The Southern African Large Telescope

David Buckley
SAAO

SALT Science Director & Astronomy Operations Manager
SALT is the optical analogue of the Arecibo radio telescope
The Arecibo Concept:

Star moves E to W on sky

Centre of curvature at radius of primary mirror

Fixed elevation spherical mirror telescope with tracking on focal surface

Spherical focal surface: 1/2 of primary mirror radius

Image moves W to E on the focal surface

Tracker (with instruments) follows focus of star.

Spherical Primary Mirror
New paradigm in design has been pioneered by the HET in Texas.
**BASIC ATTRIBUTES**

**PRIMARY MIRROR ARRAY**
- Spherical Figure
- 91 identical hexagonal segments
- Unphased (i.e. not diffraction limited 10-m, just 1-m)
- Mirrors (*Sitall*: low expansion ceramic) supported on a steel structure

**TELESCOPE TILTED AT 37°**
- Declination Coverage $+10^\circ < \delta < -75^\circ$
- Azimuth rotation for pointing only

**OBJECTS TRACKED OVER 12° FOCAL SURFACE**
- Tracker executes all precision motions (6 d.o.f.)
- Tracker contains Spherical Aberration Corrector (SAC) with 8 arcminute FoV (*Prime Focus*)

**IMAGE QUALITY**
- Telescope error budget of ~0.7 arc-second FWHM
- Designed to be seeing limited (median = 0.9 arcsec)
Spherical Aberration in the HET & SALT

If the primary were parabolic

Perfect image

... BUT the primary is spherical

Very bad Image: ~10 arcmin, about 1/3 size of moon

Therefore both HET and SALT employ a prime-focus Spherical Aberration Corrector (SAC)
Spherical aberration corrector comparisons

HET SAC

SALT SAC

Focal Plane

Large back focal distance

Spot diagrams

One arcsec boxes
SALT Spherical Aberration Corrector

- Contracted to SAGEM/REOSC (France)
- All mirrors coated with LLNL multilayer coating (Ag/Al)

![Graph of reflectance efficiency vs. wavelength](image1.png)

<table>
<thead>
<tr>
<th>Mirror</th>
<th>Type</th>
<th>Wavelength (nm)</th>
<th>Reflectance Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3</td>
<td>general asphere</td>
<td>300-2300</td>
<td>Al primary, SAC built, Total, SAC spec, Total Spec</td>
</tr>
<tr>
<td>M2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M4</td>
<td>convex</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Exit pupil

Focal plane

1.8 metres
SALT/HET Tracking Principle

Tracker off-centre and pupil partially on primary mirror array. At worst extreme, still a ~7 metre telescope.

With tracker and 11-m pupil centred on primary mirror array and central obstruction (from SAC optics), equivalent to a 9 metre telescope.

Pupil is always underfilled
Pupil is baffled at exit pupil
• controls stray light
• used to simulate pupil for calibrations
SALT tracking characteristics

Effective Collecting Area (Telescope Azimuth = 180deg)

Equivalent to unobscurred 9.2-m diameter mirror

Equivalent to unobscurred 7.9-m mirror
Annulus of visibility for SALT:

Annulus represents 12.5% of visible sky

Declination range: +10° to -75°

Observation time available = time taken to cross annulus

But tracker only has limited range ⇒ Additional azimuth moves needed to achieve full obs. time

Implies that all SALT observations have to be queue-scheduled
Observation times can be extended by successive azimuth moves for extreme Decs.
Surface defined as total track time when first acquired (i.e. at a specific H.A.) and with no azimuth move.
The SALT Visibility Tool: How to determine when a particular object is visible to SALT
Completed Telescope

• Dome

• Shutter

• Tracker & Payload

• Structure
  – TUBE
  – BASE WEDGE
  – MIRROR TRUSS

• Facility Building
  – CAT-WALK ACCESS
  – AIR CONDITIONING DUCTS
  – VENTILATION LOUVRES

• Primary Mirror Array
SALT Science Instruments

• First Generation Instruments chosen to give SALT a wide range of capabilities
• Ensure competitiveness with niche operational modes
  – UV, Fabry-Perot, high-speed, polarimetry, precision RV
• Take advantage of SALT design and *modus operandii*
• Budgeted for 3 “first generation” instruments
• First two completed & installed, third being built
  
  First two (‘first light’) instruments:
  – SALTICAM: a $0.6M sensitive “video camera” (up to ~15 Hz)
  – Robert Stobie Spectrograph (RSS): a ~$5M versatile imaging spectrograph

Last one is the fibre-fed High Resolution Spectrograph
  – Design completed 2005
  – Contract awarded (U. Durham) in 2007
  – Commissioning due to begin late-2011

• Auxillary instruments: dedicated “Aux Port” for small (<50 kg, <0.3m³)
SALTICAM (built at SAAO)
An efficient "video" camera over entire science FoV (8 arcmin).

Efficient in the UV/blue (capable down to atmospheric cutoff at 320nm (sun-burn territory!).

Capable of broad and intermediate-band imaging and high time-resolution (to ~50 ms) photometry.

Fulfills role as both an acquisition camera and science image (ACSI) and commissioning/verification instrument (VI).

SALTICAM will enable unique science, particularly UV and fast photometry (~70-50 ms).
New Filters for SALTICAM

- Sloan $u'$, $g'$, $r'$, $i'$, $z'$

![Sloan filter bands graph](image)
New Filters for SALTICAM

- Strömgren $u, v, b, y, H\beta(w)$, + red extensions
SALTICAM/RSS CCD detectors:

Frame transfer E2V (formerly Marconi, EEV) CCD44-82 chips

- back illuminated & thinned
- frame transfer & deep depletion
- “Astro-BB” coating
- 2048 x 4096 x 15 microns
- 1 unbinned pixel = 0.14 arcsec

**SALTICAM**
Two chips mosaiced to form 4k x 4k area

**RSS**
Three chips mosaiced (6k x 4k)
Aperture advantage: searching for weak periodicities

This shows simulated light-curves and periodograms obtained with ULTRACAM on the WHT and SALT. The source is an $R=16$ variable star observed during bright time in 1 arcsecond seeing using 5 millisecond exposures. The source is varying with an amplitude of 2.5% and a period of 40 milliseconds.

Detection of periodic signals greatly benefits from increased aperture
- $\text{power} \propto \text{aperture}^4$
**CCD time resolution capabilities:**

Moveable frame-transfer mask (mask half of array or use slot mode for fast readout). Will invariably use 2 x 2 binning (1 binned pixel = 0.24 arcsec)

<table>
<thead>
<tr>
<th>Mode</th>
<th>FoV</th>
<th>Read Time</th>
<th>Read Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Full Frame Readout Mode (using shutter)</strong></td>
<td>8 arcmin</td>
<td>13.8 sec (@2.3e)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.5 sec</td>
<td>(@4e)</td>
<td></td>
</tr>
<tr>
<td><strong>Frame Transfer Mode</strong></td>
<td>Half of 8 arcmin circular FoV</td>
<td>6.3 sec (@2.3e)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.4 sec</td>
<td>(@4e)</td>
</tr>
<tr>
<td><strong>Fastest windowed photometry</strong></td>
<td>Slot mode</td>
<td>0.076 sec</td>
<td>(@4 e)</td>
</tr>
<tr>
<td></td>
<td>Slot + windowed mode</td>
<td>0.050 sec</td>
<td></td>
</tr>
</tbody>
</table>

Unvignetted slot size is 64 pixels (~ 9 arcsec)
### RSS High Speed mode

<table>
<thead>
<tr>
<th>CCD 1</th>
<th>CCD 2</th>
<th>CCD 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FT Boundary</td>
</tr>
</tbody>
</table>

- Fast spectroscopy
- Fast spectropolarimetry
- Fast imaging polarimetry
SALTICAM Frame Transfer Mask in High Speed ‘Slot Mode’

Slot ~11 arcsec wide

Image/store area split

Serial Readout Registers
Slot Mode Control:

End of exposure n

Rapid row transfer of exposure n and start of exposure n+1

End of exposure n+1

Figure 2. Control scheme for fastest sampling
The Robert Stobie Spectrograph (RSS) (built at Wisconsin, Rutgers & SAAO)

An efficient and versatile Imaging Spectrograph
• capable of UV spectroscopy
• high time resolution ability
• polarimetry capability
• Fabry Perot imaging (many narrow filters)
• multiple object spectroscopy
  - Can observe ~100 objects at once

Named in memory of Bob Stobie, previous SAAO Director.

RSS in lab at Wisconsin (Feb 2005)  RSS installed on SALT (Oct 2005)
What science should RSS do?

- **SALT features**
  - very large aperture
  - good field of view (8 arcmin)
  - excellent ultraviolet throughput
  - queue scheduling
  - modest imaging

- **RSS:** emphasizes unique observing modes that do not require excellent imaging
  - UV spectroscopy down to 3200 Å (rare on large telescopes)
  - higher resolution: high-throughput grating 3200 - 9000 Å; Fabry-Perot 4300 - 9000 Å (Visible Beam); later - 1.7 μm (NIR)
  - polarimetry (circular and linear) (very rare)
  - high-speed detector mode (very rare)
Optical Layout for RSS: including NIR

- All-refractive UV optics (CaF$_2$, NaCl, fused silica) for high throughput
- “Tuneable” Volume Phase Holographic transmission gratings
- Fabry-Perot capability
- At prime focus for UV and full-field access
- NIR upgrade path: simultaneous 3200 Å – 1.7 μ (e.g. X-Shooter)
How VPH Gratings Work


Astronomical Gratings

- Created by exposing holograph material ("DiChromated Gelatin") to interference pattern from laser
- Index of refraction of DCG is modulated in space
- Large; inexpensive; custom design; efficient at high groove density
Measured efficiency in unpolarized light for the 2400 l/mm VPH grating (optimized for 532 nm) at grating angles of 27, 33, 37, and 46 degrees. The super blaze shows the envelope of peak efficiency as the grating is tuned to different grating angles.
The SALT Volume Phase Holographic Gratings

Efficiency Contours (50%, 70%, 90%)

Lines indicate both wavelength coverage & resolution range for specific grating angle (e.g. 40° & 30°)

Resolution vs wavelength for 1.2 arcsec slit

15 March 2010
NASSP OT1: Spectroscopy II
Effect of bad focus and seeing in Spectroscopy

Slit width/Slit loss

\[ \Lambda x = w \frac{\cos i f_{\text{cam}}}{\cos \theta f_{\text{coll}}} \]
Reducing Spectroscopic Data

**Calibration frames:**
- Bias frame (electronic DC level)
  - sometimes derived from “overscan” or “prescan”
- Flat field (detector sensitivity)
- Arc Lamp (wavelength calibration)
- Flux Standard
  - flux from \( \text{electrons cm}^{-2} \text{sec}^{-1} \text{Å}^{-1} \)
  - to \( \text{ergs/cm}^{-2} \text{sec}^{-1} \text{Å}^{-1} \)
- Fringe frame correction

**Basic reduction procedures:**
1. Bias correction
2. Flat fielding
3. Cosmic ray removal
4. Wavelength determination
5. Background subtraction
6. Spectrum extraction
7. Flux calibration (remove atm. effects)
Wavelength Calibrations

- Determine *wavelength* as a function of *pixel number* on the detector.
- Typically use 3\textsuperscript{rd} order polynomial fit to known wavelengths.
- Need to have *order blocking* filters to exclude 2\textsuperscript{nd} order overlap in the 1\textsuperscript{st} order, 3\textsuperscript{rd} in 2\textsuperscript{nd}, etc.
Configuring RSS

RSS Simulator Tool (Version 2.3)

Generate Spectra  Configure RSS  Make an Exposure

Imaging  Spectroscopy  Fabry-Perot

Iterations 1

Use Polarimetry

Slit Type Long slit

Slit Width 1.2 arcseconds

Slit Throughput: 0.764 (for a FWHM of 1.19")

Grating pg1800

Camera Station
73  83  93  103  113  123  75.25 deg

Grating Angle
0  10  20  30  40  50  60  70  80  90  100  37.625 deg

Order Blocking Filter pg04000

Display Throughput

Resolving Power: 3,613.4 Å

Blue Chip Edge: 6,112.5 Å

Blue Chip Gain: 6,553.0 Å - 6,573.9 Å

Central Wavelength: 6,703.2 Å

Red Chip Gain: 6,905.2 Å - 7,004.5 Å

Red Chain Filter: 7,300.7 Å
RSS Plots
Configuring SALTICAM

Set Exposure Type

- Filter Mode: Single Filter
- CCD Mode: Normal

Exposure Time per Frame(s): 100
Overhead Time: 18.22 s

- Number of Cycles: 1
- Number of Iterations: 1
- Total Readouts: 1

Total observation time for all frames, including overheads: 118 s

- Binned Rows: 2
- Binned Columns: 2
- Gain: Bright
- Readout Speed: Slow
- Filter: R-S1

Click "Exposure" to generate statistics summed over all cycles and iterations.

Comparison with other Spectrographs

Sensitivity - Low Resolution

- SALT/ IMPALAS
- Keck/ ESI
- Keck/ LRIS
- Magellan/ HES
- Gemini/ GMOS
- VLT/ FORS
- HET LRS
Up to 40 Spectra

Multi-Object Grating Spectroscopy

Filters

"VPH" Grating disperses wavelengths

Slitmasks selects objects

Hubble Deep Field (South)
Perseus A in Imaging/Fabry-Perot Spectroscopy

Fabry-Perot etalons (scans wavelength)

Perseus Cluster of Galaxies

Filters

Many wavelengths

Perseus A in Hydrogen Light
3 resolution modes:
- low (R = 320-770) ‘tuneable filter’ (full field)
- medium (R = 1250 – 1650) bullseye 3.8’ – 3.3’
- high (R ~ 9,000) bullseye ~1’

Using 150mm diameter Queensgate etalons Finesse ~30, implying 75-80% throughput
Using ~30 R = 50 interference filters (latter can also be used on their own for narrow band imagery).
Fabry-Perot Commissioning Observations

H-alpha image

Velocity Map
RSS Fabry-Perot mode: Lab tests

The RSS-FP Spectral Resolutions. Open Squares: interference filters; Diamonds: TF mode; Filled Squares: LR mode; Triangles: MR mode; X: HR mode.
RSS Polarimetry:
Not yet commissioned

- Imaging polarimetry
Spectropolarimetry Submode

Beamsplitter splits 2 polarizations

Waveplate rotates polarization

Polarization of 20 Spectra

Also works in Imaging/Fabry-Perot Modes

Hubble Deep Field (South)
Focal Plane Configuration for imaging/long slit spectropolarimetry

- O-ray image: 4'
- Focal Plane Mask: 4' x 8' FoV
- 4098 spatial rows = 8'
- Charge Transfer 1 μs/pix
- Amplifier
SALT High Resolution Spectrograph (HRS): 3rd “First Gen” SALT Instrument

Fibre-fed with dual fibres for sky subtraction and nod/shuffle.

R ~ 16,000 – 70,000
λ ~ 380 – 890 nm

Designed for very high stability
- Housed in vacuum tank
- Temperature stabilized
- Minimize air index effects
- Minimize dimension changes
- Precision radial velocities (m/s)
  - extra-solar planets

Under construction at Centre for Advanced Instrumentation, Durham University (UK)

- Started in late 2007, assembly & testing Sep 2011; commissioning late-2011
- Based on University of Canterbury CDR level design
SALT high resolution spectrograph

- R4 echelle grating
- Dual-beam (blue & red), white pupil
- VPH grating cross-dispersion
SALTHRS: Blue spectral format: Blue

E2V 44-82
2k x 4k
15 µm pixels
AstroBB coating
SALTHRS: Red spectral format

E2V
4k x 4k
15 \( \mu \)m pixels
Broad-band coating
Deep depletion
THE END!