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Change Record

Issue	Date	Section(s) Affected	Description of Change/Change Request Reference/Remarks
3.0	16/03/08	Not Applicable	Suggested table of contents
3.1	24/04/08	Section 3	Updated section on exposure metres
3.2	09/10/09	All	Removed low speed shutters and added iodine cell content
3.3	01/12/09	All	Updated observation scenarios for high stability mode
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Applicable Documents

Reference	Document Title	Document Number
A.D. 1.	Functional Performance Requirements Document	3200 AE 0015
A.D. 2.		

In case of any conflict between this document and the Applicable Documents, the information contained in this document shall take precedence.

Reference Documents

Reference	Document Title	Document Number
R.D. 1.	CELESTIA Draft Preliminary Design Document (2001)	-
R.D. 2.	The Design and Performance of High Resolution Spectrographs in Astronomy, S. Barnes, PhD Thesis (2004)	-
R.D. 3.	Instrument Control Dossier for Fibre Instrument Feed (FIF), August 2003	3400 AS 0015
R.D. 4.	The Optical Design of the Southern African Large Telescope High Resolution Spectrograph	Proc. SPIE 7014, 18 (2008)

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

Table of Contents

1 Introduction

This OCDD is intended to capture the science requirements for high-resolution echelle spectroscopy using SALT HRS and serves to illustrate how the instrument will be operated in order to fulfill its required scientific function. It describes the basic instrument concept, discusses example science cases behind some of the major design choices and informs the trade-offs to be made in the residual design work (being done by CfAI). More specific descriptions of the functional requirements and capabilities of the instrument are found in the Functional and Performance Requirements document.

2 Science Drivers

SALT HRS will deliver stable, high-resolution ($R \leq 65000$) spectra over a wide wavelength band ($\Delta\lambda \sim$ 500 nm) for a single object and a sky sample. It is not intended that SALT HRS have a multi object capability, either at first light or via an upgrade path. It is therefore principally suited to science that requires essentially complete optical spectra at high resolution, of targets with a low density on the sky. Targets with a low density, or for which complete optical coverage is needed, are ones for which multiplexed spectrographs on other telescopes offer no competitive advantage, and for which the large aperture, high stability and wide wavelength coverage of SALT HRS offer distinct advantages.

The SALT HRS science case was developed through community consultation when the instrument was undergoing its early design phases. A number of scientific applications were identified[1] which informed later design stages. Four (non-exhaustive) categories of science and the constraints they place on the design and operation of the spectrograph are set out below.

Stellar radial velocity measurements

Radial velocity measurements vary greatly in the accuracy which they require. While errors as large as several km s^{-1} (or even larger) are often tolerable for the studies of the motions of kinematically "hot" stellar populations or high-amplitude spectroscopic binary stars, studies of kinematically "cooler" populations or lower amplitude binaries have routinely achieved ~1 km s^{-1} accuracy. It goes without saying that SALT HRS will provide data for kinematic and dynamical studies of faint stellar populations in the Galaxy (e.g. in the outer halo where accreted substructures are expected to be best preserved) and some Local Group targets. However, precision radial velocities measured using high stability spectrographs, in some cases with iodine cells to help, are approaching 0.5 m s^{-1} accuracy in the search for ever-lower mass planets around other stars. In fact, many stellar studies could also have benefitted from better than 1 km s^{-1} accuracy in order to detect binaries with low inclination or very long orbital periods, for which dv_{rad}/dt is very low; 1 km s^{-1} is more a reflection of what was relatively readily achievable at echelle resolutions without high stability instruments or iodine cells.

[1] The early aspirations of the community are recorded, for example, in the Draft Preliminary Design Document for CELESTIA (October 2001), Appendix A.

SALT HRS will be installed in a vacuum tank to avoid variations in the refractive index of air with pressure or temperature which is one of the major limitations on accuracy at the sub-km s^{-1} level. The fibre-fed HARPS[2], an evacuated spectrograph on the ESO 3.6 m telescope, regularly attains 1 m s^{-1} accuracy (at *R* = 115000) without an iodine cell. Similar accuracy was to be achieved by the PRVS[3] (Gemini) instrument, which has now been cancelled as a result of funding uncertainties. With HARPS and potentially other instruments (e.g HIRES[4]) now routinely achieving a few m s^{-1} accuracy or better on planet search programmes, it is clear that SALT HRS will have to achieve comparable precision to be competitive in planet detection.

With PRVS now cancelled, it is perhaps worth noting a novel feature of that spectrograph, which is to target near-IR wavebands (1.0-1.75 microns). This is to facilitate measurements of M-dwarfs, i.e. sub-solar-mass, stars, for which the reflex velocity variation of the star is greater for a given planetary mass. The aim is thus to detect lower-mass, more earth-like planets. While SALT HRS is, in contrast, to operate at optical wavelengths, the cancellation of PRVS may increase the scientific gains to be had from maintaining good far-red performance in SALT HRS.

Stellar atmosphere analysis

Stellar atmosphere analyses cover a wide range of scientific goals, one class of which is the photospheres, chromospheres and coronae of late-type active stars, pulsating stars, stars with winds, and interacting binaries. Such studies often require the acquisition of data at high resolution of widely-separated spectral features, which is precisely the capability of cross-dispersed echelle spectrographs with simultaneous wide spectral coverage. Simultaneity at widely separated wavelengths is not only more efficient of observing time but can be crucial in the case of variable phenomena related to outbursts or orbital phase, and precludes the use of conventional spectrographs. This provides requirements for coverage extending shortward to the important chromospheric diagnostics, the Ca II 393 and 396 nm lines, as well as Balmer series lines. Doppler tomography and eclipse mapping are two examples of the unique outputs achievable from observations of this nature.

Chemical compositions of stars

Most spectra used for detailed abundance analyses of individual stars are obtained at high S/N (30-200) and in such cases they are usually photon-noise limited. For a given number of photons per nanometer, abundance studies generally benefit more from high spectral resolution than from high S/N in the continuum[5]. For this reason, high spectral resolution is usually advantageous, and this reflects the drive for high resolving-power figures --- *R* up to ~ 60000 --- rather than lower figures *R* ~ 25000[6]. The highest resolving powers are not merely beneficial but are essential for dealing with blended spectral features. For elements which present only a few spectral lines, it may be unavoidable to work with partially blended features in which case high resolving power is essential. Examples include the lines of minor-fraction isotopes (e,g, ^{6}Li) and important trace species (e.g. the neutron-capture elements, especially the radioactive nuclides Th and U). Regrettably, going to higher resolving powers usually requires a reduction in throughput, and hence the number of delivered photons per nanometre is not fixed. Not all stellar atmosphere analysis work requires or benefits from the highest resolutions; in particular work involving intrinsically broad lines such as those in rotating O and B stars. Chemical composition studies of the type set out here contribute to fields including the study of the stellar populations and chemical evolution of the Galaxy and nearby Local Group members (of which the SMC and LMC will be important SALT HRS targets). The Galactic population

[2] High Accuracy Radial Velocity Planet Searcher

[3] Precise Radial Velocity Spectrometer

[4] Johnson, J. A., Marcy, G. W., Fischer, D. A. et al. 2008, ApJ, 675, 784

[5] This comes about for two reasons: (1) at lower resolving powers, the spectral lines become more blended with the continuum which is a source of noise but not signal, and hence the spectrum requires disproportionately more photons in order to distinguish a line's equivalent width to a given accuracy; (2) in crowded spectral regions, disproportionately more photons are needed to disentangle blended spectral features to a given accuracy than to measure the features when better resolved.

[6] Multiobject spectrographs often do operate at the lower end of this range of resolving powers, for two reasons: (1) one cost of multiplexing is that only short spectral ranges of a few tens of nanometres can be recorded per star, and this wavelength range is usually greater if *R* is smaller; (2) multiobject spectrographs are designed for projects with high densities of targets, often studied in more of a survey mode in which less detailed abundance measurements suffice, such as the measurement of an overall metallicity rather than detailed composition.

studies RAVE[7] (underway on the UK Schmidt telescope) and Gaia (data release after 2015) are based around the Ca IR triplet at 870 nm, as are many other population studies involving late-type giants. It is important to cover this region with SALT HRS since it is well characterised and has shown its value in other studies as one of the few red spectral regions with high data content for population studies.

Interstellar and intergalactic absorption
The low temperature of interstellar gas seen in absorption against background sources (stars and quasars) means that resolving powers of up to one million can be valuable, and clearly SALT HRS will not compete with work having those requirements. Nevertheless, it will be one of the largest telescopes capable of simultaneously recording widely separated absorption lines and diffuse interstellar bands at moderate resolving power (R ~ 60000), and hence should make an important contribution to the study of Galactic, Local Group and high-redshift absorbers, particularly for faint sources which have been out of the reach of more modest telescopes. It is anticipated that studies of interstellar chemistry at high redshift will grow rapidly over the next decade.

Design drivers
High priorities identified for SALT HRS science include:

1. A short wavelength limit, and competitive performance, down to 380 nm, i.e. shortward of the Ca II 393, 396 nm lines.
2. A long wavelength limit that is longward of the Ca IR triplet at 870 nm.
3. Resolving power in the 15000-65000 range, provided it delivers the wide wavelength coverage described above, preferably simultaneously.
4. Wavelength stability commensurate with achieving a few m s^{-1} accuracy in velocities, to be competitive with HARPS and similar spectrographs.

3 Instrument Concept

SALT HRS is a high dispersion echelle spectrograph which will be located in the spectrograph room below the SALT telescope and fed by optical fibres from the telescope prime focus. The whole spectrograph is housed inside a vacuum tank in a temperature controlled enclosure for maximum stability. Four pairs of fibre are available to provide a range of spectral resolutions via the selected use of image slicers; each pair of fibres provides simultaneous object and adjacent sky spectra. In the lowest resolution mode without image slicers a non-and-shuffle mode is available to improve sky-subtraction accuracy. The fibres are positioned in the telescope focal plane using the Fibre Instrument Feed (RD3) and selected inside the spectrograph using a moveable mask. The spectrograph is a dual-beam white pupil design which uses volume phase holographic gratings for efficient cross dispersion. The red and blue channels have independent shutters and CCD detectors mounted on a motorised focus drive. A module within the telescope spherical aberration corrector (SAC) provides uniform focal plane illumination by thorium-argon and smooth-spectrum sources for calibration. This module duplicates the far-field illumination pattern for arbitrary telescope exposure tracks. In addition to the on-telescope calibrations, the spectrograph can be fed by a laboratory ThAr source for long term monitoring of internal drifts. A detailed description of the SALT HRS design can be found in RD4.

[7] Radial Velocity Experiment

4 Description of Operational Modes

The baseline requirement specifies three resolving powers: *R* = 16000, 37000 and 65000. In addition a high-stability mode has been added which will have R=65000 but will incorporate additional optical elements to improve long-term spectral stability. The standard observing mode will use a fixed telescope pointing, but the *R* = 16000 configuration will in addition operate with a nod and shuffle mode for improved sky subtraction. The uses are described below.

4.1 Low-Resolution Mode (with Nod and Shuffle)

The lowest resolving-power mode is low even in comparison to other echelle configurations on large telescopes, with *R* = 25000 often adopted (perhaps somewhat arbitrarily) as the minimum desirable in a general-purpose facility. SALT HRS has three resolving modes, so the R = 16000 configuration should not be seen as a general-purpose mode, but rather as a specialist mode. This configuration offers the same fibre input diameter as the *R* = 37000 mode but with two beneficial differences: 1.4× higher throughput[8], and the opportunity to use nod-and shuffle for improved sky subtraction. In nod-and-shuffle mode, a long exposure time is subdivided into nod sessions. At the end of the first nod session, the telescope is moved (nodded) to place the light from the star down what was the sky fibre of the previous session. While the telescope is nodding, the charge on the CCD is moved (shuffled) so that the charge that accumulated where previously the starlight fell now lies in the rows where previously the skylight fell, and where now the repositioned starlight will fall. The fibre that previously contained the star will now contain a new sky field, and will be imaged onto the CCD rows which previously contained the star charge (and which has now been shuffled to the other position). The nod-and-shuffle operation samples two different sky fields on either side of the target, for half of the total exposure time in each case. Also, the starlight falls on two different regions of the CCD and hence benefits from a SQRT(2) reduction in the impact of residual flat-field noise, but without an increase in read-noise.

This improvement in sky sampling and reduction in flat-field residuals will benefit observations of the faintest targets requiring the lowest resolving power. Examples where the lowest resolving power may be tolerable and where the improved background sampling might be beneficial include spectroscopy of diffuse interstellar bands against lines of sight to distant stars or quasars, and molecular band analyses of stars in Local Group galaxies.

4.2 Medium Resolution Mode

The *R* = 37000 mode is expected to be the most commonly used SALT HRS mode. It has adequately high resolving power for much of the science discussed in Section 2, but admits a larger fibre diameter and larger throughput than the *R* = 65000 mode. Studies of objects whose intrinsic line widths are broader than two resolution elements of the *R* = 65000 mode, such as rotating stars (e.g. most O and B stars), stars in which the Balmer line strength measurements are the principal aims, and studies of molecular bands at medium resolution are likely to benefit from the resolving power vs throughput tradeoff available in this mode.

4.3 High Resolution Mode

The *R* = 65000 mode is likely to be selected only by those projects for which the lower throughput compared to the *R* = 37000 mode (64% of the value[9] for that setting) is more than offset by the greater resolving power. One such category of observations will be studies of line profiles in, for example, investigations of stellar atmosphere dynamics, the measurement of isotope ratios, or the study of absorbing structures in the interstellar or intergalactic medium at the highest velocity

[8] Baseline specification
[9] Baseline specification

resolution. This resolving power will also be preferred for spectral work in crowded spectral regions, such as in efforts to detect the weak, partially blended lines of key elements in abundance analyses. Studies which benefit from fine sampling of the stellar profiles, such as the most precise radial velocity work, will also utilise this resolving power. Recall, however, that the wavelength stability of the instrument as a whole will be much higher than in traditional non-vacuum spectrographs, and astronomers may find they can achieve adequate velocity accuracy for their needs even at R = 37000 because of the improved systematics compared to other spectrographs they have used.

4.4 High Stability (Precision Radial Velocity) Mode

The precision radial velocity mode will be implemented at R = 65000, because of the importance of adequately sampling the line profiles in order to achieve sub-resolution element accuracy. (An error of 0.5 m s^{-1} corresponds to 10^{-4} of a resolution element!). Note that even at R = 65000, SALT HRS will be operating at only 57% of the resolving power of HARPS.

4.4.1 Iodine Cell

The iodine cell is used for obtaining a simultaneous absorption for calibration of high precision radial velocity measurements. The iodine cell requires heating. It takes about 30 (TBC) minutes for it to warm up. The temperature controller for the iodine cell is located in the main electronics rack and the temperature can be monitored via the SALT HRS MMI and included in the FITS headers. The temperature should be set to 50.0 degrees Celsius. Because the iodine cell adds many hundreds of additional spectral features to the final spectrum (in the region 480-600nm) it is not always appropriate to have the cell in the beam. The iodine cell is moved into the light path using a linear stage under HRS LabView control. The mechanism and cel are located outside of the vacuum chamber but inside the thermal enclosure.

4.4.2 Double Scrambler

The fibre double scrambler (Hunter and Ramsay, PASP 104, 1244) is implemented using a pair of identical plano-convex silica rod lenses of 8mm diameter. The radius of curvature is 5mm and the length is 17.00 mm. The distance of the lenses to each other is 111.2mm to allow for the insertion of the iodine cell. Irrespective of whether the iodine cell is in the beam, the double scramblers will be. The geometrical efficiency of the double scrambler is in the range 90-97%.

4.4.3 Simultaneous Th-Ar

As an alternative to the iodine cell, one of the fibre pair in the high stability mode may be connected to a fixed Th-Ar spectral source to obtain a simultaneous calibration spectrum in an adjacent fibre without the complication of the superimposed iodine lines. This is the method now used in HARPS and works best if a carefully selected catalogue of unblended Th-Ar lines is used (c.f. Lovis & Pepe, A&A 468, 1115 (2007)).

5 Generic Observing Procedures

We identify here a list of likely steps in the daytime and night-time operation of the telescope in different modes

Daytime setup and calibration

- Verify vacuum tank pressure and temperature
- CCD Check

    - Set up CCD with standard HRS parameters
    - Obtain 5 bias frames; *imcombine* selecting median
    - Obtain mean count and standard deviation; verify against online instrument log
    - If within 99% confidence limits, update instrument log; If outside 99% confidence limits, investigate
- Spectrograph setup
    - Configure spectrograph to a standard wavelength setting for the required resolving power mode (select appropriate fibre pair).
    - Check encoder readings against online instrument log
    - If within 99% confidence limits, update instrument log; If outside 99% confidence limits, investigate
- Check spectrogram position
    - Prepare ThAr lamp for acquiring spectrum
    - Obtain ThAr spectrogram with standard exposure time, including with charge shuffle if this mode to be used that night
    - Extract three spectrum along a three standard spectral orders (edge, middle, edge)
    - Cross-correlate spectra against online reference spectra to verify position of spectrum
    - If within 99% confidence limits, update instrument log. If outside 99% confidence limits, investigate
    - Prepare Flat Field lamp for acquiring spectrum
    - Obtain Flat Field spectrogram with standard exposure time, including with charge shuffle if this mode to be used that night
    - Extract standard profile across spectral orders
    - Cross-correlate profile against online reference spectrum to verify position of spectrum
    - If within 99% confidence limits, update instrument log. If outside 99% confidence limits, investigate
- Check spectrograph focus
    - Fit extracted three standard spectral orders with peak-finding algorithm and measure mean FWHM of line profiles.
    - Check inferred line width against online reference. If within 99% confidence limits, update instrument log. If outside 99% confidence limits, investigate
- Check spectrogram intensity
    - Calculate total intensity of the three standard spectral orders.
    - Check intensity against online reference. If within 99% confidence limits, update instrument log. If outside 99% confidence limits, investigate.
- Calibration sequence
    - Prepare Flat Field lamp for acquiring spectrum
    - Obtain 5 Flat Field spectrograms with standard exposure time, including with charge shuffle if this mode to be used that night
    - Extract standard profile across spectral orders
    - Cross-correlate profile against online reference spectrum to verify position of spectrum
    - If within 99% confidence limits, update instrument log. If outside 99% confidence limits, investigate
    - Prepare ThAr lamp for acquiring spectrum
    - Obtain ThAr spectrogram with standard exposure time, including with charge shuffle if this mode to be used that night
    - Extract three spectra along three standard spectral orders (edge, middle, edge)
    - Cross-correlate spectra against online reference spectra to verify position of spectrum
    - If within 99% confidence limits, update instrument log. If outside 99% confidence limits, investigate
    - Obtain dark frame exposed for standard time (1800 s?)
    - Calculate total intensity of dark frame.
    - Check intensity against online reference. If within 99% confidence limits, update instrument log. If outside 99% confidence limits, investigate.

- If time permits, obtain two additional dark frame images, *imcombine* all three selecting median, and check intensity against online reference. If within 99% confidence limits, update instrument log. If outside 99% confidence limits, investigate.

5.1 Typical Fixed Position Observing Procedure

Load and activate previously specified observe sequence

Typical observe sequence:

- Acquire target with telescope
- Load telescope pointing and instrument data into header
- Prepare ThAr lamp for acquiring spectrum
- Obtain ThAr spectrogram with standard exposure time
- Cross-correlate spectra against online reference spectra to verify position of spectrum
- If within 99% confidence limits, update instrument log. If outside 99% confidence limits, raise exception flag
- Calculate total intensity of ThAr frame.
- Check intensity against online reference. If within 99% confidence limits, update instrument log. If outside 99% confidence limits, raise exception flag.
- Prepare spectrograph for target integration
- Read and set target integration time and number of repeat exposures in sequence
- Obtain spectrogram
- Move to next step of observe sequence

Upon completion of each target exposure, initiate quick-look analysis

Typical quick look analysis

- Apply overscan, bias, flatfield and dark correction using latest *imcombined* calibration frames
- Extract target and background spectra from frame, using standard solution, modified for new position of spectra based on calibration images.
- Divide out blaze function, using standard solution, modified for new position of spectra based on calibration images
- Apply wavelength calibration using standard solution, modified for new position of spectrum based on latest ThAr frame
- Display lab-frame spectrum
- Automatically identify image type (e.g. hot star/solar type star/cool star/H II region/PN) based on small set of library images
- Make first estimate of Doppler shift correction by cross correlation with small set of library images
- Display rest-frame spectrum and adopted Doppler shift
- Depending on whether image is one of a sequence, offer observer ability to co-add spectra for redisplay.
- Allow observer to modify observe sequence currently being executed, based on results to date.

5.2 Typical Nod and Shuffle Observing Procedure

Load and activate previously specified observe sequence

Typical observe sequence:

- Acquire target with telescope
- Load telescope pointing and instrument data into header
- Prepare ThAr lamp for acquiring spectrum
- Obtain ThAr spectrogram with standard exposure time for nod-and-shuffle ThAr, <u>and performing charge shuffle</u>

- Cross-correlate spectra against online reference spectra to verify position of spectrum
- If within 99% confidence limits, update instrument log. If outside 99% confidence limits, raise exception flag
- Calculate total intensity of ThAr frame.
- Check intensity against online reference. If within 99% confidence limits, update instrument log. If outside 99% confidence limits, raise exception flag.
- Prepare spectrograph for target integration
- Read and set target integration time, number of repeat exposures in sequence, and nod-and-shuffle session length
- Begin integration spectrogram; after nod session length, mask fibre output (using fast shutter), nod telescope (5 seconds) and shuffle charge (0.15 seconds), then unmask fibre output; begin second nod session; continue nod-and-shuffle sequence until complete
- Move to next step of observe sequence

Upon completion of each target exposure, initiate quick-look analysis

Typical quick look analysis

- Apply overscan, bias, flatfield and dark correction using latest *imcombined* calibration frames
- Extract target and background spectra from frame, using standard solution for nod-and-shuffle mode, modified for new position of spectra based on calibration images.
- Divide out blaze function, using standard solution for nod-and-shuffle mode, modified for new position of spectra based on calibration images
- Apply wavelength calibration using standard solution for nod-and-shuffle mode, modified for new position of spectrum based on latest ThAr frame
- Display lab-frame spectrum
- Automatically identify image type (e.g. hot star/solar type star/cool star/H II region/PN) based on small set of library images
- Make first estimate of Doppler shift correction by cross correlation with small set of library images
- Display rest-frame spectrum and adopted Doppler shift
- Depending on whether image is one of a sequence, offer observer ability to co-add spectra for redisplay.
- Allow observer to modify observe sequence currently being executed, based on results to date.

6 Data Reduction

6.1 Typical processing strategies for full data reduction

Brief description of the data reduction strategies.

6.2 Reduced requirements for quick look data reduction

Basic quality control parameters to check for in quick look reduction.

7 Potential Upgrades

TBA

- End of document -