Centre for Ådvanced Instrumentation

Durham University

Document Title	**Functional Performance Requirements Document**		
Document Number	**3200 AE 0015**		
Issue	**4.3**		
Date	**14 April 2010**		
Prepared by	**D. G. Bramall**	Signature	Date
Reviewed by			
Approved by			

Change Record

Issue	Date	Section(s) Affected	Description of Change/Change Request Reference/Remarks
2.1	15/03/05	Not Applicable	University of Canterbury - CDR version
3.0	18/12/07	All	CfAI controlled version - Draft issued for comment
4.0	18/08/08	All	Updated with information from S. Barnes' SPIE paper. Esp. image quality and resolving power specification
4.1	27/05/09		Typos corrected RD35 changed goal to agree with *SALT High-Resolution Spectrograph Proposals for Spectrograph Enclosure document (informal)* RD25 ThAr is now *in place* of sky fibre Red blue exposure controlled by one shutter RT05 Precision RV mode figures added (with TBC)
4.2			Typos corrected
4.3			TDB's removed

Applicable Documents

	Title	Document Number

Reference Documents

	Title	Document Number
RD1	Operational Concepts Definition Document	3200 AE 0018 (Currently under review)
RD2	The optical design of the Southern African Large Telescope High Resolution spectrograph: SALT HRS, Barnes *et al.,* 2008. SPIE Marseille.	

Acronyms and Abbreviations

AD	Applicable Document
CfAI	Centre for Advanced Instrumentation of Durham University
SALT	Southern African Large Telescope
SALT HRS	SALT High-Resolution Spectrograph
FIF	Fibre Input Feed
RV	Radial Velocity
CCD	Charge Coupled Detector
VPHG	Volume phase holographic grating

Requirement labels

A	Assumption
RD	Requirement satisfied by design
RT	Requirement verified by test

Table of Contents

1 Introduction

This document establishes the functional performance requirements for the Southern African Large Telescope High Resolution Spectrograph (SALT HRS). It specifies the capabilities and performance requirements that SALT HRS should meet to satisfy the overall science ambitions of the instrument which are elucidated in RD1.

Version 3.0 of this document superseded Issue 2.1 which was written by the University of Canterbury. Version 3.0 and subsequent versions are controlled and issued by CfAI.

2 SALT HRS Nominal Capability and Operating Parameters

SALT HRS is designed to be a single-object high-resolution, fibre-fed échelle spectrograph producing fixed format echellograms. The HRS is made up of:

- Input optics
- Main spectrograph optics
- Two fully dioptric cameras
- Two CCD detectors and controller electronics
- Vacuum vessel and temperature stabilised enclosure
- Calibration system
- Instrument control (hardware & software)
- Quick look data reduction software package

HRS has the following capabilities:

2.1 Input Optics

The spectrograph will be fed by pairs of optical fibres from the Fibre Input Feed at the SALT prime focus.

A 01. *It is assumed that a 500μm fibre placed at the telescope focal plane will capture at least 80% of the energy from a point source given a telescope image quality of EE(80) = 2.1 ".*
A 02. *At least four pairs of slots (including one pair for the precision Radial Velocity (RV) stability mode) will be available on the FIF with variable fibre separation.*
A 03. *The spectrograph will require approximately 35m of optical fibre. The curvature of the fibre will vary as the telescope tracker moves.*

SALT HRS is designed to operate in one of several modes, each being fed from a separate pair of fibres and having different trade-offs between resolving power and throughput (see Specification and Performance section).

RD 01. *A low resolution mode (with direct injection of light), a medium resolution mode and a high resolution mode* shall be provided.
RD 02. *An option to include a mode dedicated to precision radial velocity work shall be incorporated. This option would utilise fibre double-scrambling techniques.*
RD 03. *The instrument will allow the SALT Astronomer to switch between different resolving power modes without manual intervention.*
RD 04. *The medium and high resolution modes shall each have image slicers that divide the image into 3 slices per fibre, and an intermediate slit mask. The precision RV mode will also be sliced, the optical design duplicates that of the high resolution mode.*

The spectrograph will accept light from pairs of fibres positioned in the telescope focal plane. Normally, one fibre will be illuminated by the object under observation and the companion fibre will be fed by adjacent sky, allowing simultaneous source and sky spectra to be taken. For low resolving power exposures, where accurate sky subtraction is required, the fibres will capable of being re-positioned (nodded) simultaneously with the charge being moved (shuffled) on the CCD providing on chip summing of source and sky samples. Once an observation has been initiated by the SALT astronomer, the HRS will be responsible for sequencing the nods of the telescope (by instructing the TCS to move the telescope as required.)

RD 05. *The instrument control software shall provide nod and shuffle mode for the lowest resolving power configuration with user-selectable nod frequency.*

2.2 Spectrograph

This section describes the key requirements for achieving the desired performance of the opto-mechanical systems of SALT HRS.

2.2.1 Mirrors

The SALT HRS "white pupil" design requires the following mirrors to be manufactured and aligned on the optical bench:

- Collimator mirror with dual use as both a collimator and a pupil transfer mirror (after échelle dispersion)
- Red and blue pupil mirrors
- Dichroic mirror with near zero angle of incidence to obtain maximum efficiency.
- Red and blue fold mirrors which allow the camera focal planes to be brought close together.

RD 06. *All mirrors are to be coated with appropriate coatings to maximise the efficiency of HRS.*
RD 07. *All mirrors shall have appropriate dimensional tolerances and minimum wavefront distortion specified (typically less than λ/5).*
RD 08. *Mirror mounts shall have appropriate mechanisms for correct optical alignment.*
RD 09. *Mirror mounts shall be designed to minimise distortion to the optics.*
RD 10. *No optical components should protrude from their mounts to avoid accidental damage.*

2.3 Input Optics

The medium resolution, high resolution and high precision radial velocity modes are fed through optical fibre slicers for resolution enhancement. As the medium resolution works with a 500 µm fibre and the high resolution modes work with 350 µm, the slicer designs differ slightly. All spectrograph modes are available with object and background sampling. (The high precision radial velocity mode may sacrifice some or all of the sky slit to provide adequate spacing for simultaneous ThAr spectra.) Currently, a Bowen-Walraven design of slicers is assumed.

RD 11. *The pupil shall be located at the grating, with an over-sized collimator to avoid vignetting.*
RD 12. *The input optics shall have no moving parts and shall be contained within the vacuum chamber for stability.*
RD 13. *If possible, an intermediate pupil shall be provided in the input optics to provide stray light rejection.*

2.3.1 Gratings

SALT HRS uses a single échelle grating blazed at 76º and mounted face-down in quasi-Littrow configuration giving a peak theoretical blaze efficiency of ~75%. Cross dispersion is provided by two volume phase holographic gratings (VPH), one for each of the red and blue cameras. The gratings shall be optimised to provide maximum possible order separation whilst maintaining complete wavelength coverage.

RD 14. *The échelle grating shall be a replica of master MR166, catalogue number 53050ZD01-425E. This has a groove frequency of 41.59 g/mm with 76º blaze angle. The substrate will be Zerodur (or similar) for its low CTE.*
RD 15. *The exact angle of illumination with respect to the grating facet normal (nominally 0.3-0.5º) will be adjustable during commissioning to precisely centre the blaze function on the CCD.*

2.3.2 Mechanisms

SALT HRS requires several motion mechanisms to control exposures during observation runs.

- *The cameras are to be focussed by moving the red and pupil mirrors using motorised and encoded micrometers. In the thermally controlled environment camera focussing should not be routinely required.*
- *Independent control exposure of red and blue arms shall be provided through software control of the shutter and chip readout intervals.*

RD 16. SALT HRS shall be focussed by moving the pupil mirrors to compensate for (i) change in focus from moving from atmospheric press to vacuum and (ii) for changes in temperature.

The mechanical design of SALT HRS shall use as few moving parts as possible. Where mechanisms inside the vacuum vessel are unavoidable they shall be designed to be maintenance free and be as reliable as possible.

RD 17. *Mechanisms shall be designed to operate reliably under vacuum without maintenance.*
RD 18. *Motors shall be powered down when not in use.*

For the optional precision RV mode, mechanical stability is of prime importance as **any** mechanical imprecision is likely to be detrimental to the final radial velocity precision attained.

RD 19. *No part of optical train of the precision RV mode shall be mounted on the moving part of a mechanism.*

2.3.3 Exposure meter

For observations, a real-time photon counting exposure meter is required.

RD 20. *An exposure meter is required to operate on 4-5% of light incident on the échelle (which is reflected by a small mirror placed in the gap between the ruled areas on the grating)*
RD 21. *The exposure meter is required to display a real-time count to allow "peaking up" of the acquired target.*

2.3.4 Materials

As a precision instrument SALT HRS will be built using only new and high grade materials that are suitable for their intended use.

RD 22. *All materials and lubricants should be vacuum compatible i.e. low outgassing.*
RD 23. *All surfaces inside the vacuum vessel shall be blackened, with black anodising as the preferred method for aluminium parts.*

2.4 Calibration System

Primary wavelength calibration of SALT HRS will be by means of injecting of light from a laboratory ThAr arc lamp. Alternatively, the SALT instrument calibration system (AD 15?? AS 0000) can be used to feed light into the fibres at the FIF (although not at the same time as star light). Additionally, for the precision RV mode simultaneous ThAr injection will be available in which a laboratory emission line source will be fed into the science fibres.

RD 24. *SALT HRS will provide a dedicated 100 μm core reference calibration fibre illuminated from a laboratory ThAr source sited in the Spectrometer Room.*
RD 25. *The precision RV mode shall incorporate simultaneous ThAr injection in place of the sky fibre.*
RD 26. *The calibration light source intensity will be controllable.*

Please note the following changes that have been made to the design requirements since CDR.

- In the high-precision radial velocity mode, an iodine cell is foreseen.

- Due to the low level of pixel-to-pixel variations expected of the science-grade CCDs, no *on instrument* flat field lamps are included. Flat fielding using the SAC optics will still be possible prior to making observations with low S/N ratios.

2.5 Detector and Controllers

The detector system is critical to the performance of SALT HRS. The specification governing the detectors' required performance is extremely important. The integration of detectors is technically challenging and will require careful collaboration with vendors.

RD 27. *The detector system shall comprise two science-grade detectors (one for each for the red and blue arms), cryogenically cooled detector housings with compressor, array controller electronics & interface cards and power supplies.*
RD 28. *The vacuum inside the detector cryostats shall be passively maintained over a six month period.*
RD 29. *The array control electronics shall provide at least two gain settings, under software control.*
RD 30. *The array control electronics shall provide pre-binning of 1 x 1 to 9 x 9, independently adjustable in each direction.*
RD 31. *The array control electronics shall be capable of operating at readout speeds of up to 1 million pixels / second.*
RD 32. *The array control electronics shall permit up to 5 readout windows to be selected.*
RD 33. *For charge shuffling the CCDs must be aligned with their columns in the direction of cross-dispersion.*

2.6 Vacuum vessel and Temperature Stabilised Enclosure

The optical and mechanical design of the spectrograph will be such that the radial velocity precision and the line profile will be intrinsically stable. The spectrograph (including input optics) will be entirely housed inside a vacuum chamber to give immunity from changes in barometric pressure, temperature effects and particulate contamination of optical surfaces. This will in turn be located inside a pre-fabricated, temperature controlled room to be constructed in the Spectrometer Room at the SALT facility.

RD 34. *The spectrograph will be mechanically isolated via passive vibration isolators from the telescope facility.*
RD 35. *The temperature inside the vacuum tank will be stable to better than ± 1^{o}C over a 24 hour period with a goal to achieve a temperature stability approaching 1mK for the spectrograph internal components.*
RD 36. *The vacuum inside the tank shall be passively maintained at <2 mbar over a three month period.*

2.7 Instrument Control Software

The instrument control software must be compatible with the existing SALT facility systems and, for ease of maintenance, shall adhere to all applicable SALT hardware and software standards.

RD 37. *The instrument shall be controlled by standard PCs running Windows 2000 (or XP) and LabVIEW-Compatible interface cards.*
RD 38. *The instrument interface and control software will be developed in LabVIEW version 6.1 and C.*
RD 39. *SALT HRS should have a single point of entry (datasocket) for control purposes.*

There will be software provided for:

RD 40. *Control of spectrograph mode (i.e. fibre feed selection)*
RD 41. *Control of science and calibration exposures*
RD 42. *Communication with TCS (restricted to HRS control server level)*
RD 43. *Control of camera focus*

RD 44. *Monitoring and logging of the temperature and pressure (data to be made available for incorporating in FITS headers)*

RD 45. *Emergency shutdown into safe state*

2.8 Data Reduction and Image Archiving Software

Échelle spectroscopy requires specialist data reduction pipelines. The processing steps necessary for échelle quick look data reduction and the full data reduction package are essentially the same. The distinction is that for the quick look data reduction, a goal of providing results in <5 min (TBC) is stipulated. [The present quick look data reduction PC at SALT (QCPC) is a Linux machine which currently has IRAF and PyRAF installed.]

There will be software provided for:

RD 46. *Quick-look data extraction for displaying preliminary spectral information obtained from exposures on the SALT QCPC (as a minimum).*

RD 47. *Appending correct FITS header information (including data from TCS) to exposure data files.*

RD 48. *Automatically sending FITS datafiles across the data network to SALT QCPC/Image Archiving PC with an agreed naming convention.*

2.9 Interfaces

The HRS will be physically located in the Spectrometer Room at SALT.

A 04. The SALT facility will provide power, water, air and vacuum services and network points for connection to the control (100 Mbit/s) and data networks (*gigabit)*.

RD 49. *The interfaces between SALT HRS and the SALT facility shall be defined in an Interface Control document.*

3 Specification and Performance

The performance of SALT HRS relative to the specification laid out below will be assessed during final acceptance testing. Where appropriate, the performance of individual sub-systems (primarily sub-contracted optical items) will also be checked prior to integration with the main instrument.

3.1 Fibre

RT 01. *The fibres will introduce no more than 20% focal ratio degradation for telecentric input at the telescope focal plane at f/4.2.*

3.2 Wavelength Coverage

The spectrograph will be capable of complete wavelength coverage from 370nm to 890nm (in a single exposure) but with a 'blind spot' at the dichroic wavelengths.

RT 02. *The instrument shall cover all wavelengths from one order below 370nm to the order in which λ = 890nm is located.*

RT 03. *The dichroic 'blind spot' should be at 555 nm with a goal of <10nm interruption.*

RT 04. *The wavelengths in which the dichroic transition occurs should be imaged on both detectors.*

3.3 Resolving Power

SALT HRS is designed to operate in four configurations, each having different resolving powers. The resolving power is not determined solely by the slit width at the collimator focus as both the spectrograph's optics and detector will degrade the image of the slit, broadening the line spread function. Each mode shall have a resolving power[1] of better than 90% of the predicted value at the central blaze wavelength for each order, as show in the table below:

RT 05. Target resolving powers (from S. Barnes' predictions published in RD2, Barnes *et al* 2008)

Mode	Nominal resolving power (λ/δλ)	Fibre diameter (arcsecs)	Slit width (arcsecs)	Effective resolving power (λ/δλ)	
				Blue arm	Red arm
Low resolution	16,300	2.23	1.673	16,200	16,200
Medium resolution IS	38,400	2.23	0.710	36,600	37,300
High resolution IS	77,900	1.56	0.355	64,400	69,200
Precision RV IS	77,900	1.56†	0.355†	64,400	69,200

† the precision RV mode is a duplicate of the HR mode. Highest possible resolution is required because of the importance of adequately sampling the line profiles in order to achieve sub-resolution element accuracy; see RD1.

3.4 Throughput

The SALT HRS throughput (from the fibre entrance to the CCD detector) will deliver throughput as a function of wavelength and resolving power of at least 75% of the target throughputs (for a maximally-illuminated pupil) at a wavelength of ≈ 650nm as shown in the following table. Not withstanding any throughput requirements on individual components (described elsewhere in this document) a minimum image quality for the spectrograph as a whole, operating in each of its modes, is specified as follows.

RT 06. Target throughputs (from S. Barnes' predictions published in RD2, Barnes *et al* 2008)

Resolving power	Throughput (%) excluding telescope	
	Blue arm	Red arm
16,000	21.5	29.2
37,000	15.1	20.3
65,000	9.6	12.9
Precision RV mode	As 65,000 mode but with losses for I2 cell and double scramblers	

3.5 Signal-to-Noise Ratio

Using the predicted efficiencies, it is expected that SALT HRS should be capable of obtaining a S/N of 100:1 of a V = 13.6 object in ≈ 5 minutes at R ≈ 16,000, and the same limit would be reached for a V = 15.8 object after half an hour. Observations of stars around V = 19 should allow S/N between 10 and 20 after an hour's exposure.

3.6 Image Quality

Notwithstanding the image quality required of individual components (described elsewhere in this document) a minimum image quality for the spectrograph as a whole is quoted.

RT 07. *At all wavelengths from 370 to 555nm that are within one half a free spectral range from the blaze wavelength, the blue camera shall deliver a minimum image quality of 80% encircled energy within a 25μm square box.*

[1] *as delivered* resolving power (averaged between arms) i.e, *after* data reduction predicted using the method outlined to S. Barnes by H. Dekker

RT 08. *At all wavelengths from 555 to 800nm that are within one half a free spectral range from the blaze wavelength, the red camera shall deliver a minimum image quality of 80% encircled energy within a 25μm square box.*

RT 09. *The image quality from 800 to 890nm is degraded to deliver approximately 80% encircled energy within a 30-35 μm square box.*

3.7 Spectral Format

The dispersive elements shall provide sufficient two-dimensional dispersion to achieve the resolving power, wavelength coverage and background sky subtraction requirements in all operational modes, including nod and shuffle.

RT 10. *Inter-order spacing shall be >11 arcsec in each arm.*

RT 11. *There will be at least 5 un-illuminated rows on the CCD (75μm) between adjacent spectra.*

RT 12. *The échelle shall be adjustable so that the blaze function can be centered on the CCD.*

3.8 Radial Velocity Precision (TBC)

High radial velocity precision is a goal of the instrument and many of the functional requirements listed in section 2 are imposed to ensure that the instrument achieves the following stability.

RT 13. *The intrinsic stability of the instrument shall show no more than 0.001 pixel shift in the centroided position of a set of ThAr arc lines over the period of one hour.*

RT 14. *The minimum requirement is for 10 ms^{-1} radial velocity precision in the medium resolution mode*

RT 15. *The precision radial velocity mode should have a baseline design requirement of 3-4 ms^{-1} and a goal of 1 ms^{-1}.*

[We need to say how we define radial velocity precision:
Radial velocity precision will be measured e.g. the RMS scatter of observations of a sharp-lined dwarf star taken with S/N > 100 for a short exposure and at central track]

3.9 Calibration line profile stability

The laboratory calibration light source is required to be relatively stable.

RT 16. *Minimum requirement of less than 1% change in the wavelength calibration lamp line profile over a 12 hour period for a fully illuminated pupil.*

RT 17. *The calibration lamp line intensity must remain stable to within 10% over 12 hours.*

3.10 Scattered Light

Appropriate baffling and blackening of components should minimise stray light to below the level specified below.

RT 18. *A maximum of 5% stray light will be allowed, where stray light is defined as the ratio of the average inter-order light from both sides of the spectrum to the continuum spectrum intensity at the following wavelengths and corresponding source temperatures.*

Wavelength (nm)	Source temperature (K)
460	6,500
700	4,300

3.11 Ghost Images

The optical design should be validated to ensure no significant ghosts occur.

RT 19. *Ghost images are to be less than 1% of the local continuum averaged over the orders centred on the blaze wavelength.*

RT 20. *Peak intensities of any ghosts of an arc emission line are to be less than 0.1% of the measured central intensity of that line.*

3.12 Optics

Individual optical elements will all be the subject of a full technical specification and apposite acceptance testing in due course. The following section lists the basic performance criteria for the key optical elements.

3.12.1 Input Optics

RT 21. *The image slicers shall degrade resolving powers by no more than 10% as a goal.*
RT 22. *The image slicers shall have a minimum image quality of 80% encircled energy within 80μm diameter for each fibre.*

3.12.2 Collimator

RT 23. *The collimator will accept and collimate 95% of the light exiting the fibres or image slicers into a 200mm collimated beam assuming less than 10% focal ratio degradation from the fibres.*

3.12.3 Échelle

The échelle grating shall be tested by the manufacturer to ensure that it is suitable for the intended application. The following quantities shall be part of the criteria evaluated during acceptance testing.

- *Spectral defects*
- *Efficiency measurement*
- *Wavefront*
- *Scattered light*

3.12.4 VPH gratings

RT 24. *The VPH grating parameters should be specified such that the gratings are capable of complete wavelength coverage.*

3.12.5 Cameras

The cameras comprise several optical elements whose specification must be optimised during design and revised sequentially in manufacture to achieve the ultimate performance which is required to be:

RT 25. The cameras are required to ensure Nyquist sampling by two pixels at the highest resolving power and be capable of complete wavelength coverage.

3.13 CCD System for Blue Camera

The blue detector is a 2k x 4k CCD with 15μm square pixels. [The detector is an E2V CCD44-82 Grade 1 (thinned, back illuminated) with an astronomy broadband antireflection coating.]

The minimum performance requirements for the **blue** detector are:

RT 26. *The charge transfer efficiency [of the blue CCD] shall be > 99.999%*

RT 27. *Full well: the peak charge storage [of the blue CCD] shall be ≥150 ke$^-$/pixel minimum*

RT 28. *The dark current [of the blue CCD] shall be <1 e$^-$/pixel/hour at 150K*

RT 29. *The blue CCD flatness shall be <20μm peak-to-valley*

RT 30. *The quantum efficiency of the blue CCD as a function of wavelength shall be as described in the following table:*

Wavelength (nm)	QE (%)
350	>40
400	>70
500	>75

RT 31. *The read noise of the blue CCD shall be as described in the following table:*

Readout frequency (kHz)	**Noise (e^- RMS per pixel)**
20	<3
100	<4
400	<5
1000	<8

RT 32. *The blue CCD cosmetic defects (as defined by E2V) shall equal of better the values shown in the table below:*

Column defects	≤6
White spots	≤500
Traps	≤30
Total spots	≤1250

3.14 CCD System for Red Camera

The red detector is a 4k x 4k CCD with 15µm square pixels. [The detector is an E2V CCD231-84 Grade 1 (deep depletion silicon, back illuminated) with the Extra Red Plus antireflection coating and fringe suppression process.]

The minimum performance requirements for the **red** detector are:

RT 33. *The charge transfer efficiency [of the red CCD] shall be > 99.999%*

RT 34. *Full well: the peak charge storage [of the red CCD] shall be ≥150 ke^-/pixel minimum*

RT 35. *The dark current [of the red CCD] shall be <2 e^-/pixel/hour at 150K*

RT 36. *The red CCD flatness shall be <20µm peak-to-valley*

RT 37. *The quantum efficiency of the red CCD as a function of wavelength shall be as described in the following table:*

Wavelength (nm)	**QE (%)**
550	>80
650	>80
800	>80
900	>45

RT 38. *The read noise of the red CCD shall be as described in the following table:*

Readout frequency (kHz)	**Noise (e^- RMS per pixel)**
20	<3
100	<4
400	<5
1000	<8

RT 39. *The red CCD cosmetic defects (as defined by E2V) shall equal of better the values shown in the table below:*

Column defects	≤10
White spots	≤800
Traps	≤15
Total spots	≤1500

- Last page -