Completion and Commissioning of the Southern African Large Telescope

David A. H. Buckley, Gerhard P. Swart & Jacobus G. Meiring

SALT Foundation, Observatory Rd, Observatory, Cape Town 7935, South Africa

ABSTRACT

The Southern African Large Telescope (SALT) was completed in 2005 and began initial scientific operations in August of that year. Built in just under 6 years and on budget, SALT has been a good example of a successfully managed telescope project where systems engineering disciplines have been applied to good effect. This paper discusses the experiences of completing and commissioning SALT and its first-light instruments and the early scientific operations. Lessons learned in integrating the various telescope subsystems and implementation of the telescope control system are presented. First Light was announced on 1 September 2005 following the installation of the last of the 91 mirror segments and the commissioning of the UV-visible imager, SALTICAM. This was soon followed by the first scientific observations and the beginning of the commissioning phase for the active optics system.

Keywords: large telescopes, SALT, telescope construction, project management, systems engineering, commissioning

1. INTRODUCTION

In 2005, South Africa, together with ten international partners from five countries, 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), at McDonald Observatory (Texas), which began science operations in October 1999[1,2]. 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 with spherical surfaces, directs light to a 4-mirror spherical aberration corrector (SAC), mounted on a moving tracker at the prime focus. Significant design changes and enhancements were made to SALT[3] following upon the experiences and lessons learned with the HET in its early operations phase, and these are described in Section 4.

SALT is owned by a Foundation, set up to fund its construction and operation, which represents a collaboration of universities and institutes from Africa, Europe, New Zealand and North America. The South African National Research Foundation is a majority shareholder with 34% of the observing shares. Other major shareholders are Dartmouth College (14%), University of Wisconsin-Madison (14%), Nicolaus Copernicus Astronomical Centre of the Polish Academy of Sciences (11%) and Rutgers University of New Jersey (10%). Other shareholders (at < 5% level) include the Carnegie Mellon University, University of Canterbury, University of North Carolina, Göttingen University and the UK SALT Consortium representing the Universities of Central Lancashire, Keele, Nottingham and Southampton, the Open University and the Armagh Observatory. Participation in SALT was attractive to its partners for a number of reasons, the most notable being:

- Access to a 10-m class telescope with versatile observational capabilities
- Access to the southern hemisphere
- Affordable ownership ($19.85M for telescope; $5.65M for first-light instruments; $11.5M for 10 years operations)
- Good observatory site (50% photometric; 75% spectroscopic; 0.9” median seeing; dark; dry; 1800 m altitude)
- Synergies with other facilities accessible by SALT partners (e.g. HET, WIYN, SOAR)
- Relatively inexpensive queue-scheduled service operations
- Assisting in the development of science & technology and educational opportunities in South Africa

The SALT project team 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 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.

Figure 1: The completed SALT. The primary mirror array (91 segments) is seen to the bottom right, on top of the supporting truss, while the prime focus tracker and payload are seen at top left (in black), mounted on the "top hex" of the structure. The night time ventilation louvers can be seen in ring-wall, as can the daytime air conditioning conduits.

2. SALT SCIENCE REQUIREMENTS

A set of science requirements for SALT were defined 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 in turn 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[4,5].

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[6]. 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[7] 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)[8].

As many exciting science programs utilize the light gathering power of SALT to the limit where sky background becomes dominant, minimizing 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 maximizing the collecting area of the telescope, minimizing 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[6]. Telescope efficiency, particularly minimizing the time needed to acquire and guide on an object, was also a crucial factor in maximizing scientific productivity.

In choosing the attributes for SALT and its science instruments, we were careful to ensure that we took full advantage of SALT's enhanced capabilities and observational "niches"[7]. Examples where we believe this has an impact include:

- spectroscopy (with up to R ~10,000) from the atmospheric UV cut-off (320-900 nm), long-slit and MOS
- all-Stokes polarimetry and spectropolarimetry (i.e. linear and circular, simultaneous if necessary)
- high-speed (~10 Hz) time resolved imaging photometry, polarimetry, spectroscopy and spectropolarimetry.
- Fabry-Perot imaging spectroscopy (R = 350-10,000), 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 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), SALT's first generation instrument suite differs significantly from that of the HET.

Provision was made within the SALT construction budget, through a combination of both cash and "in-kind" funding, for two first-light prime focus science instruments[9]. SALTICAM is an optical imager, with good UV sensitivity and high-speed capability, while the Robert Stobie Spectrograph (RSS, formerly known as the Prime Focus Imaging Spectrograph, or PFIS), is a versatile multi-purpose imaging spectrograph, also capable in the UV. Both instruments were built by SALT consortium partners and were installed in mid- to late-2005, respectively. A third instrument, the High Resolution Spectrograph fed by optical fibres from the Fibre Instrument Feed (FIF), was intended to complete a suit of three "First Generation" instrument, but technical and funding delays have meant that it only completed its Critical Design Review in April 2005, and funding problems have meant that construction has not yet begun.

3. SPECIFIED PERFORMANCE

As noted previously[4,5], the SALT project team applied a top-down approach to the development. The Science Requirements defined above are translated into technical requirements, to the detail required to design, subcontract or procure subsystems and components. Highlights from the System Specification and Operational Requirement are presented in the following table:

Table 1: SALT's high-level performance specifications

a.	Telescope Type	Steerable Azimuth, Elevation range 31º-43º
b.	Tracking time between azimuth moves	12° in Hour Angle. Total time dependent on Dec (0.8 to 3 h)
c.	Declination range	+10º to -75º
b.	Operating mode	Primarily Queue-Scheduled with PI's applying for time via the SALT website
c.	Maximum time lost between successive observations (science shutter closed), including telescope re-positioning, acquisition and guidance activation.	≤360s
d.	Image Quality degradation contributable to the telescope	EE(50) ≤ 0.6 arcsec
e.	Image Quality degradation due to building and heat sources (dome seeing) – included in item d. above.	EE(50) ≤ 0.2 arcsec
e.	Field-of-View	Circular, diameter 8 arcmin
f.	Guidance Field-of-View	Probe positionable in science FoV plus another 1 arcmin annulus outside that
g.	Pointing accuracy	≤15 arcsec RMS
h.	Guidance accuracy	≤0.1 arcsec RMS
i.	Mirror re-alignment night time lost	≤2h per five nights
j.	Light throughput taking into account only reflective losses	≥62% at 320nm ≥65% at 850nm ≥78% at 1300nm
k.	Additional Light throughput loss due to obscuration and optical effects	≤25% to 40% (depending on tracker angle)
l.	Mirror surface area	≥77m²
m.	Science focal stations	4, each with their own set of guide probes, one with no additional optics in path

4. SALT DESIGN ENHANCEMENTS

Although the basic design of SALT is similar to that of the Hobby-Eberly Telescope (HET), there are significant departures brought about to enhance capability and performance and take advantage of the lessons learned with the HET. Almost every subsystem on SALT has been redesigned, resulting in expected improvements in performance. These design changes included:

- A redesigned spherical aberration corrector[6] (SAC), giving a larger field of view (8 arcmin diameter), improved imaging quality (EE50 < 0.2 arcsec) and using multi-layer protected Ag/Al coatings on the four mirrors, to enhance its sensitivity at short wavelengths (capable down to 320 nm).

- An active primary mirror alignment system[10], which includes re-designed flexure-based mirror supports, a precision actuation system and utilization of capacitive edge sensors[11] to measure primary mirror segment movement. In addition, a Shack-Hartmann wavefront system is used for initial optical alignment of all the segments.

- A facility building utilizing air conditioning during the day and natural ventilation at night, with controllable louvers, and measures employed to remove all heat sources inside the telescope chamber in order to minimize dome seeing[12]. These measures include using glycol cooling of powered subsystems, which are installed inside insulated cabinets, and forced ventilation under a false observing floor during the night.

- A greatly enhanced Prime Focus Payload[13] with 4 focal stations, and including a sensitive science grade acquisition camera (SALTICAM), separate focus and auto-guiding cameras, a facility atmospheric dispersion compensator, a moving exit pupil baffle and calibration system for flat-fields and arcs.

- An active payload alignment system, which uses both a laser auto-collimator and a Mach-Zender distance measuring interferometer to keep it optimally aligned in tip/tilt and distance with respect to the primary mirror.

- A robust, integrated, holistic and capable Telescope Control System, based on Lab-VIEW, which is more easily integrated, tested, commissioned and maintained[14].

- A set of first-light instruments that will take advantage of the expected improvements in telescope image quality, larger science field of view (8 arcmin diameter) and good UV/blue response[7, 9].

5. MANAGEMENT AND ORGANISATION

In order to facilitate transparency and accountability in a multinational project of this kind, a private company, the "SALT Foundation (Pty) Ltd", was registered in South Africa in 2000, in which all SALT partners are shareholders. This company oversaw the construction of SALT and it now owns the telescope. The company is governed by a Board of twelve Directors, one nominated by each partner and two by South Africa, the major shareholder. During the construction period, the Project Manager and Project Scientist reported to the Board, who met twice per year. The chairperson of the Board, the Board secretary and the Chief Financial Officer all resided in South Africa, which facilitated efficient administration. The SALT project team had an office in Cape Town, on the grounds of the South African Astronomical Observatory (SAAO), and team members regularly spent time at the observatory site at Sutherland, about 380 km away. Certain SALT team members lived on site while the systems they were responsible for were being installed, integrated and commissioned – for example, the SALT Systems Engineer lived on site for the last two years, during integration and early commissioning phase.

The SALT project management organization was small and compact, which made it easy to manage and communicate, and the fact that it was structured as an independent company substantially reduced the bureaucracy which can accompany similar projects carried out inside big organizations. SALT was divided into five sub-projects, and project managers were appointed for these. A business manager, looking after all financial, legal and administrative affairs, provided support to the project managers. The SALT Business Manager was also the Board secretary during the construction period. A systems engineer, together with both an optical and controls engineer, provided the necessary analytical support, while a draughtsman and software engineers were employed once all specifications and high level designs were in place. At the height of construction period the Project Team consisted of 18 people, including the Project Manager and Project Scientist, three mechanical engineers, two electronics engineers, five software engineers, one optical engineer, one civil engineer, the Systems Engineer, a draughtsman, the Business Manager and an administrative assistant. The team structure followed the hardware breakdown structure (Fig. 2) to ensure easily identifiable responsibility and accountability. Project managers were appointed for the facility (building and ancillary services), structure & dome (one manager for both), the primary mirror system, the tracker & payload (one manager for both), and the telescope control system (TCS).

The TCS development was done by the team of software engineers on the Project Team, under the management of the Systems Engineer. The construction of the science instruments was overseen by the Project Scientist, who worked closely with the Principal Investigators and instrument teams. Additional support also came from the SAAO for some of the design work and fabrication (e.g. some of the prime focus payload subsystems).

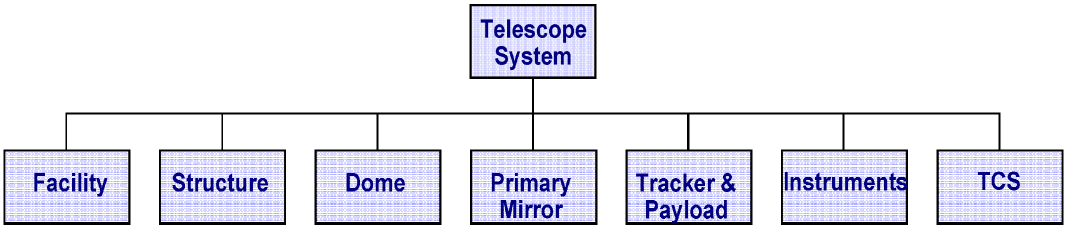

Figure 2: SALT's Hardware Breakdown Structure

6. DESIGNING TO THE SCIENCE AND OPERATIONS REQUIREMENTS

For SALT much effort and thought went into correctly defining the top-level "science requirements" of the telescope as a whole and then the specifications for the SALT system[4], subsystem and their constituent components. In addition, the entire design process was one based upon *systems engineering*: an iterative process whereby the high level goals or requirements of the astronomers were converted, or translated, into a set of technical engineering specifications. While a systems engineering approach was crucial for the successful design of SALT and its subsystem, it also played a role in the subsequent phases of the project, particularly in the integration, implementation and acceptance testing stages[5].

In addition to the science driven requirements[7], which determined many of the design specifications at the system and subsystem level, operational considerations were also considered in defining these specifications. These included those relating to the scientific productivity and efficiency, like the telescope scheduling, remote observing, data handling, processing and archiving, creation of observing proposals and observing scripts, etc. Equally important were the issues relating to maintenance, component lifetimes, spares, safety (personnel, equipment and data), reliability, etc. For SALT, these issues were heeded in the subsystem and system design phases, where such things as component reliability and lifetimes were used to assess the long-term viability of certain design solutions.

In designing SALT, the basic overall operational criteria aimed at for the total system (i.e. telescope) was condensed into several key efficiency parameters, as presented in Table 2. The figures apply to the fractions of *useable* night time hours. The SALT figures represent the specified performance (first row) and the actual performance at the present time, during the commissioning phase (second row). Figures for other telescope were drawn from references in earlier SPIE Proceedings, so could well be somewhat dated. SALT's active mirror segment control (part of column 3), which uses edge sensors and actuators, was part of the SALT design from the outset, rather than retro-fitted as was the case for HET, and is specified to take <2h every >5d. In terms of the telescope's efficiency at acquisition, the timeline specified in the SALT Systems specification gives a total acquisition time of < 360 sec. Slewing to a new target involves the parallel execution of several Telescope Control System (TCS) commands (e.g. dome rotate, structure rotate, tracker position, guide probe position, payload configuration). Most of these commands are transparent to the SALT Operator and Astronomer, who simply issue commands to 'go to next target', selected from a list of viable targets, via a single mouse click, rather than issuing a sequence of subsystem commands.

While the SALT specification numbers in Table 2 may seem somewhat over-optimistic compared to the reality of other telescopes, particularly the HET, the efforts put in at the early design stages have been aimed at delivering such efficiencies. Early planning was crucial in achieving the required efficiencies, since it is difficult to change afterwards, once the total system is integrated, if the design was not optimal. In comparison to other large telescopes, the SALT performance values are quite typical, although in the current commissioning phase, expected to last until late-2006, the numbers are still someway from being optimal. We are optimistic, however, that these specifications will be met. The larger numbers for "Engineering" and "Overheads" are mostly due to: 1.) the continuing image quality and system testing and 2.) the incomplete implementation of full TCS functionality with Payload subsystems (auto-guiding, auto-focussing, calibrations), which will improve during the current commissioning phase.

Table 2: Telescope efficiency comparisons

Telescope	Technical problems	Engineering, mirror alignment and calibrations	Overheads including setup, moving, acquisition	Science shutter open
SALT (spec)	4%	9%	20%	67%
SALT (now)	20%	33%	27%	20%
HET (2003)	9%	26%	28%	37%
HET (2005)	8%	12%	30%	50%
Keck	5%	13%	31%	51%
Gemini	4%	12%	19%	65%
VLT	2%	6%	18%	74%

Calibration observations are somewhat of an unknown at present, although it is clear that such observations will need to be done both during the night (e.g. spectral calibrations with arc lamps) and during the day (e.g. flat fields simulating the pupil motions for completed observation).

7. THE SALT OPERATIONS STAFFING MODEL

The SAAO has been contracted by the SALT Board to operate and maintain SALT for a period of 10 years, with annual reviews of the operational performance. Staffing levels for steady-state operations were determined by way of Logistic Support Analysis (LSA), a method used very successfully in, among others, the aviation and military industries, and from real experience at other telescopes (e.g. HET). The original operations team was appointed in accordance with the results of the LSA, but this has been tailored as real life operational experience and information becomes available. Although there are the expected teething problems, handover has gone remarkably well.

SALT required a complement of operations staff with varying experience and qualifications. Different operational scenarios were discussed for sometime, and the current staffing model arose from a review process, that was formulated in light of experience at other observatories, notably the HET, plus the very real experience of running SALT during the integration and initial commissioning phases, some 2 or more years before handover in mid-2005. The latter involved the Operations staff, principally engineers and technicians, working closely with the Project Team during this integration period. Operations staff were recruited for the specific skills needed to efficiently run a modern software intensive telescope, like SALT. Existing SAAO staff with the required skills, were also drawn into supporting the operation of SALT, both in the scientific and engineering areas. The following Table shows the existing Operations staff complement at this time, during the current commissioning and ramp up phase to full operations, which has a total of 34 individuals involved and ~26 FTEs. The difference simply reflects that some positions are not full-time on SALT, and that there are other non-SALT funded activities.

While science operations has begun, albeit at a low level, the full functionality of SALT and its instruments will only be achieved by late-2006, when performance verification science operations is expected to begin. Once SALT has reached a "steady state" operation, anticipated for sometime in 2007, it is expected that the required operations staff required will decrease somewhat.

Table 3: The current SALT Operations staff breakdown during the commissioning/ramp-up phase

Position	**Situated**	**# of People**	**SALT FTEs**
Eng. Ops. Manager & Systems Engineer	Sutherland	1	1
Astronomy Operations Manager	Cape Town	1	0.8
SALT Operators	Sutherland	3	3
SALT Astronomers	Cape Town	6	4.2
Electrical Engineer	Sutherland	1	1
Mechanical Engineer	Sutherland	1	1
Software Engineers	Sutherland / Cape Town	1 / 4	1 /3.5
Electronics & Software Technicians	Sutherland	3	3
Mechanical Technicians	Sutherland	3	2.18
IT & Software Technician	Sutherland	1	0.5
Technical Assistants	Sutherland	2	2
Administrative Assistant	Sutherland / Cape Town	1 / 1	1 / 0.5
Logistics Support Administrator	Sutherland	1	0.3
Optical Engineer	Cape Town	1	0.15
Opto-Mechanical Engineer	Cape Town	1	0.15
CAD Draughtsman	Cape Town	1	0.4
IT Support	Cape Town	1	0.2
TOTAL	*(Sutherland/Cape Town)*	*34 (17/ 17)*	*25.88 (15.98 / 9.9)*

8. TELESCOPE COMMISSIONING

8.1 Planning and schedule

In order to communicate the responsibilities, activities and schedule related to commissioning, a Commissioning Plan was developed by the Systems Engineer in co-operation with Project Manager, Project Scientist and the subsystem managers. The commissioning and testing process[5] was agreed, and did indeed form the basis of the actual work that took place. The following steps show this incremental process:

a) The subsystem assemblies or components (depending on the amount of work subcontracted on that subsystem), were required to pass Factory Acceptance Tests prior to delivery to the telescope.
b) These assemblies and components were integrated at the telescope and tested, using their own subsystem controlling computer(s)[a].
c) Once a subsystem had shown adequate maturity and compliance with its own subsystem specification, it was integrated with the TCS in a progressive fashion.
d) The TCS had various "builds"[b], designed to provide certain functionality to the SALT Operator and/or SALT Astronomer. These builds started from a simple base, controlling the telescope Structure and Dome and progressively included more subsystems and complex functionality.
e) When the integration of a subsystem was "completed", it was tested on the telescope to reveal any further inadequacies.
f) As soon as possible, on-sky testing was started to identify any possible shortcomings or errors. These tests were of a diagnostic nature, not intended to actually verify performance.
g) As certain aspects of the telescope's performance became stable (not being greatly influenced by further integration activities), they were tested in a more formal fashion against the System Specification. This process was somewhat iterative, depending on the success achieved and the subsequent changes made to the telescope configuration and is on-going.
h) When basic telescope performance was adequate (especially in terms of Image Quality), the integration of instrumentation was started. An instrument being treated much like the other telescope subsystems, and also subject to incremental TCS builds, providing growing functionality, reliability and performance.
i) Although the handover to the operational team was a progressive process, there was a specific point at which the responsibility needed to transfer from one organisation to another. This occurred when the bulk of the commissioning and testing has been completed and when it was more effective to utilise the Operations staff to perform testing as part of their training. This process is detailed in Section 10.

It is important to define "completion" correctly. Spending too much effort to resolve all outstanding problems before proceeding can be very inefficient and expensive, but too much haste means increasing the number of errors only found later, with the associated correction and re-test expense. A balanced approach was required.

An important function of the Commissioning Plan was to allocate the responsibilities between the Subsystem Managers, Safety Manager, Operational Team, Project Scientist and the Systems Engineer (who was the integration leader). The Commissioning Plan contained a preliminary schedule that was subsequently revised several times to incorporate delays from suppliers, technical difficulties and changes in strategy. It served as a monitor of progress, ensuring the logical nature of the integration process and communicating intended events to all concerned. Due to the myriad of uncertainties in this process, it could not be used to predict the future!

8.2 Telescope Tests and Results

As the intended testing process has been described previously[5], only a brief description of the system-level tests are provided in Table 4 below. These tests form part of the process of demonstrating that the telescope meets its intended performance, as documented in the System Specification. Each test group was allocated to a specific person on the team, and recorded in a separate test procedure and/or test report. Even though science operation has started, thorough testing is considered important and will still continue for some time.

Table 4: SALT System Level Testing

Test Description	Completion Status
Image Quality Tests: The overall image quality of the telescope is verified by testing and the major contributors are verified by testing or analysis.	Specs met over restricted range, but not over entire FoV; more tests to follow
Design Verification: This covers all the specification items that will not be tested but that can be verified by reviewing the design in detail	Nearly complete

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[a] The system architecture was specifically chosen to achieve this level of testing prior to integration of that subsystem with the Telescope Control System (TCS)[4,14].

[b] A "build" is a specific subset of the final TCS software suite that was required to provide certain functions and interface to certain subsystems[14].

Basic Functionality and Operational Performance Test: The demonstration of specific functionality called for and the verification of quantifiable performance not covered in other tests.	Basic functionality verified; efficiency tests require longer operation
Pointing and Tracking tests: Verification of Open loop Tracking, Tracking rates, Acquisition accuracy	Basic pointing and tracking verified; longer term calibrations required
Thermal tests: Maximum surface temperatures, air temperature inside telescope	Complete
Environmental requirements: Some testing and analysis to show that the telescope achieves performance throughout the environmental envelope	Full envelope still to be explored
Safety compliance: verification that the required safety measures have been incorporated	Complete

Some of the test results completed to date are provided in the following table:

Table 5: Current status of System Level testing

Requirement	Specification Value	Achieved?	Comment
Science FoV	8 arcmin	Yes	Up to 10 arcmin for SALTICAM
f/ratio	3.6 to 4.5	Yes	f/4.2 Acceptable compromise (fibres & opt. design)
Pupil diameter	10.6 ± 0.4 m	Yes	11-m (15% increased light collection)
Total Image Quality (in median seeing)	EE(50) ≤ 1.3” (at 37^o zenith distance)	Not yet	Best achieved ~1.2-1.5” (meets spec), typically ~2” Field dependent low-order aberrations & focus
IQ retention	degrades <10% in 5d	No	Not tested yet. Awaiting full edge sensor operation
Collecting area	77 m^2	Yes	77.1m^2 Total effective mirror surface, not incl. obscur.
Max. effective area	57.8 m^2	No	55 m^2 TBC, includes central obscur., tracker, top hex
Obscuration	<25%, centred tracker <40%, 8.5° offset	No Yes?	29% (but system total throughput spec. met) 35% (estimates, TBC experimentally)
Total Reflectance Throughput	340-450 nm >65% 450-800 nm >70% 800-250 nm >80%	Yes Yes ?	~80% (imaging throughput tests) ~80% Not measured; expected to be >85%
Maximum Total Throughput	340-450 nm >49% 450-800 nm >53% 800-2500nm >60%	Yes Yes ?	~57% (assumes on-axis tracker) ~57% Not measured; expected to be >61% from theory
Low dome seeing	<0.2 arcsec	Yes	single segment sub-arcsec images seen in good seeing
Sky Accessibility	-75°22’ < δ < +10°37’	Yes	
Track times	>12° in RA	Yes	Mostly better than spec.
Pointing accuracy	<15” peak-to-peak	Yes?	15-30”; sufficient; expected to be improved
Azimuth & tracker slew time	<3 min 90% of time <5 min 99% of time	Mostly	Highly dependent on Tracker/TCS reliability Often achieves spec. when no faults present
Closed Loop tracking accuracy	<0.1 arcsec rms	Yes	0.08” Tested with guidance system and SALTICAM More testing required
Min. brightness of guidance star	R = 19 star with <10sec integrations	Probably	Successfully guided on V=18 with 1 sec integrations

8.3 Telescope Performance Examples

The following are two specific examples of SALT’s performance, namely the reflectance throughput of the telescopes mirrors and the tracking/observation times.

8.3.1 Reflectance Throughput

Before photons reach the SALT focal plane, they undergo five or six reflections, depending on the specific focus. For the straight-through position, where the RSS is mounted, reflections occur at the primary mirror (Al) and then four additional reflections inside the SAC (Al & Ag multi-layer LLNL coatings). For the other foci, including SALTICAM, the Fibre Instrument Feed (FIF) and the Auxiliary Focus, there is an additional reflection off a 45^o fold mirror (LLNL coating). Figure 3 shows the expected total reflectance for the RSS focus, based on witness samples of coatings, together with actual measured throughput results taken in March 2006. The results indicate excellent performance of the SAC mirrors, demonstrating the considerable gains in UV/blue throughput (<450 nm).

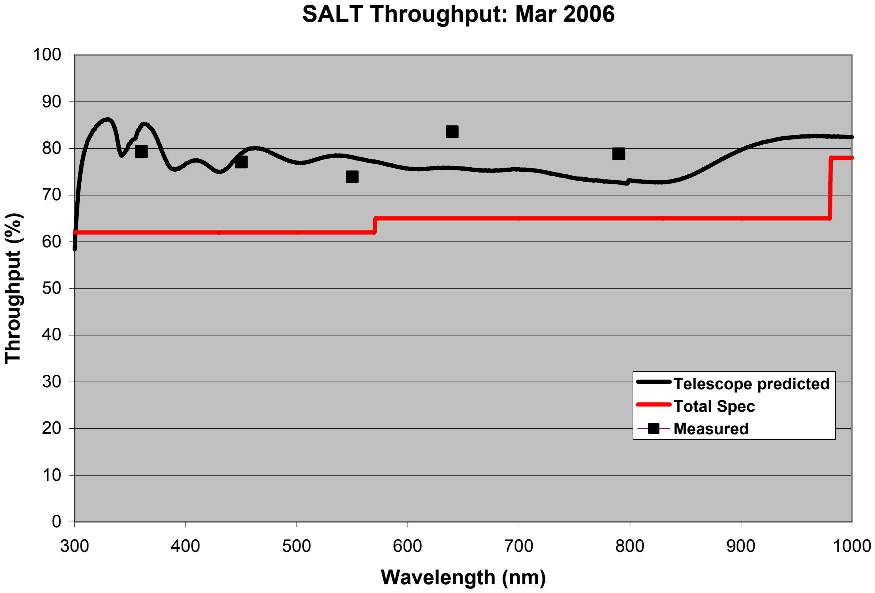


Figure 3: Specified, predicted and measured total SALT mirror reflectance efficiency.

8.3.2 Observation Time

The total available observation time for a specific target varies considerably for telescopes like SALT and HET. Whereas the massive ~100 tonne structure of SALT is tilted at a fixed altitude angle of 53º and remains stationary in azimuth between slews, the prime focus tracker can execute motions of ±1.6 metres in X & Y, and tip/tilt angles ±6º about those axes. This translates to an ability to track objects inside a region defined in- altitude-azimuth. In terms of observation time, this is highly dependent on the declination of the object. The following two figures demonstrate how the track time varies, depending on position and the time at which a target is acquired.

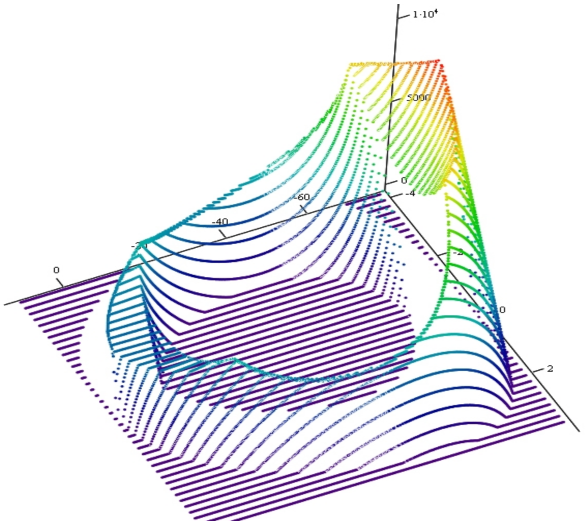


Figure 4: SALT "Tracking Surface" as a function of Declination and Hour Angle at which a target is *first* acquired. Axes are HA, Dec (x,y) and time (z).

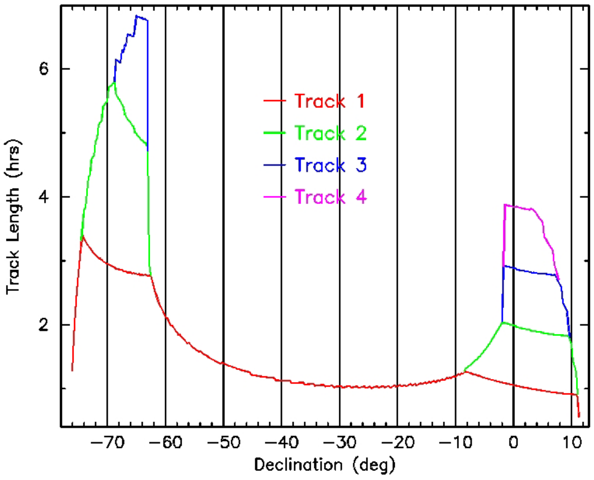


Figure 5: Potential total track times assuming the azimuth is chosen to ensure the earliest acquisition of a target (lower curve), and then allowing for successive azimuth moves to the West, where appropriate (2 moves in the South; 3 moves in the North).

8.4 Payload completion

One of the major telescope sub-systems to experience delays in completion was the Prime Focus Payload[13], which contains many of the supporting "facility" instrumentation, like the acquisition, guidance and focussing systems, the moving baffles, the atmospheric dispersion compensator and the instrument calibration system. Almost all of these were designed and integrated in-house, and specific subsystems contracted out (e.g. the guidance probe mechanisms, the ADC prisms). Integration and alignment of these subsystems, including installation of the control electronics and development of control software, became a major task, more than originally envisaged. The fact that the Payload was very space constrained, and once installed on the telescope, very difficult to access, meant that work proceeded much more slowly than anticipated. Additional staff involved in the Payload may have also helped lessen the completion time.

8.5 Instrument Commissioning

While the telescope and subsystems were designed, contracted and managed by the SALT Project Team, the first-light instruments were built by consortium partners whose Principal Investigators (PIs) were responsible for the overall management. Monthly technical and quarterly management, budget and schedule reports were sent to the SALT Project Scientist, who had overall responsibility for the instruments. Instrument review meetings were called for by the Project Scientist, who appointed external reviewers who met with representatives of the SALT Science Working Group and Instrument Teams.

As might be expected with one-off science instrument projects, despite the best attempts at defining realistic schedules, these inevitably slipped. The inter-connection of various tasks, and the consequences of delays in different subsystems, were difficult to predict. In hindsight it is clear that at least in the case of RSS, additional personnel may have alleviated these schedule pressures. For both instruments a delay of ~1 year was experienced in final delivery, although due to telescope delays of a similar amount, this did not have as significant an impact as it might have.

It also became clear after installation on the telescope that the acceptance tests conducted in the laboratory were not always adequate to test the instruments in the real telescope environment (e.g. temperature extremes). Although jigs were set up to test the instruments at the different nominal gravity vectors, it became clear that these were insufficient to test for all the degrees of freedom, particularly instrument rotation on an inclined plane. Mechanisms on SALTICAM failed early on due to both of these effects, and although temporary measures were employed to address them, some re-design has also been necessary. Similarly for RSS, the most complex mechanism, used to exchange focal plane slit masks from a "juke box", ran into alignment problems, and has had to be redesigned.

On a positive note, however, both first-light instruments are now operational and some science data is being obtained as part of the on-going commissioning process. Finally, in terms of final costs the two instruments, SALTICAM and RSS were, respectively within 5% and 9% of their original baseline cost estimates defined at PDR, namely \$0.564M and \$4.374M respectively, which included risk provision (15% and 20% respectively). The cost increases for SALTICAM were largely due to exchange rate fluctuations.

9. LESSONS LEARNT

9.1 Start preparations early

Although the technical, schedule and financial success of the project only becomes apparent towards the end of the commissioning process, it is actually determined mostly by the activities preceding commissioning. SALT's application of a tailored Systems Engineering process to these activities reduced the risk and ensured that the SALT subsystems, when integrated, did indeed have a high probability of fulfilling the Science Requirements. This does not eliminate risk totally, but does minimise the exponential cost and time associated with the deficiencies found at that time.

9.2 Keep the score

It is very easy to lose perspective during the frantic activity called commissioning. Several tools can be used to keep track of the priorities and maintain the advantage of pro-active, focussed attention:

- Fault Tracking: An internet-based system was used to capture faults that were identified. The system would send e-mails to the responsible people and allow status and follow-up information to be entered until the problem was resolved.
- Schedule planning and monitoring: By keeping a schedule up to date, and communicating the intended commissioning activities to the full team, there were clear longer-term goals to aim for, and people could pre-empt certain events. A daily on-site meeting and weekly co-ordination meeting with Cape Town, served to update the

activity plan and identify short-term priorities. In hindsight, the schedule was not updated as realistically or as frequently as possible.

- Testing: Where possible, even engineering tests were based on the formal requirements and their results documented. This highlights specific shortcomings that can be addressed in further detail.
- Reporting: During the high-activity period, commissioning reports were written to crystallize available information and summarise the status. This was especially valuable when communicating with outside parties.

9.3 Involve the science and operational community with testing

Subsystem integration was performed primarily by engineering staff, but it was essential to involve the astronomers with on-sky work. Their knowledge and experience would allow quicker identification of problems, greater understanding of observed data and faster test progress. This also served as a period of training to the SALT Astronomers, SALT Operators and maintenance staff, forming greater cohesion between the project team and the operational staff. Later, when the telescope had matured somewhat, a phase of "Trial Operation" was entered, where the Astronomers and Operators would operate the telescope, conducting shared-risk science and engineering tests, under the guidance of the project team. This highlighted several operational issues which would otherwise have been discovered very late.

9.4 Watch the detail

Achieving a status of 90% complete on all integrated items, was "easy", it was the last 10% that proved painful. It is important to plan enough time and resources for this part of the work. In particular, activities such as optical alignment, pointing calibration, mirror edge sensor characterisation and achieving software consistency, proved time-consuming. This was worsened by delays on critical optical subsystems, such as the telescope payload. The latter was also late due to an underestimation of the detailed complexity.

9.5 Resources

Ultimately it is the people who need to make things work. Their motivation, dedication and expertise are critically important. Two of the important lessons here are:

- Plan for the effect of a remote telescope site. With a travel time of four hours to the telescope, it was essential that key staff lived at Sutherland during the commissioning process. Not everyone could uproot their families to achieve this, causing significant time losses.
- Appoint the operational team early, especially their leadership. This will allow adequate overlap of key skills and knowledge, will provide extra resources to commissioning activities and form a "client" user community to ensure that long-term operation is adequately addressed.

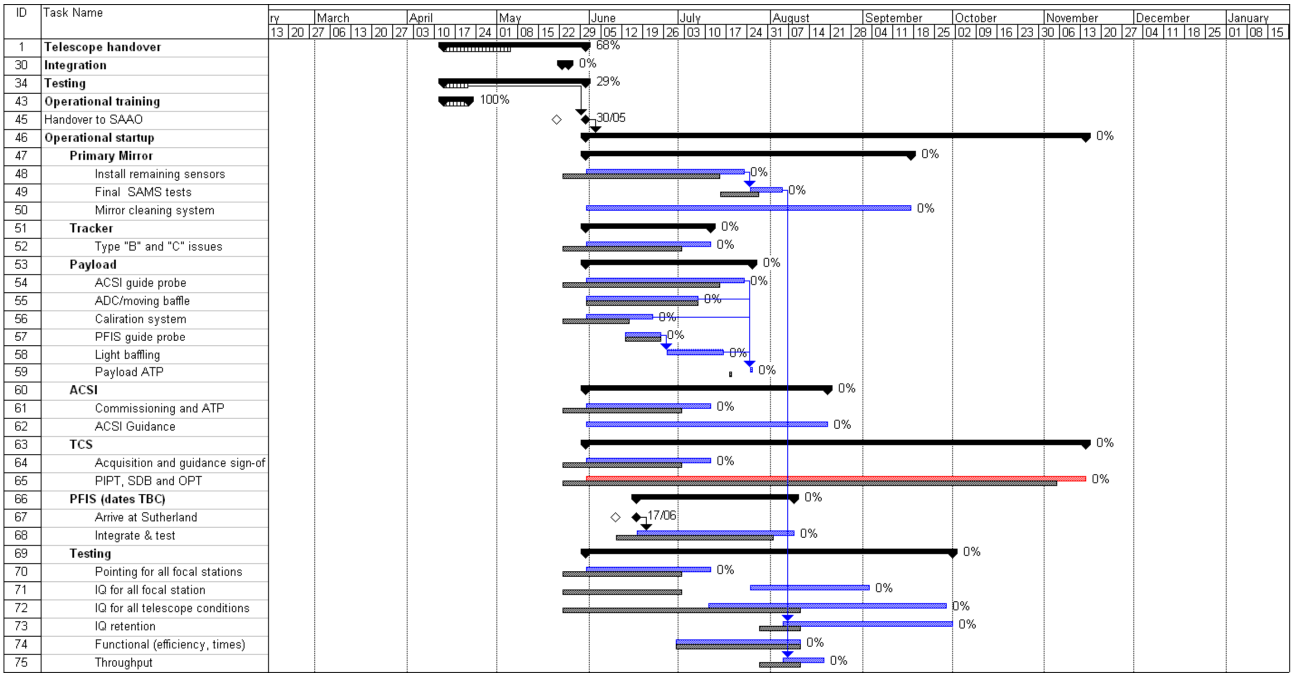
9.6 Have contingency plans

Nothing ever happens as planned, so it is vitally important to have a "Plan B". The hardware and software configuration for tests need to be flexible, but then will also need to be documented to provide clarity when interpreting the results. An important example for SALT was the late arrival of the Spherical Aberration Corrector (SAC), a critical element of the optical path. A "surrogate SAC" was borrowed from the HET, allowing on-sky commissioning of the TCS and Tracker to proceed, albeit with different optical parameters. Although allowing work to proceed, such contingencies do not alleviate the full effect of delays and should not be allowed to create a false sense of progress.

10. SYSTEM HANDOVER TO OPERATIONS TEAM

Handing over a complex, high technology machine, such as SALT, from construction into operation is a non-trivial task and it was planned in fair detail. This plan addressed integration, testing, operational training, operation start-up, shared risk science and finally the start of limited operations. An excerpt of the handover plan is shown in Figure 6.

The operations team consists of some original SAAO technicians and astronomers, but mostly newly appointed personnel. The SAAO started assembling this team about 18 months before handover, and operations members assisted in the completion and commissioning of the telescope. There was thus a solid period of "on the job" training, combined with formal training conducted by the SALT Project Team. Operations Team members were checked out and "licensed" by the SALT Project Team. The SALT project team handed over the "ownership" and responsibility of the telescope to the operations team on 31 May 2005. The project team remained in place, gradually reducing capacity until year end. This transfer of ownership and responsibility, while Project Team members still remained available, were key success factors in the handover. A subset of the Project Team, namely the Telescope Control System software team, were retained to complete the observatory control system (OCS) software and to ensure that operational lessons learned were implemented.



ID	Task Name
1	**Telescope handover**
30	**Integration**
34	**Testing**
43	**Operational training**
45	Handover to SAAO
46	**Operational startup**
47	**Primary Mirror**
48	Install remaining sensors
49	Final SAMS tests
50	Mirror cleaning system
51	**Tracker**
52	Type "B" and "C" issues
53	**Payload**
54	ACSI guide probe
55	ADC/moving baffle
56	Caliration system
57	PFIS guide probe
58	Light baffling
59	Payload ATP
60	**ACSI**
61	Commissioning and ATP
62	ACSI Guidance
63	**TCS**
64	Acquisition and guidance sign-of
65	PIPT, SDB and OPT
66	**PFIS (dates TBC)**
67	Arrive at Sutherland
68	Integrate & test
69	**Testing**
70	Pointing for all focal stations
71	IQ for all focal station
72	IQ for all telescope conditions
73	IQ retention
74	Functional (efficiency, times)
75	Throughput

Figure 6: Excerpt of the SALT handover schedule

11. EARLY OPERATIONS AND SCIENCE

With the installation of the imaging camera, SALTICAM, in July 2005 came the opportunity to attempt “first light” observations with SALT (see Fig. 7). Although images had been obtained with SALT as early as 2003, these were the first observations with all 91 mirror segments installed and the SAC in place, allowing maximum throughput and field coverage. However, these images were taken with the telescope still some way from being fully functional. The guidance system was not yet installed and the edge sensor system, used to keep the primary mirror segments actively aligned, was also not yet commissioned. Thus the first-light observations, and subsequent commissioning science observations, were achieved using open-loop tracking and an uncontrolled primary mirror. Despite this situation, the first light images, released on 1 September 2005, indicated that SALT was basically on-track to be an operational telescope meeting its overall specifications.

Scientific observations with SALT commenced in August 2005, with SALTICAM commissioning. One of the first programs attempted was high time resolution photometry of eclipses of accretion hot-spots in magnetic cataclysmic binary stars (see Fig. 8), also known as Polars, or AM Herculis stars. This first science program was chosen partly to exercise the high-speed (down to 100 ms) photometry mode of SALTICAM, but also because the observations were relatively easy to do, even without closed-loop guidance being implemented. The relative brightness of these objects (V ~15 – 16 outside eclipse) made them ideal commissioning targets, even in bright Moon, in poor seeing or for non-optimal image quality.

Other SALT science programs have also begun as part of the commissioning and “performance verification” (P-V), phase, which is expected to extend until late 2006. These observations have been obtained with SALTICAM (broad-band and high-speed imaging) and RSS long-slit spectroscopy, high speed spectroscopy and narrow band imaging. However the current priorities are observations in support of engineering and acceptance tests (e.g. image quality). During this time we will be completing the commissioning of the supporting Payload instrumentation (e.g. auto-guidance, auto-focus, atmospheric dispersion compensation, exit pupil baffling, calibrations) and optimizing telescope image quality, which currently suffers from low order field dependent aberrations. This will likely involve some adjustments to the SAC optics. Once most of these items are completed, progress is anticipated in adding further instrument functionality, in particular commissioning the remaining modes of RSS (e.g. multi-object spectroscopy, Fabry-Perot imaging).

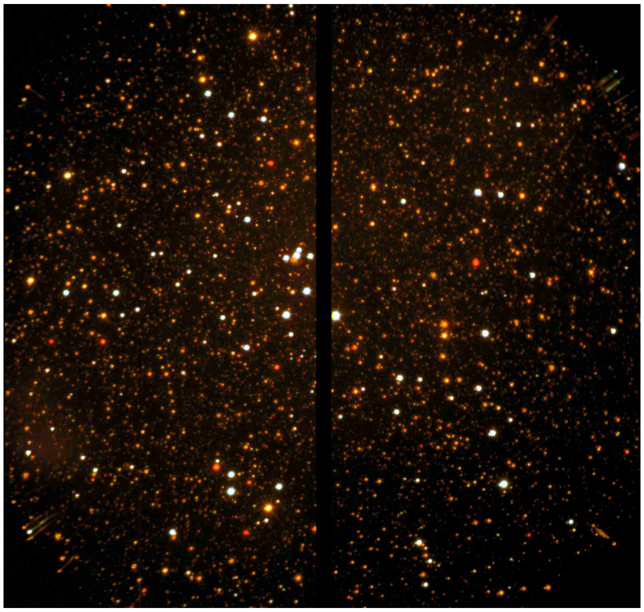


Figure 7: A first light SALT image of the open cluster NGC6152. This was produced from short (10 s) composite BVI exposures using the imaging camera, SALTICAM, which consists of a mosaic of two 2048 x 4096 pixel CCDs. The images in this image are typically 1.4 arcsec FWHM, close to the specification for image quality, given the ~1.2 arcsec seeing conditions at the time.

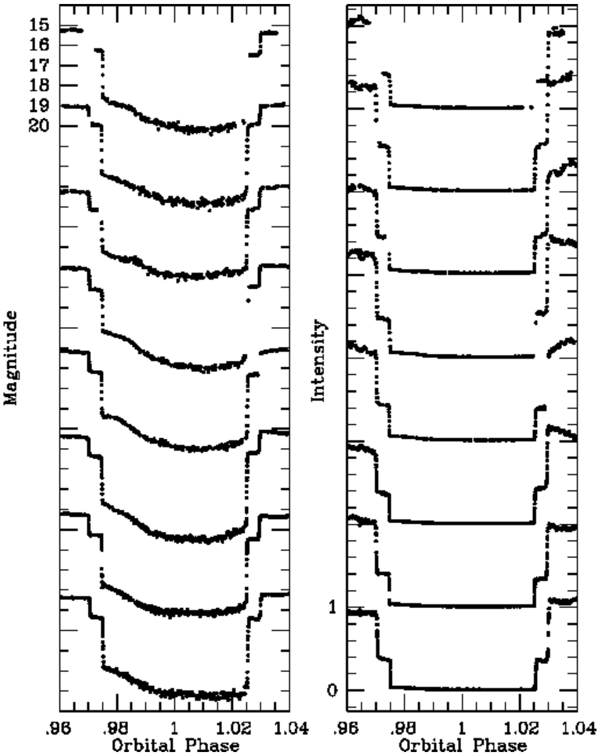


Figure 8: Light curves (white-light) of eclipses of the polar SDSS015543+002807, taken by SALTICAM with 0.1 to 0.3 s resolution. The left plot is in the logarithmic units of magnitudes, while the right plots are in flux density. The distinct steps in the ingress (dimming) and egress (brightening) part of the light curves are due to the successive disappearance and reappearance of the two bright accreting hot-spots near the magnetic poles.

12. FUTURE DEVELOPMENTS

Although our current focus is on completion of the commissioning phase, plans for future developments of SALT are currently being discussed by the SALT Board and Science Working Group. The next SALT instrument is likely to be a near IR extension to the Robert Stobie Spectrograph (RSS) and a conceptual design has already been presented. The instrument will operate from 0.9µm to between 1.4 and 1.9 µm, depending upon the complexity of cooling employed. This option was designed in the RSS support structure from the outset, and provision was made for installing a dichroic, allowing simultaneous observation from the UV to NIR, which allow for some exciting science programs. Polarimetric and Fabry-Perot options are also being considered.

Future second generation instruments may include a multi-fibre fed medium resolution (R ~10,000–20,000) spectrograph(s), possibly with multiple IFUs. A niche instrument currently under consideration is a fibre fed super-conducting tunnel junction (STJ) camera, allowing for very high-speed spectrophotometry.

Telescope developments that have been proposed include phasing the primary mirror array by developing a specialised phasing camera to operate from the centre of curvature on the CCAS tower. This would be a prelude to a potential A-O system. Another proposal has been for the development of a wider field SAC which would place SALT in a very competitive position for dedicated survey science. While it is maybe considered premature to discuss such future developments now, given that SALT has not yet begun routine science operations, the typical gestation period of these is many years, so planning for these should begin now.

13. CONCLUSIONS

Construction of SALT was completed in 2005, ~6 years since the project began, 5 years following ground-breaking and, remarkably, at a cost ($19.85M), within 1% of the originally defined baseline budget. The latter feat was even more astounding given that the original budget was based on the premise the SALT would essentially be a copy of HET, whereas most subsystems underwent significant redesign. We are currently in the middle of the commissioning phase, expected to be concluded by the end of 2006, and are effectively 12–18 months behind the originally defined schedule. Nonetheless, SALT has achieved some significant milestones, and the detailed planning and systems engineering approach has resulted in a well designed and integrated telescope and suite of first generation instruments. While all activities at SALT at the present time are focussed on to the successful completion of both telescope and instrument commissioning, some scientific observations have been attempted which demonstrate the science capabilities. Although there are still some outstanding issues to be addressed, particularly the image quality over the full science field, and acceptance tests need to be completed, we are optimistic that SALT will meet its full potential.

14. ACKNOWLEDGMENTS

SALT has been a very successful engineering project, testament to the talents and skills of many people, including those in the Project Team, the instrument teams, the SALT Operations team and many of the staff of the SAAO. It is now up to the SALT partnership to ensure it is equally successful scientifically. We are grateful to many people from numerous observatories and institutions (e.g. HET, Keck Foundation, ING, ATC, AAO, ESO, Carnegie Observatories, NOAO, NOT) who have assisted us over the years in many ways.

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