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Completion of the Southern African Large Telescope

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Abstract. The Southern African Large Telescope (SALT) was completed, on budget, in November 2005, in just under 6 years, and is currently in the middle of its commissioning and performance verification phase, expected to be concluded by early 2007. SALT partners have already been obtaining observations during this shake-down period, and night time hours devoted to science time has slowly risen to 65-75%. Already some scientific results have been obtained and the first SALT science paper accepted for publication. SALT promises to be ideally suited to many survey follow-up programs and indeed for surveys of its own, for which observational cosmology will definitely benefit.
The capabilities and innovative aspects of SALTs "first light" instruments are described. These instruments, which are all designed as seeing-limited, operate in the UV-visible region (320−900 nm), and will provide capabilities for broad and narrow band imaging, long-slit and multi-object spectroscopy (R $\sim$ 6000 for seeing limit), spectropolarimetry and Fabry-Perot and tuneable filter imaging (R $\sim$ 320 to 9000, depending on etalon choice). Time resolved studies are supported by the use of fast readout CCD detectors, capable of high speed operation (10−20 Hz).

1. Introduction & Background

In 2005, South Africa, together with ten international partners from five countries (South Africa, Poland, USA, Germany, UK and New Zealand), completed the construction and inauguration − on 10 Nov 2005 − of the Southern African Large Telescope (SALT), at a cost of US$19.9M (excluding first-light instruments). SALT is based on the innovative design pioneered by the Hobby−Eberly Telescope (HET; Ramsey et al. 1998), at McDonald Observatory (Texas), which began science operations in October 1999. These telescopes represent a completely new design paradigm for optical/IR telescopes, being optical analogues of the Arecibo radio telescope. A segmented spherical primary mirror array of diameter 11-m, consisting of 91 identical hexagonal segments, directs light to a 4-mirror spherical aberration corrector (SAC), mounted on a moving tracker at the prime focus. Also included in the prime focus "payload" are facility instruments like the acquisition and guidance cameras, the atmospheric dispersion corrector and the calibration system. In addition, the two science instruments SALTICAM and the Robert Stobie Spectrograph (RSS) are mounted on the payload, as is the Fibre Instrument Feed (FIF) used to convey light through optical fibres to future instruments situated in the spectrometer room underneath the telescope. The first-light instruments were funded through a combination of cash and "in kind" (i.e. non-cash) contributions from the SALT partners.

Significant design changes and enhancements were made to SALT (Meiring & Buckley 2004) following upon the experiences and lessons learned with the HET in its early operations phase, and these are described shortly. The SALT project team, comprising mostly of South African engineers, was hired by early 2000 and the first major milestone was the ground breaking ceremony, held on 1 September 2000. Many of the major components of the telescope, including the building, were completed in 2002, and the first mirrors were installed in December of that year. October 2003 saw the commencement of the first on-sky engineering tests, following the installation of the Prime Focus Tracker & Payload the previous month. By the end of the year the first closed loop guided observations were obtained, with 18 mirror segments installed and using a "surrogate" spherical aberration corrector (SAC), borrowed from the HET. The SALT SAC was finally installed in July 2004, and installation of the primary mirror segment's capacitive edge sensors also began in that year. The end of 2004 saw further progress with the on-sky testing, including the guidance and focus system, and general maturing of the telescope control system (TCS). The final batch of mirrors was installed in May 2005, followed by the testing of the first science instrument, SALTICAM, an optical imager. Commissioning observations with this instrument began in August 2005, which was followed on 1 September by the declaration of "first light", with all mirrors in place and SALTICAM fully operational − exactly five years following ground-breaking.

The remainder of 2005 was taken up with continuing engineering shakedown, testing of the edge sensor system, plus "performance verification" observations with SALTICAM. This was the first opportunity for all astronomers within the SALT partnership to obtain data. October 2005 saw the installation and beginning of commissioning of the second "first generation" instrument, the Robert Stobie Spectrograph (RSS), named in honour of Bob Stobie, one of the instigators of SALT, its first Board Chairperson and SAAO Director, until his untimely death in May 2002. At the time of this meeting, the first science paper, based on SALTICAM data, has been submitted, and the telescope is in the middle of an expected 12−18 month commissioning period.

2. SALT Science Requirements

A set of science requirements for SALT were defined early on in the project in order to meet the scientific goals of the SALT partners. These high level requirements were in turn used to define the overall system technical specification and the subsystem and component specifications. This is in keeping with a standard Systems Engineering approach, involving a structured development process, which was adopted throughout the SALT project (Swart & Meiring 2003; Swart & Buckley 2004).

SALT is designed to be seeing-limited and will be most competitive spectroscopically, although its imaging capability has been greatly enhanced compared to the HET due to its redesigned SAC (O'Donoghue & Swat 2001). The science field diameter is 8 arcmin and the image quality specified, in terms of enclosed energy (EE) diameter, to be EE(80) $<$ 0.9 arcsec (i.e. 80% of the energy of the PSF falls within a 0.9 arcsec diameter circle) and EE(50) $<$ 0.6 arcsec, where the median zenithal seeing FWHM is 0.9 arcsec). Thus SALT is designed to not significantly degrade images produced by the natural site seeing, and its instruments are designed to be seeing-limited. While the primary mirror of SALT is not phased, due consideration was given to allow a possible upgrade for phasing in the future, e.g. by defining the appropriate specifications on the mirror actuators and edge sensors.

Other requirements for SALT included an accurate tracking capability, including field rotation, nodding and offset auto-guiding and auto-focussing. Operational efficiency was also of prime importance, requiring an ability to quickly acquire and centre objects on instrument entrance slits, apertures, fibres, etc. Many of the science drivers for SALT (Buckley et al. 2003) require an ability to operate at short wavelengths, down to the UV atmospheric cut-off at ∼320 nm. This led to a requirement for high telescope throughput from 320 to 2500 nm. This was indeed achieved by using newly developed multi-layer coatings, using both Al and Ag, on the SAC mirrors provided by Lawrence Livermore National Labs (LLNL).

As many exciting science programs utilise the light gathering power of SALT to the limit where sky background becomes dominant, minimising scattered and stray light was important. An efficient and accurate calibration system, excellent tracking and atmospheric dispersion compensation, were also key telescope requirements. The restricted viewing window of SALT required that as much astrophysical information should be obtained per unit time interval as possible. This implied maximising the collecting area of the telescope, minimising light losses, and optimising the track trajectory to ensure maximum photon flux. The first requirement led to the choice of an 11-m diameter entrance pupil, following the SAC redesign. Telescope efficiency, particularly minimising the time needed to acquire and guide on an object, was also a crucial factor in maximising scientific productivity.

In choosing the attributes for SALT and its science instruments, we were careful to ensure that we took full advantage of SALTs enhanced capabilities and observational "niches" (Buckley et al. 2003). Examples where we believe this has an impact include:

- long-slit and MOS (multi-object) spectroscopy (with up to R ∼10,000) from the atmospheric UV cut-off (∼320 nm).

- all-Stokes polarimetry and spectropolarimetry (i.e. linear and circular, simultaneous if necessary).

- high-speed (∼10−20 Hz) time resolved imaging photometry, polarimetry, spectroscopy and spectropolarimetry.

- Fabry-Perot imaging spectroscopy (R = 350−10,000), using dual etalons at the highest resolutions, and with a unique imaging spectropolarimetric mode.

- synoptic observations over a range of timescales (days to years).

- very stable fibre-fed high dispersion (R = 70,000) spectroscopy capable of few m/sec radial velocity accuracy.

Although SALT was initially conceived, like HET, to be primarily a spectroscopic telescope, with the advent of the redesigned SAC, giving a respectable science field of 8 arcmin diameter, the imaging capability has been fully exploited. The capabilities of SALT will initially be confined to the visible domain (320−900 nm), although an upgrade path to support near IR imaging and spectroscopy is being pursued. Because of both the significant differences in the SALT science drivers compared to those of the HET and the enhanced capabilities mentioned above (particularly with regard to the field of view and sensitivity at shorter wavelengths), SALTs first generation instrument suite differs significantly from that of the HET.

3. SALT Design Improvements

Almost every subsystem on SALT has been redesigned resulting in expected improvements in performance. These design changes have given SALT new scientific capabilities, particularly regarding the enhanced UV/blue throughput and the ability to mount larger and more massive instrumentation at the prime focus. The major effects of these design changes are itemised here:

- A redesigned spherical aberration corrector (SAC; O'Donoghue & Swat 2001), which gave a larger field of view (8 arcmin diameter), improved imaging quality, a larger entrance pupil (11-m diameter) and, consequently, a ∼15% increase in light collection. These improvements have led to the development of imaging instruments on SALT (e.g. SALTICAM, RSS imaging modes).

• By using multi-layer protected Ag/Al coatings (Wolfe et al. 2003) on the four mirrors, sensitivity at short wavelengths have been enhanced, allowing observations down to the atmospheric cut-off at 320 nm.

• An active primary mirror and prime focus payload alignment system, including capacitive edge sensors on the former and laser auto-collimator and a Mach-Zender distance measuring interferometer on the latter. This is expected to improve image quality retention.

• A greatly enhanced Prime Focus Payload with 4 focal stations, and including a sensitive science grade acquisition camera (SALTICAM), separate focus and auto-guiding cameras, a facility atmospheric dispersion corrector, a moving exit pupil baffle and calibration system for flat-fields and arcs.

The set of first-light instruments (Buckley et al. 2000, 2003) were therefore designed to take full advantage of the expected improvements in telescope image quality, the larger science field of view (8 arcmin diameter) and good UV/blue response.

4. SALT's First-Generation Instruments

Initial plans were to fund three first-generation SALT science instruments from the SALT construction budget, through a combination of both cash and "in-kind" funding from SALT consortium partners. These three instruments were:

1. SALTICAM, a broad-band imaging camera
2. RSS, the Robert Stobie Spectrograph, formerly known as the Prime Focus Imaging Spectrograph (PFIS)
3. SALTHRS, a fibre fed high resolution échelle spectrograph, primarily designed for single objects.

All three instruments were to be built by SALT consortium members, but by the time SALT was completed in 2005, only two of these instruments (SALTICAM and RSS) were built and installed on the telescope. Both are now referred to as the SALT "first light" instruments. The third instrument, SALTHRS, has had both technical and funding difficulties, leading to a delay in its development, although construction is expected to start in late 2006. All three first-generation instruments were designed to be seeing-limited (where the zenith median site seeing in the V-band is 0.9 arcsec FWHM) and will operate over the UV-visible band from 320 to 900 nm (SALTHRS is currently designed to operate over 370−890 nm). SALTICAM and RSS are both mounted at prime focus, thus taking full advantage of the good UV/blue performance afforded by the high efficiency SAC mirror coatings. The following sections discuss the designs of these instruments.

4.1. SALTICAM: SALT Imaging Camera

SALTICAM was built at the South African Astronomical Observatory (SAAO), where Darragh O'Donoghue was the Principal Investigator. This instrument was conceived as a multi-purpose device, capable of performing roles as both an efficient acquisition camera and a scientific imaging photometer (Buckley et al. 2003; O'Donoghue et al. 2003).

SALTICAM was partially completed in September 2003, and was used for the first on-sky tests of SALT, including acquisition, tracking and guidance observations, and throughput tests. In the January 2005 SALTICAM was removed from the telescope and underwent a transformation in which focal reducing fore-optics were mounted. In July 2005 SALTICAM was installed at its final position, at one of the prime foci, fed by a 45° mirror. The fore-optics provide focal reduction (from f/4.2 to f/2) enabling a more suitable plate scale and allowing for the entire 8 arcmin diameter science field and the surrounding 1 arcmin wide guidance annulus to be imaged onto the mosaiced 4K × 4K detector area (i.e. a field of 10 × 10 arcmin). The current filter set available is $UBVR_cI_c$, although there are plans to procure both Strömgren and SLOAN filter sets in the near future. The CCDs are frame transfer devices, allowing fast photometry (10−20 Hz).

4.2. The Robert Stobie Spectrograph

This instrument, which began life as the Prime Focus Imaging Spectrograph (PFIS), was renamed in memory of Robert S. Stobie. It was installed on SALT in October 2005, and has become the initial work-horse instrument on SALT. RSS was built at the University of Wisconsin-Madison, where the Principal Investigator is Ken Nordsieck and the Instrument Scientist is Eric Burgh. Two other SALT partners were also involved in building RSS: Rutgers University (under Ted Williams) were responsible for the Fabry-Perot subsystem and the Invar structure, while the SAAO, under the direction of Darragh O'Donoghue, built the RSS CCD detector system.

RSS resides at the direct prime focus, where it takes advantage of the direct access to the focal plane, and was designed to have a range of capabilities and observing modes, each one remotely and rapidly reconfigurable (Buckley et al. 2003; Burgh et al. 2003; Kobulnicky et al. 2003). In keeping with the overall philosophy of exploiting the niche areas where SALT has a competitive edge, the instrument has several unique, or rare, capabilities, some afforded by various enabling technologies. These capabilities include:

• The ability to observe down to the UV atmospheric cut-off, (∼320 nm). This is achieved by the judicious use of UV transmitting materials in the optical design, including fused silica, fused quartz, CaF_2 and NaCl (the latter used as central elements in sealed triplets). High throughput has demanded the use of efficient anti-reflection coatings, including Solgel on interior (sealed) lens surfaces (Burgh et al. 2003).

• A fully articulating camera/detector used with Volume Phase Holographic transmission gratings (VPHGs). This is, to our knowledge, only the second spectrograph designed to take full advantage of VPHGs with varying incidence angle and full articulation, the other being the Goodman Spectrograph on SOAR (Clemens et al. 2004).

• All-Stokes mode spectropolarimetry and imaging polarimetry using either one or both half and quarter waveplate retarders and a large Wollaston beam-splitter mosaic, giving two completely off-set O- and E-images on the detector (Nordsieck et al. 2003). High-speed and simultaneous modes will also be available, which is particularly pertinent for time varying polarised sources.

• Fabry-Perot imaging spectroscopy in the range 430−860 nm using three etalons, in dual mode for medium and high resolution, providing three resolution regimes of R = 320−770, 1250−1650 and 9000.

• The use of fast frame-transfer CCDs allowing for high-speed observations in all observing modes.

In addition, RSS is capable of:

• Wavelength coverage from 320 to 900 nm, including the provision of an upgrade path for a near IR arm (to between 1.4 and 1.7 microns) using a dichroic beamsplitter.

• Low to medium resolution spectroscopy (up to R ∼ 5500 with 1 arcsec slits; R ∼ 10000 with 0.6 arcsec slits) using efficient and tuneable VPH gratings.

• Multiple object spectroscopy (MOS) using laser cut graphite focal plane slit masks, of up to ∼100 objects at a time. A "nod and shuffle" mode will also be employed for accurate background subtraction.

• Narrowband and tuneable filter imaging.

• Low resolution (R ∼ 50) imaging spectropolarimetry.

5. SALT Science

Already some significant scientific observations have been obtained with SALT during the on-going commissioning and "performance verification" phases. Science highlights to date include the following:

• Unprecedented quality high-speed CCD photometry of eclipses of magnetic cataclysmic variables as part of the commissioning observations of SALTICAM. This was the subject of the first SALT science paper, soon to be published (O'Donoghue et al. 2006).

• The first SALT detection of the afterglow of a Gamma Ray Burst identified by SALT spectroscopy as a distant Lyman break galaxy at a redshift of 3.8 (see Fig. 1).

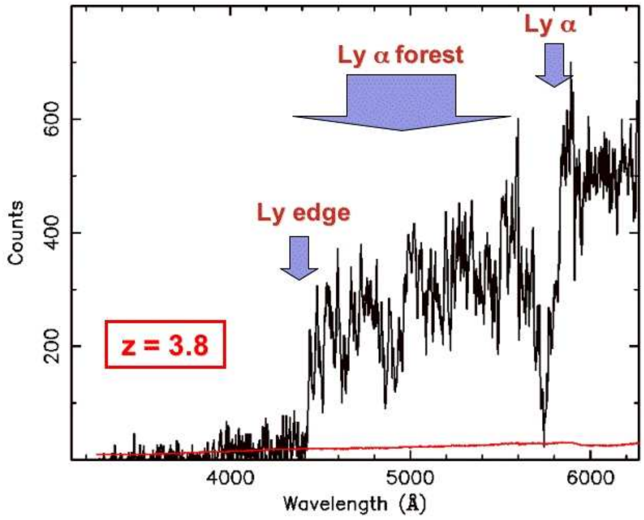

Fig. 1. SALT RSS spectrum (2400 sec exposure) of the V ∼ 20 afterglow of GRB060605, identified as a Lyman break galaxy at z = 3.8.

• Other results have been in such areas as the chemistry of dwarf galaxies, the first pulsations detected in a sdO star, detection of diffuse interstellar bands, kinematics of a dwarf elliptical galaxy, star formation in a spiral merger galaxy and the study of distant supernovae.

Many of the planned future SALT programs include cosomological studies, either as supporting imaging surveys or undertaking photometric or spectroscopic surveys. Multiwavelength - from radio to gamma ray - studies, utilising SALT for the UV-visible domain, are also planned, some of which are expected to be coordinated with other facilities for simultaneous or contemporaneous observations.

References

Buckley, D. A. H., et al., 2000, Proc. SPIE, 4008, 72
Buckley, D. A. H., et al., 2003, Proc. SPIE, 4834, 264
Buckley, D. A. H., et al., 2004, Proc. SPIE, 5492, 60
Burgh, E. B., et al., 2003, Proc. SPIE, 4841, 1463
Clemens, J. C., Crain, J. A., & Anderson, R., 2004, Proc. SPIE, 5492, 331
Kobulnicky, H. A., et al., 2003, Proc. SPIE, 4841, 1634
Meiring, J. G. & Buckley, D. A. H., 2004, Proc. SPIE, 5489, 592
Nordsieck, K. H., et al., 2003, Proc. SPIE, 4843, 170
O'Dononghue, D. & Swat, A., 2001, Proc. SPIE, 4411, 72
O'Donoghue, D., et al., 2003, Proc. SPIE, 4841, 465
O'Donoghue, D., et al., 2006, MNRAS, 372, 151
Ramsey, L. W., et al., 1998, Proc. SPIE, 3352, 34
Swart, G. & Buckley, D. A. H., 2004, Proc. SPIE, 5497, 62
Swart, G. & Meiring, J. G., 2003, Proc. SPIE, 4837, 166
Wolfe, J., et al., 2003, Proc. SPIE, 4842, 343