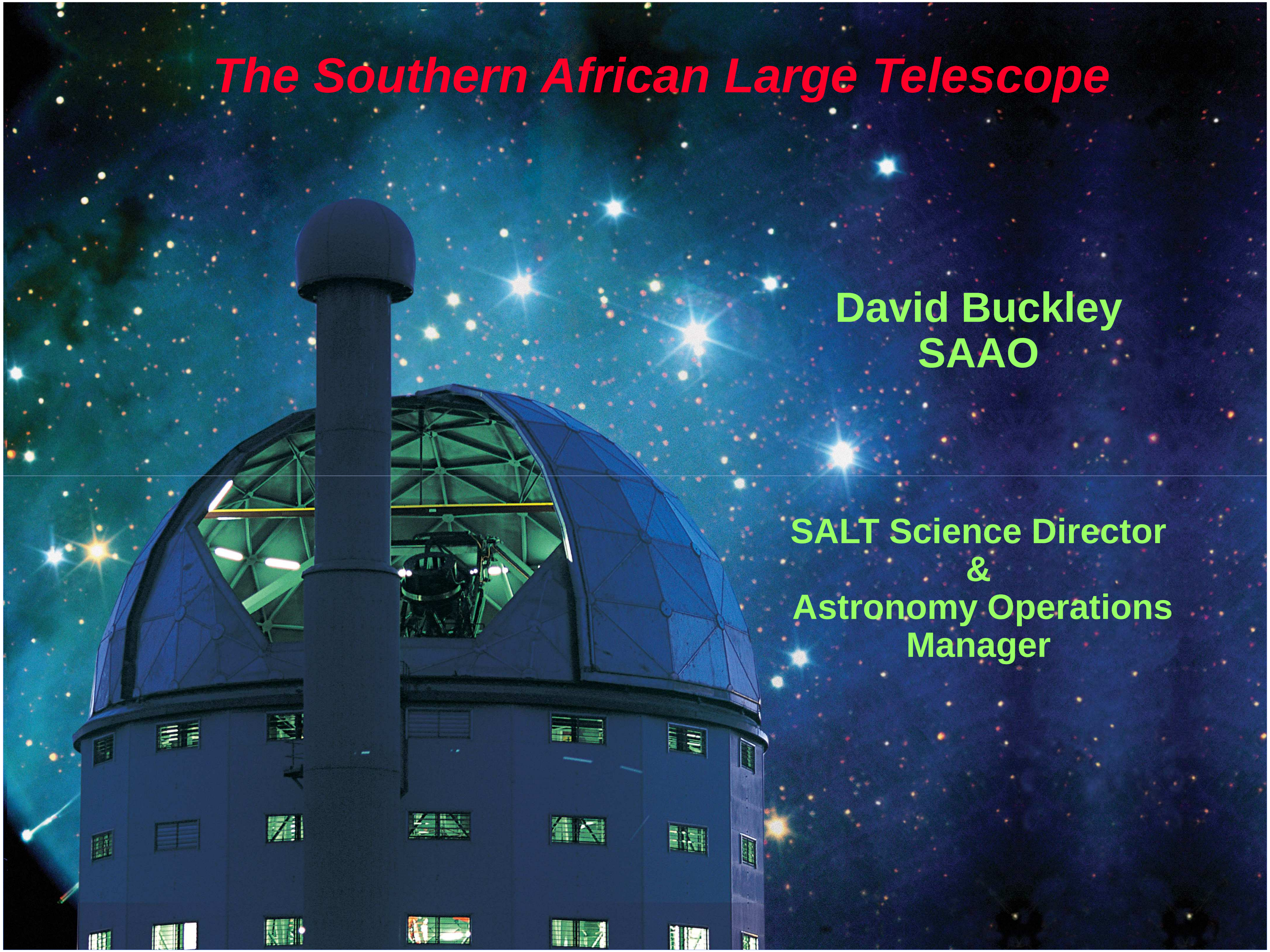
The Southern African Large Telescope



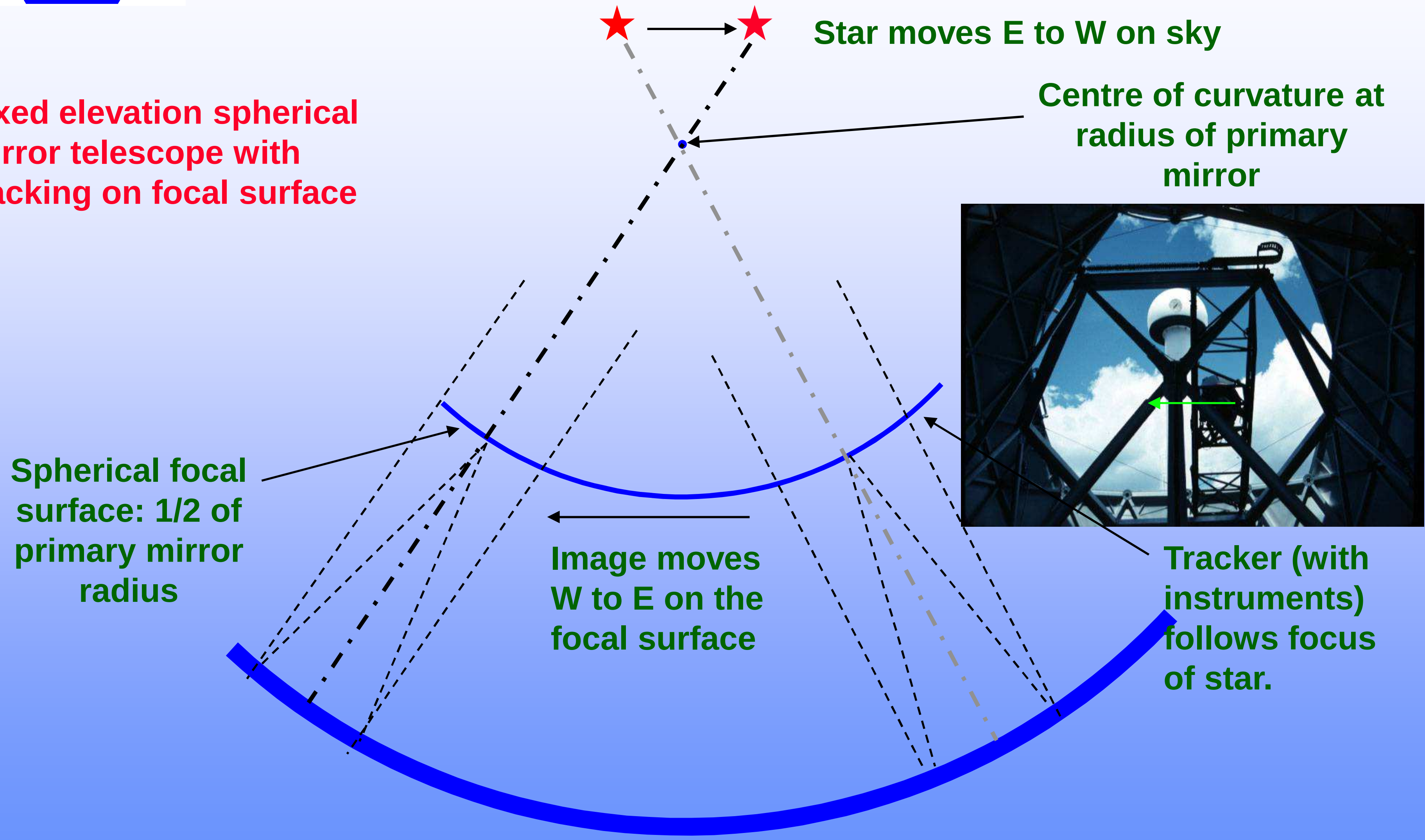
David Buckley
SAAO

SALT Science Director
&
Astronomy Operations Manager

SALT is the optical analogue of the Arecibo radio telescope

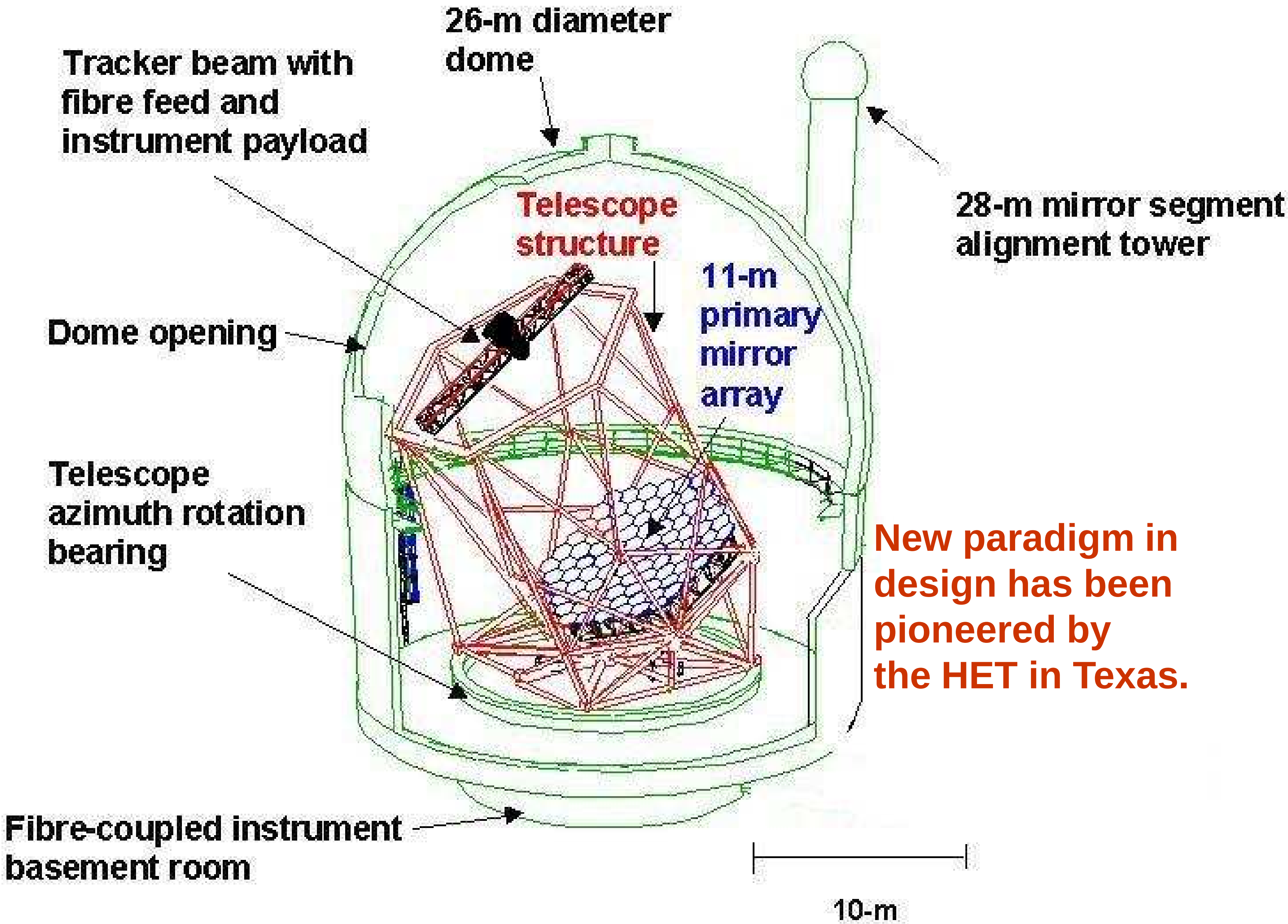
The Arecibo Concept:

Fixed elevation spherical mirror telescope with tracking on focal surface



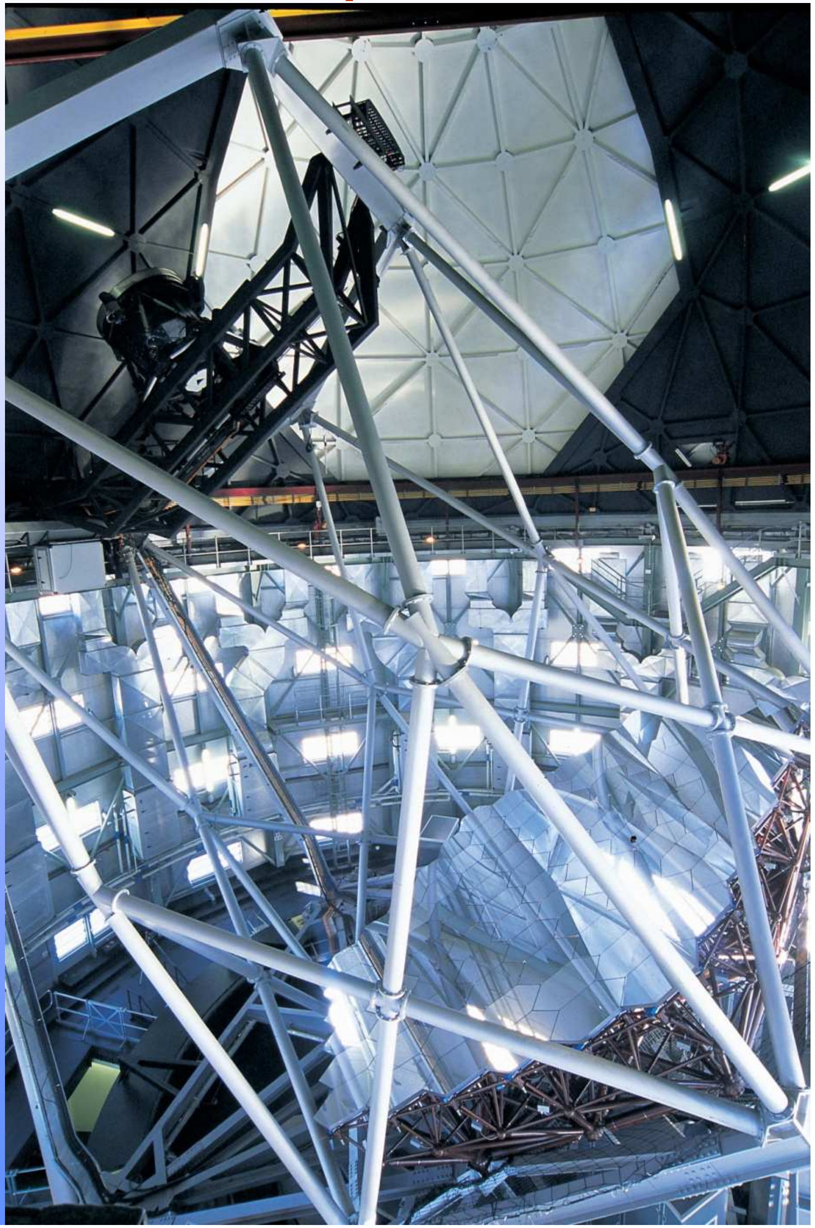
Spherical Primary Mirror

Southern African Large Telescope



New paradigm in design has been pioneered by the HET in Texas.

SALT: *A Tilted Arecibo-like Optical-IR Telescope modelled on the Hobby-Eberly Telescope*



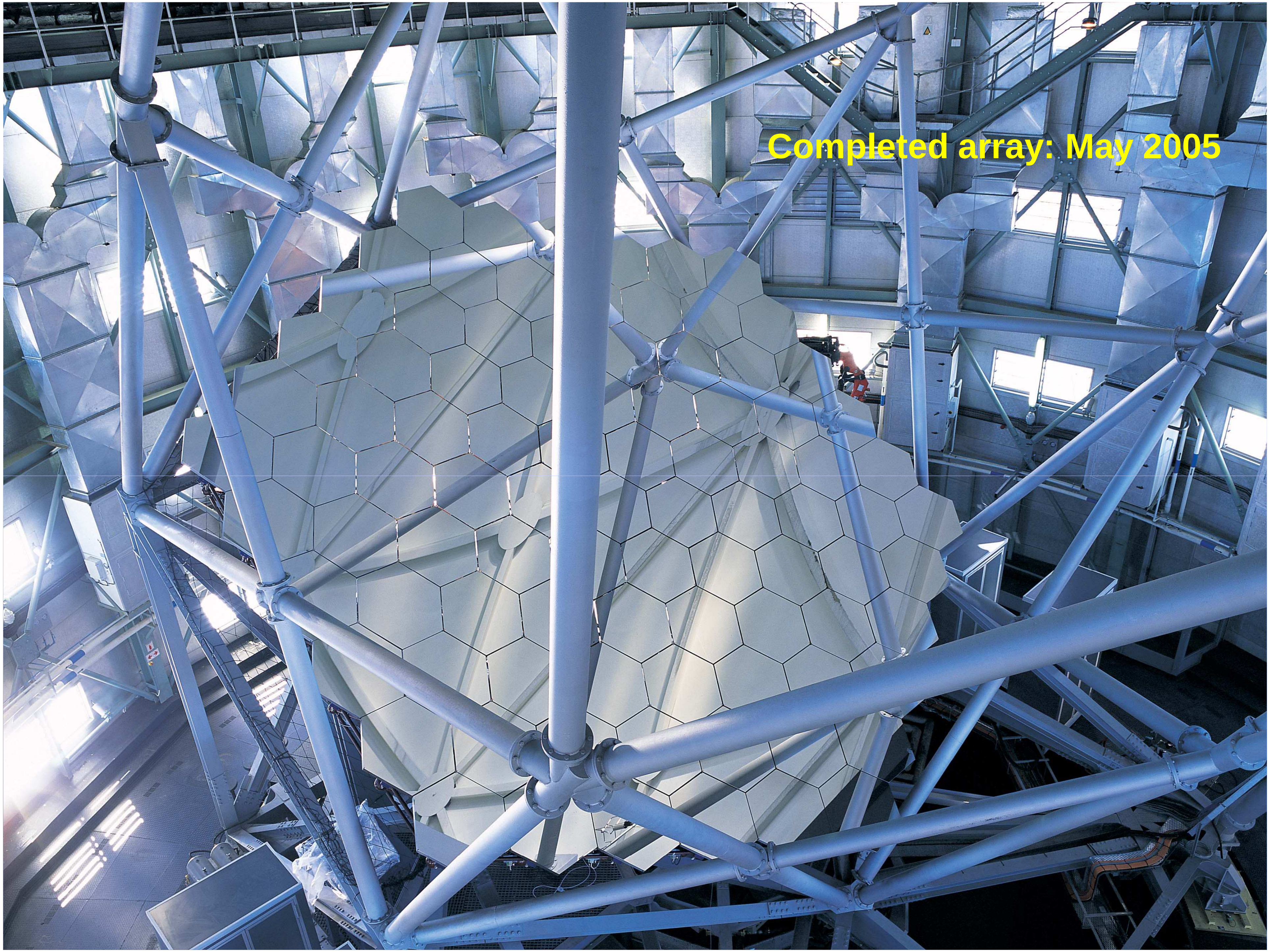
BASIC ATTRIBUTES

- **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^o**
  - **Declination Coverage +10^o < δ < -75^o**
  - **Azimuth rotation for pointing only**

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

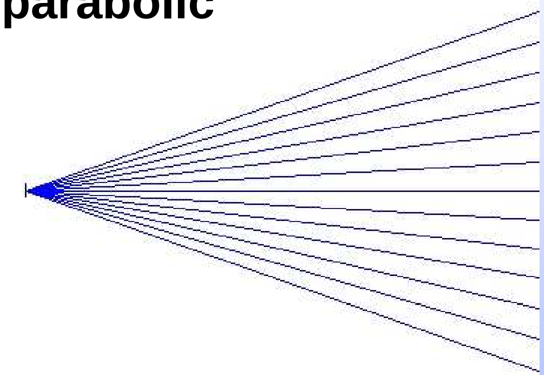
- **IMAGE QUALITY**
  - **Telescope error budget of ~0.7 arc-second FWHM**
  - **Designed to be seeing limited (median = 0.9 arcsec)**


Completed array: May 2005

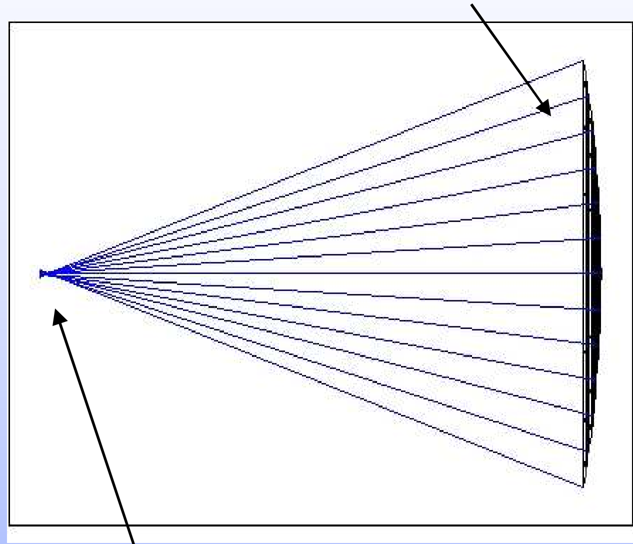
Spherical Aberration in the HET & SALT

Perfect image

If the primary were parabolic



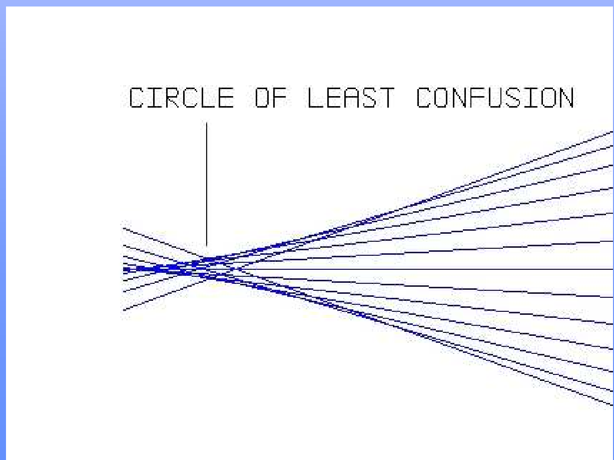
Primary Mirror array



Prime Focus

… BUT the primary is spherical

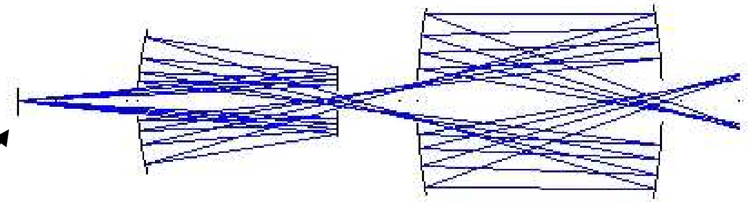
Very bad Image: ~10 arcmin, about 1/3 size of moon



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

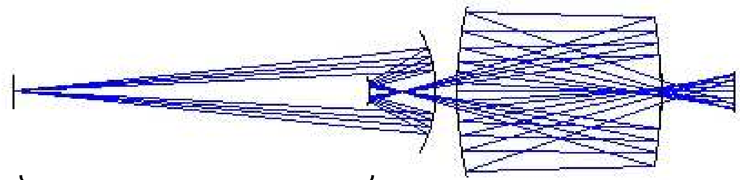
Spherical aberration corrector comparisons

HET SAC

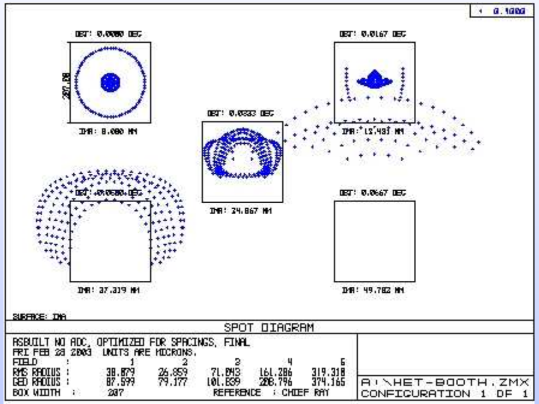


Focal Plane

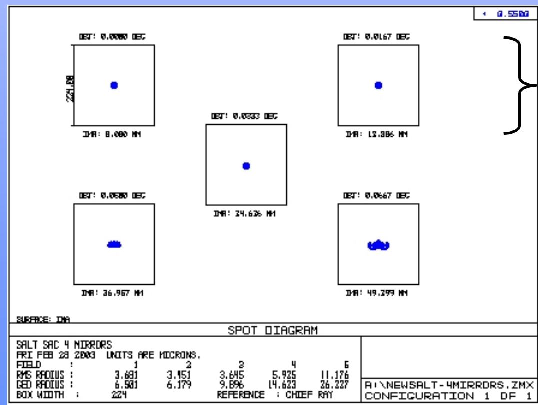
SALT SAC



Large back focal distance



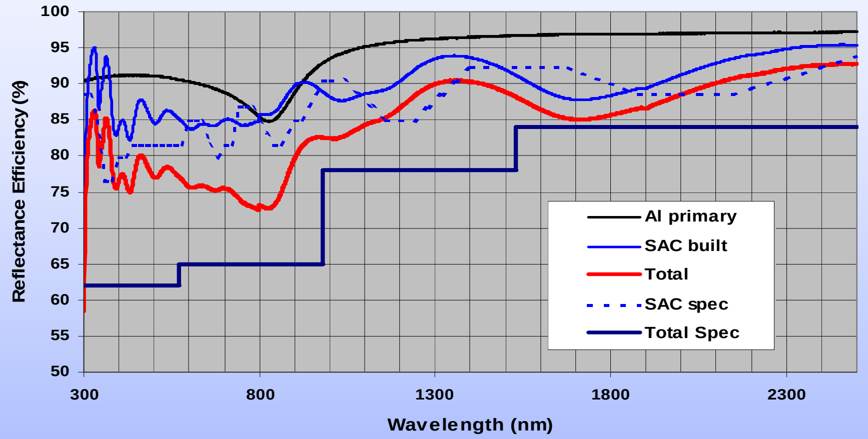
Spot diagrams

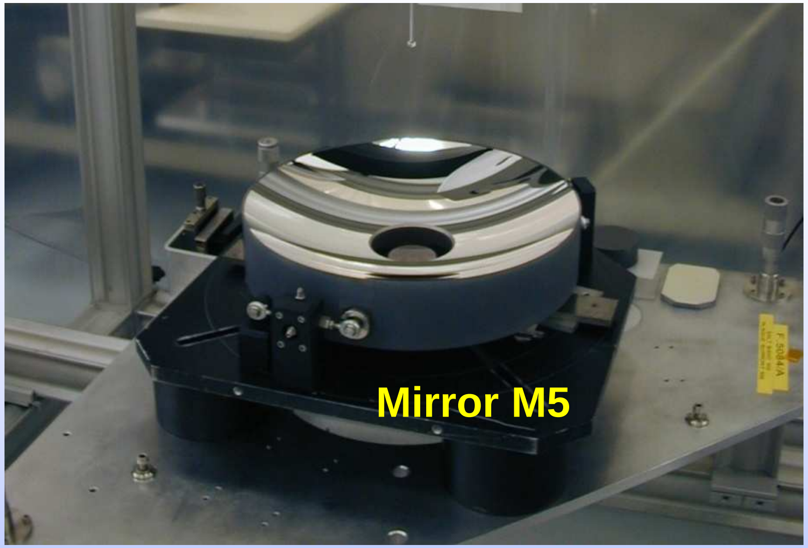


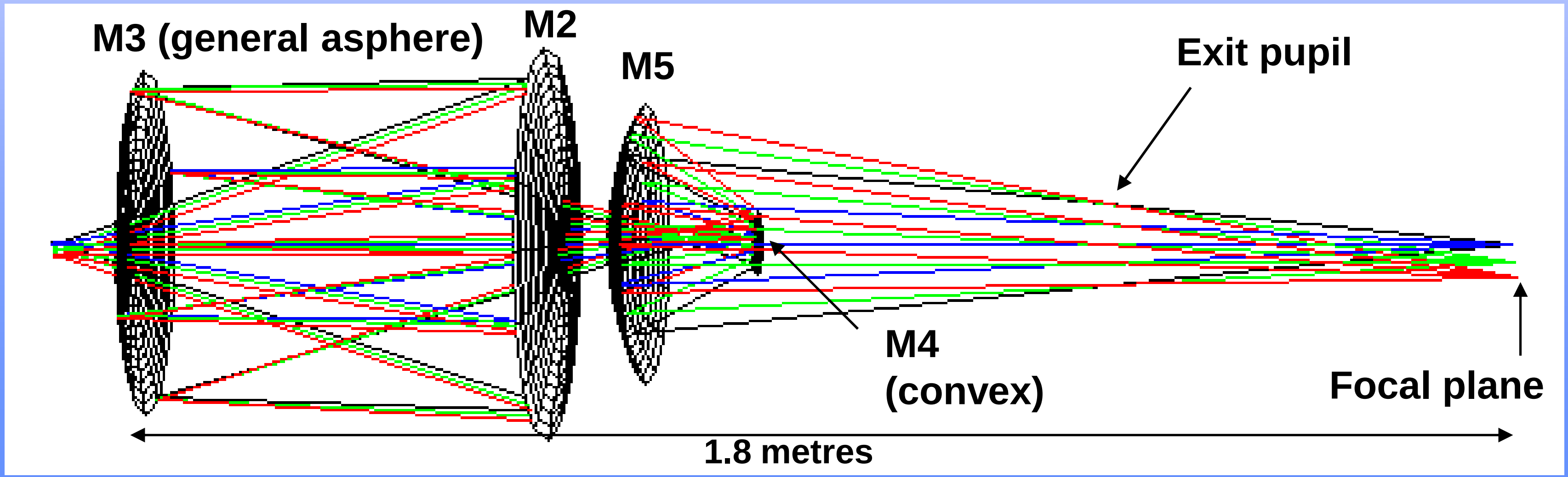
One arcsec boxes

SALT Spherical Aberration Corrector

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







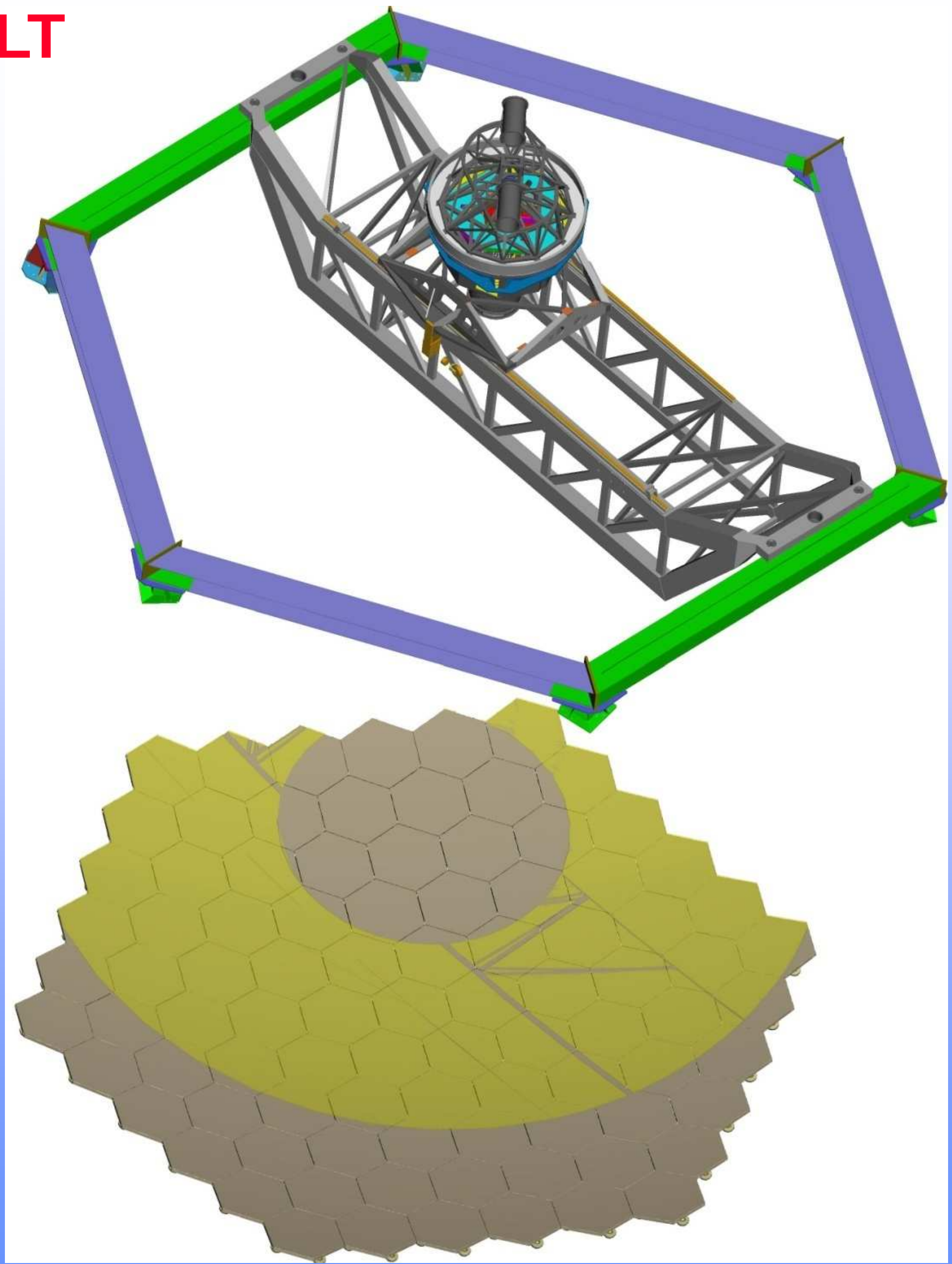
Peculiarities of SALT

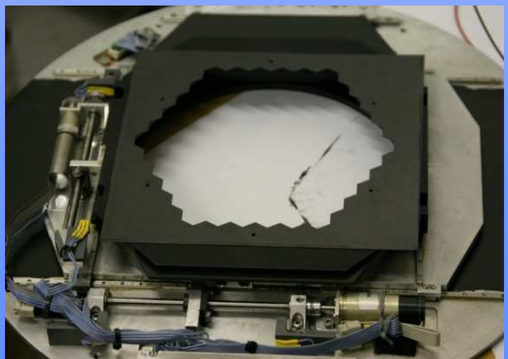
SALT/HET Tracking Principle

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

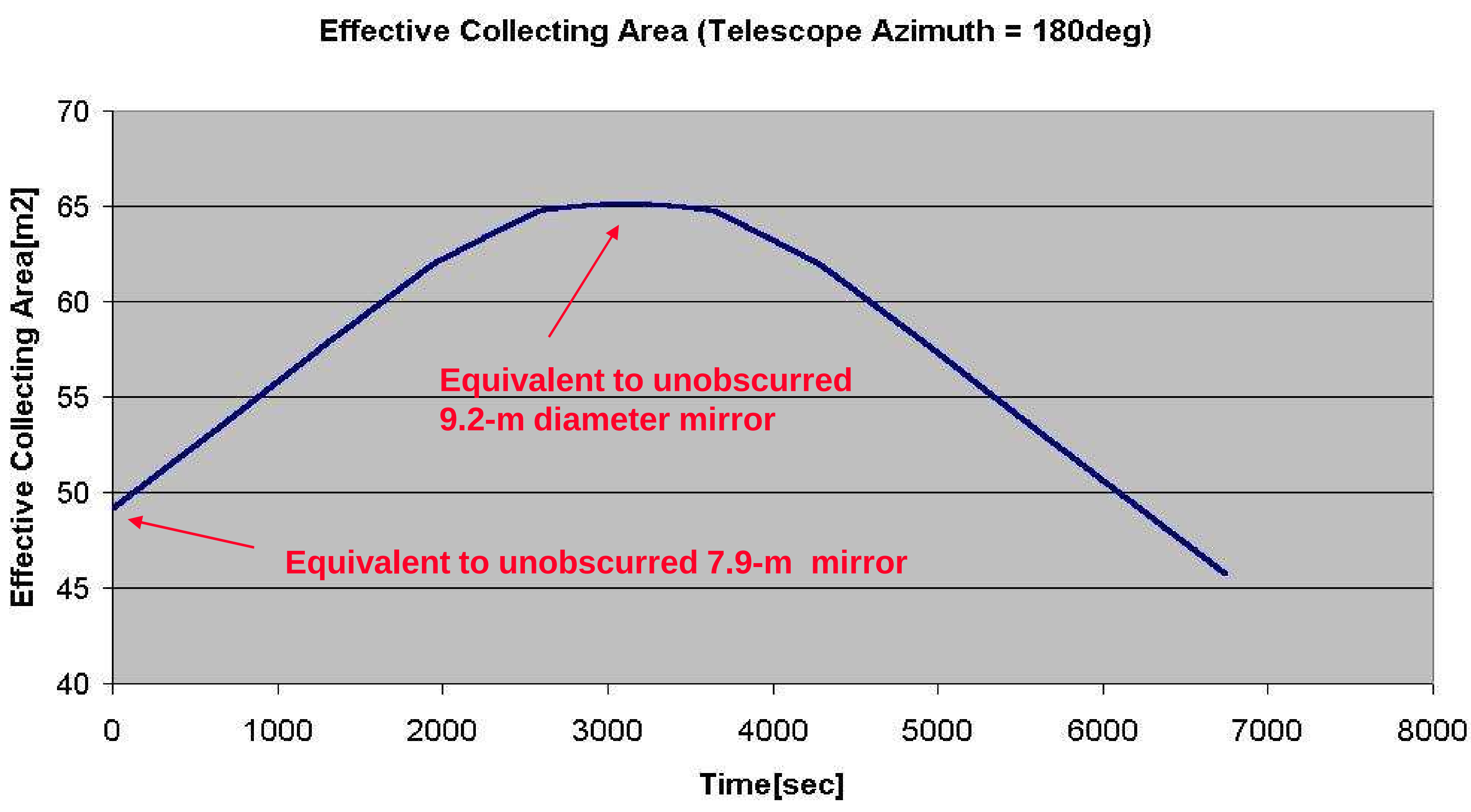
With tracker and 11-m pupil centred on primary mirror array and central obstruction (from SAC optics), equivalent to a 9 metre telescope.

Pupil is always underfilled
Pupil is baffled at exit pupil
- controls stray light
- used to simulate pupil for calibrations





SALT tracking characteristics



How SALT Observes: Restricted Viewing Window

Annulus of visibility for SALT:

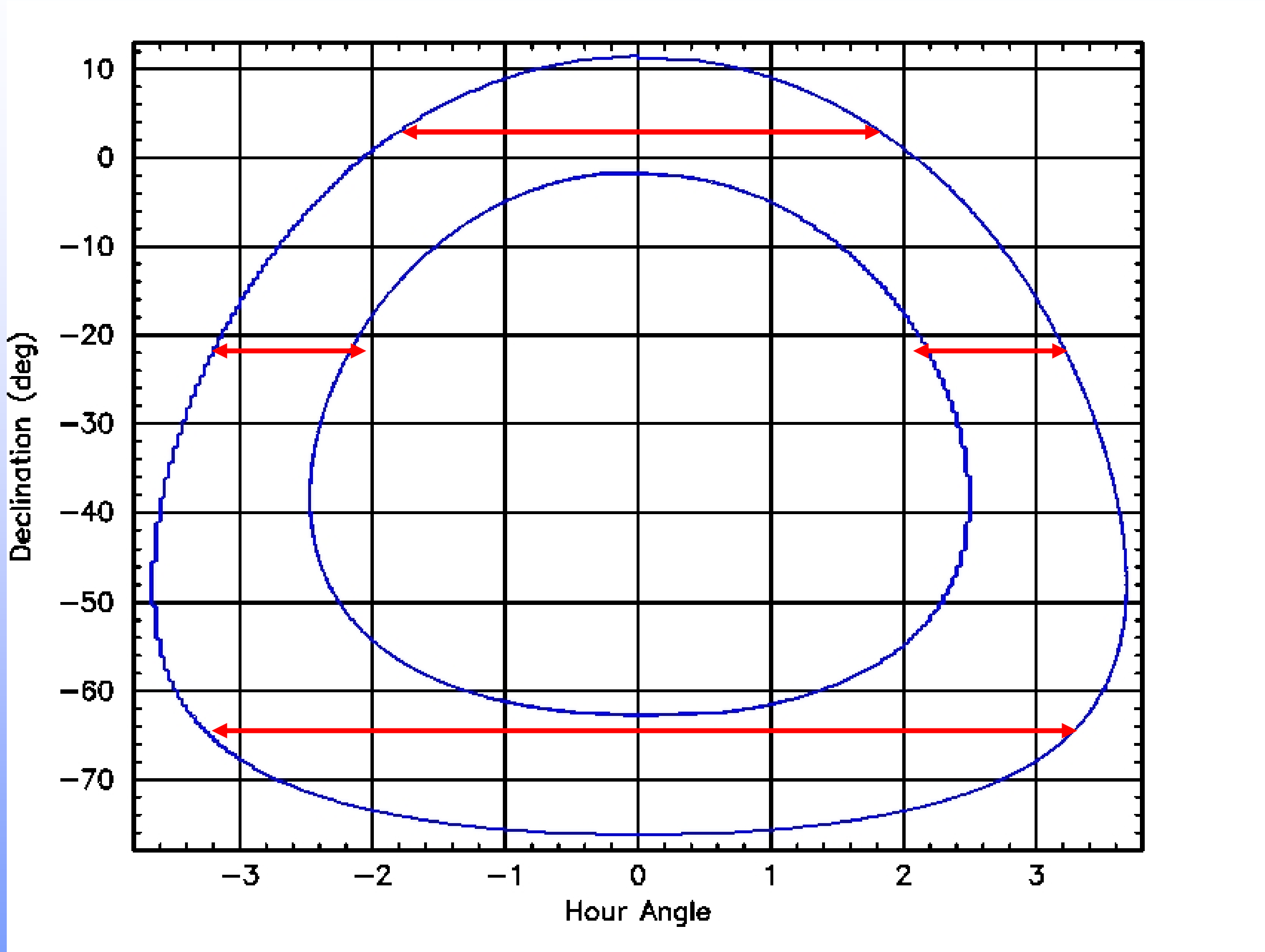
Annulus represents 12.5% of visible sky

Declination range: +10º to -75º

Observation time available = time taken to cross annulus

***But* tracker only has limited range ⇒**

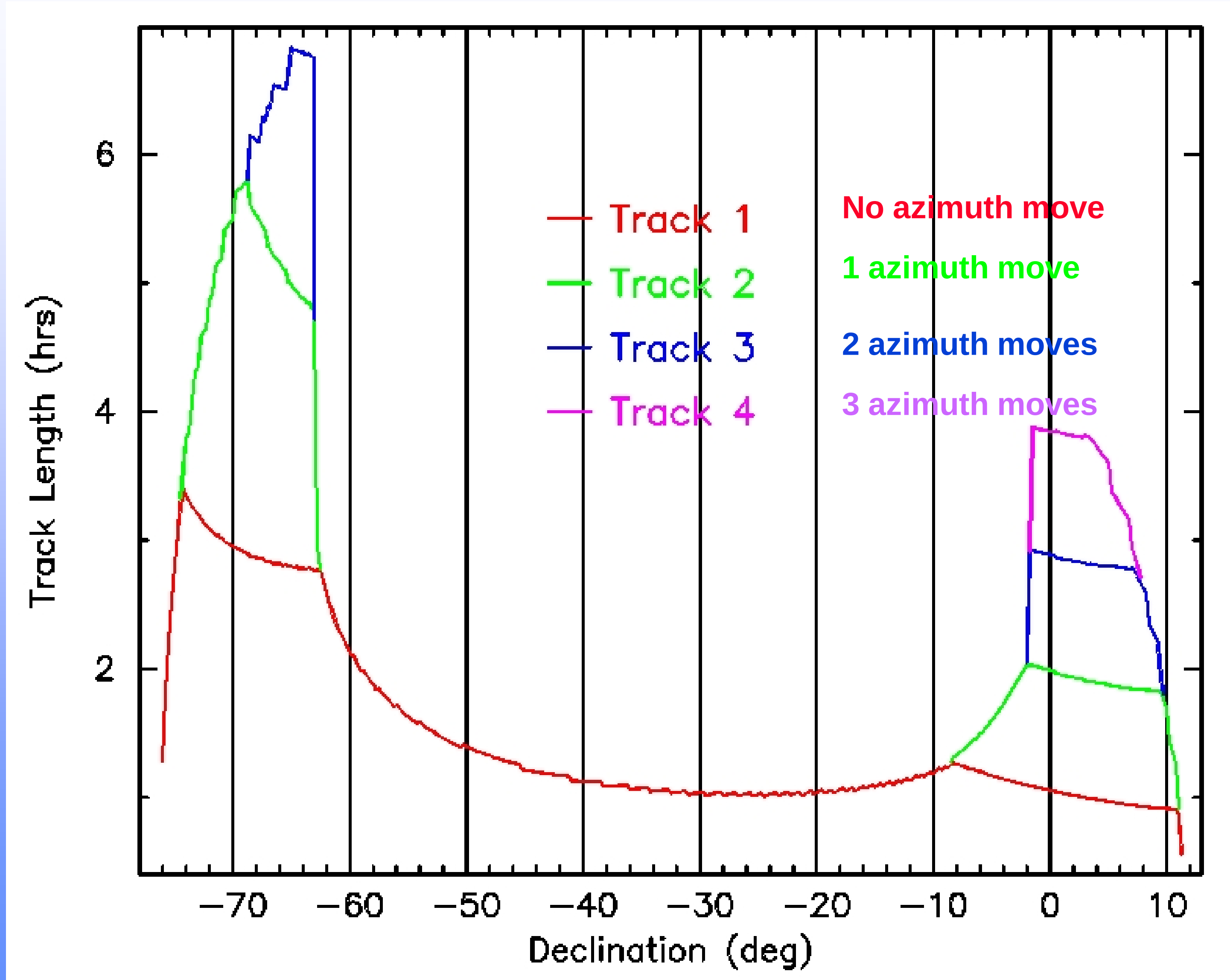
Additional azimuth moves needed to achieve full obs. time



Implies that all SALT observations have to be queue-scheduled

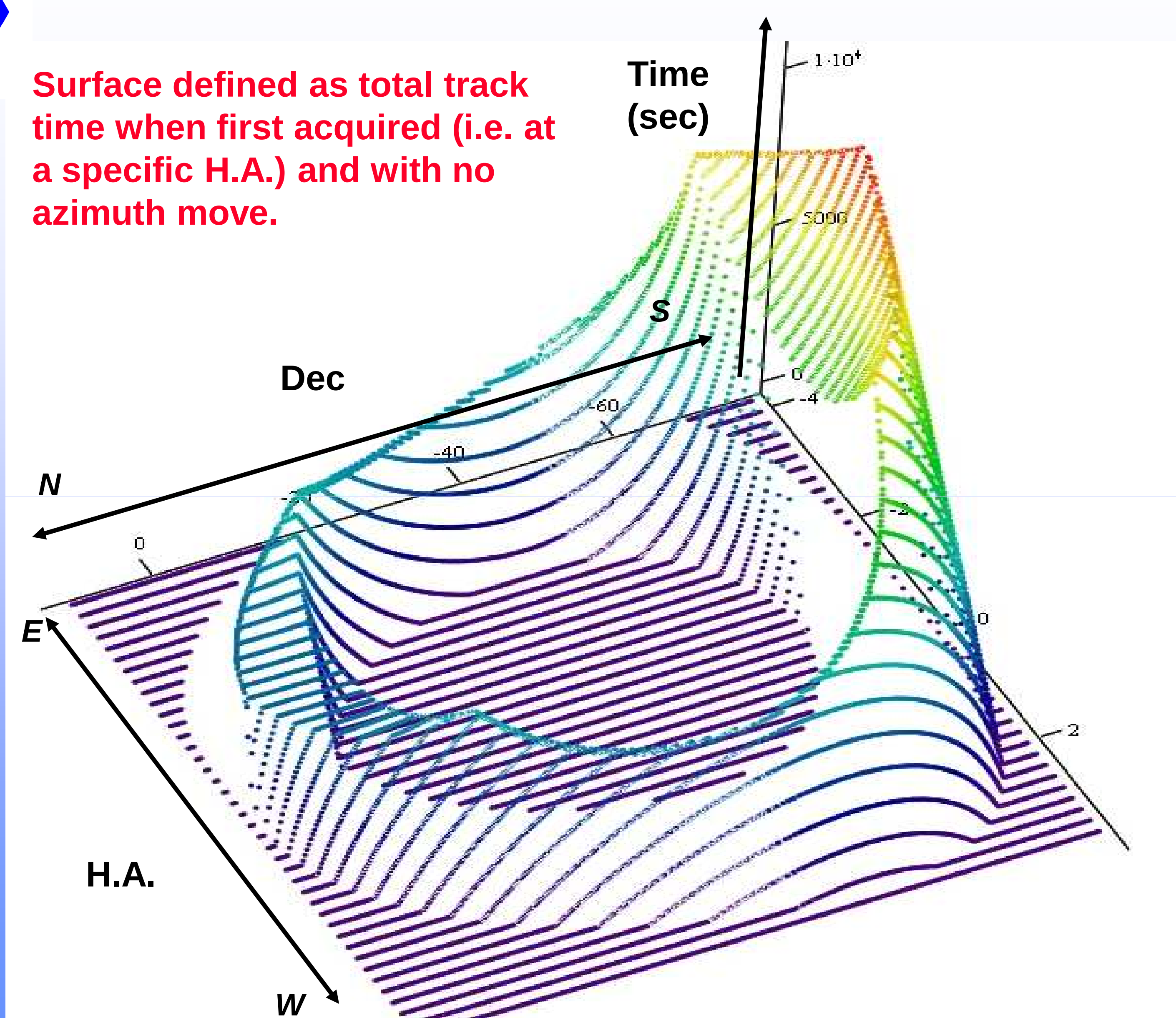
SALT Track Times

Observation times can be extended by successive azimuth moves for extreme Decs

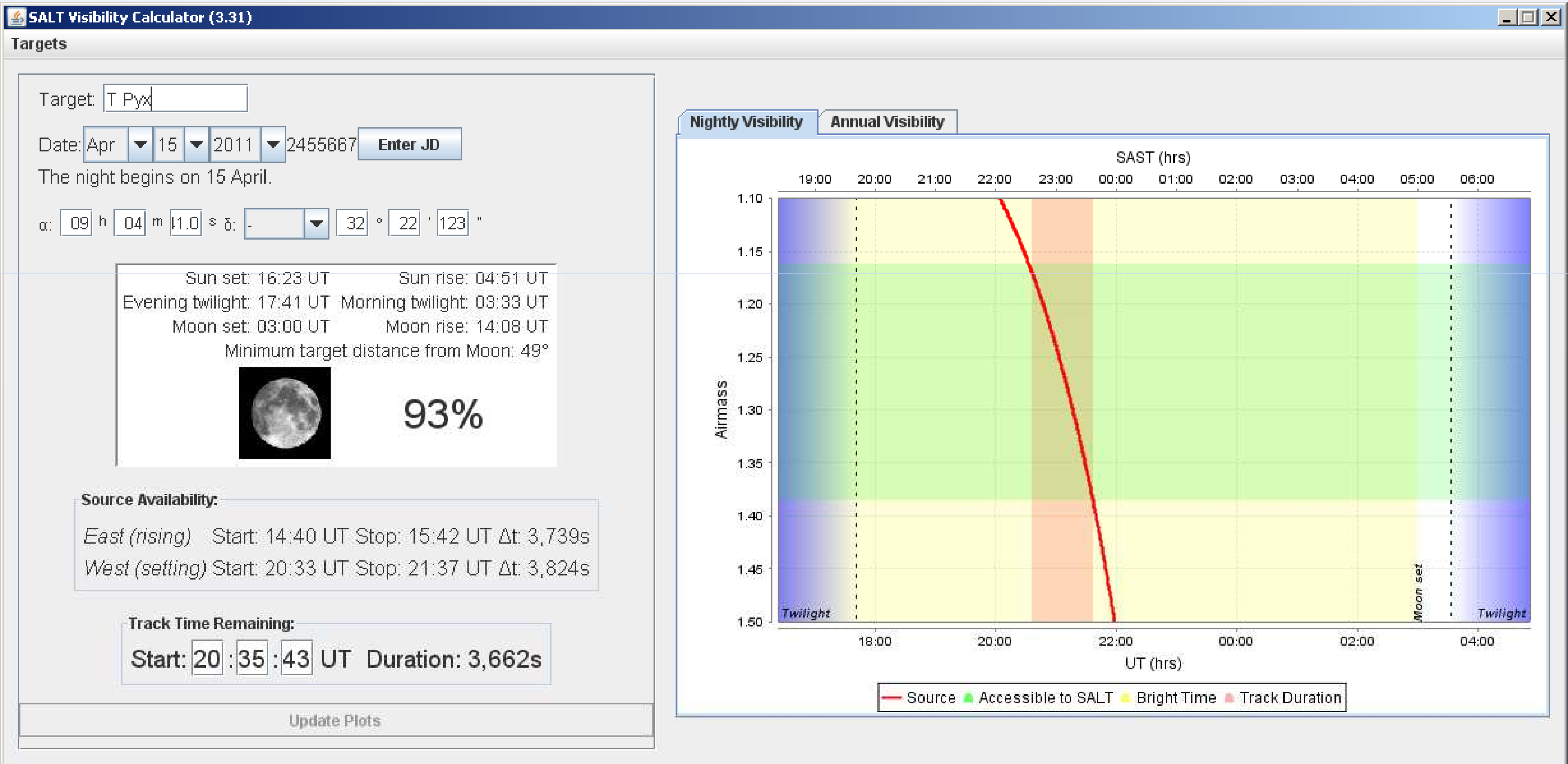


SALT Track Surface

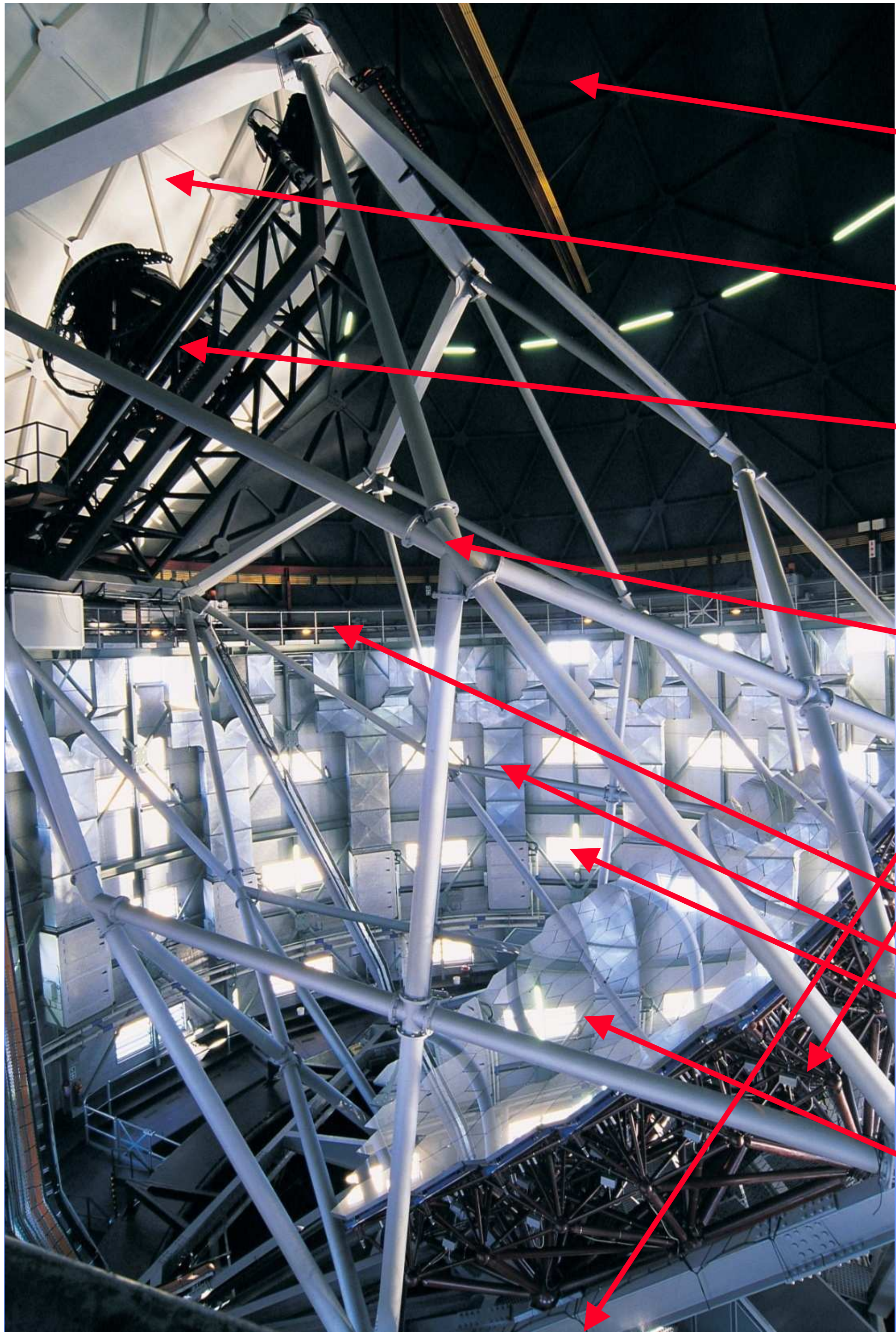
Surface defined as total track time when first acquired (i.e. at a specific H.A.) and with no azimuth move.



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, <0.3m^3)

SALTICAM (built at SAAO)

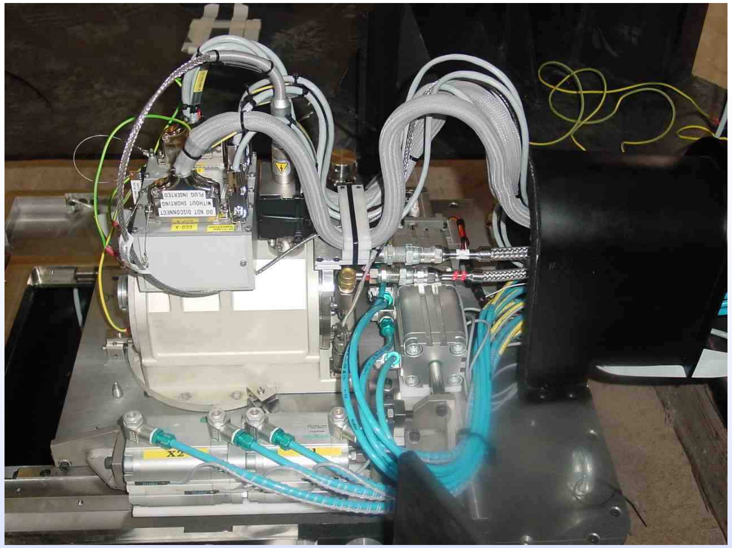
An efficient "video" camera over entire science FoV (8 arcmin).

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

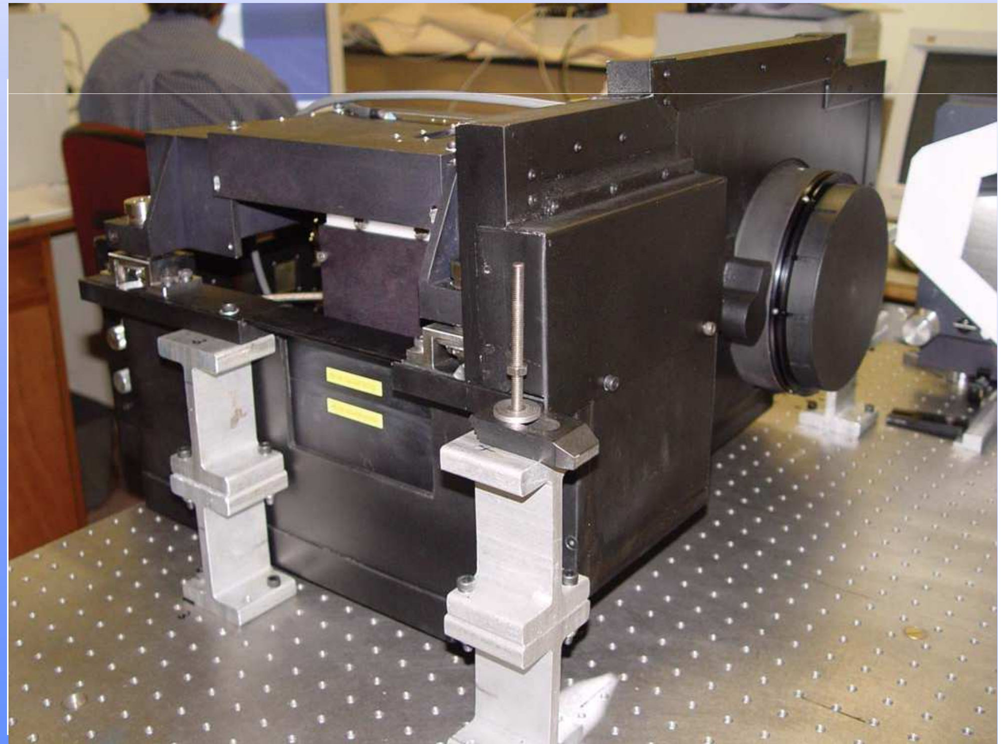
Capable of broad and intermediate-band imaging and high time-resolution (to ~50 ms) photometry.

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).



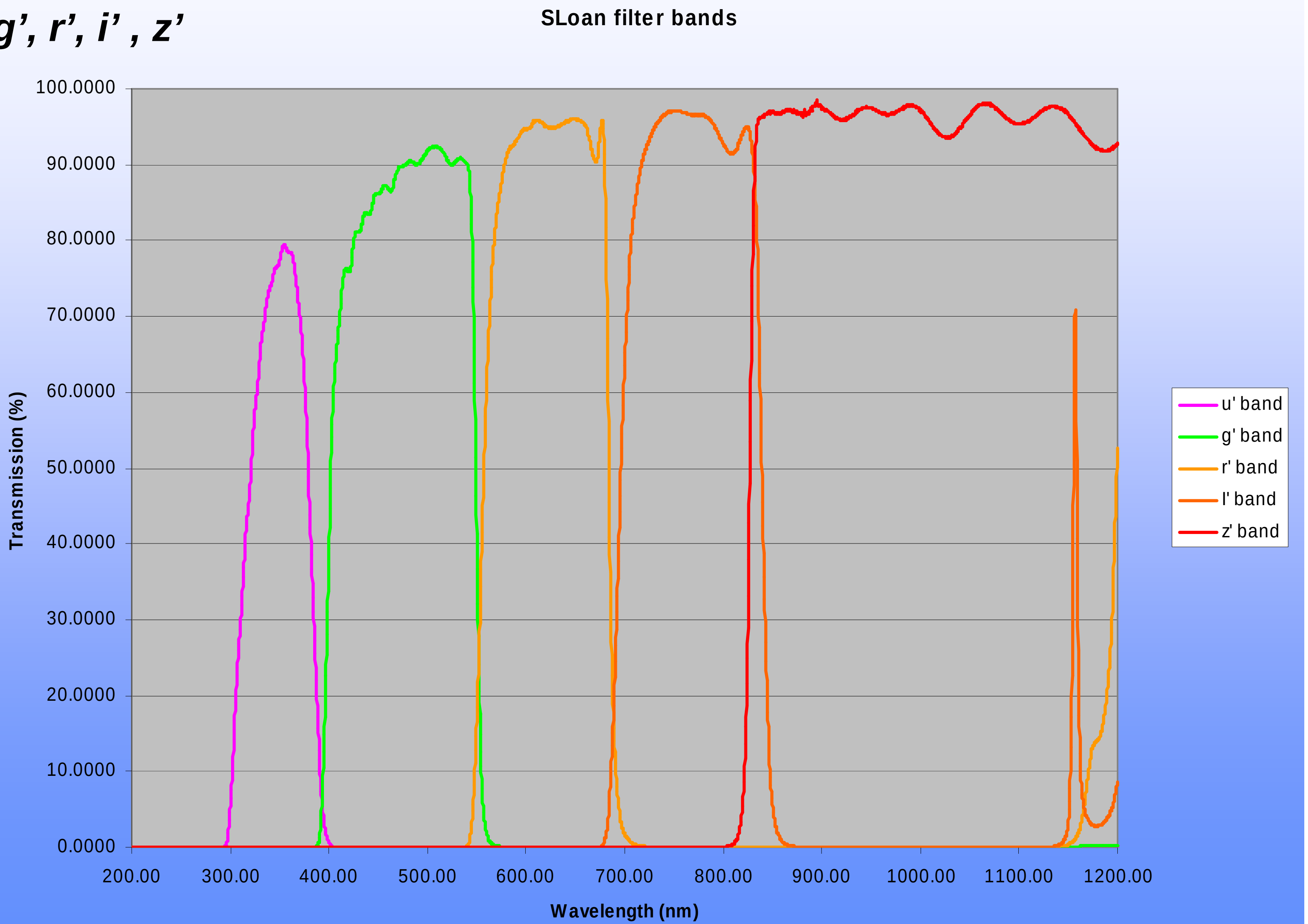
SALTICAM VI



SALTICAM ACSI

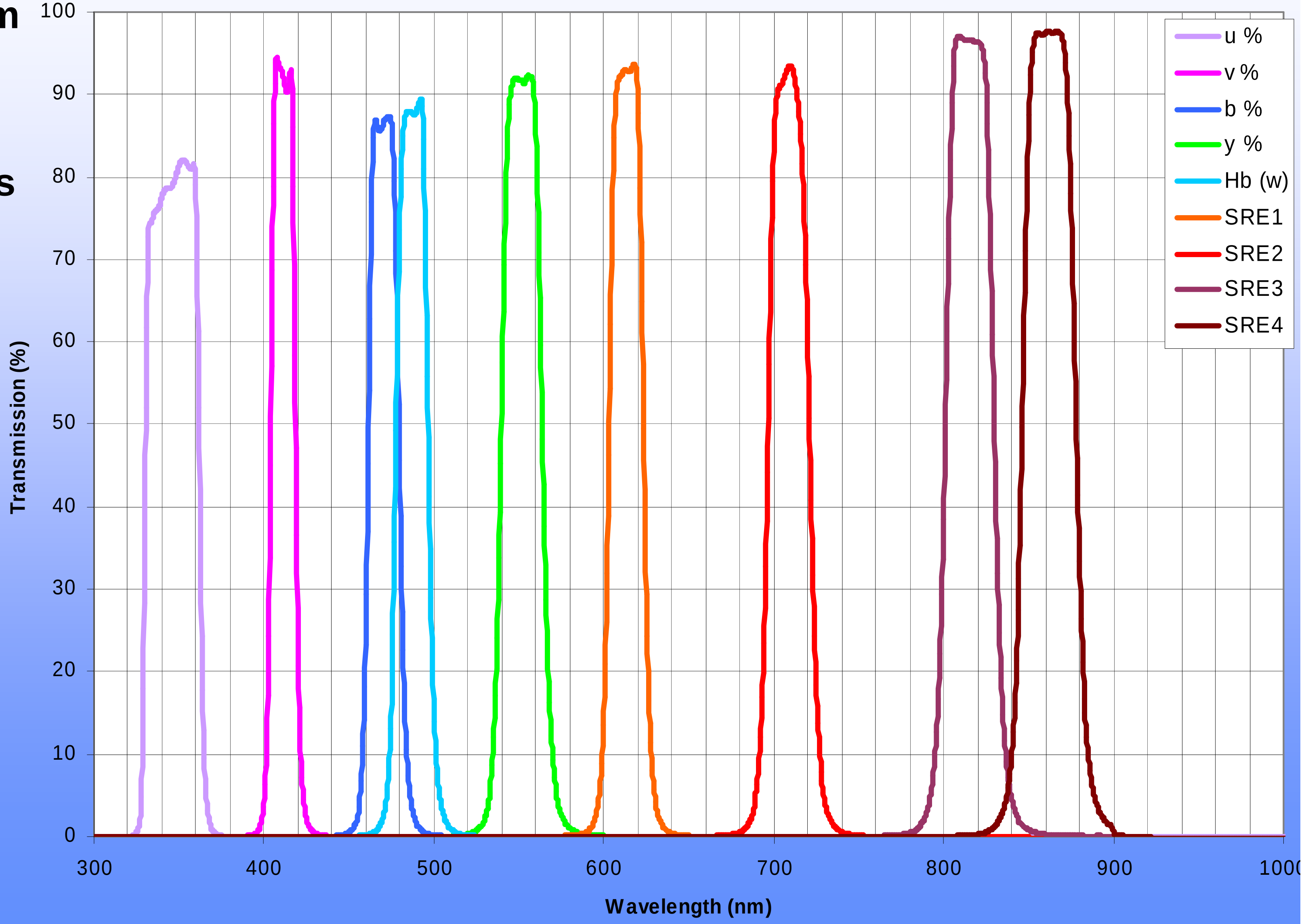
New Filters for SALTICAM

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



New Filters for SALTICAM

- **Strömgrem *u, v, b, y, Hβ(w)*, + red extensions**



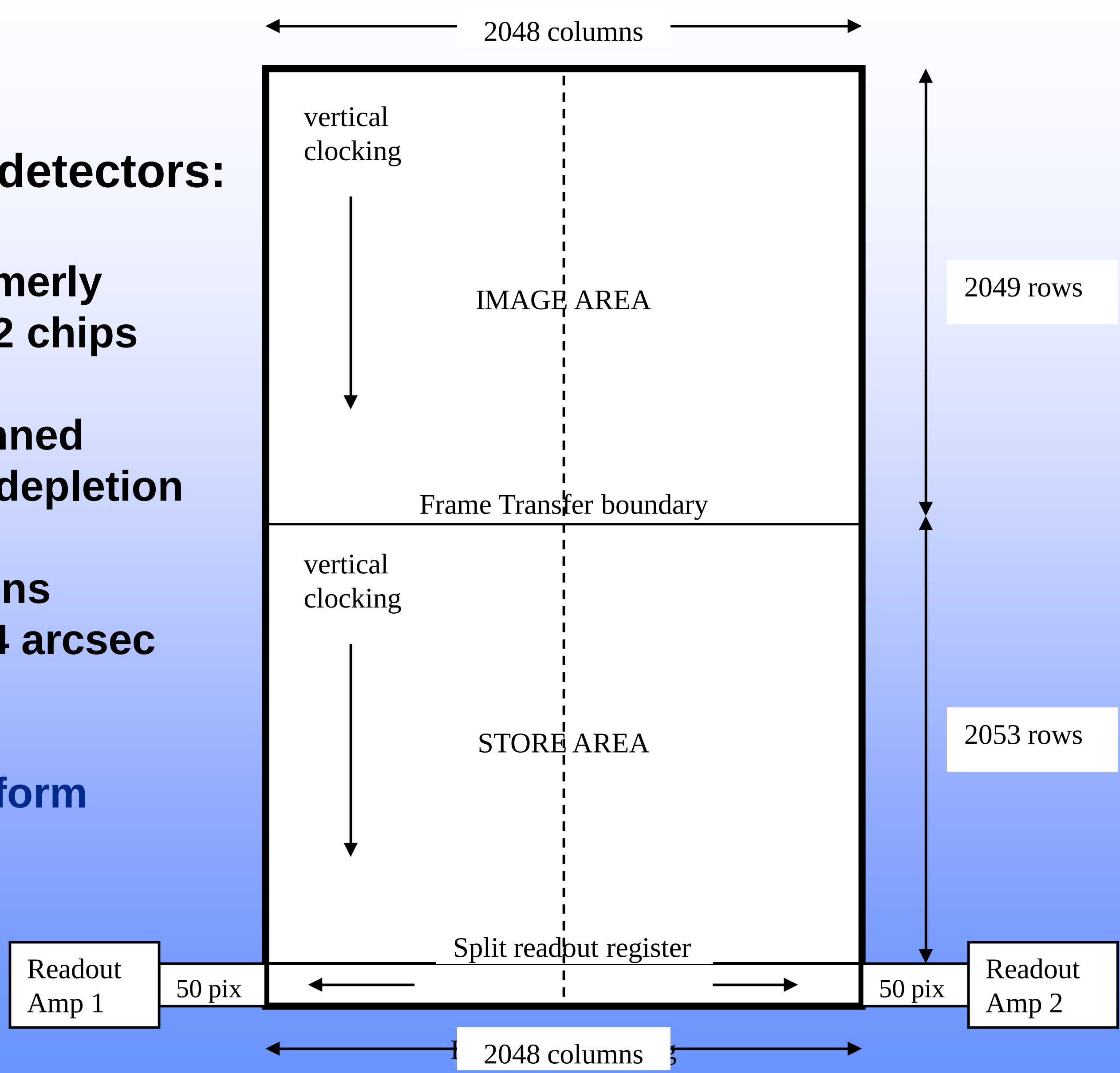
SALTICAM/RSS CCD detectors:

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

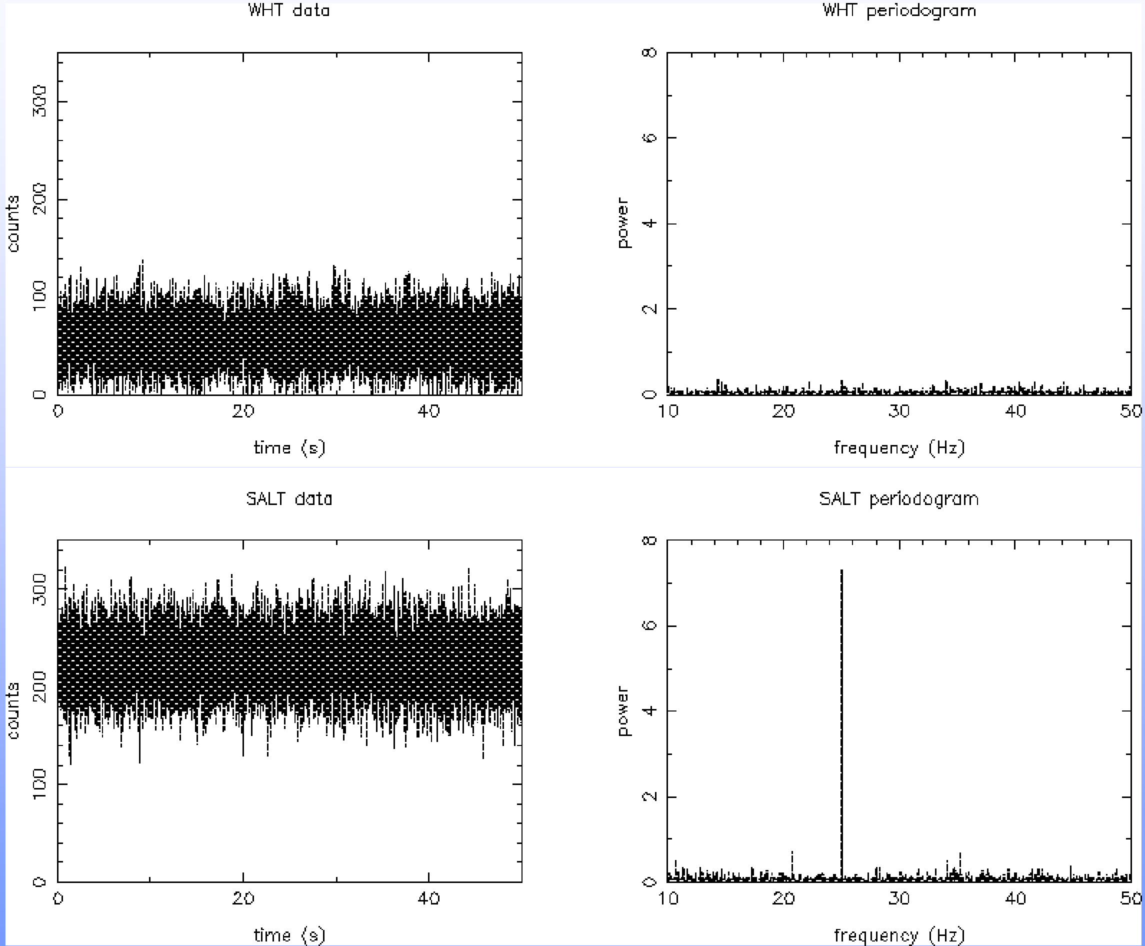
Two chips mosaiced to form 4k x 4k area



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

- ***power*** $\propto$ ***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)

Full Frame Readout Mode (using shutter)

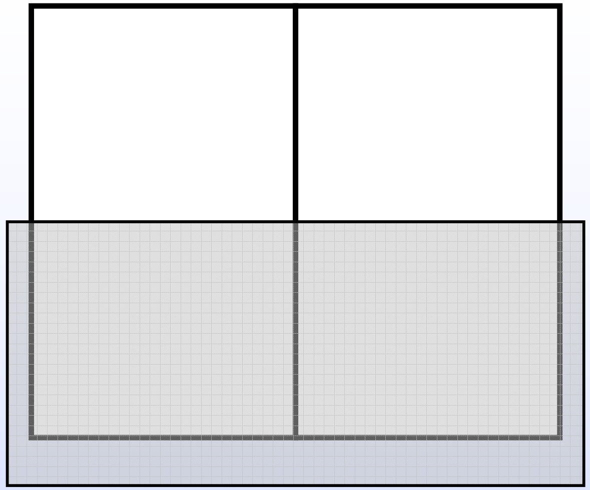
8 arcmin FoV:	**13.8 sec (@2.3e read noise)**
	5.5 sec (@4e)

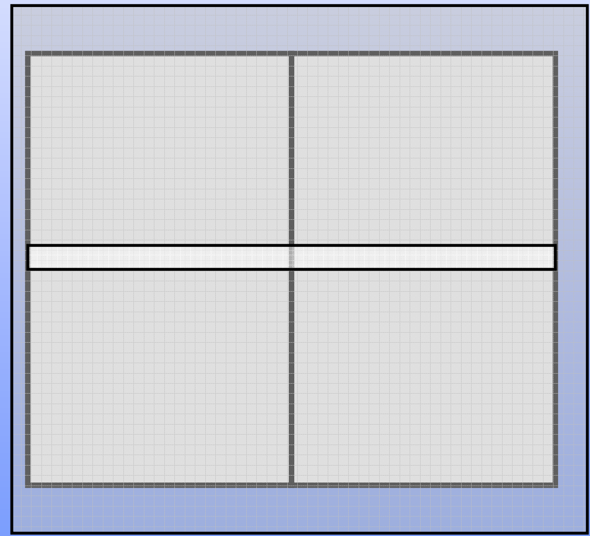
Frame Transfer Mode

Half of 8 arcmin circular FoV	6.3 sec (@2.3e)
	2.4 sec (@4e)

Fastest windowed photometry

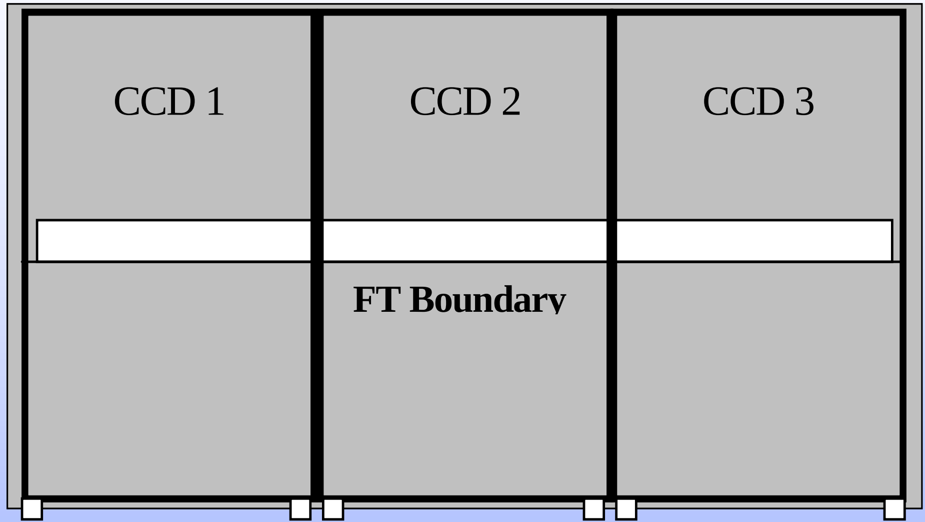
Slot mode	0.076 sec (@4 e)
Slot + windowed mode	0.050 sec

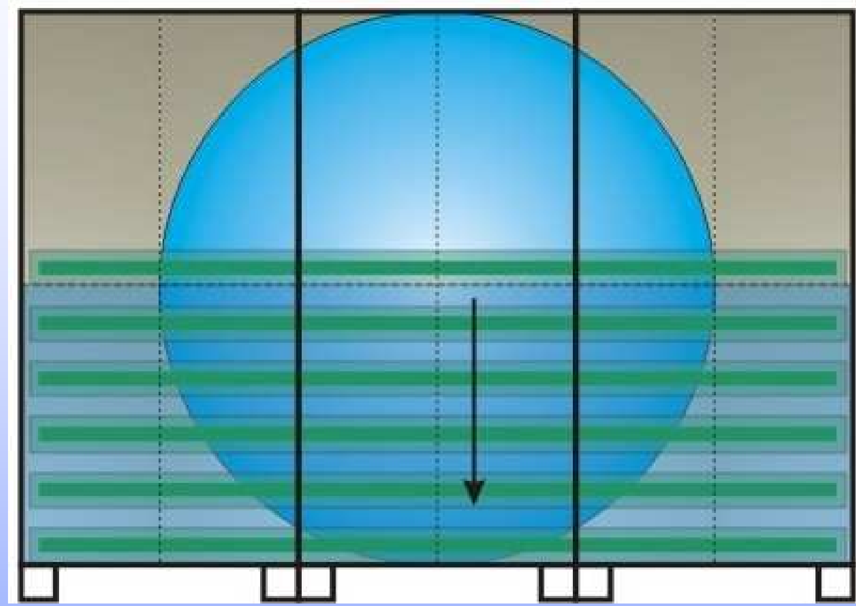




Unvignetted slot size is 64 pixels (~ 9 arcsec)

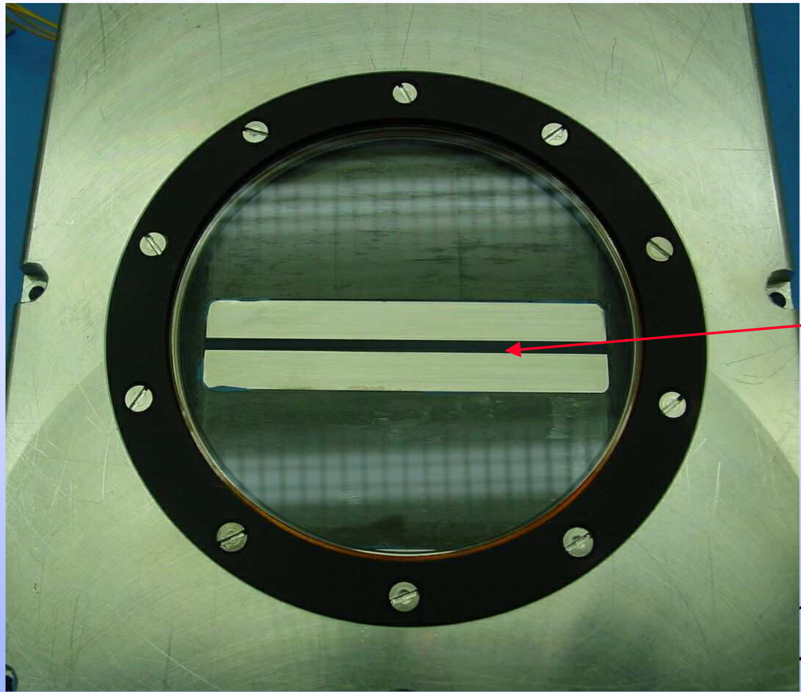
RSS High Speed mode





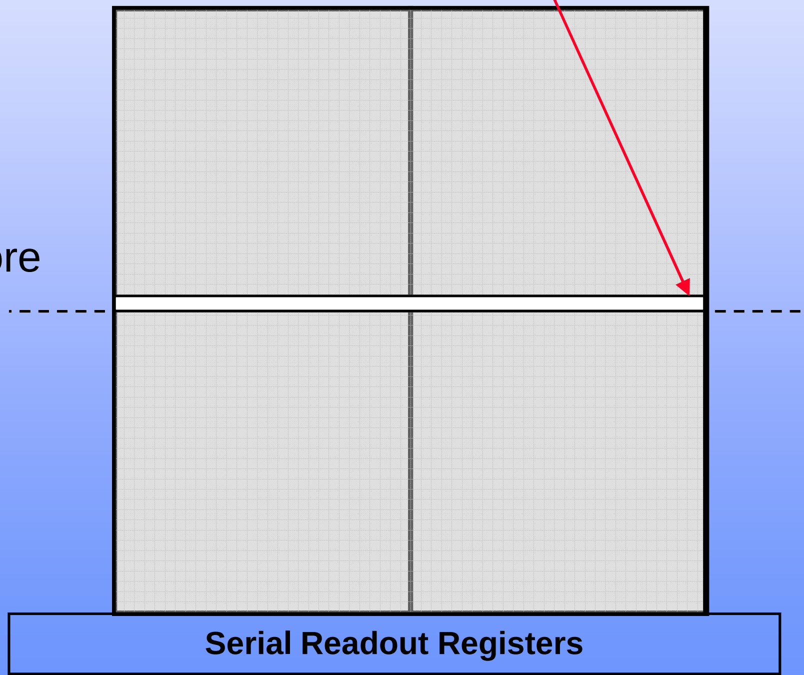
Fast spectroscopy
Fast spectropolarimetry
Fast imaging polarimetry

SALTICAM Frame Transfer Mask in High Speed ‘Slot Mode’



Slot ~11 arcsec wide

nage/store
rea split



Slot Mode Control:

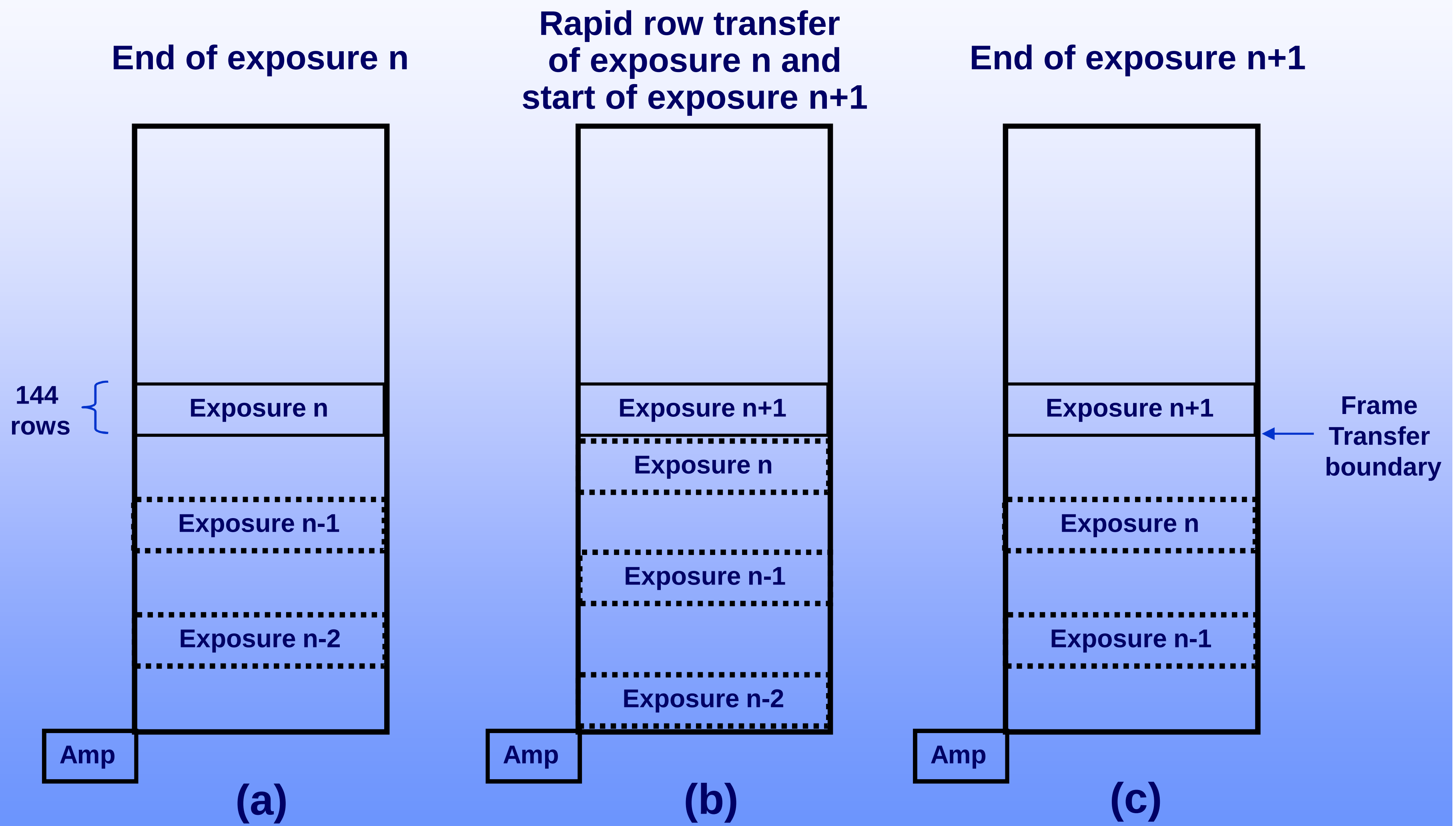
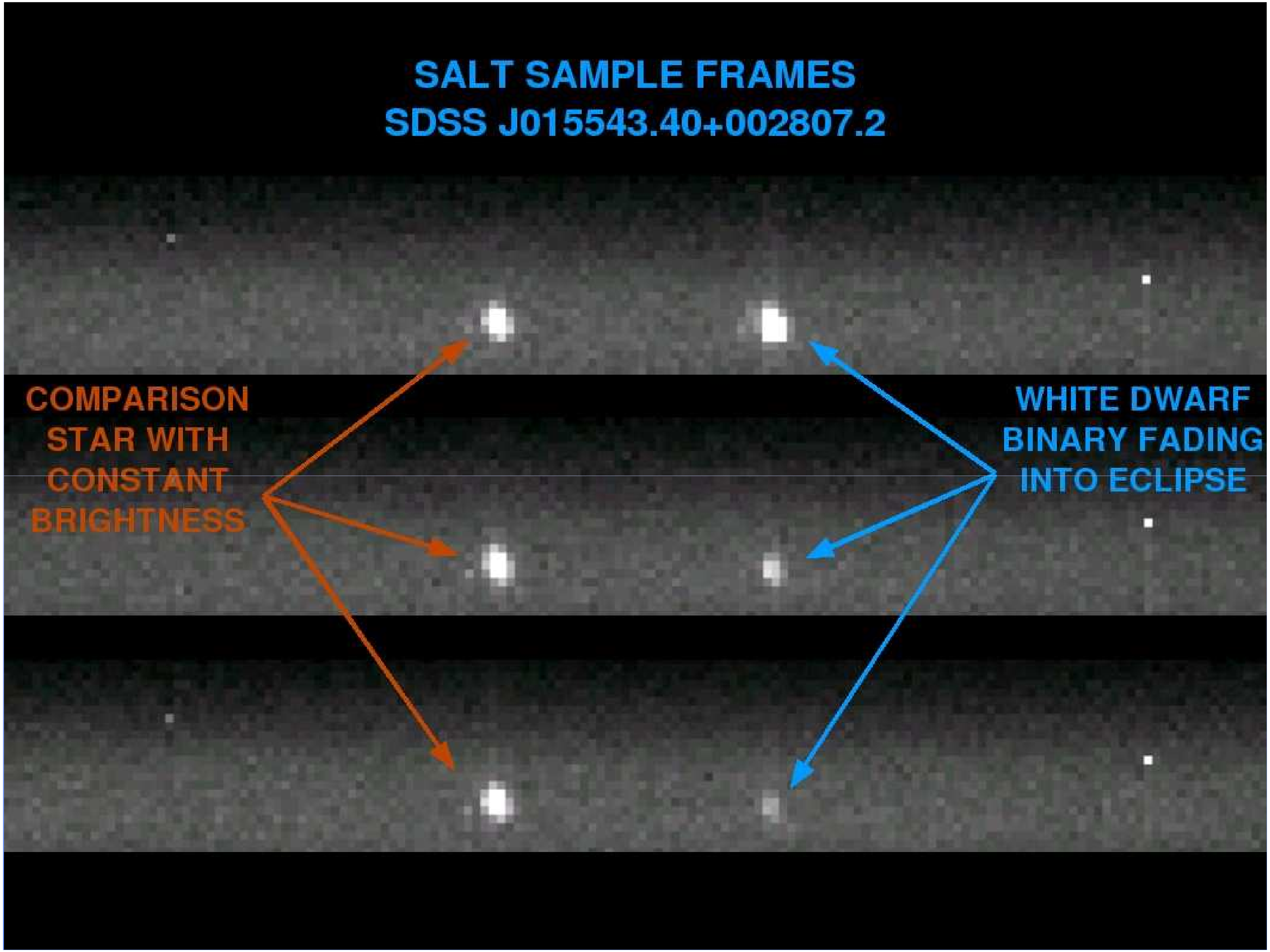
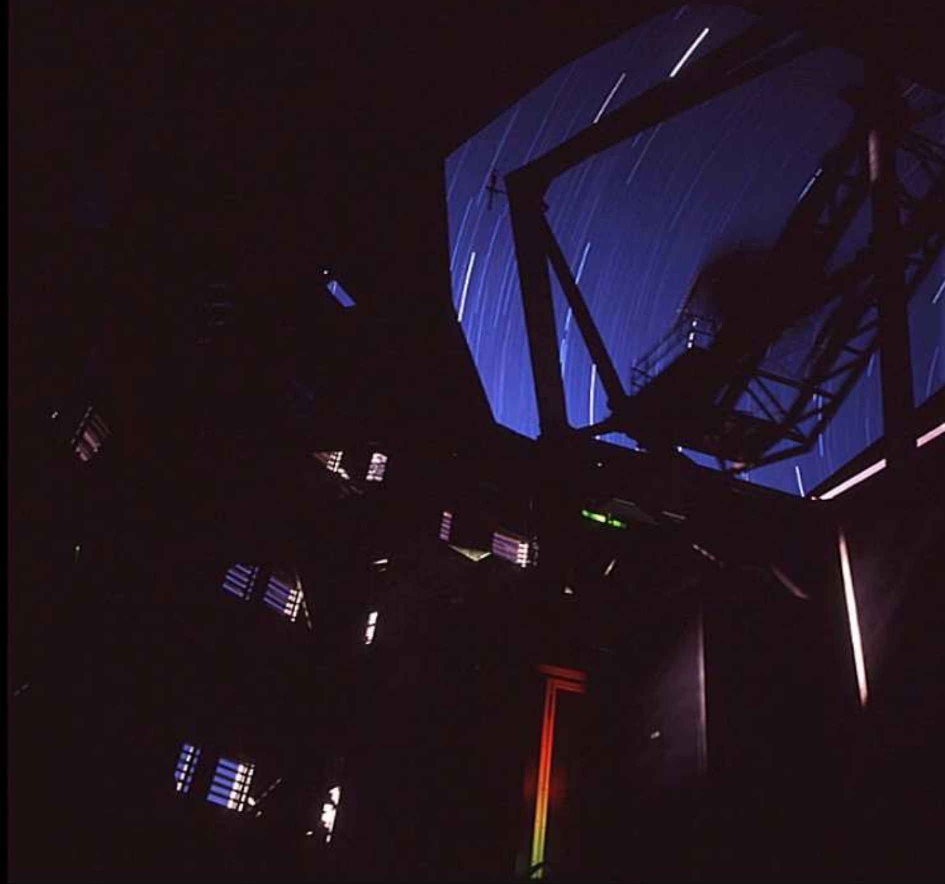
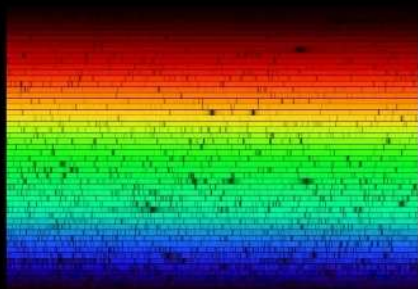


Figure 2. Control scheme for fastest sampling


SALT SAMPLE FRAMES
SDSS J015543.40+002807.2
COMPARISON STAR WITH CONSTANT BRIGHTNESS
WHITE DWARF BINARY FADING INTO ECLIPSE

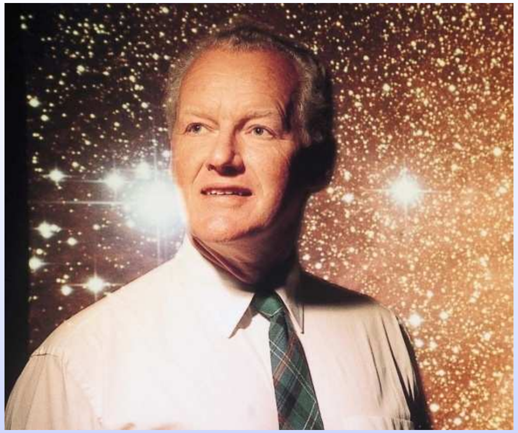
FINGERPRINTING STARLIGHT





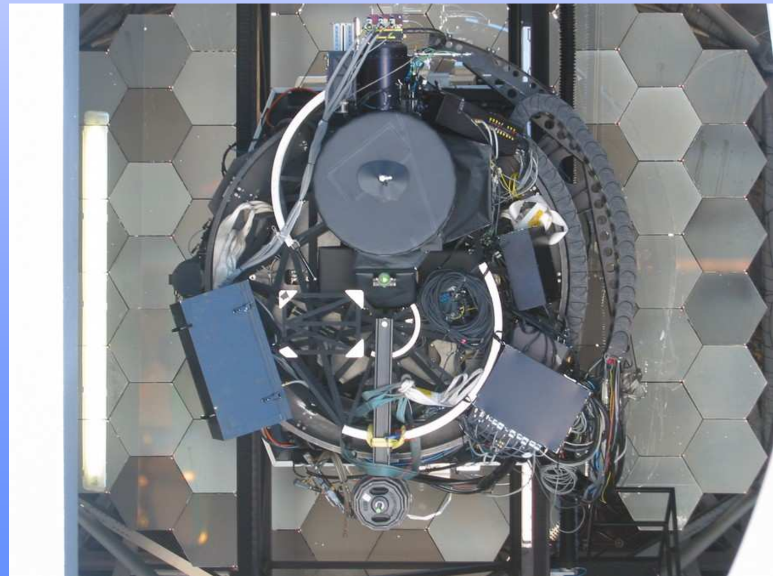
The Robert Stobie Spectrograph (RSS)
(built at Wisconsin, Rutgers & SAAO)

An efficient and versatile Imaging Spectrograph
- **capable of UV spectroscopy**
- **high time resolution ablility**
- **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)



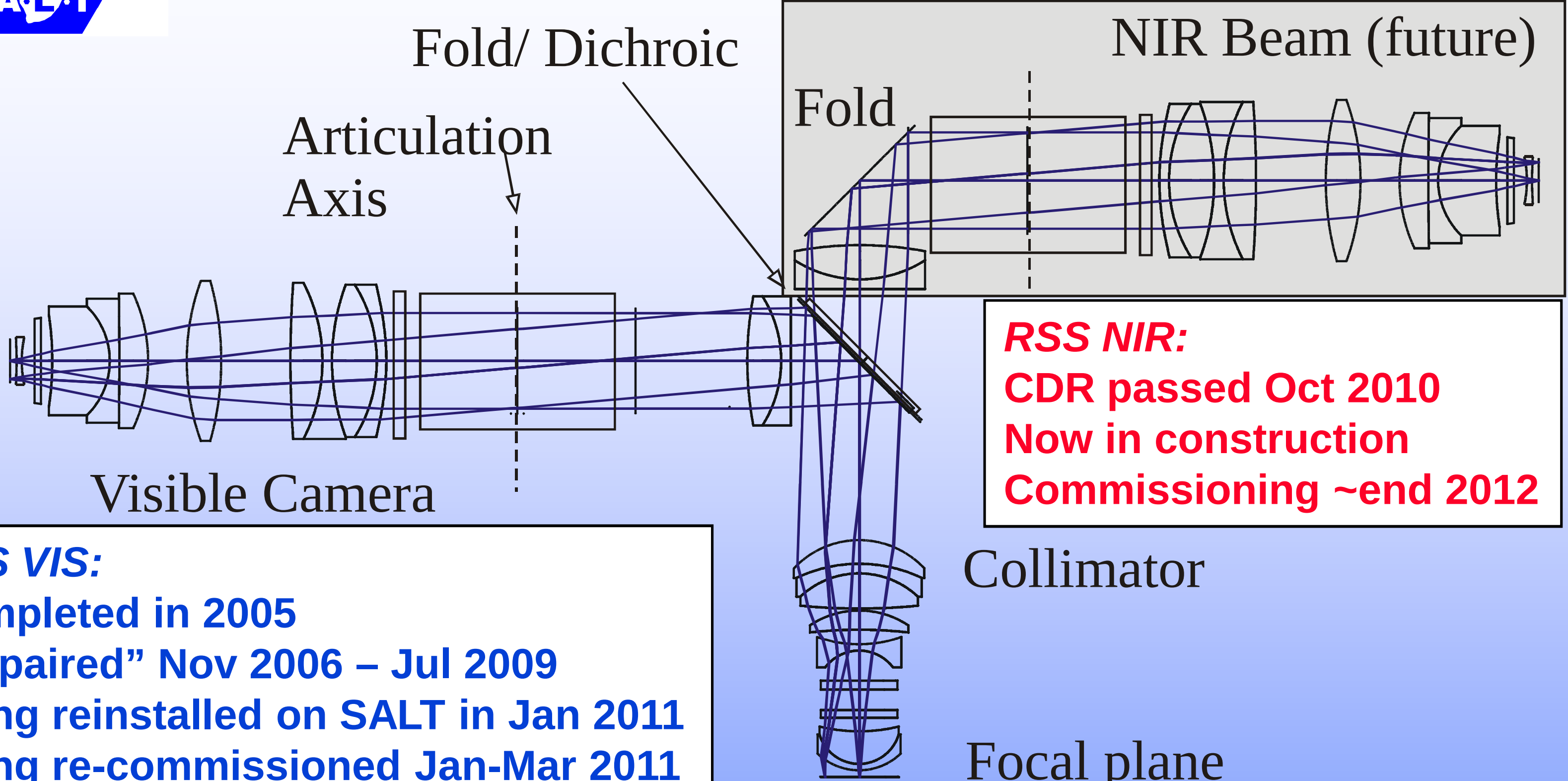
RSS installed on SALT (Oct 2005)

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



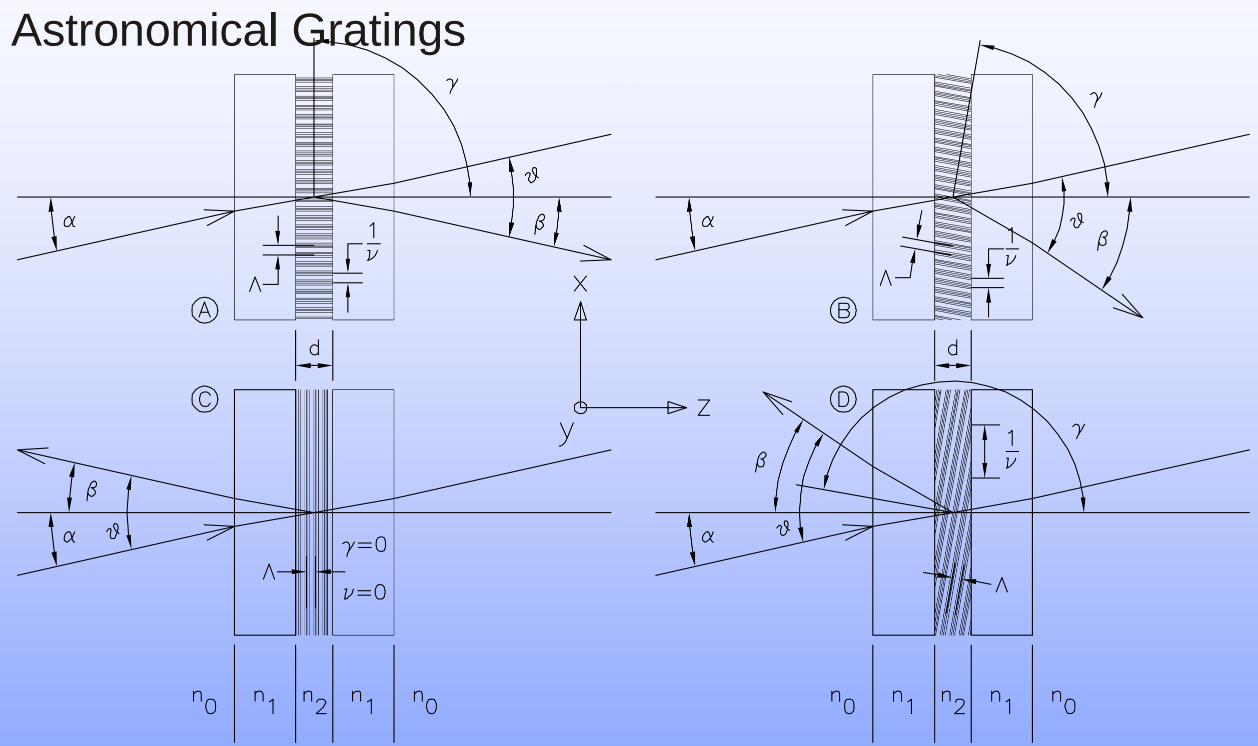
RSS NIR:
CDR passed Oct 2010
Now in construction
Commissioning ~end 2012

RSS VIS:
Completed in 2005
"Repaired" Nov 2006 – Jul 2009
Being reinstalled on SALT in Jan 2011
Being re-commissioned Jan-Mar 2011

- **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 Ǻ – 1.7 μ (e.g. X-Shooter)**

How VPH Gratings Work

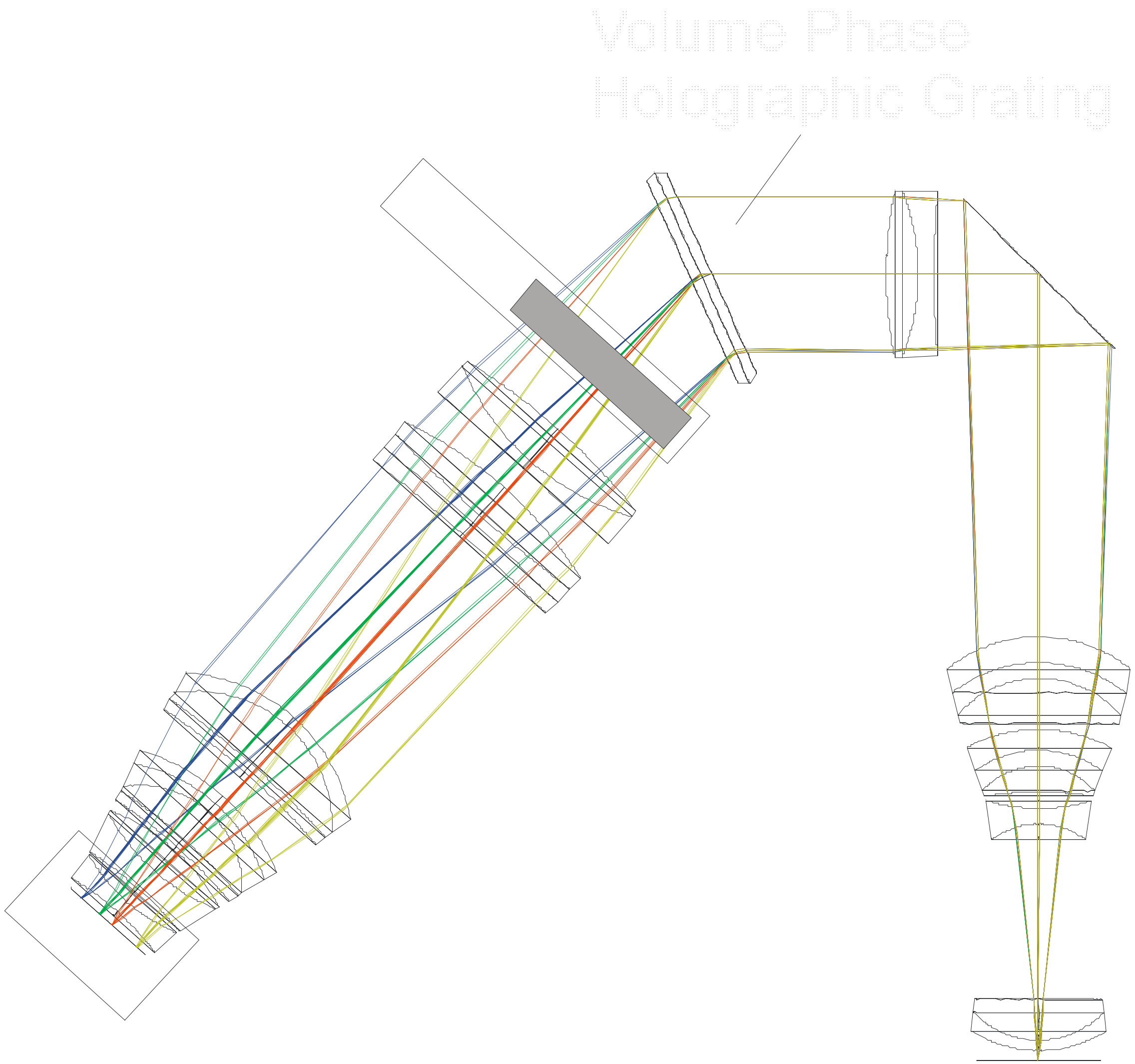
VPH Gratings. From Barden, et al, 2000, PASP

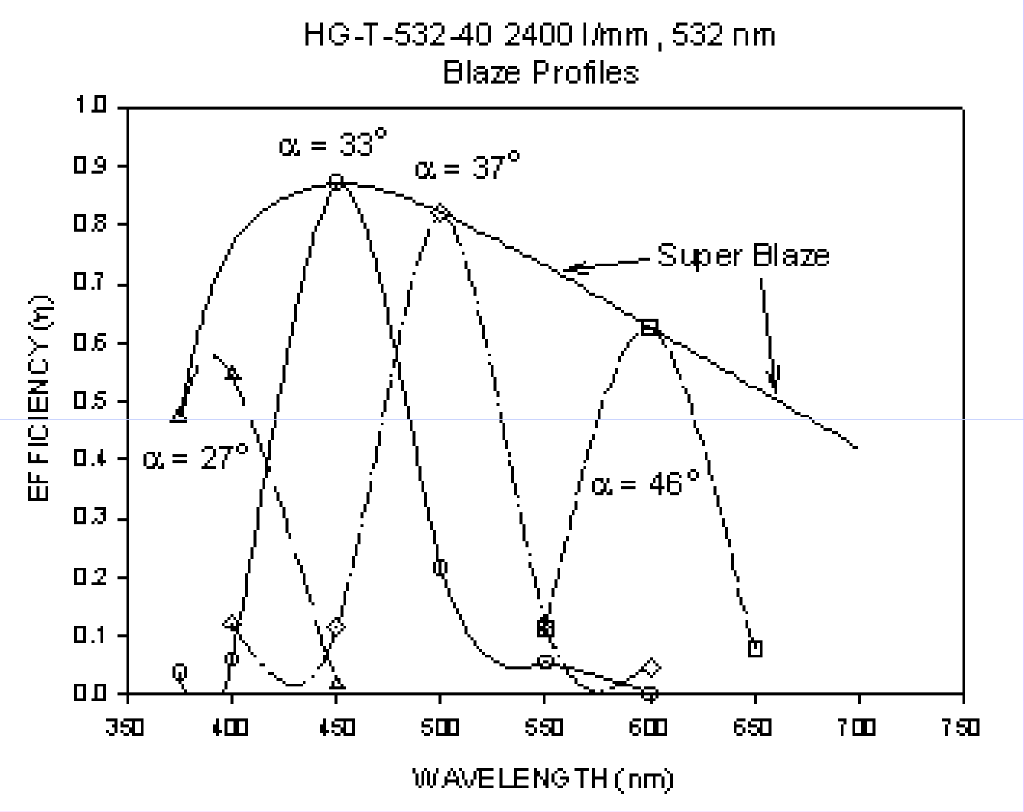


- **Created by exposing holograph material ("DiChromated Gelatin") to interference pattern from laser**
- **Index of refraction of DCG is modulated in space**
- **Large; inexpensive; custom design; efficient at high groove density**

ftp://saltdata.salt.ac.za/2011-3-RSA_OTH-025.20120328.tar.bz2

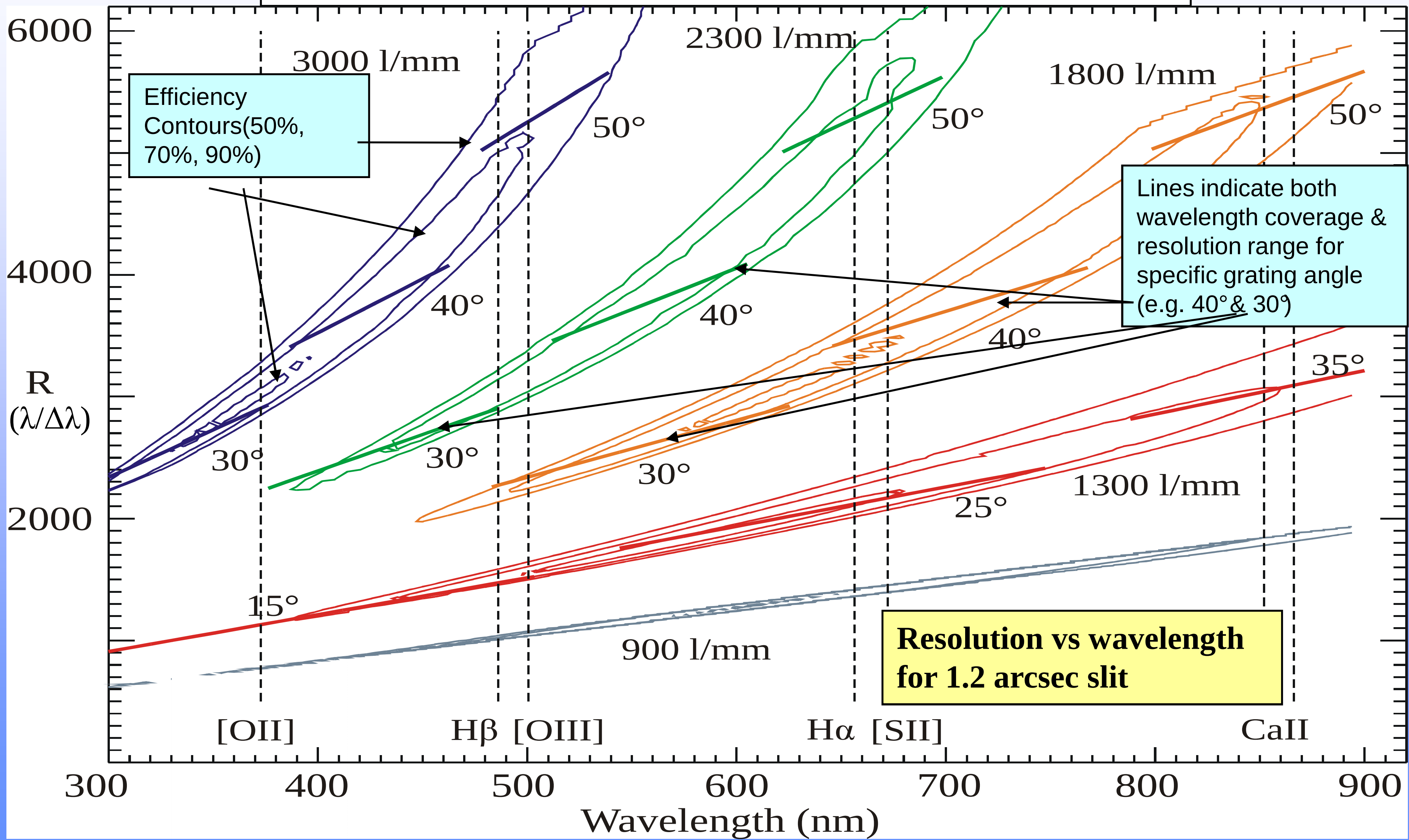
RSS Spectroscopy





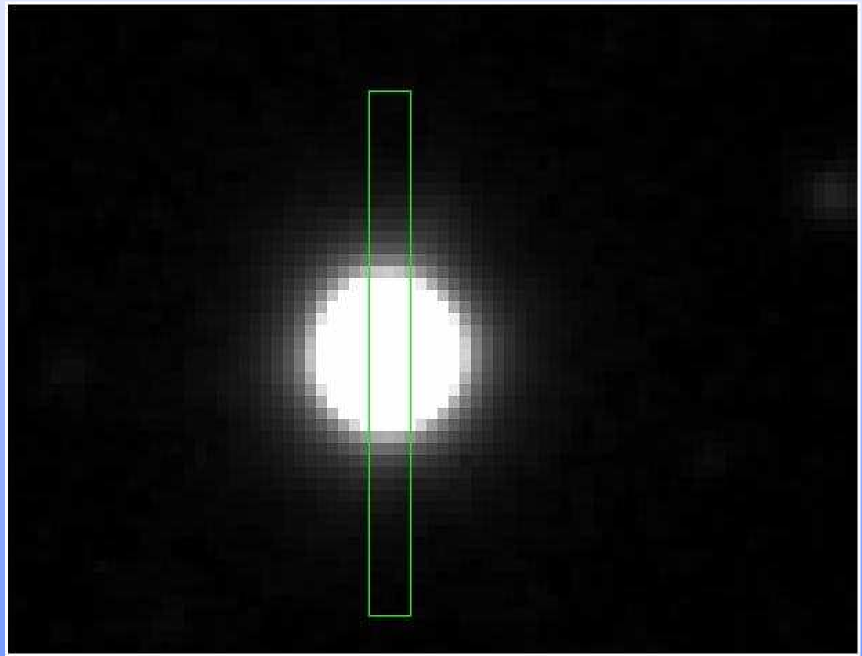
Measured efficiency in unpolarized light for the 2400 l/mm VPH grating (optimized for 532 nm) at grating angles of 27, 33, 37, and 46 degrees. The super blaze shows the envelope of peak efficiency as the grating is tuned to different grating angles.

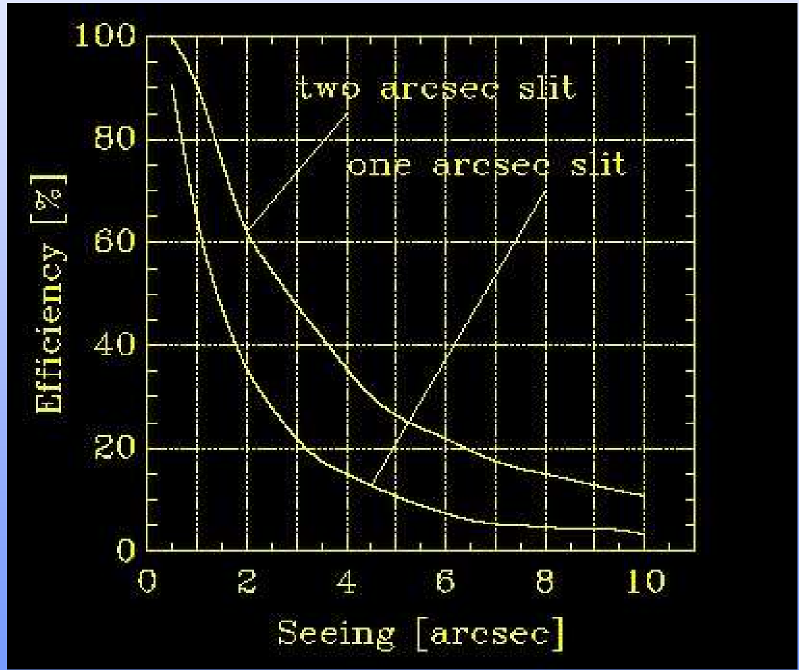
The SALT Volume Phase Holographic Gratings



Effect of bad focus and seeing in Spectroscopy

Slit width/ Slit loss





$$\Delta x = w \frac{\cos i}{\cos \theta} \frac{f_{\rm cam}}{f_{\rm coll}}$$

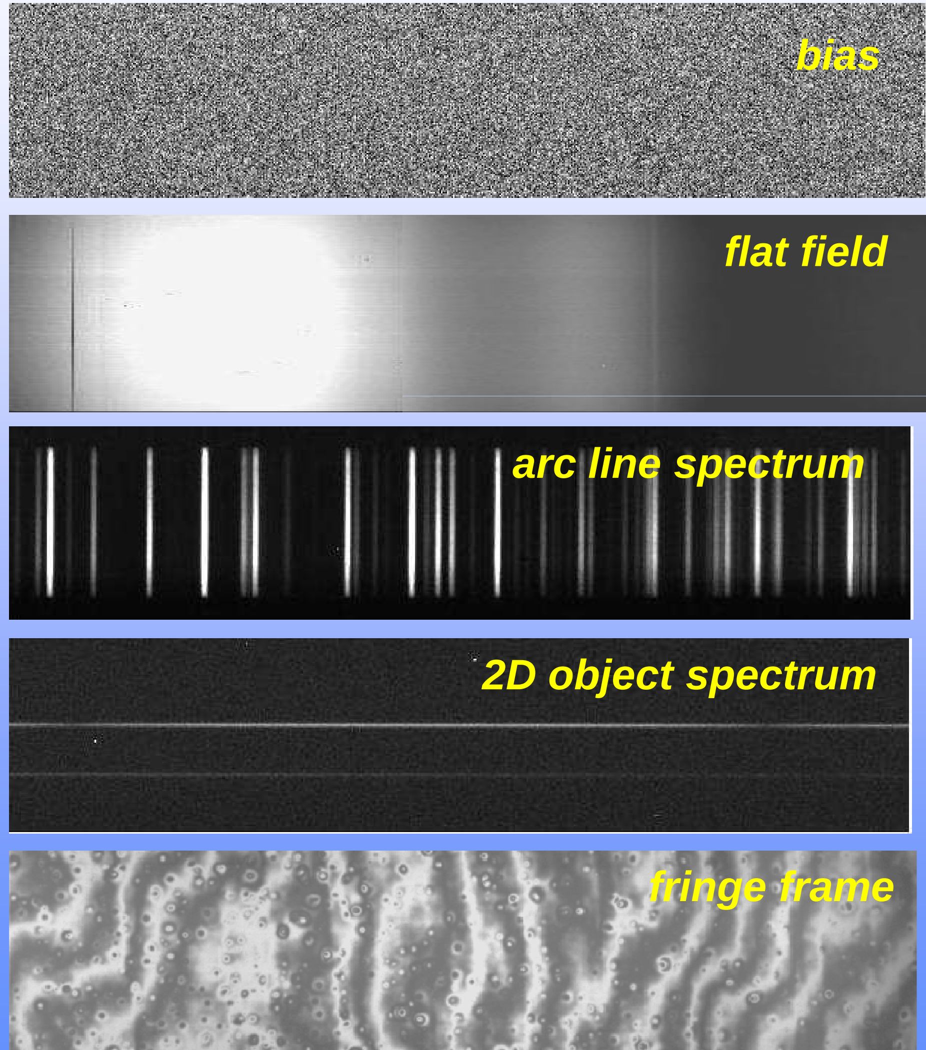
Reducing Spectroscopic Data

Calibration frames:

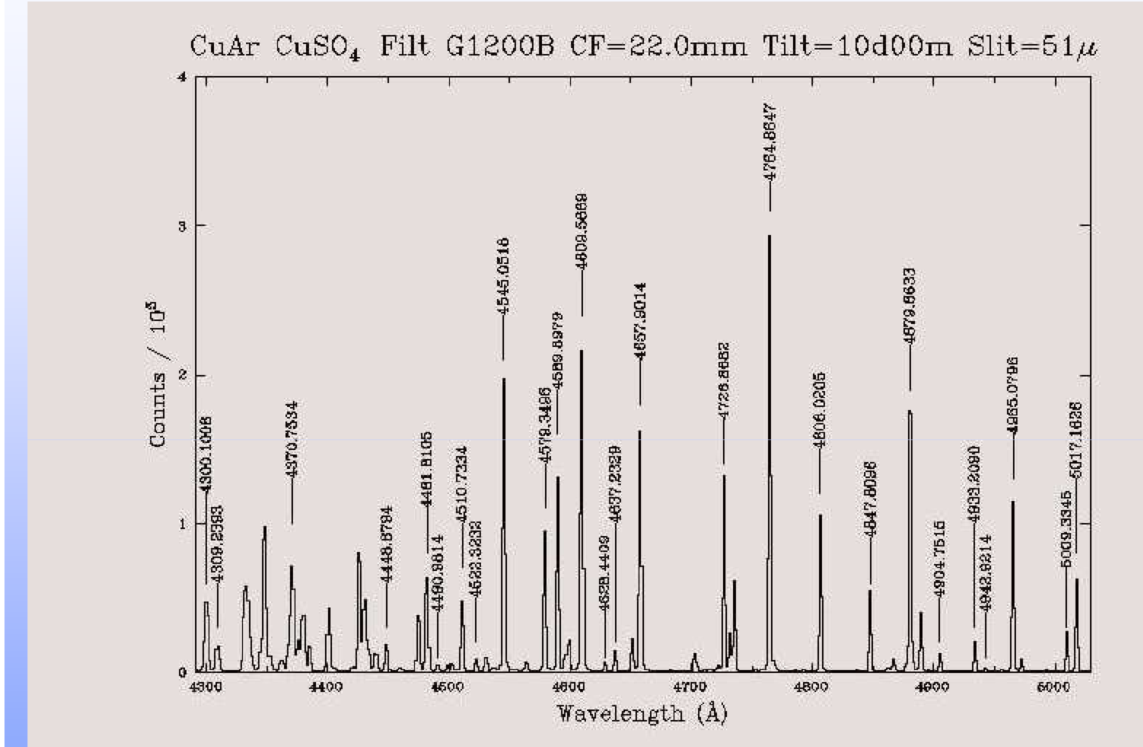
* **Bias frame (electronic DC level)**
   - sometimes derived from "overscan" or "prescan"
* **Flat field (detector sensitivity)**
* **Arc Lamp (wavelength calibration)**
* **Flux Standard**
   - flux from *electrons* cm^{-2} sec^{-1} $Å^{-1}$
   to *ergs*/cm^{-2} sec^{-1} $Å^{-1}$
* **Fringe frame correction**

Basic reduction procedures:

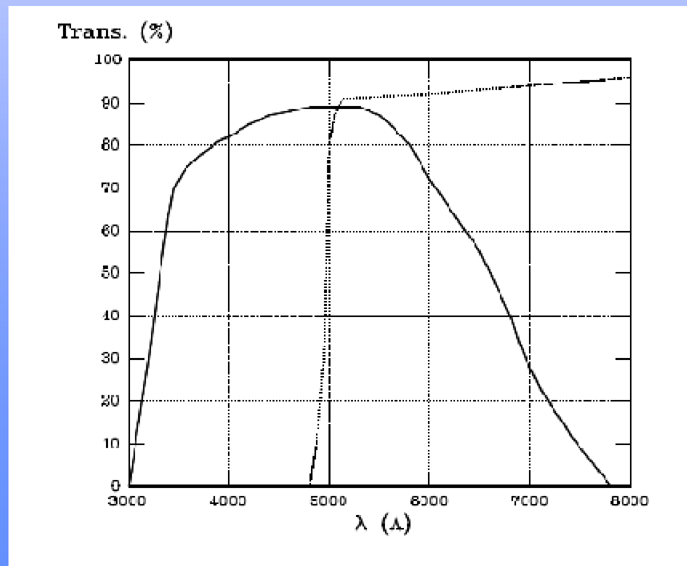
1. Bias correction
2. Flat fielding
3. Cosmic ray removal
4. Wavelength determination
5. Background subtraction
6. Spectrum extraction
7. Flux calibration (remove atm. effects)



Wavelength Calibrations

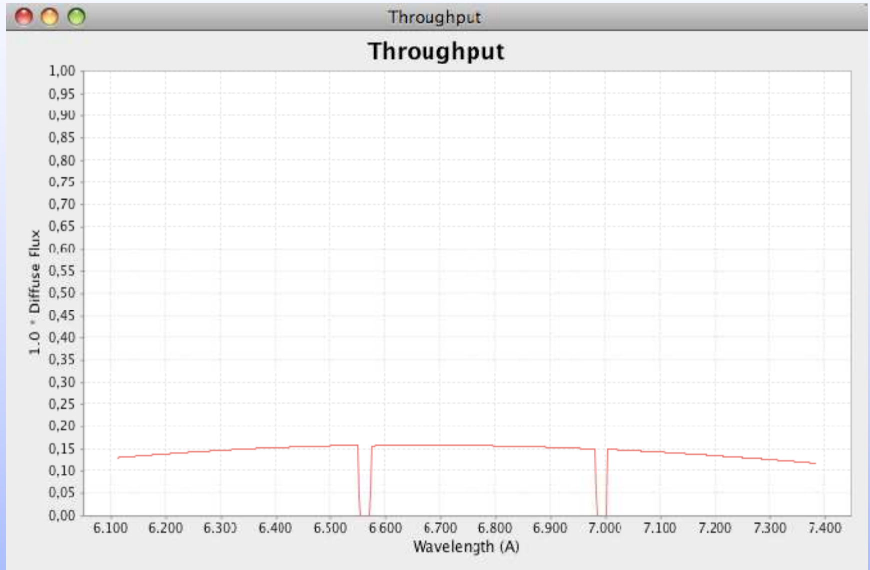


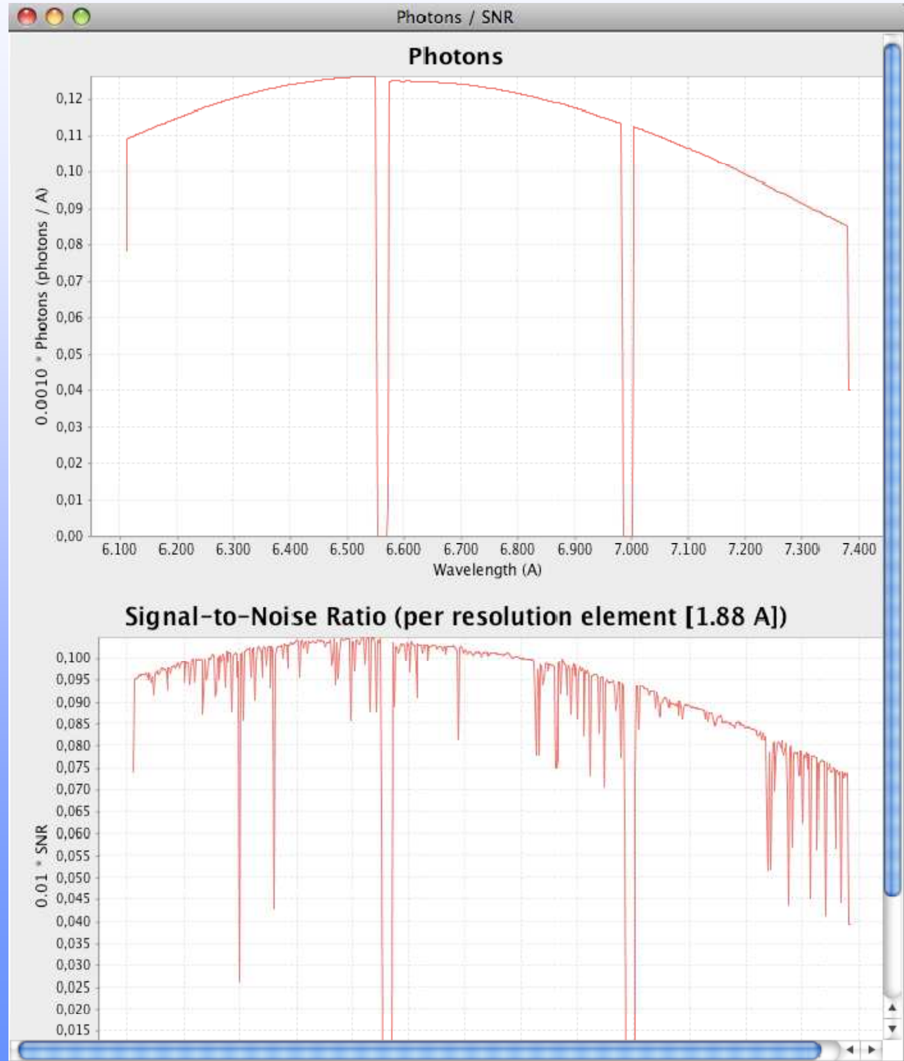
- Determine ***wavelength*** as a function of ***pixel number*** on the detector
- Typically use 3rd order polynomial fit to known wavelengths
- Need to have ***order blocking*** filters to exclude 2nd order overlap in the 1st order, 3rd in 2nd, etc.



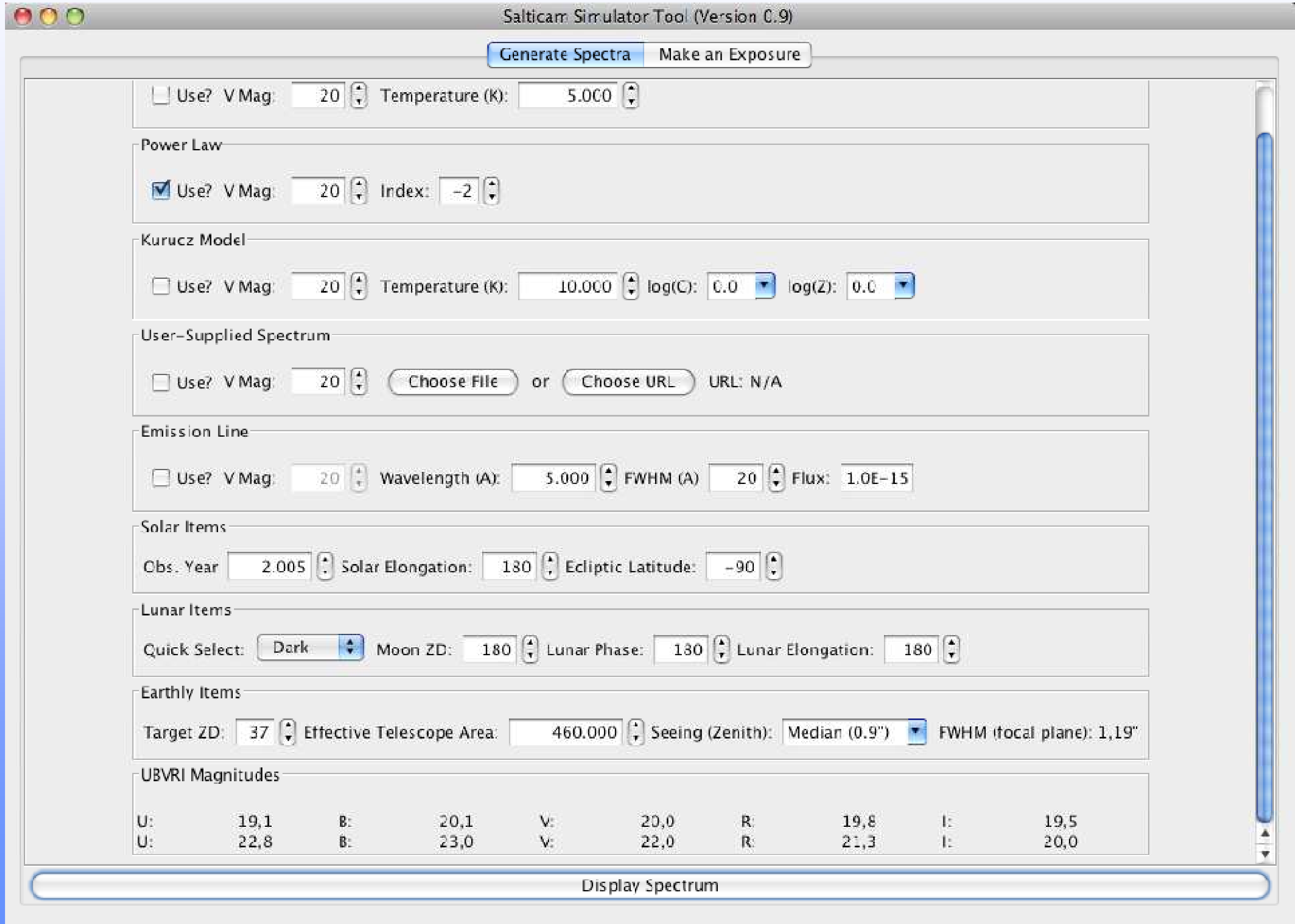
Configuring RSS

RSS Plots

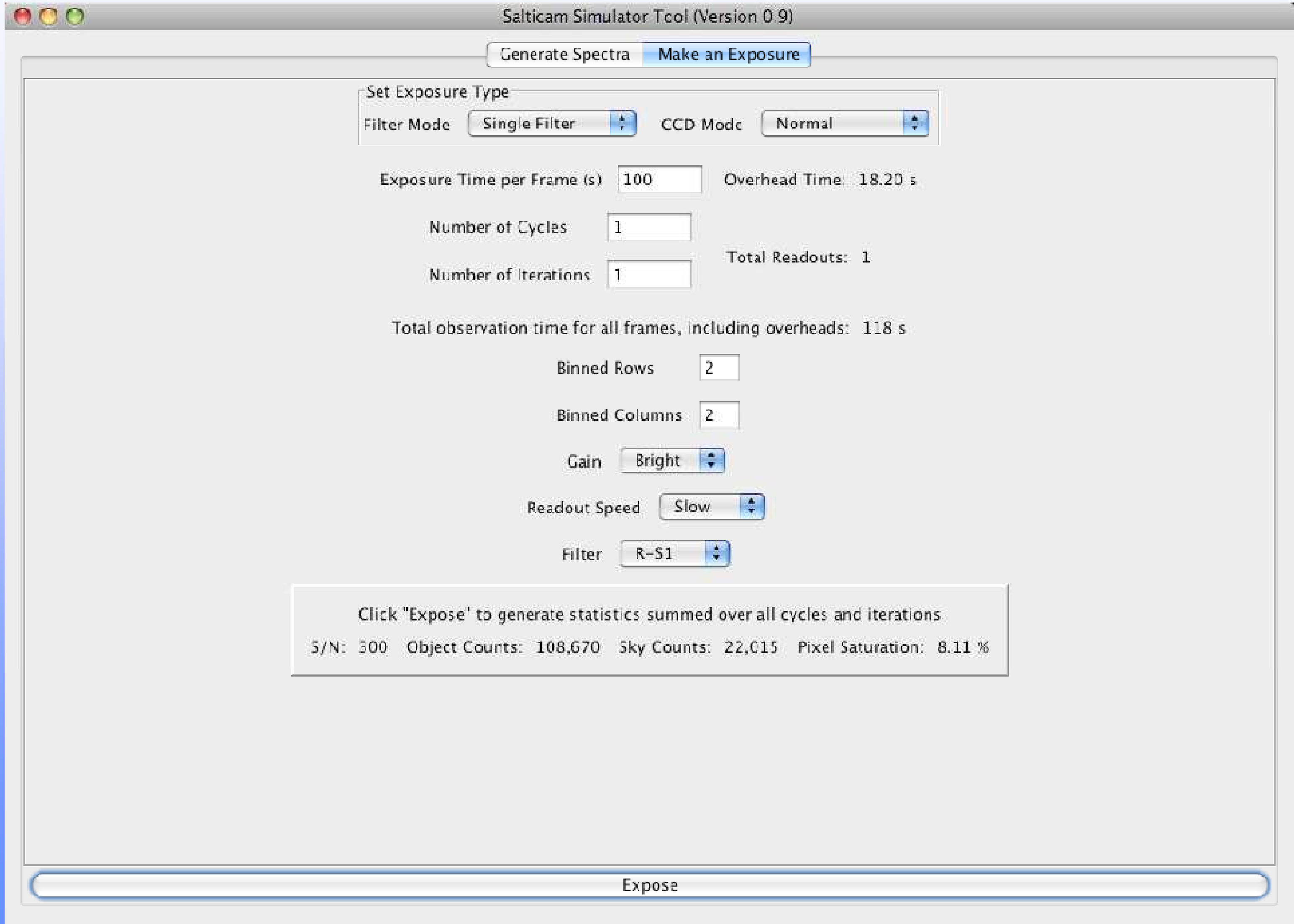

Throughput
Throughput
1.0 * Diffuse Flux
Wavelength (A)


Photons / SNR
Photons
0.0010 * Photons (photons / A)
Wavelength (A)
Signal-to-Noise Ratio (per resolution element [1.88 A])
0.01 * SNR

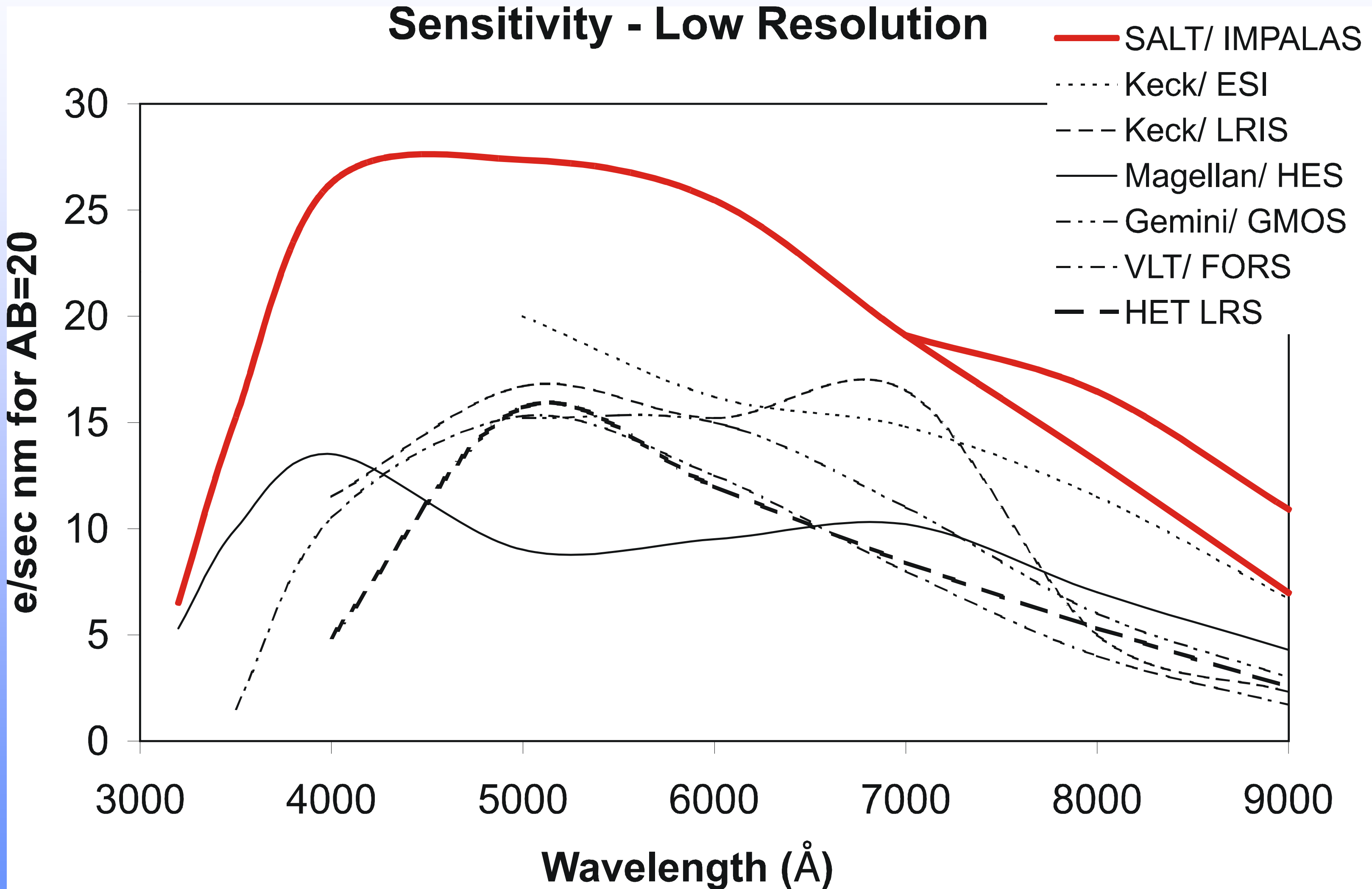
Configuring SALTICAM



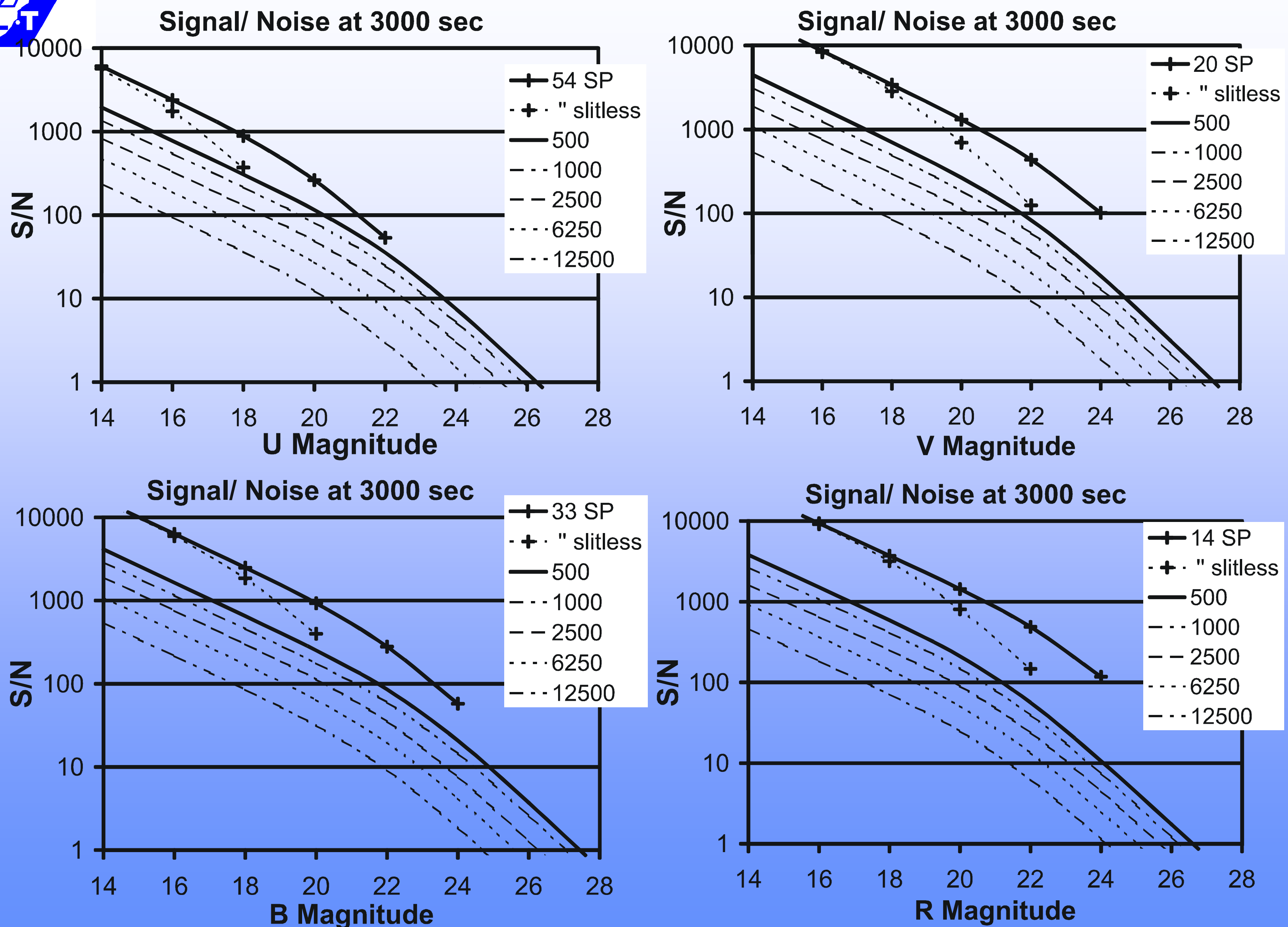
Configuring SALTICAM



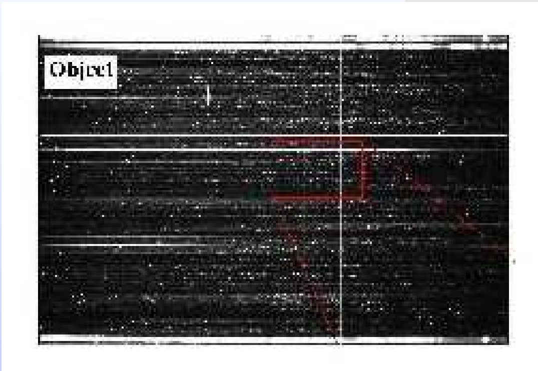
Comparison with other Spectrographs



Signal/ Noise vs mag

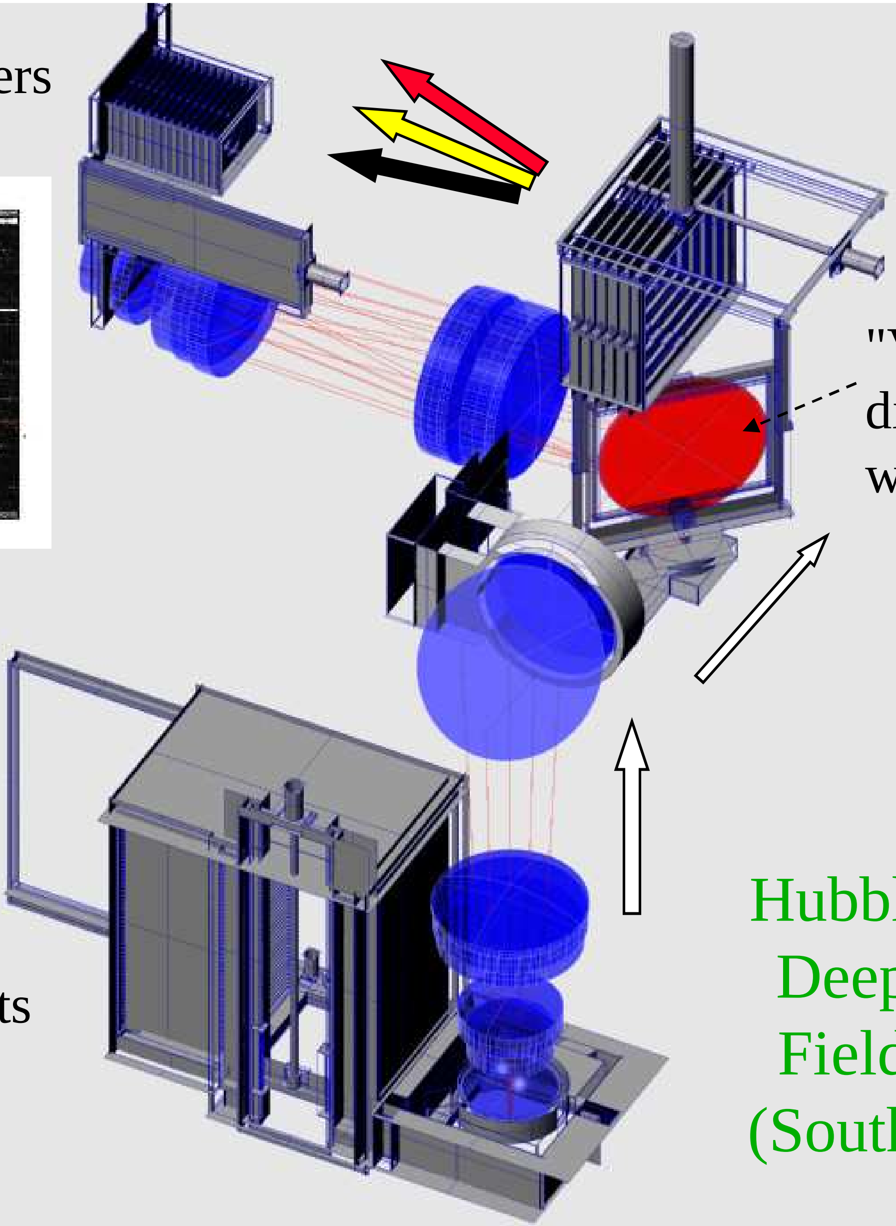


Multi-Object Grating Spectroscopy



Up to 40 Spectra

Filters

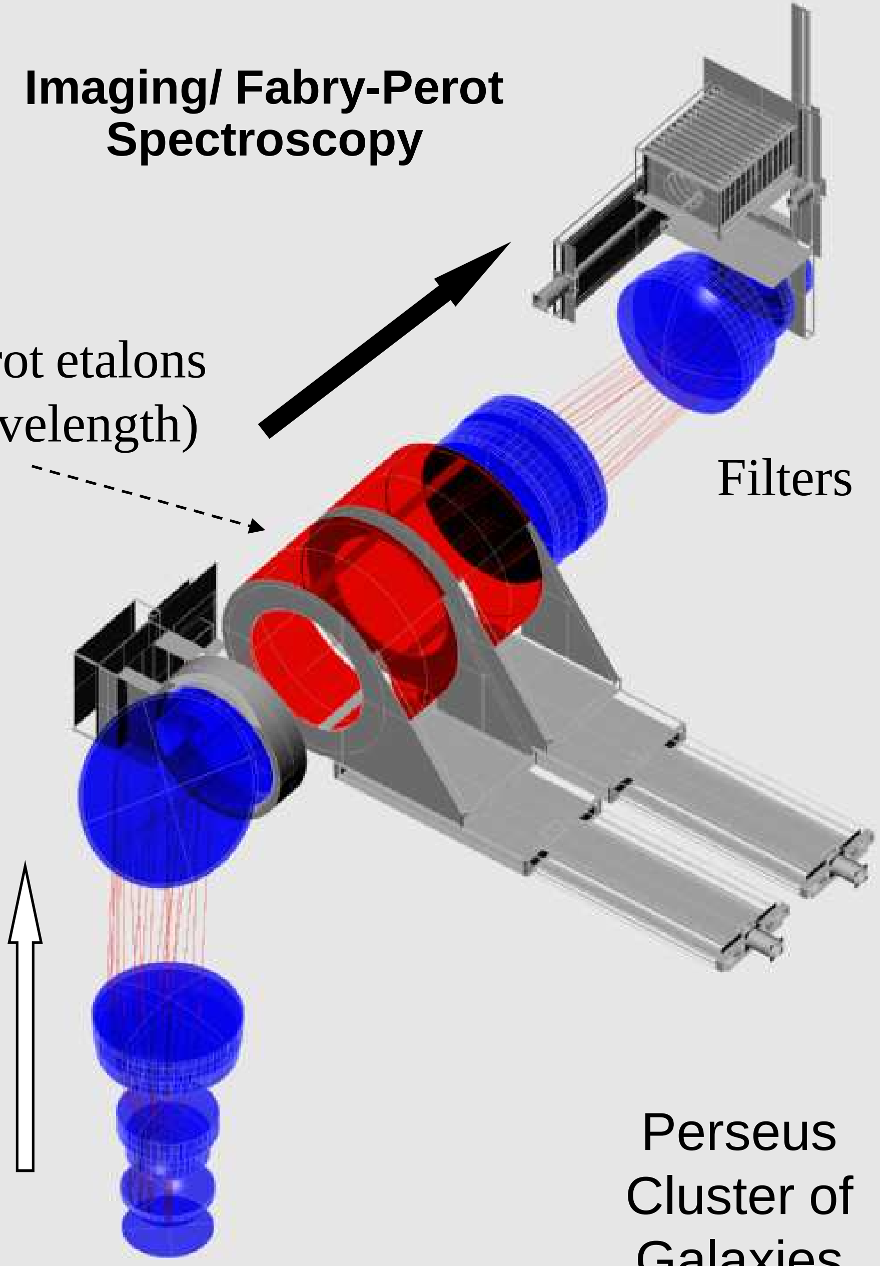


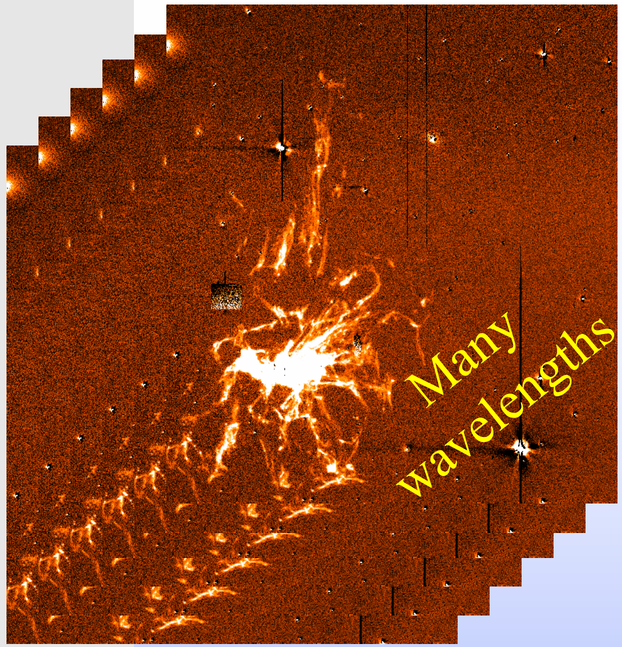
"VPH" Grating disperses wavelengths

Slitmasks selects objects

Hubble Deep Field (South)

Imaging/ Fabry-Perot Spectroscopy





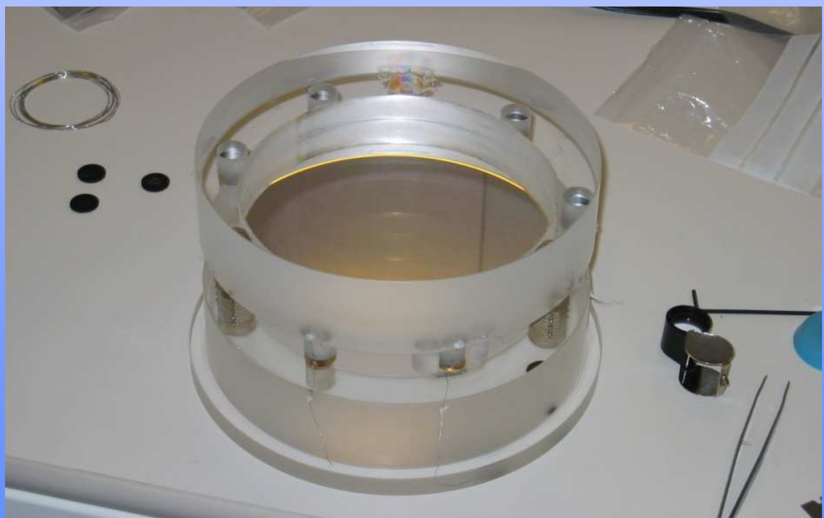
Perseus A in Hydrogen Light

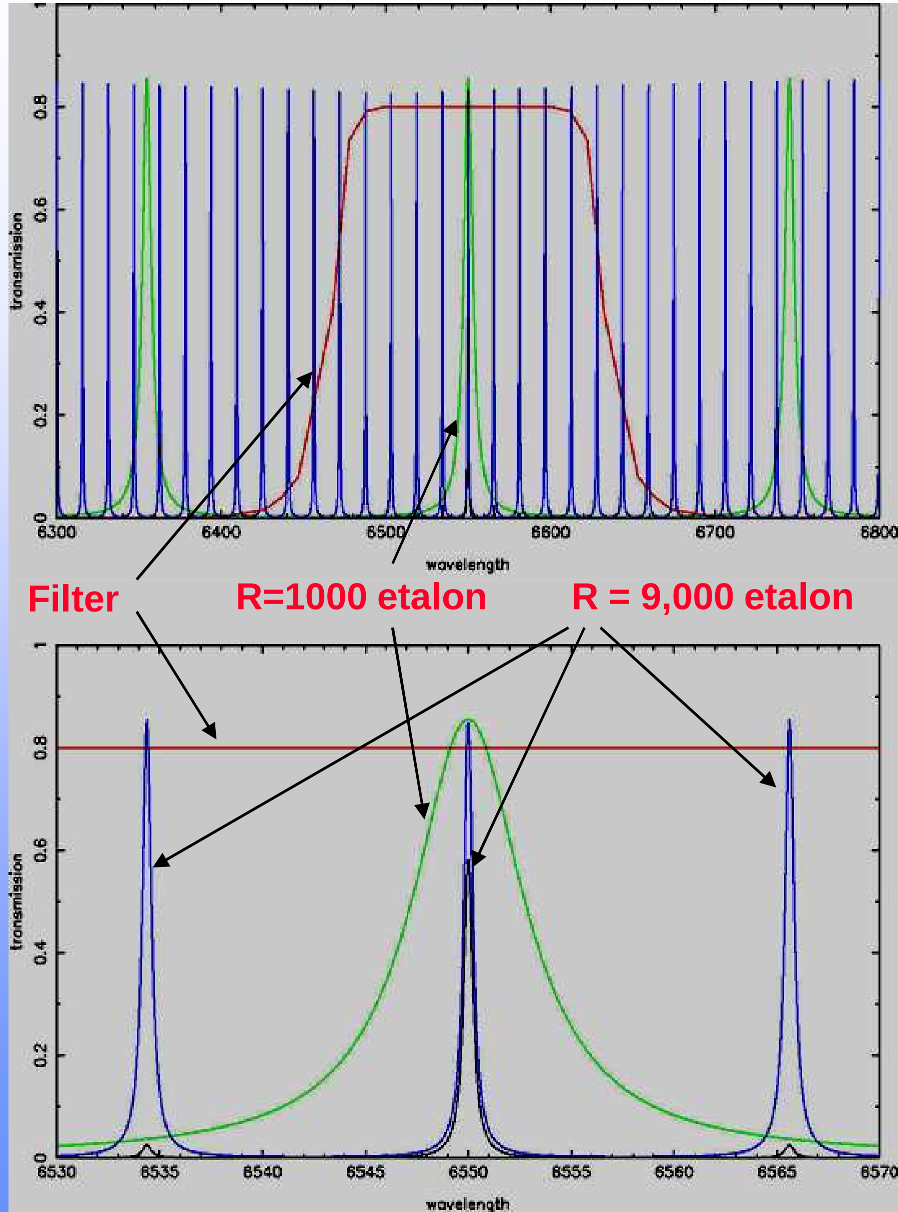
Perseus Cluster of Galaxies

RSS: Fabry-Perot mode

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'**

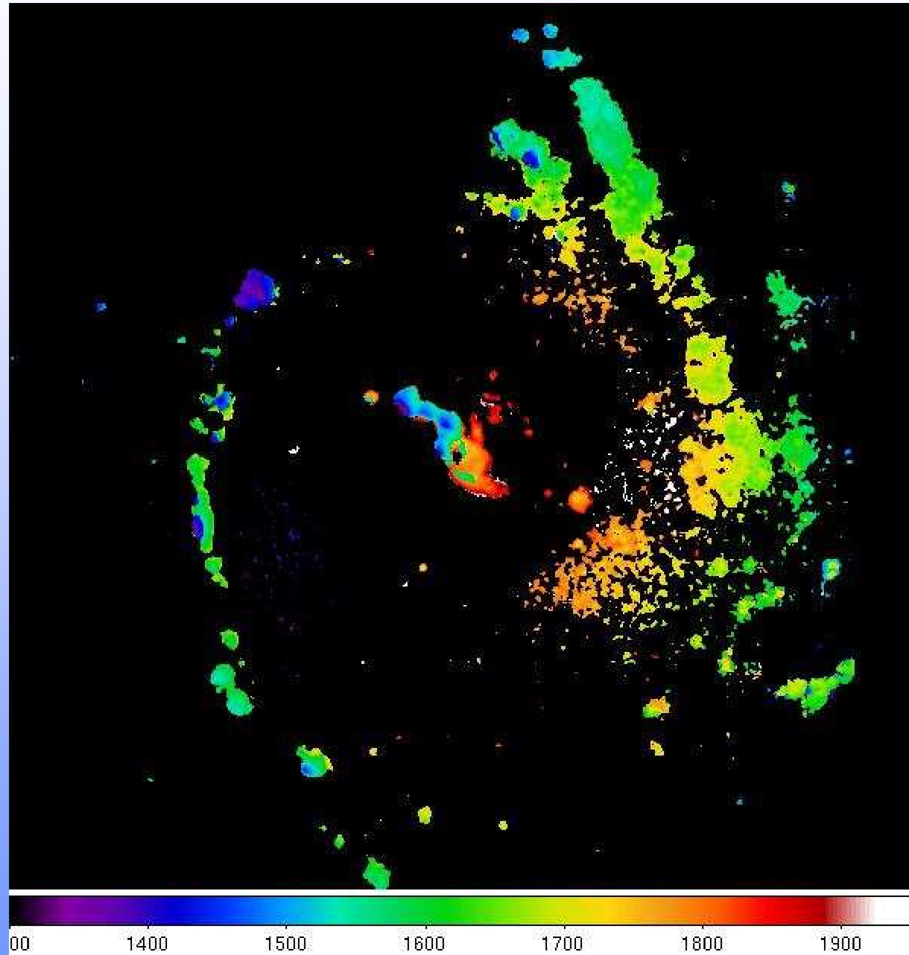
Using 150mm diameter *Queensgate* etalons Finesse ~30, implying 75-80% throughput Using ~30 R = 50 interference filters (latter can also be used on their own for narrow band imagery).





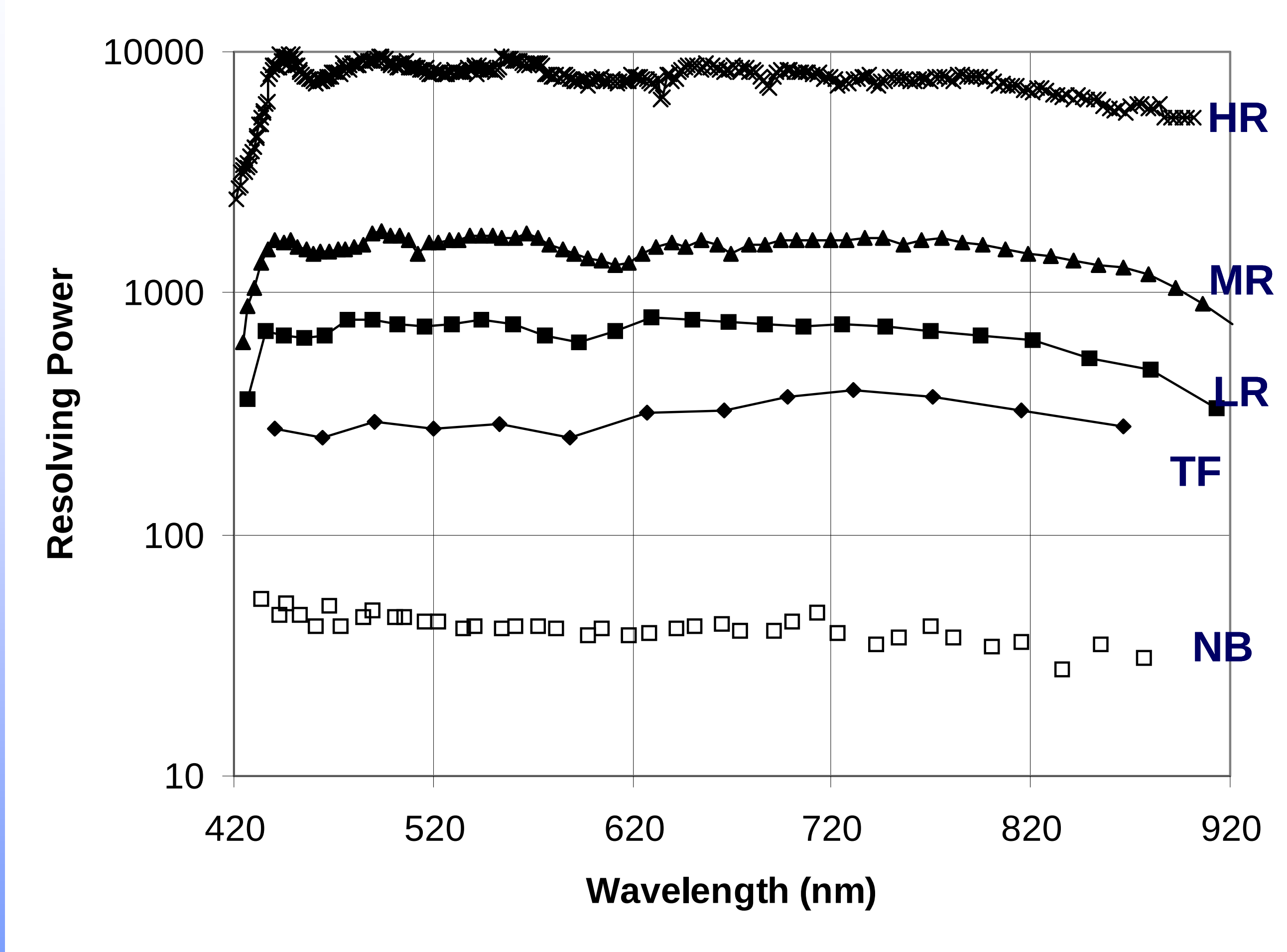
Fabry-Perot Commissioning Observations

H-alpha image



Velocity Map

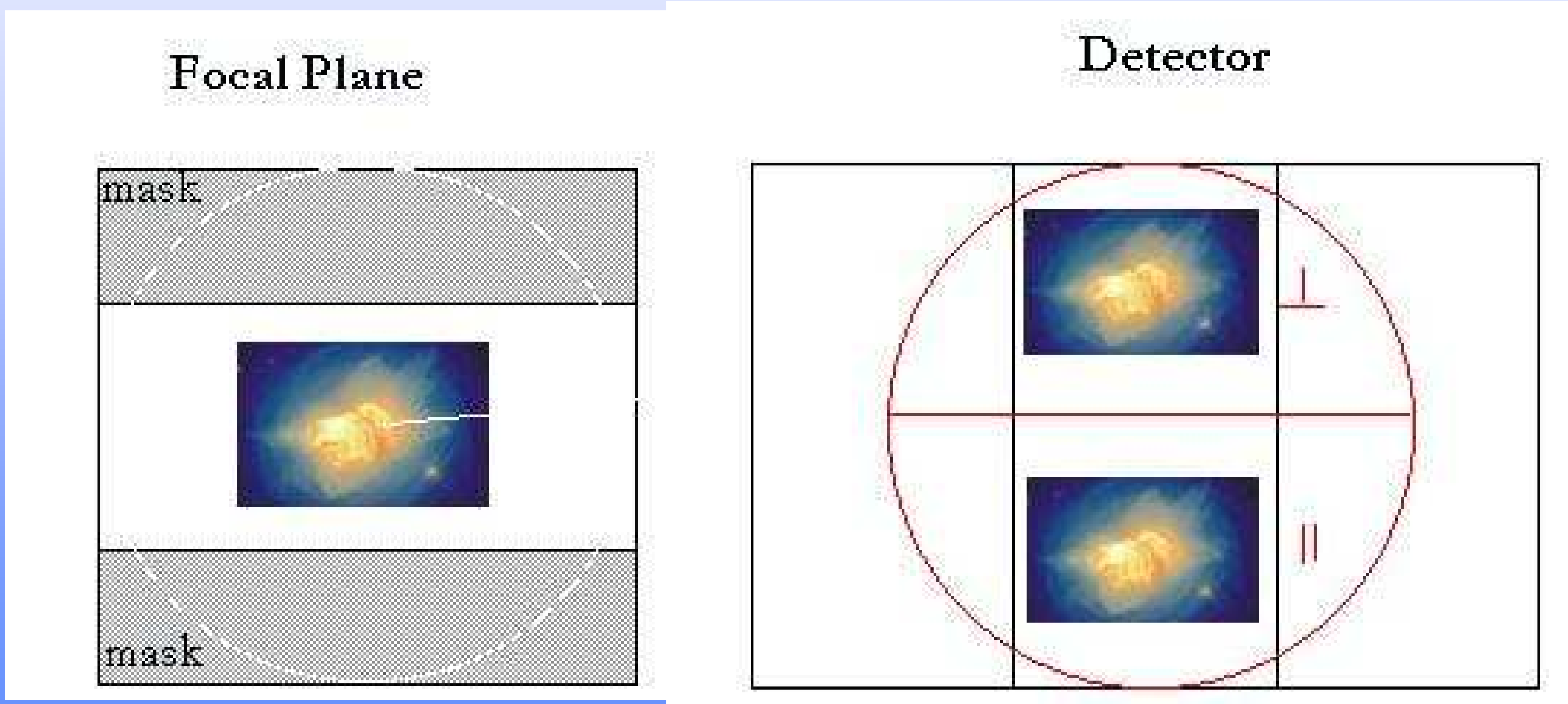
RSS Fabry-Perot mode: Lab tests



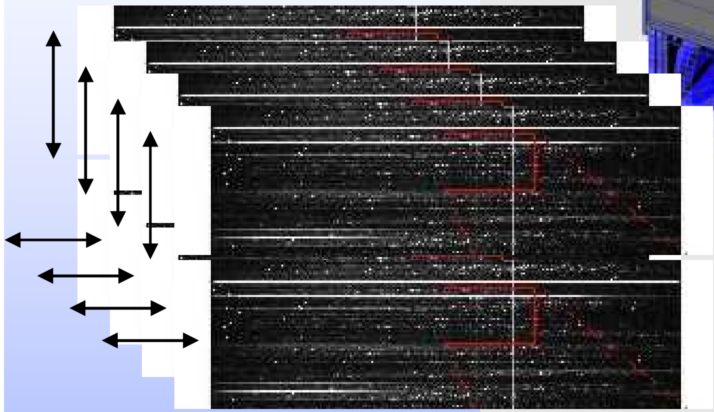
The RSS-FP Spectral Resolutions. Open Squares: interference filters; Diamonds: TF mode; Filled Squares: LR mode; Triangles: MR mode; X: HR mode.

RSS Polarimetry:
Not yet commissioned

- **Imaging polarimetry**

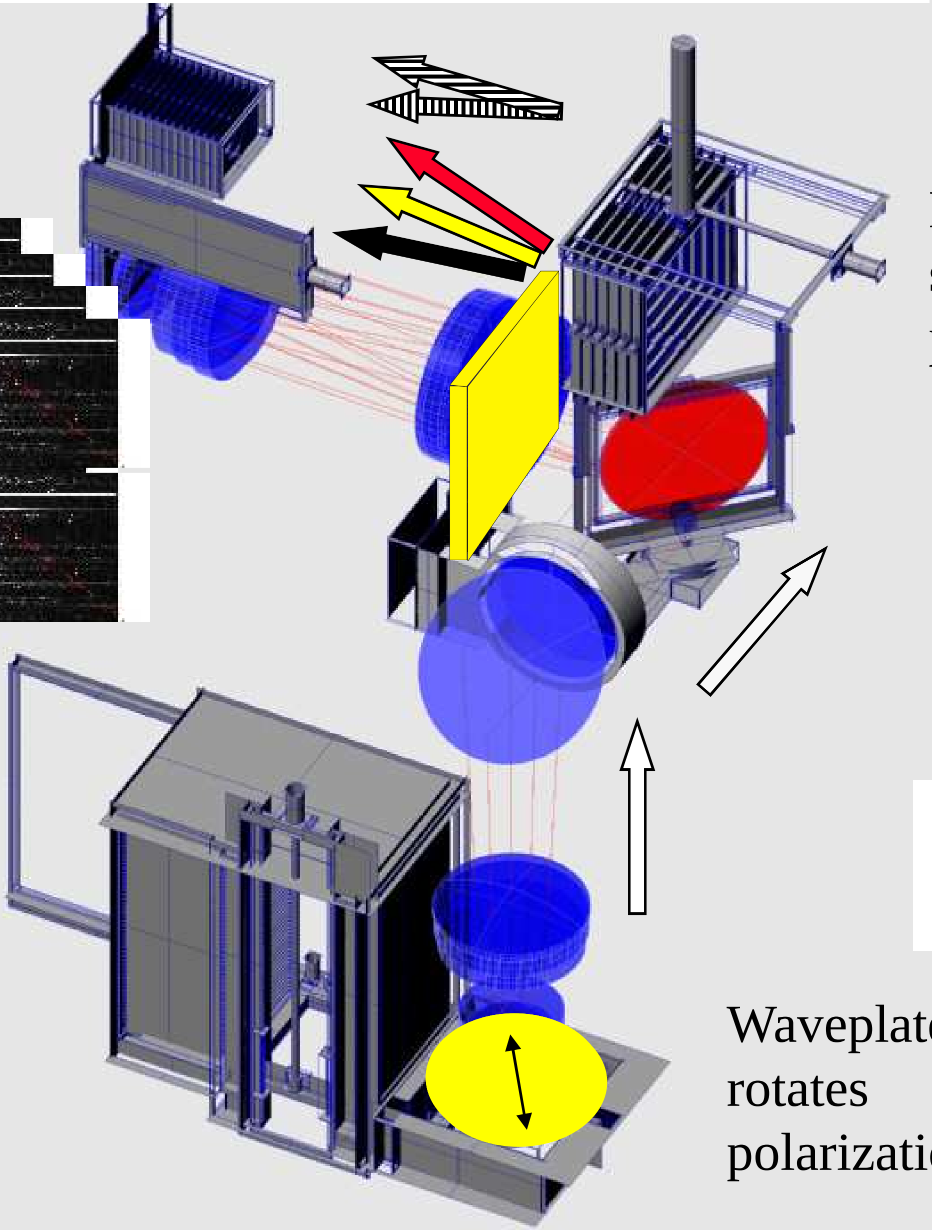


Spectropolarimetry Submode



Polarization of 20 Spectra

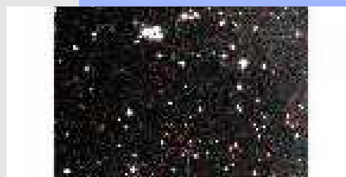
Also works in Imaging/ Fabry-Perot Modes



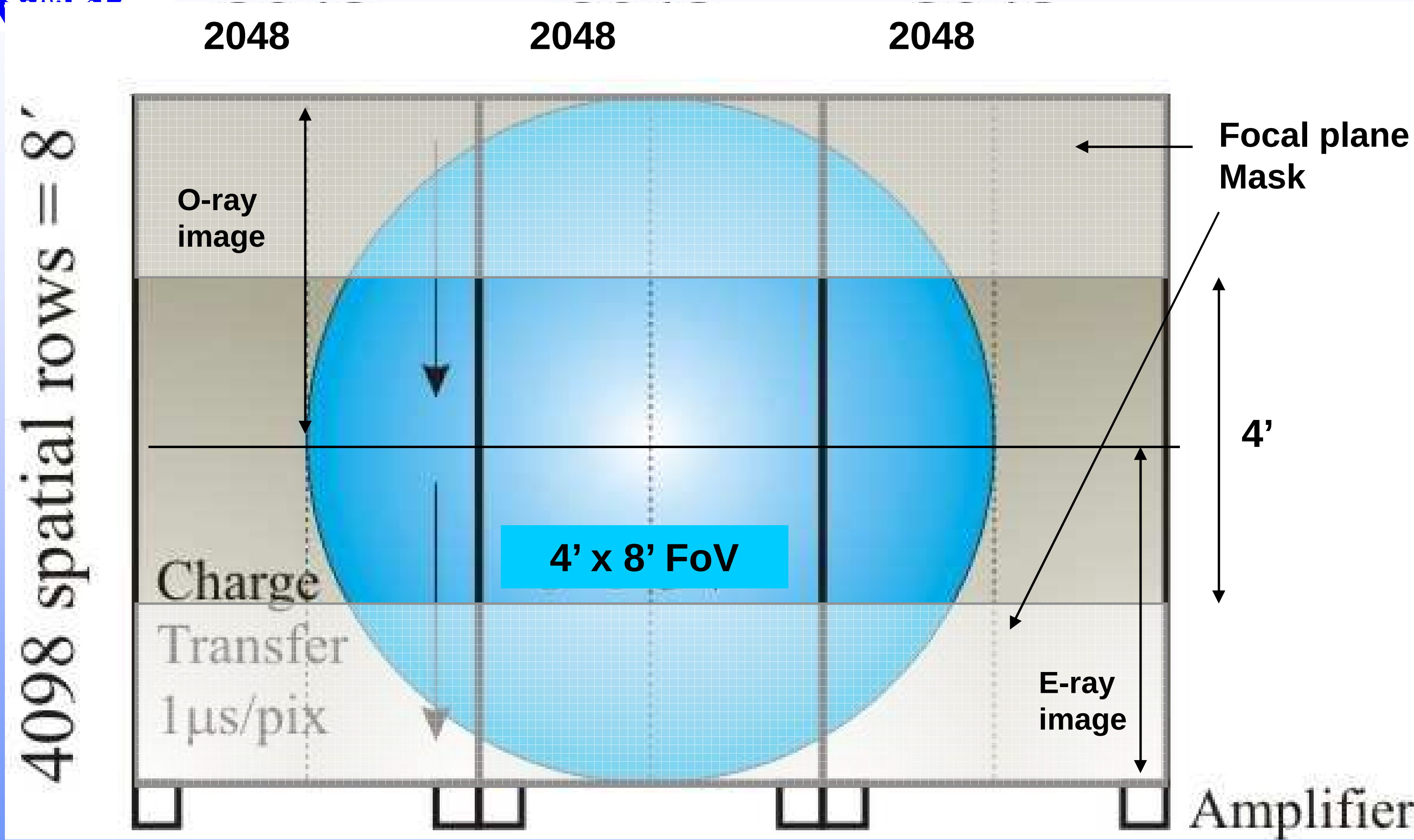
Beamsplitter splits 2 polarizations

Waveplate rotates polarization

Hubble Deep Field (South)



Focal Plane Configuration for imaging/ long slit spectropolarimetry



SALT High Resolution Spectrograph (HRS):
3rd "First Gen" SALT Instrument

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

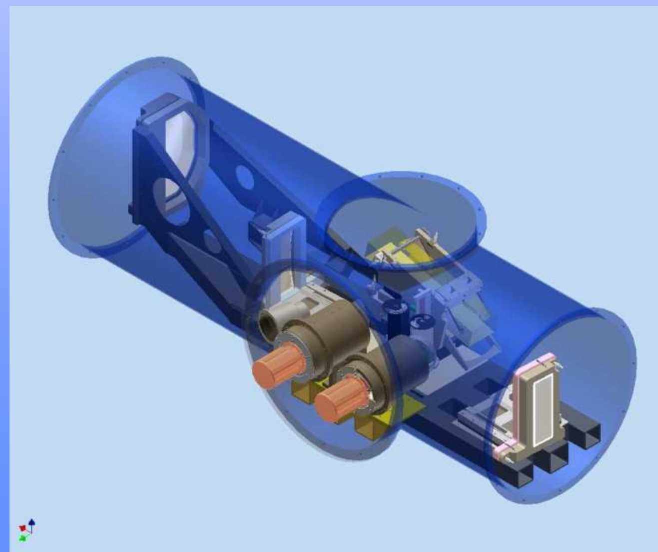
R ~ 16,000 – 70,000
λ ~ 380 – 890 nm

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)

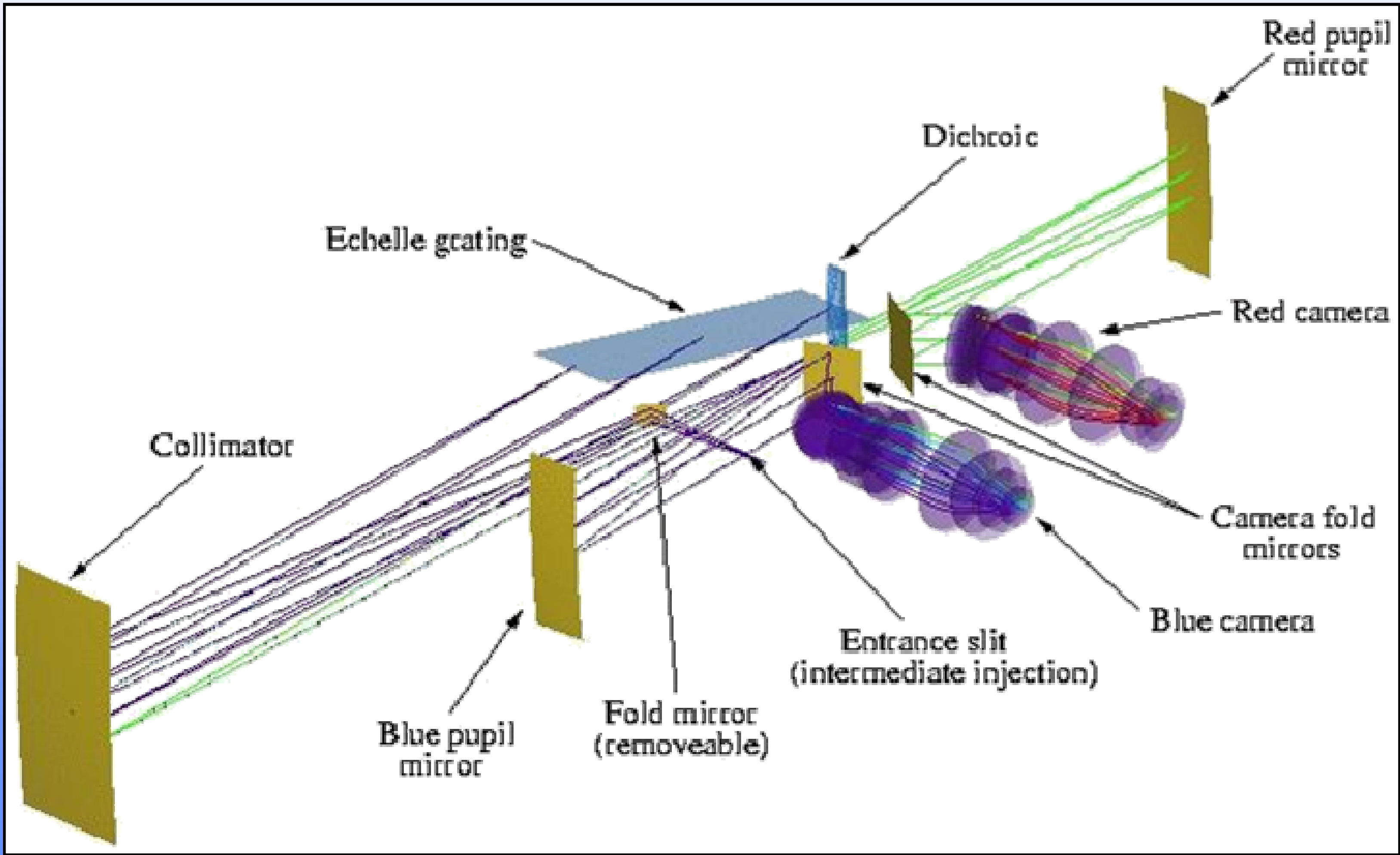
- **Started in late 2007, assembly & testing Sep 2011; commissioning late-2011**

- **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



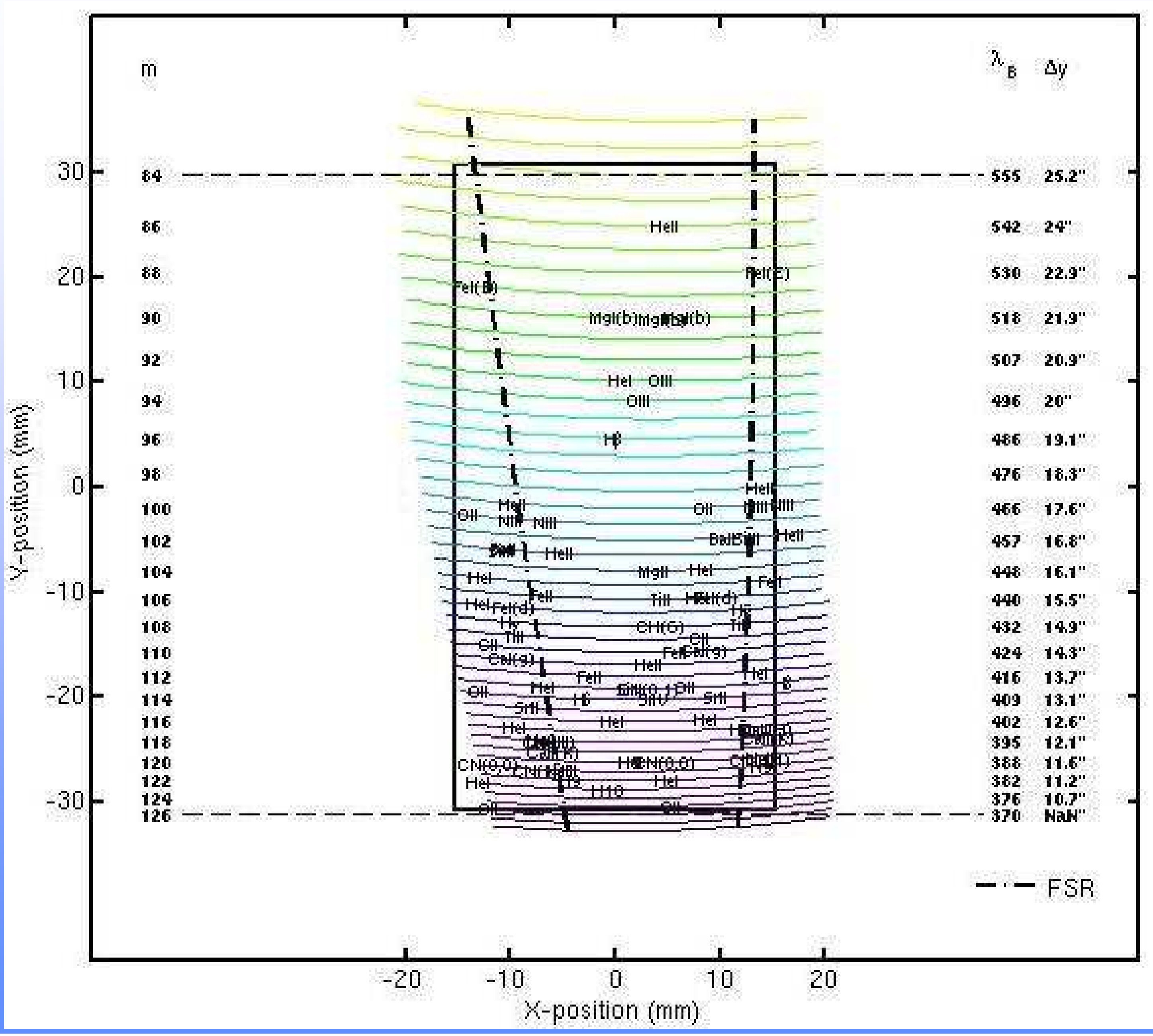
SALTHRS: Blue spectral format: Blue

E2V 44-82

2k x 4k

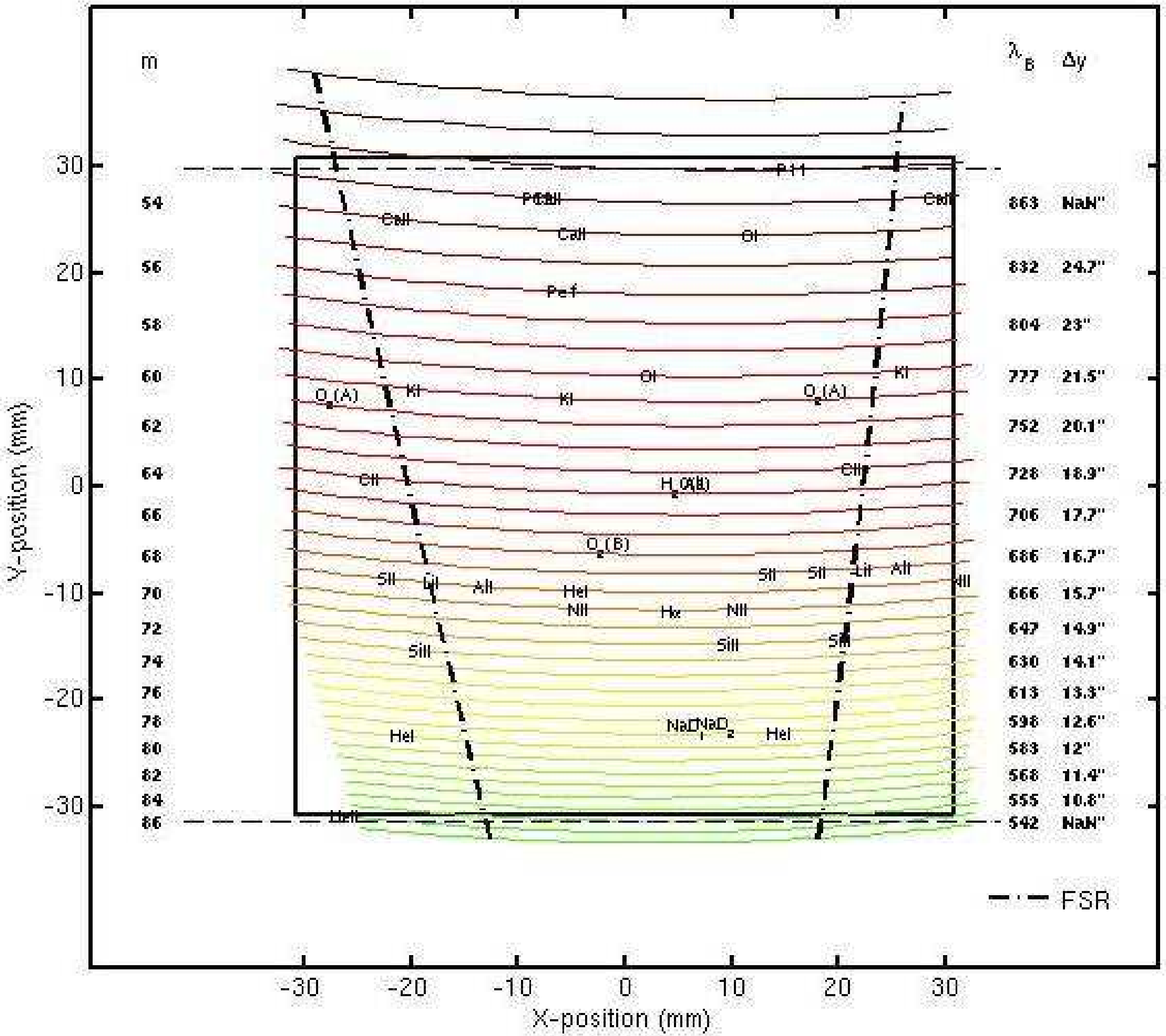
15 µm pixels

AstroBB coating

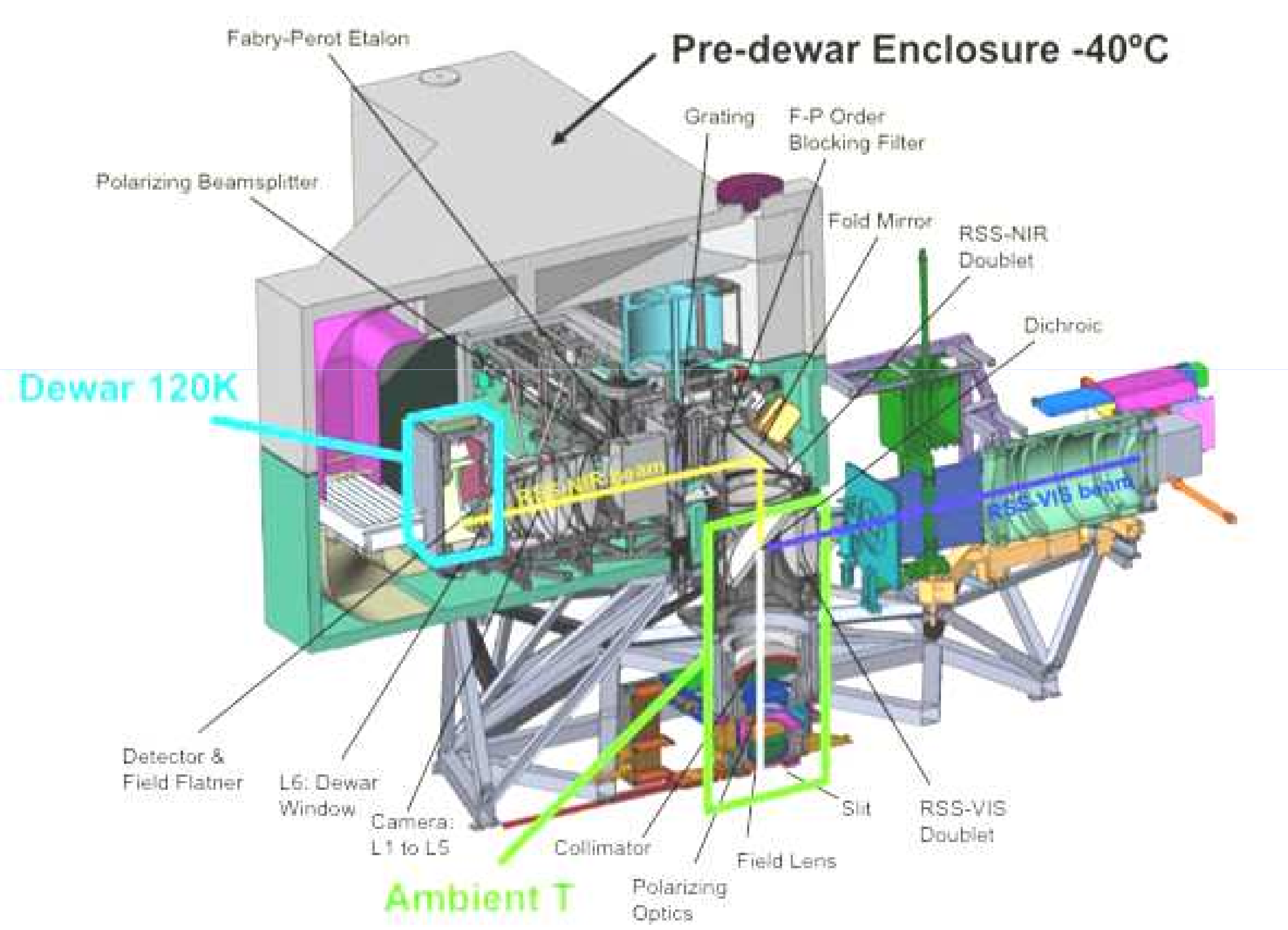


SALTHRS: Red spectral format

- E2V
- 4k x 4k
- 15 µm pixels
- Broad-band coating
- Deep depletion



RSS VIS-NIR Schematic




THE END!