1.9′ which can complicate acquisition in some fields. For these edge cases the ability to use an alternative imager for acquisition is offered, which provides a sub-optimal but adequate precision.

4.7. *LOTUS*

The **L**ow resolution **O**p**T**ical near-**U**V **S**pectrograph (LOTUS: Steele et al. 2015, submitted) was conceived, built and deployed in the second half of 2015. It is a very simple instrument with no moving parts, and was designed and built at very low cost. The singular scientific goal of this instrument is UV spectroscopic observations of the extended emission from the comet 67P/Churyumov-Gerasimenko, in concert with the local observations made with the *Rosetta* spacecraft (Glassmeier et al. 2007), although LOTUS is also available for general

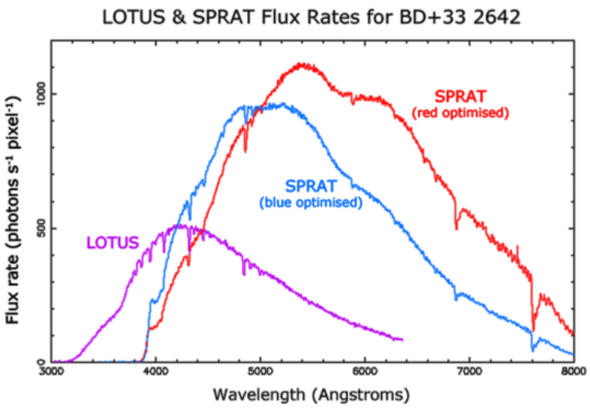

Fig. 2. Relative flux rates in photons per second per 4.7Å pixel from LOTUS and the blue and red optimized modes of SPRAT for the spectrophotometric standard star BD+33 2642.

use. The instrument contains a Starlight Xpress SX35 CCD Camera operated in 4×4 binning mode giving 1008×672 pixels at a spatial pixel scale of $0.6''$/px. The slit has 'narrow' ($2.5'' \times 95''$) and 'wide' ($5'' \times 25''$) regions to allow optimal spectral resolution or flux calibration. There are no arc lamps available for wavelength calibration: a default wavelength calibration based on arc and twilight sky data taken during commissioning is applied to all data and is thought to be good to better than 10 Angstroms. The wavelength coverage is from 3200 – 6300 Å at a dispersion of 4.7Å/px, although the sensitivity of the instrument is considerably lower than SPRAT, meaning that for wavelengths greater than 4100 Å, SPRAT is always the superior choice (Figure 2). The reduced sensitivity of LOTUS is entirely down to the choice of camera which was made for reasons of cost: given a strong science need the camera could potentially be upgraded in the future.

4.8. *SkyCams*

As well as the seven instruments mounted on the telescope, also available are three 'SkyCams': a project aimed at providing simultaneous wide-field observations in parallel with normal LT data acquisition (Mawson et al. 2013). All three SkyCams use Andor ikon-M DU934N-BV cameras and take a 10 second exposure once per minute. SkyCam-A uses a 1.55 mm $f/2.0$ 180° fish-eye lens to provide horizon-to-horizon coverage down to about $R \sim 6$. SkyCam-T parallel points with the telescope, and uses a Zeiss Planar T 85mm $f/1.4$ ZF2 lens which yields a pixel scale of $31.6''$ and a field-of-view of roughly 9°. The faintest sources detectable are about $R \sim$ 13–14,

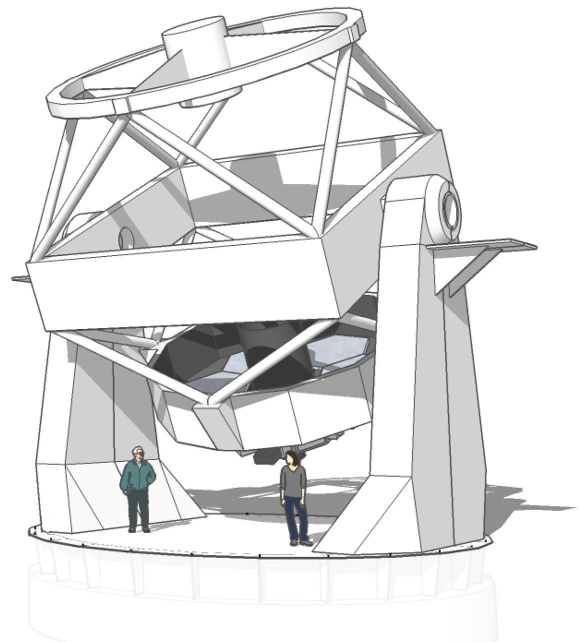

Fig. 3. Design concept for Liverpool Telescope 2

though in uncrowded fields SkyCam-T is 90 per cent complete down to $R \sim 11.7$. Finally SkyCam-Z also parallel points with the telescope and is mounted inside an Orion Optics AG8 telescope. This provides a 1° field-of-view with a plate scale of $3''$/px, and can detect sources down to $R \sim 18$.

5. LIVERPOOL TELESCOPE 2

In 2012 development began on a successor to the LT, with the working title 'Liverpool Telescope 2' (LT2, Figure 3). It was recognised that the next generation of optical synoptic survey facilities such as LSST (Ivezic et al. 2008) will bring about a new era in transient science. Such surveys will not only report transients at much fainter magnitudes, but will also observe with a cadence such that much of the long term photometric monitoring currently provided by follow-up telescopes like the LT will be provided 'for free' by the survey telescope itself. As well as the optical surveys, the time variable sky will be probed across the electromagnetic spectrum, with facilities such as SVOM, SKA and CTA. It is also anticipated that Advanced LIGO and Virgo will directly detect gravitational wave emission within the next few years, opening an entirely new window onto the Universe. A new generation of robotic telescopes will be required to capitalise on this new era of time domain astronomy. A detailed overview of the scientific goals of LT2 is provided in Copperwheat et al. (2015).

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LT2 will be a Ritchey-Chrétien design with a 4 metre clear aperture. A core technical requirement is the capability for a world leading response to an electronically transmitted alert from another facility, which will potentially be an important advantage as we open the window on the faint/fast region of the transient phase space. We aim that LT2 will, on average, be able to start obtaining data within 30 seconds of receipt of a trigger. This will make LT2 an unmatched tool for the study of fast-fading transients such as gamma-ray burst afterglows. Additionally, reduced observational overheads are vital for the large scale programmes of spectroscopic classification which will be required in the LSST era to uncover the rare subtypes amongst the expected vast yield of transient detections. Like LT, LT2 will have at least five focal stations for the simultaneous mounting of a diverse array of instrumentation. The first light complement is not yet decided, although the main instrument is anticipated to be a low/intermediate resolution spectrograph, for classification and exploitation of explosive transients. The LT2 design concept is described in more detail in Copperwheat et al. (2014).

LT2 will be co-located with LT at the Observatorio del Roque de los Muchachos. Specifically, the site of the Automatic Transit Circle (formerly the Carlsberg Telescope) will shortly be available, and has been offered by the *Instituto de Astrofísica de Canarias* as part of their contribution to the project. Having both telescopes on the same site offers interesting scientific possibilities. With LT2 expected to focus on spectroscopic follow-up, we intend to replace the instrument suite on the LT with a single prime-focus imager. This camera would be equipped with a filter wheel and would provide a total on-sky area of $\sim 2.8 \mathrm{deg}^2$. This instrument would be used for surveys, for the localisation of transients with large positional uncertainties (such as gravitational wave counterparts) and for educational work via the NSO.

Phase 1 of the LT2 project began in September 2012 with the commencement of the feasibility study. In the summer of 2015 we began phase 2, during which we will produce a detailed design for the telescope and complete the funding consortium. We aim to begin construction in 2017, with the beginning of science operations in 2020-21.

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