The Liverpool Telescope Robotic Operations

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ABSTRACT

The Liverpool Telescope (LT) is a fully robotic 2m optical telescope at a world-class observatory site. It runs autonomously without direct human control either on site or remotely. It is not operated primarily for a single science project, but rather is a common-user facility, time allocated by an open, peer-review process and conducting a variety of optical and IR imaging, spectroscopic and polarimetric programs. This paper describes some of aspects of the site infrastructure and instrument suite designed specifically to support robust and reliable unsupervised operations. Aside from the telescope hardware, the other aspect of robotic operations is the mechanisms whereby users interact with the telescope and its automated scheduler. We describe how these have been implemented for the LT. Observing routinely since 2004, the LT has demonstrated it is possible to operate a large, common-user robotic observatory. Making the most of the flexibility afforded by fully robotic operations, development continues in collaboration with both observers and other observatories to develop observing modes to enable new science across the broad discipline of time-domain astrophysics.

Keywords: telescopes, robotic, automated, design, operations, user interfaces

1. INTRODUCTION

The Liverpool Telescope[1] (LT) is a fully robotic astronomical telescope owned and operated by the Astrophysics Research Institute of Liverpool John Moores University (JMU) in North-West England. It is a two-metre Ritchey-Chrétien Cassegrain reflector on an alt-azimuth mount and is sited at Observatorio del Roque de los Muchachos on La Palma in the Canary Islands. Though many other robotic telescopes exist, most are dedicated to or strongly dominated by a single science program. The specific objective of the Liverpool Telescope was to provide a common user research facility, supported and allocated by several independent time allocation panels and offering a broad suite of instrumentation in a manner similar to any national facility telescope.

The robotic control system and dynamic scheduling software therefore need to balance the technical requirements of diverse science programs as well as "fairness" between the partner organizations. Time on the telescope is allocated through a peer review process by several independent time allocation committees, each dealing with one of

- UK funded open application time
- Spanish open application time as host nation of the telescope site
- Liverpool JMU astrophysical research
- Liverpool JMU undergraduate teaching
- UK schools via the National Schools' Observatory[2,3]
- European OPTICON transnational access program
- International collaboration projects via the La Palma site agreements
- Amateur research projects

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The science priorities of the user constituencies vary, but in general terms most LT users work on varied aspects of time domain astrophysics.

- Rapid robotic reaction to unpredictable phenomena and their systematic follow-up
- Serendipitous source follow-up
- Monitoring of variable objects on all timescales from seconds to years
- Simultaneous coordinated observations with other ground and space-based facilities

The robotic operations model was designed to address these by freeing the telescope from the constraints of rigid advance scheduling. The robotic control software and instrumentation were all developed in-house by the telescope operations team within the Astrophysics Research Institute of JMU. The telescope achieved first light in July 2003 and has been in nightly unsupervised operation since early 2004.

This paper is divided between four main topics. Section 2 discusses the objectives and merits of robotic operations in the particular context of the LT's science goals. Sections 3 and 4 describe the telescope and some pertinent aspects of site infrastructure and instrumentation. Section 5 describes how users actually use the telescope and Section 6 is a summary of how the operating model is actually implemented within our telescope operations staff, most particularly which tasks are fully autonomous and where we still depend on human interaction with the telescope.

2. ROBOTIC OPERATIONS

We define "fully robotic" as meaning a facility that can operate from night-to-night without any human supervision of the observation process. Sensors and software processes must autonomously decide whether it is safe to observe, perform all the startup procedures, select which targets to observe appropriate to the prevailing atmospheric and engineering conditions, perform observations and associated calibrations and finally shut down all systems safely at the end of the night. The system must detect and act on fault states, preferably by fixing them, but where that is not possible, by making the system safe to await investigation by staff the following day. Our objective is only to remove staff from nighttime operations and we do provide a very limited daytime staff presence to perform safety checks and routine maintenance. Fault diagnosis is typical carried out remotely and major repairs necessitate staff to travel to the telescope site.

Rather than the optical or mechanical design, the observatory's distinguishing feature is using a robotic operating model on a common user facility. In contrast to most fully autonomous telescopes, it is not dedicated or dominated by a particular primary science program, but rather time is allocated by Time Allocations Committees (TACs) on a peer review basis. Allocation rounds are held twice a year and though long term proposals are accepted, the observatory systems must be able to handle highly flexible observing schedules covering the changing requirements of the optical time-domain astrophysics community, including visible and IR imaging, spectroscopy and polarimetry. The telescope does not use a specified schedule at all, but rather has a database of observation requests and dynamically schedules during the night.

The advantages of fully autonomous operations are largely obvious but some are briefly listed here. Some observatory costs can be greatly reduced, but it is important to recognize that removing observer staff does not make operation of the telescope free. At its simplest, you simply move staff effort from telescope operators to software engineers. It is however true that costs and time associated with night working and traveling to and from site are saved. Also reduced are the human factors of providing a comfortable, safe, night working environment at the telescope.

More interesting scientifically than simply running an existing telescope more cheaply is what new domains of research can be opened up? Dynamic scheduling allows the telescope to respond immediately to changing weather conditions. It is also very simple for disparate science programs requiring monitoring on wildly different timescales to share the same telescope. Response to targets of opportunity is also painless; since the telescope is continuously rescheduling anyway, no particular observer gets overridden and inconvenienced when a target of opportunity suddenly becomes available.

Perhaps a less obvious advantage is that all observations are performed in a rigourously repeatable manner. This provides better continuity and consistency of data quality for long term monitoring programs and makes fully automated data reduction pipelines more reliable. Similarly it is possible to operate a single observatory-wide program of instrumental calibration observations and make then equally available and applicable to all observers' data.

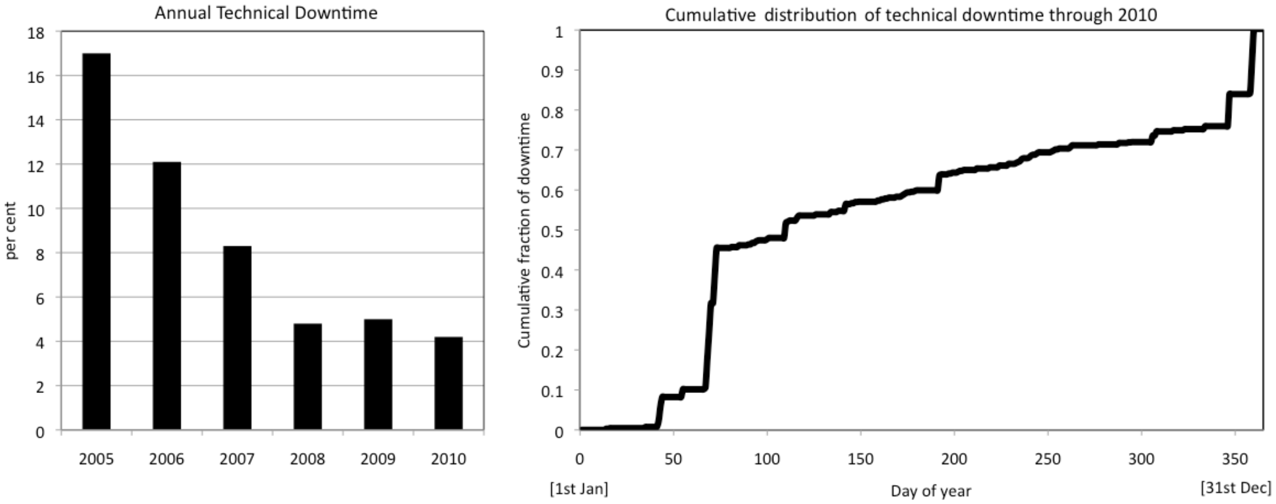

Figure 1. Left panel shows total annual technical downtime. Time lost to weather is not included. In the right panel the distribution of the downtime through year 2010 is shown as an example, but is typical of all years. Very small increments of time are lost from night-to-night, but the great majority of downtime came from two events in March and December, each of which led to loss of multiple consecutive nights. In these cases, both were computer failure, but in previous years similar patterns have arisen from failure of different electronic and mechanical components.

Robotic operations will of course create new problems not faced by the classical observatory. Since “robotic” could mean so many different operating models we here mention just those main challenges distinct to our specific operations.

We must provide suitable interfaces for widely distributed users to access the telescope and data. Those interfaces need to be usable by scientists who have never visited the telescope and should not require any detailed engineering knowledge of the telescope. How this is implemented for the LT is main topic of this paper and not discussed further now.

Our diverse and distributed user base means a degree of fairness must be maintained between all partner communities in line with the international agreement governing access to observing time. This is conceptually not anything difficult but requires rigourous accounting of every observation to be logged against each time allocation committee. This can be much simpler for a classical block scheduled telescope where a partner’s allocation is simply a fixed number of nights clearly marked on a calendar.

In the specific case of our operating model where we do not have a full engineering team local to the observatory, telescope reliability is a major consideration. It would of course be possible to operate a telescope robotically at night but still have a full day crew for maintenance. This is not the case for the Liverpool Telescope. In the left panel of Figure 1 we show the annual technical downtime from our first complete year of autonomous operation (2005) to present. The down time is seen to fall rapidly as the various systems were fully commissioned, stabilizing to between four and five per cent. Significantly however, this downtime is not evenly distributed as a few minutes every night though the year. When an error occurs and cannot be recovered by the automated fault recovery software, the remainder of the night is lost and a series of small steps can be seen in the cumulative distribution plot in the right hand panel where this has happened. More significantly, when a major hardware system fails and cannot be repaired remotely it is likely to be a minimum of two to three days before an engineer can fly out to the telescope on La Palma with replacement parts. The result is that almost all technical downtime is concentrated into complete shutdowns of between one and five nights. The implications for observers differs from a block scheduled telescope. Whereas a lost night in block scheduling would result in a complete loss for a single observer, in our context every observer is inconvenienced slightly, but it is unlikely that any one faces a complete loss of their target availability.

Table 1. Liverpool Telescope key performance specifications

Item	**Specification**
Clear aperture	2.0 meters
Focal length	20.0 meters
Image quality (on axis)	0.4 arcsec (80% encircled energy)
Image quality (6 arcmin off axis)	< 0.6 arcsec (80% encircled energy)
Pointing accuracy	< 10 arcsec RMS
Open loop tracking	< 0.4 arcsec in 10 minutes
Closed loop tracking	< 0.2 arcsec in one hour
Slew speed	2 deg per sec

3. TELESCOPE HARDWARE AND CONTROL SYSTEMS

3.1 The Liverpool Telescope

In Table 1 we list the key performance specifications for the Liverpool Telescope. These were derived at the start of the project from an analysis of the science use cases, and served to constrain the design and implementation of all telescope and instrument systems. Though there are certainly innovative solutions to the specific design details such as the active mirror cell and axis control servo models, the overall telescope structure was deliberately designed as a conventional Ritchey-Chrétien Cassegrain reflector on an alt-azimuth mount. The novel aspects of the telescope were intended to derive from the software control. A detailed optical prescription and mechanical description of the telescope is available in previous publications[1].

3.2 Site Infrastructure

In order to be fail-safe in unsupervised operation, extra infrastructure beyond what might be required for a classical telescope is desirable. Power is provided from the public mains network with an on-site generator as backup. All systems are also protected by battery uninterruptable power supplies (UPS) which also function as line conditioners. These only provide sufficient power to enable an ordered shutdown and we do not attempt to operate the telescope in the absence of external or backup generator mains supply. The most important UPS is that on the enclosure which has sufficient capacity to close the dome twice. However any time it is closed under battery power, it will not re-open until mains power has returned and been stable for a defined period of time.

Most computers are equipped with pairs of redundant power supplies and connected to remotely addressable power switches which may be used as a last resort either by staff or the automated fault recovery systems in order to reset unresponsive machines.

External gates into the site and all doors that access the observing floor are protected by interlock switches which engage brakes and shut down power to the telescope drive motors. All safety controls such as these are implemented in Programmable Logic Controllers (PLC) as site infrastructure rather than being in the Robotic Control System (RCS). The RCS is regarded as a software implementation of the observer and as such has no privileges which would not be afforded to a visiting astronomer.

A dedicated Weather Monitoring System (WMS) based on a Vaisala QLI50 data logger is installed on a mast adjacent to the telescope. Though we harvest weather data from weather sensors belonging to other nearby telescopes, decisions to open or close the dome are based only on our own WMS. Sensors are included for air temperature, humidity, dew point, wind speed and direction, insolation, rain droplets or dew and 10micron sky temperature for cloud sensing[4]. There are also several webcams though these are for human use only and there is no machine vision image processing.

Figure 2. A full 360° panorama of the telescope site on a rare occasion with the enclosure open during daylight for maintenance. This image illustrates how exposed the telescope is when the clamshell enclosure is full opened. Visible at the left of the frame is the pump room containing all the electrical and hydraulic plant equipment. Together with an even smaller blockhouse just visible behind the telescope these are the total site buildings. The entire facility is extremely compact for a 2 meter telescope. From left to right, the other obviously visible telescope domes are Mercator, Isaac Newton, Jacobus Kapteyn and William Herschell.

Notably lacking from the site infrastructure are a potable water supply and the various facilities required for comfortable occupation of the site by human observers. This can be seen from the small buildings in figure 2. Though slightly inconvenient, these are available nearby at the observatory's shared residence when required during maintenance visits.

3.3 Software Infrastructure

We here briefly define the main observatory subsystems and describe how the robotic control is integrated with the human user interfaces. We concentrate only the high level responsibilities of each system, rather than the detailed software engineering implementation. Much of the software run by the observatory is conceptually very similar to that for any classical observatory.

Telescope hardware control systems: The telescope hardware control was within the scope of supply for the telescope's original builders and includes movement and servo control of all telescope mechanisms. Principally this means astrometric slewing and tracking and alignment of optics. It provides a fully functional telescope suitable for use by a human observer and not any autonomous observing functionality. It was however explicitly designed to support robotic operations, giving it three important features.

- A single, well specified software control interface with a consistent syntax to access all telescope sub-systems.
- Extensive software watchdogs, self-diagnosis and automated error state recovery procedures. Almost all telescope software and mechanical systems are continuously monitored and on errors are reset by the telescope's supervisory control software without input from an external control.
- Monitoring, storage and distribution of detailed engineering telemetry. Easy access to logs of subsystem performance is required for remote fault diagnosis.

Robotic Control System (RCS): The Robotic Control System is one of the two processes fulfilling human replacement roles and is closely analogous to the simplest concept of a telescope operator's job. The RCS looks after deciding when to open and close the dome (subject to low-level safety interlocks, just like a human observer), initiating twilight calibration procedures, monitoring the prevailing observing conditions (seeing, cloud, twilight, Moon position and phase etc) and requesting the dynamic scheduler to nominate the observation which best fits those constraints. Observation groups are passed to the RCS as fully defined sequences and it executes those sequences as written with minimal interpretation. It has no direct control of telescope or instrument hardware and operates the observatory using same command set as is available to a human observer. For human observers there is of course an additional layer of graphical user interface, not required by the RCS.

Instrument Control Systems (ICS): An Instrument Control System[5] (ICS) running on each science instrument exclusively controls all its own hardware (e.g., filter wheels) and cannot directly control any other instrument or telescope hardware. When necessary, the ICS may request focus or pointing offsets via the RCS.

Observatory Support System (OSS): The Observatory Support System[6] (OSS) is a rather heterogeneous collection of all the other software tasks required to reliably operate the observatory for science operations. Included are tasks such as

- collecting and maintaining a database of the requested observations
- maintaining a database of all users, their time allocations and consumption
- validating the legality of observation requests both technically and within the time allocation
- the real-time scheduler[7,8] which selects the next group to be executed from the database of possibilities
- feedback to users on success or failure of individual observations

In some aspects the OSS operates as the human observer replacement since it incorporates the scheduling decisions of which target to observe.

The computing systems all reside on a dedicated LAN, access to which is strictly controlled by firewalls. Remote management by observatory staff is possible through a Virtual Private Network (VPN). There are also secure proxies with very limited access to allow observers to interact with the observation database[9].

4. INSTRUMENTATION

The observatory's goals require the telescope to be broadly instrumented in order to respond to the constantly changing range of science programs it is conducting. A Cassegrain-mounted Acquisition and Guidance (A&G) unit provides a system of retractable, rotatable, tertiary fold mirrors that are used to direct the optical beam to any one of the permanently mounted instruments. These fold mirrors include options to use fixed folds, tip-tilt and dichroics depending which instrument is to be used. Though not available to observers at the time of publication, on-axis guiding and simultaneous multi-instrument observing modes using the dichroics are under development and already partially implemented. With all instruments permanently mounted and powered, instrument changes take less than thirty seconds and observation requests are accepted which require any combinations of instruments on the same night.

The maximum unvignetted field of view for the telescope is 42 arc minutes at the straight through port, but all instruments fed from the fold mirrors are limited to 10 arc minutes and we have no wide-field instruments. Provision has been made in the design of the A&G unit for a two-element wide-field corrector, fabricated from fused silica, that would provide a high degree of field curvature correction for imaging applications if it were needed in future.

Most instruments have to varying degrees been developed in collaboration with other organizations but always controlled by the LT group in order to ensure compatibility with our operations model. A few design features are common to all our instruments[5]. Instruments are expected to operate for timescales of typically a month without any scheduled maintenance meaning they should be mechanically simple and robust. Most only have one or two moving parts. This both increases the time between required service and promotes data stability for long term monitoring programs. All are powered 24 hours a day and continuously ready for use. Generally servo mechanisms are avoided and precision is obtained through mechanical means. Simple mechanical limits are simpler to diagnose and monitor remotely and tend to be robust for long-term unsupervised operation. It should be noted that simple need not mean mundane and we have demonstrated this design philosophy can lead to the rapid development and deployment of innovative and even unique instrument concepts (e.g., RINGO2). Fabrication is typically outsourced but components are then integrated in-house. Most importantly, all software development has been carried out in-house. It is the control interfaces more than anything that enables use of the instrument in the robotic environment.

Many of the above paradigms strongly discourage the use of any visiting instruments and indeed we do not offer any visiting instrument program. Flexibility of the observing process for the astronomer depends on rigourous control of the instrument development process.

There is a single, common command set[5] used by all instruments. The RCS needs to know nothing about the internal workings of the instrument and simply passes observation requests from the scheduler to the instrument once the telescope is in position and ready to observe. This leads to a very large proportion of code re-use.

The degree of commonality between instruments also simplified maintenance of processing pipelines and a single, modular data reduction pipeline is used to perform basic reductions for all instruments. Extra plug-in modules are easily added to handle idiosyncrasies of any new instrument whilst the basic functions of bias, dark, over-scan, flat-field, image statistics, source detection and world co-ordinate system[10,11] (WCS) fitting are common across them all.

The current and near future instruments are described in the following sections. More up to date technical details about current instruments and full information required to plan observations are maintained in the online documentation at the telescope web site[12].

4.1 RATCam; CCD optical imager

RATCam was the first light instrument and still the workhorse direct imager though will be replaced in that role during 2011 by IO. RATCam is a 2048×2048, thinned, back illuminated CCD with a image scale of 0.135 arcsec per pixel to give a 4.6 arcmin field of view. The array is cooled to 163K by a CryoTiger closed cycle cooler. Two overlapping filter wheels provide a u'g'r'i'z' filter set, Johnson B and V and a single H-alpha narrow band filter. The read-out time of a little less than ten seconds makes the camera suitable for photometric monitoring down to timescales of about one minute.

4.2 FRODOSpec; dual-beam optical spectrometer

FRODOSpec[13] (designed collaboratively with Southampton University) is a dual beam spectrometer. Low resolution ($R \approx 2500$) transmission gratings cover the entire visible atmospheric window over the blue and red arms. Volume phase holographic (VPH) grisms are used in the intermediate resolution ($R \approx 2500$) modes. The use of a grism allows the grating angle to be simultaneously optimized for both configurations without the need to articulate the spectrometer arms; an example of designing specifically to reduce moving mechanisms. The spectrometer optics are bench mounted for long term stability and fibre-fed from a 12×12 lenslet integral field unit (IFU). The ability to rapidly and repeatably (< 0.15 arcsec on sky) swap between instruments means there is no dedicated acquisition camera and any of the science imagers may be used for the purpose.

4.3 RISE; fast imager

A second imager, RISE, provides a 10 arcmin field of view through use of transmission fore-optics. A single, very broad V-plus-R filter is permanently in the beam. There is no shutter. The integration time is defined by use of a frame transfer CCD and fast read-out means the minimum integration time for time series is 0.6 sec. In contrast to RATCam, this imager is appropriate for photometric monitoring on timescales of a few seconds. The camera was developed in collaboration with Queens University Belfast expressly for an exoplanet timing experiment in support of the SuperWASP[14] planet search, but is fully integrated with the LT data flow and is openly available to all telescope users.

4.4 THOR; ultra-fast imager

THOR is an interesting case that illustrates one advantage of the common software architecture across all instruments. It was originally designed and installed to function as a tip-tilt wave-front sensor but by re-using the control system from the other CCD imagers we obtain a new common user science instrument almost for free. From an observer perspective, requests may be submitted to THOR using exactly the same software interface as the main science cameras. Like RISE, it has a fixed V-plus-R filter but uses an EMCCD with extremely fast read-out in excess of ten full frames per second. By windowing the array to function as a single-object fast photometer it has been used at integration and read, full-cycle times as short as six milli-seconds for occultation timing observations. It may also be used for "Lucky imaging" style shift-and-add techniques[15].

4.5 RINGO2

The RINGO2[16] polarimeter is an upgraded version of our earlier RINGO[17] instrument, improving sensitivity by about two magnitudes and time resolution for bright, variable polarimetric sources down to one second. It was designed specifically to the requirements of investigating polarization in the prompt flash of gamma-ray bursts (GRBs), but like RISE is available as a common user instrument. The optical beam passes through a spinning Polaroid filter which for a polarized source modulates the flux with a period equal to the filter rotation of about one second. The detector is an EMCCD running at an electron multiplying gain of 100. Read-out is directly synchronized to the rotating filter giving precisely eight image frames per filter rotation with a read noise of less then one photo-electron. The modulation of the observed flux as the filter rotates can be translated into Stokes parameters using the formulae described in Clarke & Neumayer 2002[18]. Though it is theoretically possible to extract a polarization signal from a single rotation, typically many frames are stacked at data processing meaning that it is possible to trade sensitivity against time resolution after data acquisition. This is important for GRBs where the object flux is rapidly varying and not predictable at the time of observation.

4.6 IO; combined optical-near IR imager

IO will be a combined near-IR and optical imager incorporating a 10 arcmin (4096×4096 back-illuminated) CCD array and a 6 arcmin (Hawaii 2RG) infrared array that may be used simultaneously or individually. It also incorporates a tip-tilt correction system (THOR). A staged deployment is underway. At the time of publication, the hardware other than the detector array cryostats themselves have been installed on the telescope and the optical arm of IO is anticipated to replace RATCam as the primary optical imager within the next year. The infra-red arm will follow later.

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5. THE OBSERVERS' PERSPECTIVE

Most aspects of the user experience are similar to many other observatories. No observers ever visit the telescope itself but that is becoming increasingly common for many observatories with service observing queues. We divide the data acquisition into two phases.

A "phase 1" application is submitted to the Time Allocation Committee (TAC) outlining the science case, the total amount of time requested and illustrating the general form the observations will take. If the TAC awards time, the observer proceeds to "phase 2" in which the actual observations to be made are precisely defined. It is in phase 2 that the observatory needs to collect details such as target coordinates, instrument configurations, etc. Originally this detailed observation specification was a collaborative process between observer and staff support astronomer but through a process described in detail in a previous paper[6], the "phase 2" specification has been completely turned over to the observer themselves allowing real time access to the live database of scheduling requests. Though they have no direct access to the telescope controls, they can modify their observing requests at any time of day or night and the new or modified requests are available immediately to the robotic scheduler. Observers may request input from support astronomers (available following business day) but it is not required in order to submit an observation change.

The data flow from time application to final data analysis is illustrated in figure 3, separated out according to who performs each task; the observer, observatory staff or automated software. Note that though the support astronomer is involved at all stages, they are never on the critical path. They provide a supervisory oversight role and on-demand technical support for the users.

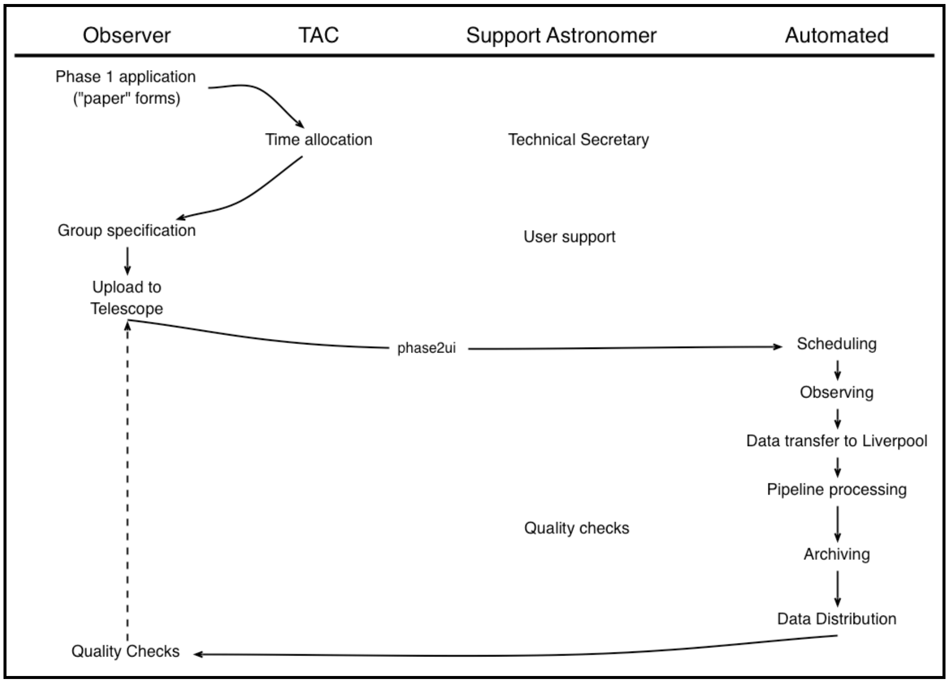


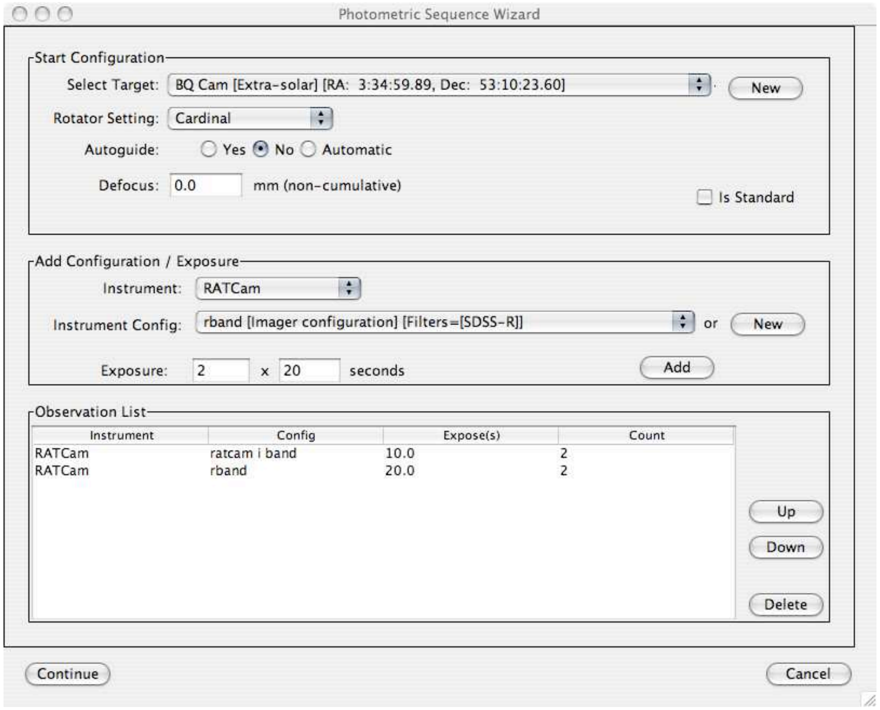
Figure 3. Simplified representation of data flow showing who is responsible for action at each point of the data flow. All decisions regarding how the observations are specified are handled by the observer. The actual observing, from scheduling to data distribution, is automated in software.

5.1 Data entry interfaces

Once allocated time by a TAC, most observers simply submit all their observing requests into the scheduler's phase 2 database. Requests are submitted though the Phase2UI, a Java 5 application distributed via Java Web Start (JavaWS) and launched from a web browser. Web Start downloads the Java executable binary to the user's computer and runs it locally. Every time it is launched, the Web Start framework automatically checks the locally cached executable ensuring the latest version is always automatically downloaded and installed. This ensures that the user is always using an up-to-date list of which instruments, filters etc are installed on the telescope. The Phase2ui directly accesses and modifies the live scheduler database so requires an active internet connection, but since the database is local to the telescope site, execution of existing observations continue uninterrupted through any failure of network communications to the La Palma summit.

The user is presented a fairly conventional menu driven graphical user interface (figures 4, 5). A collapsible tree structure lists all the programs, proposals and groups in the database for which that user has some level of access permission. A user may create an observation group in any proposal for which they have write access permission and the GUI provides menu lists to populate that group with timing and other observing constraints (zenith distance, seeing, photometricity, sky brightness, etc) which guide the scheduler's decisions.

There are two observation sequence creation modes in the GUI. If a user simply wants to use the default observing modes, they use the wizards (figure 4) to create orthodox sequences with a minimum level of user input. The Phase2ui wizards are self-contained dialogue screens that collect observational requirements from the user and then handle construction of an observation sequence. Within the dialogue box, common options are already selected, leaving the user to specify their unique parameters such as the target and integration times. Most of the complications of constructing a legal sequence are handled automatically. This frees the observer from requiring detailed engineering knowledge of individual instruments and attempts to automatically configure the system to best fulfill the astronomical requirements they have defined. The user specifies only what they want, not how to obtain it.



Photometric Sequence Wizard

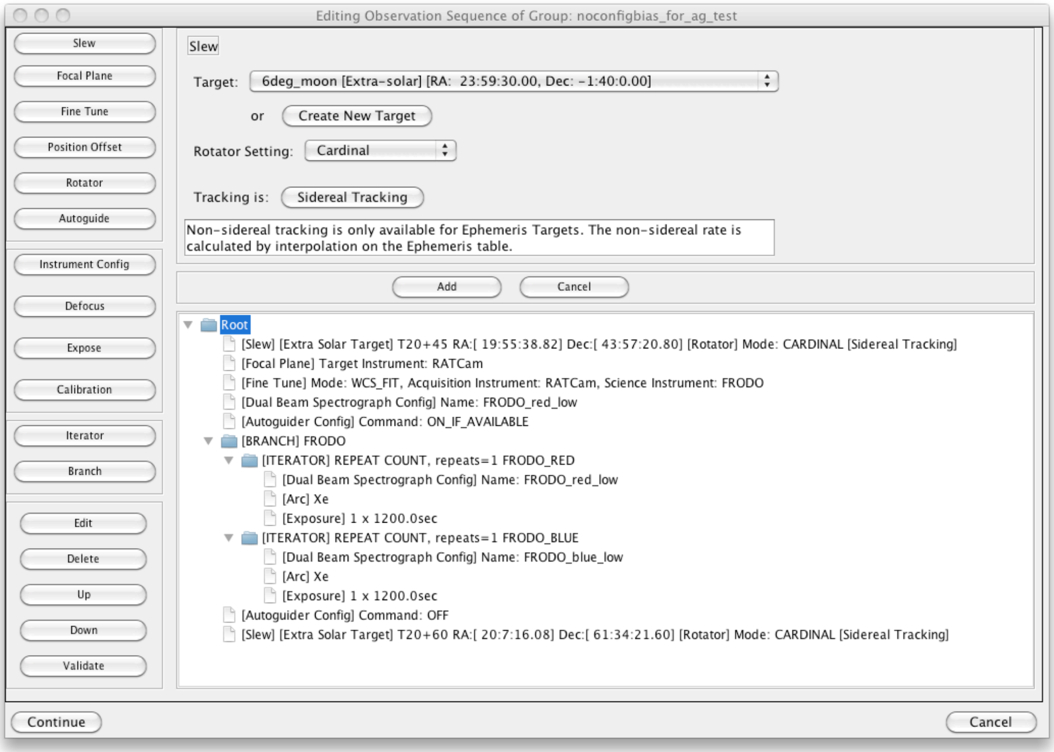
Start Configuration
Select Target: BQ Cam [Extra-solar] [RA: 3:34:59.89, Dec: 53:10:23.60]
Rotator Setting: Cardinal
Autoguide: ○ Yes ● No ○ Automatic
Defocus: 0.0 mm (non-cumulative)
☐ Is Standard

Add Configuration / Exposure
Instrument: RATCam
Instrument Config: rband [Imager configuration] [Filters=[SDSS-R]]
Exposure: 2 x 20 seconds

Observation List

Instrument	Config	Expose(s)	Count
RATCam	ratcam i band	10.0	2
RATCam	rband	20.0	2

Figure 4. One of the sequence creation "wizards", this one dealing with direct imaging and photometry. The user specifies the data products they want to receive and the software constructs them into a sequence.



Editing Observation Sequence of Group: noconfigbias_for_ag_test

Slew

Target: 6deg_moon [Extra-solar] [RA: 23:59:30.00, Dec: -1:40:0.00]

or Create New Target

Rotator Setting: Cardinal

Tracking is: Sidereal Tracking

Non-sidereal tracking is only available for Ephemeris Targets. The non-sidereal rate is calculated by interpolation on the Ephemeris table.

```
Root
    [Slew] [Extra Solar Target] T20+45 RA:[ 19:55:38.82] Dec:[ 43:57:20.80] [Rotator] Mode: CARDINAL [Sidereal Tracking]
    [Focal Plane] Target Instrument: RATCam
    [Fine Tune] Mode: WCS_FIT, Acquisition Instrument: RATCam, Science Instrument: FRODO
    [Dual Beam Spectrograph Config] Name: FRODO_red_low
    [Autoguider Config] Command: ON_IF_AVAILABLE
    [BRANCH] FRODO
        [ITERATOR] REPEAT COUNT, repeats=1 FRODO_RED
            [Dual Beam Spectrograph Config] Name: FRODO_red_low
            [Arc] Xe
            [Exposure] 1 x 1200.0sec
        [ITERATOR] REPEAT COUNT, repeats=1 FRODO_BLUE
            [Dual Beam Spectrograph Config] Name: FRODO_blue_low
            [Arc] Xe
            [Exposure] 1 x 1200.0sec
    [Autoguider Config] Command: OFF
    [Slew] [Extra Solar Target] T20+60 RA:[ 20:7:16.08] Dec:[ 61:34:21.60] [Rotator] Mode: CARDINAL [Sidereal Tracking]
```

Figure 5. The sequence editor screen. Down the left are buttons to access each individual instruction which can be issued to the telescope. The observation sequence is represented as a tree on the lower right. Every element in the tree is an instruction that may be edited, deleted or re-ordered to build up the desired sequence.

For unusually complicated observation sequences the sequence editor (figure 5) may be used. This provides full flexibility for the user to build arbitrarily complicated observation sequences that might involve multiples targets or instrument changes. Any observer using the sequence editor is expected to have some past experience using the LT and have thoroughly read all the documentation. It is entirely possible to construct illegal observation sequences which would yield no useful data or even be rejected by the telescope when execution was attempted. In most cases it is best to allow the wizard to assemble the basic structure of a legal group and then use the sequence editor to adapt and extend it to any particular needs.

These sequences are submitted directly to the telescope without being inspected by the support astronomer. In such a self-service system the automatic validation of observing requests is very important. Most data fields are tested for legal values at the point of entry and users are alerted immediately of invalid values. Some configurations and the interplay between particular options cannot however be tested until the group and sequence are complete. Users are thus provided a validation tool to test the entire group and its contents against a set of criteria defined by the operations staff. We distinguish three separate levels of error:

- DANGEROUS means any action which could cause human injury or damage equipment. As previously described this is already handled at a lower level in the control systems and a variety of hardware and software interlocks ensure the telescope is self-protecting. The RCS and by extension the phase 2 scheduler cannot override any of these safety interlocks so this level of error is not considered within the phase 2 system. If a circumstance were discovered where the scheduler could do something physically dangerous then our design paradigm requires that trapping and handling it safely must be implemented at a lower level where the new safety interlock would apply equally to either robotic or manual observers.

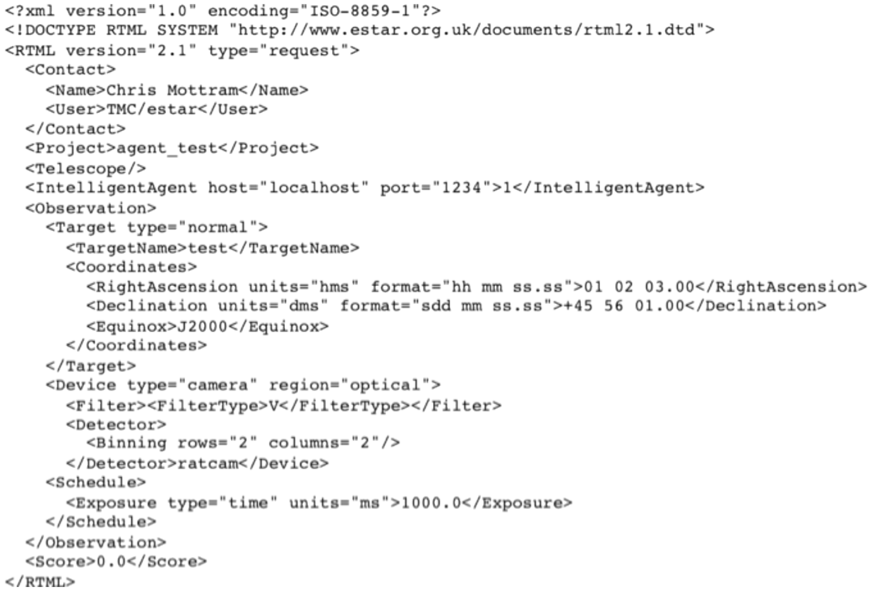
- VALIDATION FAILURE. An observation which physically cannot be performed with the telescope or instrument is flagged as a failure and the user informed. The most common causes of failures are simple procedural errors such as not specifying the mandatory timing constraint or requesting an integration without having first specified an instrument configuration. These are not faults that would damage anything. They are incomplete group specifications so the RCS could not proceed without further information and the group would never be attempted.
- VALIDATION WARNING. This signifies a request we believe is probably wrong. In almost all cases, an observation subject to a warning message will produce useless or sub-optimal data, however it is not the job of the Phase2ui to teach astronomers how to observe and we do not prevent non-standard observing techniques; we wish to encourage imaginative use of the facility. An example is an observation sequence which does not contain a target slew command. In this case the observation would be performed wherever the telescope happened to be pointing. We cannot currently conceive of any use for this, but since it is technically possible and damages nothing, we do not legislate against it.

5.2 Target of Opportunity, Rapid Response and other interfaces

It is also possible for authorized users to inject observing requests directly into the scheduler database using the Robotic Telescope Markup Language (RTML) protocols defined by the Heterogeneous Telescopes Network[19] (HTN). Once loaded to the scheduler these requests are treated exactly like those loaded via the user interface. HTN provides projects coordinating observations from multiple telescopes with a common software interface for all their submissions without needing to consider the user environment of each observatory.

Finally, the LT also has a fully automated rapid-response mode, which does not depend on any human intervention. Authorized software control agents such as that used for observing gamma ray bursts[20] can override the scheduler and communicate directly with the RCS in response to alert triggers. Observations are controlled dynamically by the software control agent and do not interact with the normal scheduled operations. A bespoke control agent needs to be developed for any new science project.

Using a combination of these interfaces, target of opportunity response can be as simple or complicated as desired. For example, we have programs operating which first demand an immediate override observation but also insert a less time critical follow-up into the scheduler database. The GRB response software even analyses the optical transient's light curve automatically and makes decisions on follow-up instrument changes accordingly.



```xml
<?xml version="1.0" encoding="ISO-8859-1"?>
<!DOCTYPE RTML SYSTEM "http://www.estar.org.uk/documents/rtml2.1.dtd">
<RTML version="2.1" type="request">
  <Contact>
    <Name>Chris Mottram</Name>
    <User>TMC/estar</User>
  </Contact>
  <Project>agent_test</Project>
  <Telescope/>
  <IntelligentAgent host="localhost" port="1234">1</IntelligentAgent>
  <Observation>
    <Target type="normal">
      <TargetName>test</TargetName>
      <Coordinates>
        <RightAscension units="hms" format="hh mm ss.ss">01 02 03.00</RightAscension>
        <Declination units="dms" format="sdd mm ss.ss">+45 56 01.00</Declination>
        <Equinox>J2000</Equinox>
      </Coordinates>
    </Target>
    <Device type="camera" region="optical">
      <Filter><FilterType>V</FilterType></Filter>
      <Detector>
        <Binning rows="2" columns="2"/>
      </Detector>ratcam</Device>
    <Schedule>
      <Exposure type="time" units="ms">1000.0</Exposure>
    </Schedule>
  </Observation>
  <Score>0.0</Score>
</RTML>
```

Figure 6. While the graphical user interface provides a human-machine interface to the phase2 database, software agents may submit requests in Robotic Telescope Markup Language (RTML).

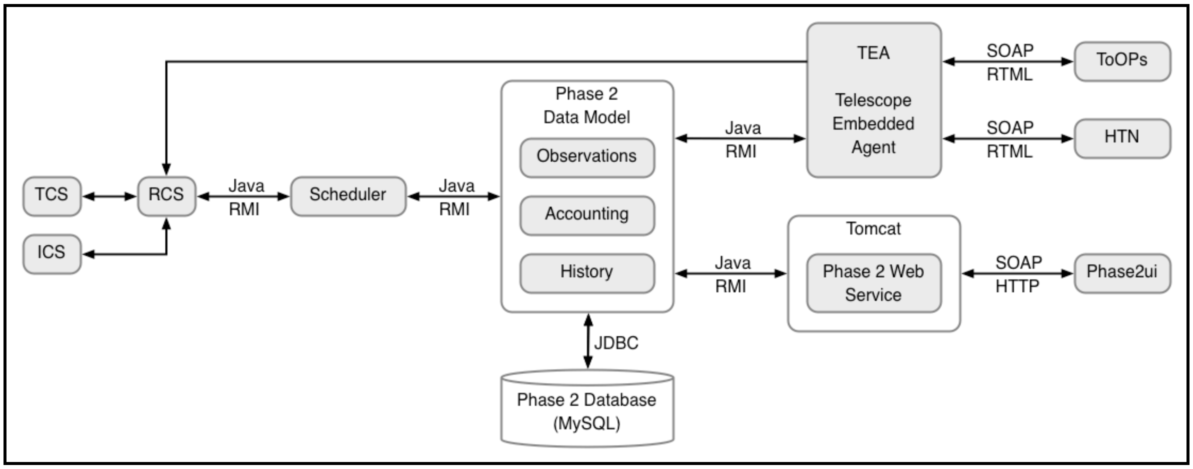


Figure 7. An overview of the main software components of the phase 2 definition and observation systems including communication protocols. Most users only interact with the database through the Phase2ui. The interfaces through the Telescope Embedded Agent (TEA) are principally used by automated rapid response software agents.

5.3 Data access and pipeline processing

Corrections for basic instrumental signatures (i.e., bias, dark, flat) are applied automatically to data from all instruments before distribution. QuickLook reductions are performed immediately and made available for observers to download from the telescope web site about two minutes after the shutter closes. On the basis of these data, the user may wish to log into the phase2ui and modify their observing strategy. The following morning a full re-reduction of all data is performed since at this point we have the advantage of dawn twilight calibrations and possibly arcs or standards which had not yet have been obtained when the QuickLook was run. These daily reductions are loaded to the searchable on-line data archive and the astronomer is alerted by email. In some cases, such as FRODOSpec, science level derived products, in this case wavelength-calibrated extracted spectra, are also produced for all users. Raw data products are stored and available if the user wishes.

6. DAILY OPERATIONS

The observatory system is capable of running totally unsupervised and has on occasions been operated for several days at a time without any human intervention at all, either planned or by result of loss of network communications to the mountaintop site on La Palma. In practice however there are three staff members with daily operational duties; Site Maintenance Technician, Data Scientist and Duty Officer. Importantly though, since there are no observers at the telescope, the observatory never needs to provide any nighttime observer support.

6.1 Site Maintenance

The telescope employs a single, part-time contractor on La Palma. They visit the site on most normal business days and perform a routine site inspection. They look after site infrastructure, general maintenance and act as on island liaison to organize shipping and local purchase of consumables. They perform preventative maintenance on the telescope itself including tasks such as monthly vacuum pumping of cryostats and can also assist with repair tasks when observatory staff visit site. Their presence on site is not required for daily operations and their most important role is simply always being available to attend site the next day following any technical fault. There is no nighttime call-out.

6.2 Data Scientist

One task of the Support Astronomer is the role of Data Scientist. All data from the telescope are briefly, visually inspected. Analysis is not detailed or rigourous and principally fulfils a desire to identify obvious technical failures as soon as possible, before the data are sent to users. This is only performed normal business days (five days a week) and if it could not be performed any particular day, all data would be able to flow to the users without quality control.

6.3 Duty Officer

We operate a rota of duty officers who have a brief list of daily operational duties, typically occupying a total of about one hour's staff effort per day. The majority of the observatory staff participates in this rota, including both astronomers and software engineers. This reduces the out-of-hours workload on the astronomers but also allows software engineers to develop a better understanding of how their code incorporates into the overall observatory operation.

The role is principally one of coordinating safety officer. It ensures that though any member of staff could log into the telescope at any time, there is a single nominated person responsible for coordinating any such work and available on-call for emergencies.

Their secondary role is to perform simple aliveness checks on the telescope and instruments twice a day, in the afternoon early enough to take action if any fault is identified and again after observations have started that night. This check of system aliveness to ensure that the telescope actually has opened up and is observing is the only night working we operate. After this post-startup check, the telescope is left unsupervised for the night. The duty officer will also normally check the telescope has shut down in the morning and update the publicly accessible night log with a record of any problems that occurred overnight.

Finally, the duty officer has the authority to shut down or prevent startup operations at any time. Typically such a decision is made in consultation with other observatory staff during daytime due to existence of local dust storms or known engineering faults.

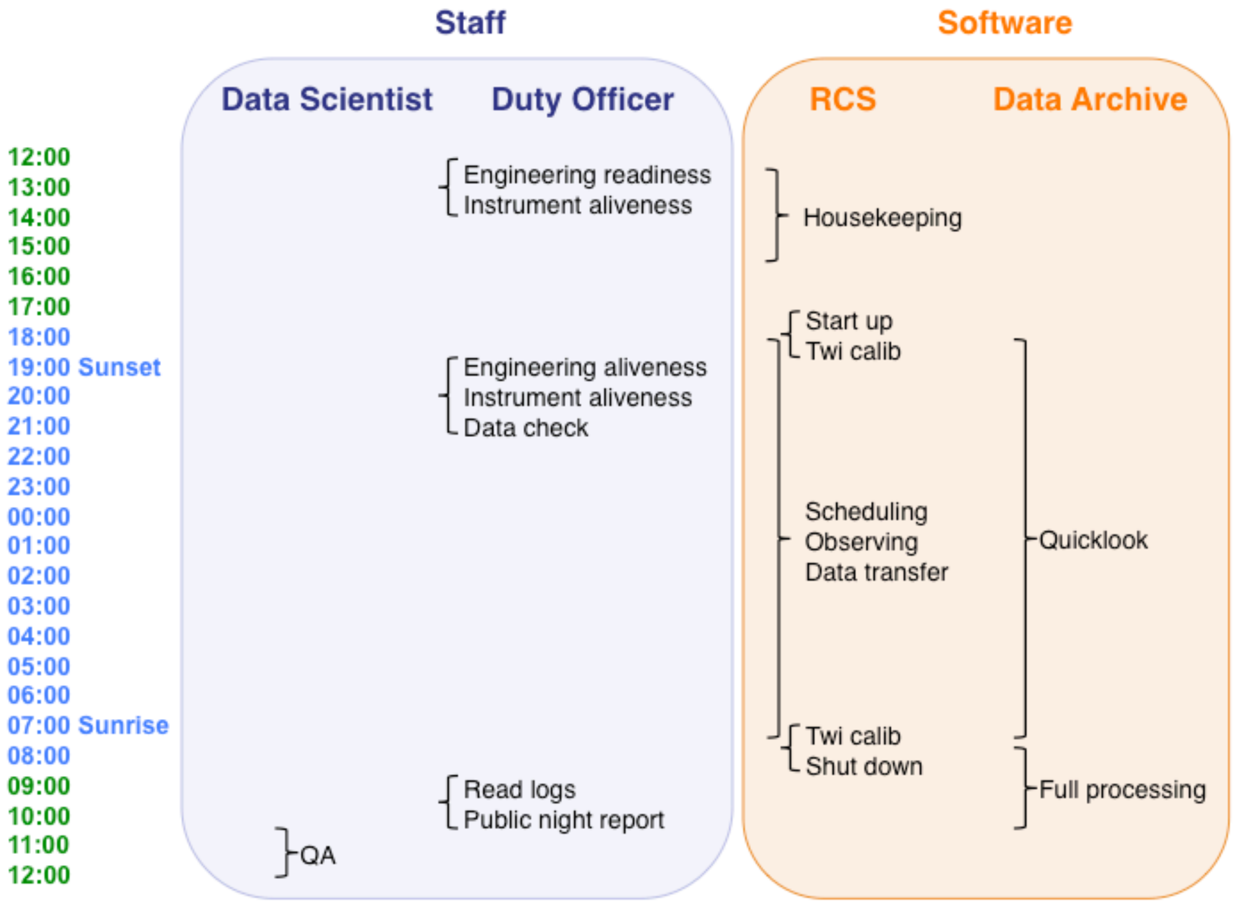


Figure 8. A timetable of daily operations tasks running from Noon to Noon showing that virtually all nighttime tasks are performed in software. One member of staff on a rota as the Duty Officer does perform a series of system aliveness tests after the telescope has started itself up and can at that point intervene to fix any problems before the night's observing. Should they be unable to contact the telescope due to loss of internet connectivity it would carry on unsupervised.

7. SUMMARY

The combination of a broad instrument suite and a very flexible scheduling policy has been demonstrated on the Liverpool Telescope to deliver high impact science results. The flexible dynamic scheduling has many advantages. It enables qualitatively new science such as very rapid response to transient sources and high cadence, long term monitoring programs that have never been practicable for block-scheduled telescopes. It also allows schools' and public observing programs to co-exist on a professional class telescope with essentially no impact at all on the science observations because they are generally very brief integrations, easily incorporated into the schedule. In order to take advantage of these new capabilities the site infrastructure and instruments must be carefully designed and well integrated. Though considerably more expensive than the simplest concept of a robotic telescope (i.e., an unsupervised system following a single, well defined sequence of observations), this form of robotic telescope can operate more economically than a fully night staffed telescope. Lastly, our experience has been that this operations model has encouraged and benefitted from collaborative development with our observers of novel observing modes enabling new science across all disciplines of time-domain astrophysics.

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