Astro 500

Techniques of Modern Observational Astrophysics

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SALT: Future-Generation Telescope

Outline:

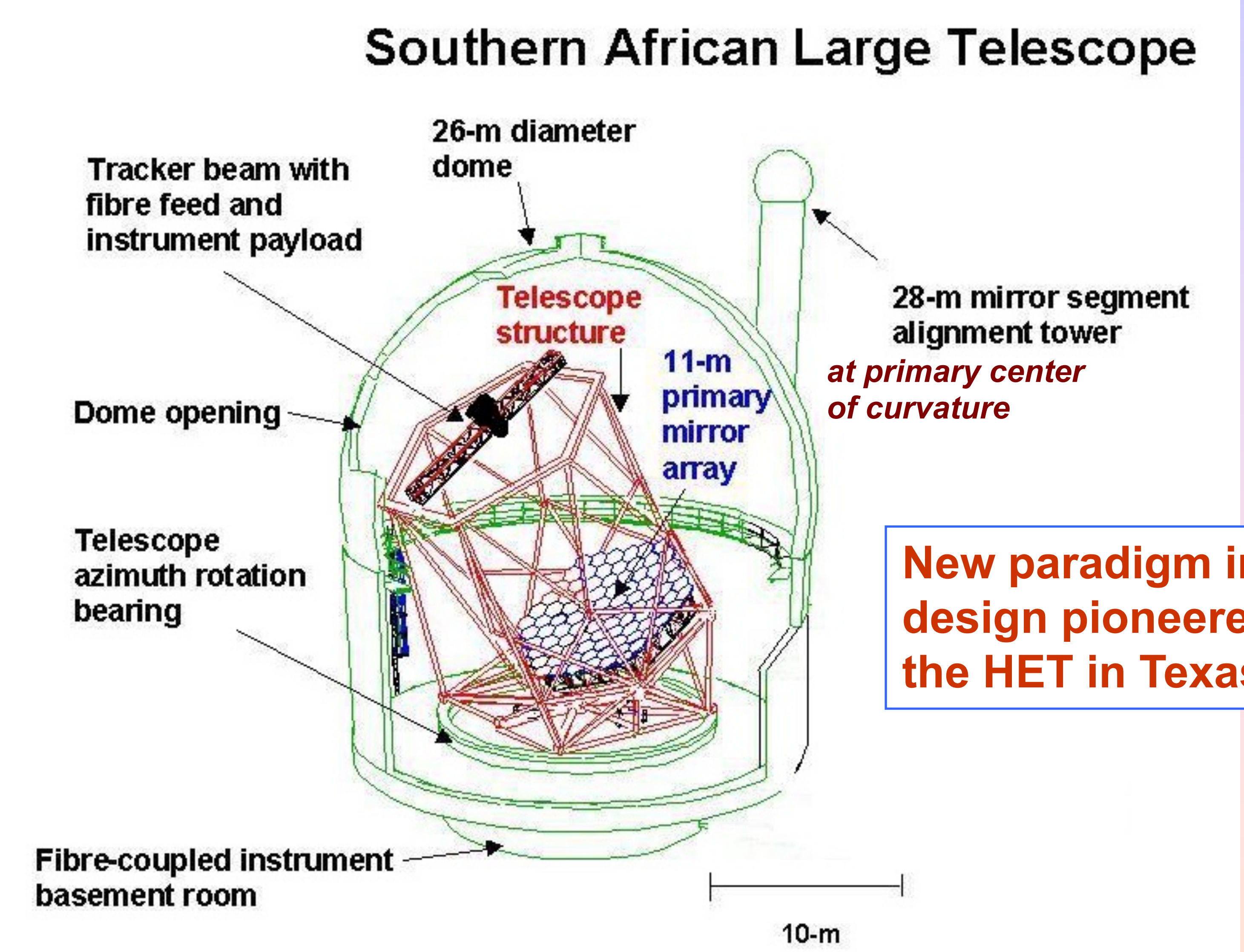
- What is SALT ?
- Design and performance
- First science instruments
- Construction history

SALT: Southern African Large Telescope

<u>BASIC ATTRIBUTES:</u>* *Tilted Arecibo-like Optical-IR Telescope modeled on the Hobby-Eberly Telescope

- **PRIMARY MIRROR ARRAY**
  - **Spherical Figure**
  - **91 identical hexagonal segments**
  - **Unphased (i.e. not diffraction limited 10-m, just 1-m)**
  - **Mirrors 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. to 5μm accuracy)**
  - **Tracker contains <u>S</u>pherical <u>A</u>berration <u>C</u>orrector (SAC) with 8′ FoV (*Prime Focus*)**
  - **Large spectrograph instruments fibre-coupled**
- **IMAGE QUALITY**
  - **Telescope error budget of 0.5 " FWHM over 8′ field of view**
  - **Delivered EE(50) < 0.6", EE(80) < 0.9"**

What is SALT ?



New paradigm in design pioneered by the HET in Texas.

An International Partnership

SHAREHOLDERS of SALT FOUNDATION (Pty) Ltd:

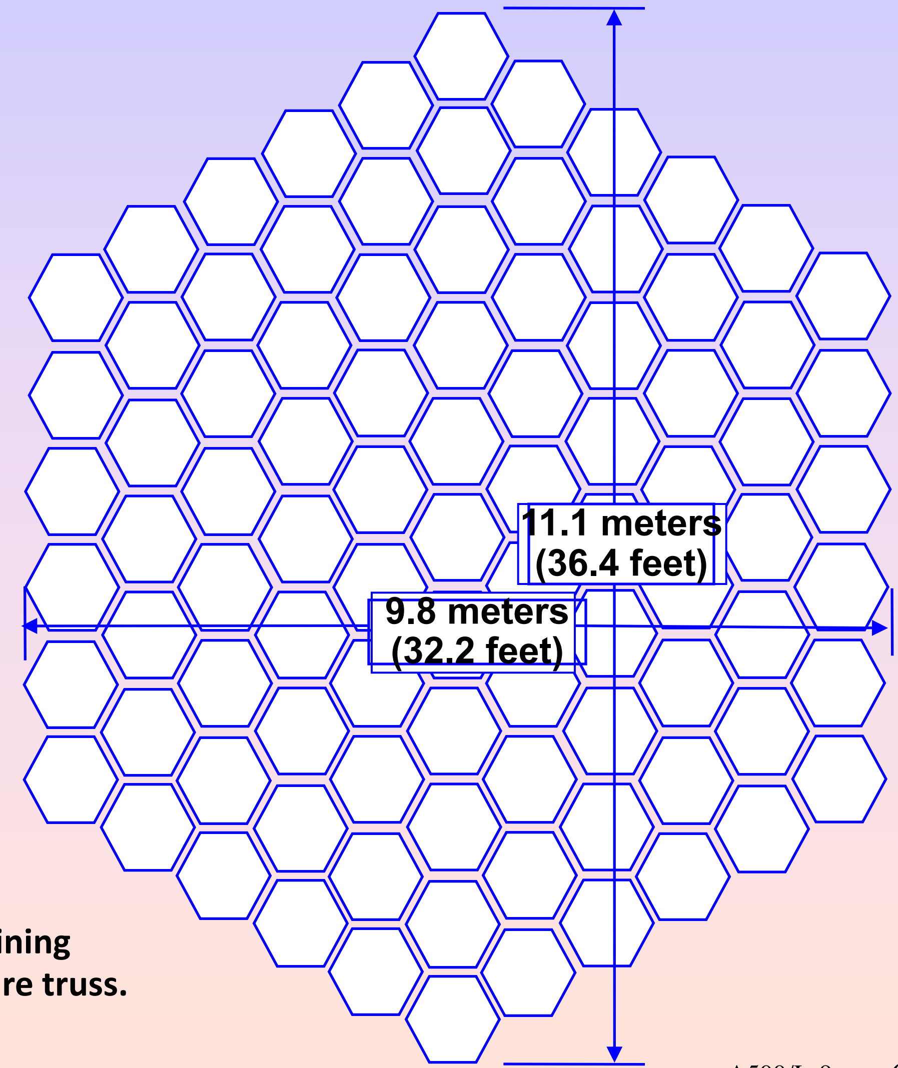
• National Research Foundation	~~32.0%~~ 58%
• University of Wisconsin – Madison	~~15.1%~~ 7%
• CAMK (Poland)	9%
• Rutgers University	9%
• Dartmouth College	8%
• IUCCA (India)	6%
~~• Goettingen University (Germany)~~	~~4.9%~~
~~• University of Canterbury (NZ)~~	~~3.1%~~
• United Kingdom SALT Consortium	2%
~~• University of North Carolina~~	~~2.3%~~
~~• Carnegie - Mellon University~~	~~2.3%~~
• AMNH (NYC)	1%

Primary Mirror Array

Attributes:

- Segmented array of 91 hexagons: Astro-Sitall, each 1 meter wide (edge-to-edge, inscribed diameter) and 50 mm thick
- Radius of curvature*: 26.165 m*
- maximum mirror diameter (entrance pupil diameter): *11.0 m*
- accuracy of mirror surface: *< 1/15th wavelength of light (@ 630 nm)*
- *Science* field of view: *8 arcmin*
- *Usable* field of view: *10 arcmin*
- Resolution: *0.6 arcsec (EE50)*

Mirror array supported on steel ‘space frame’ truss containing 1,747 struts and 383 nodes, precise to 4 mm over the entire truss.



Where is SALT ?

Sutherland site:

Good dark astronomical site:

Aseasonal with 75% nights useable

Median seeing of 0.9 arcsec

~1800 m altitude

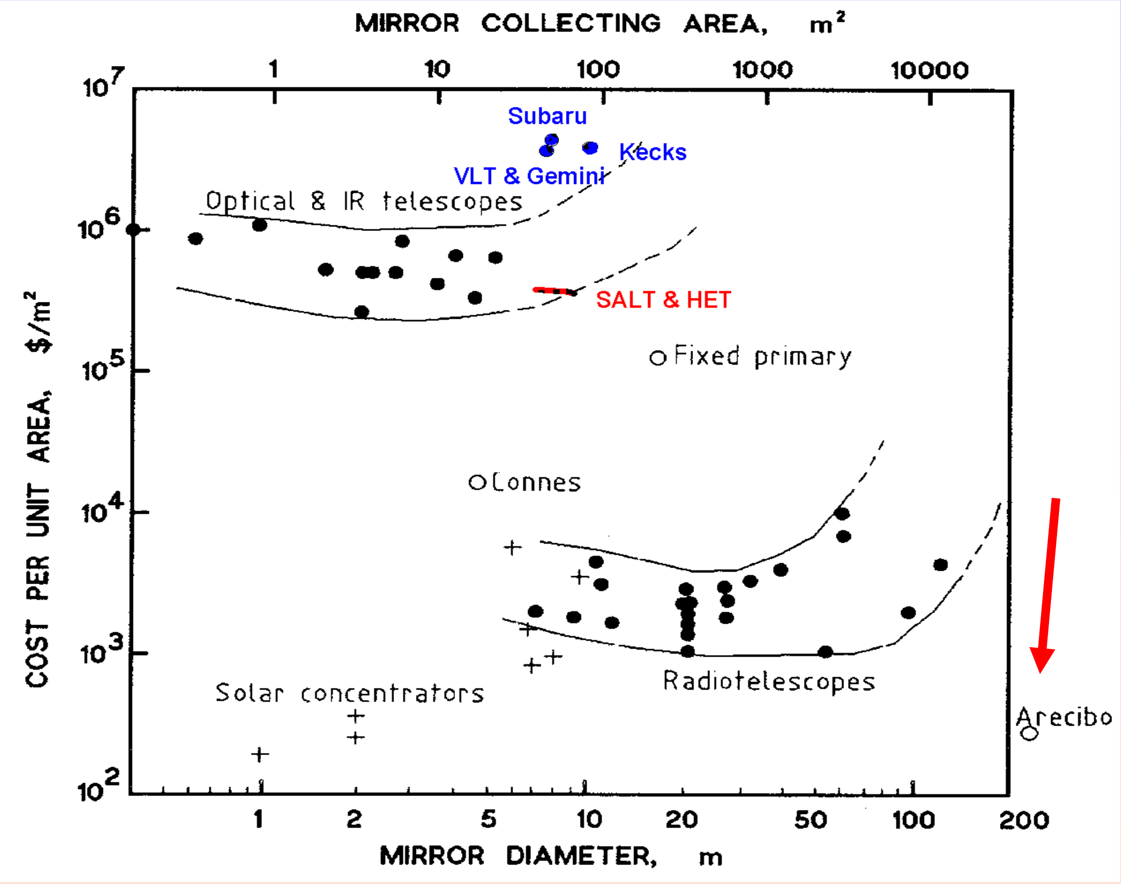
South African Astronomical Observatory (SAAO):

The host institution for the SALT project and Operating contract for SALT.

Why SALT?

A cost-effective and innovative design for a large 10-m class telescope

70% of the sky accessible (12.5% at a time) for only 10-20% of the cost of a 'conventional' telescope.

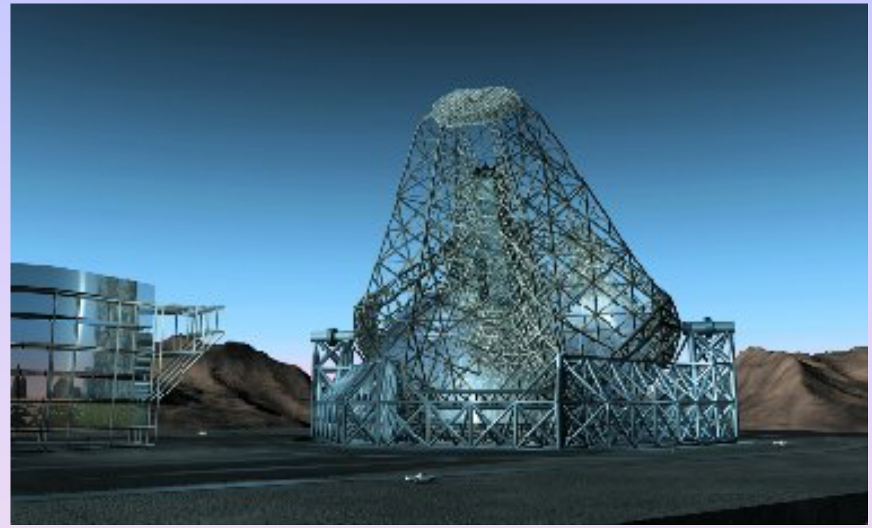


- **A paradigm for affordable telescopes of even greater size.**
- **For South Africa and international partners: collateral benefits in education, science & technology empowerment, technology development. *The* 'flagship' SA science project.**

A fore-runner of much bigger telescopes

- **Highly segmented**
  - **Serial production**
- **Spherical primary**
  - **“small” correcting optics**

- **Fixed elevation**
- **Rotation in azimuth**
- **Tracking prime-focus**
  - ➢ **These last 3 have additional major cost savings**



Owl: European 100m telescope ~3000 mirrors, by 2016 (dream state)

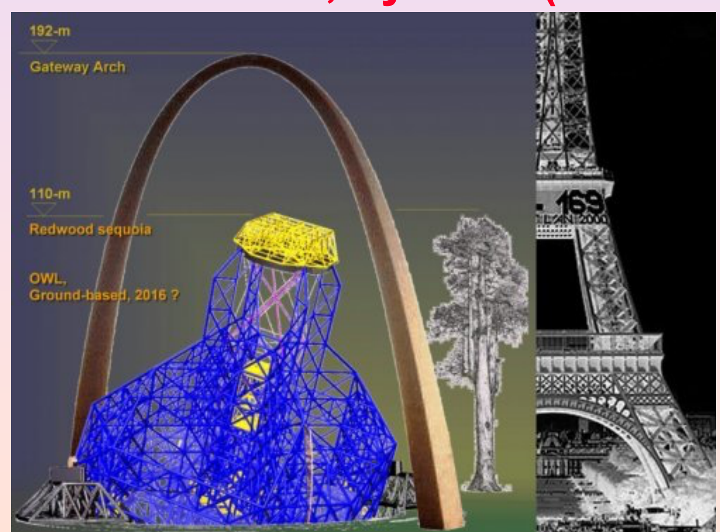


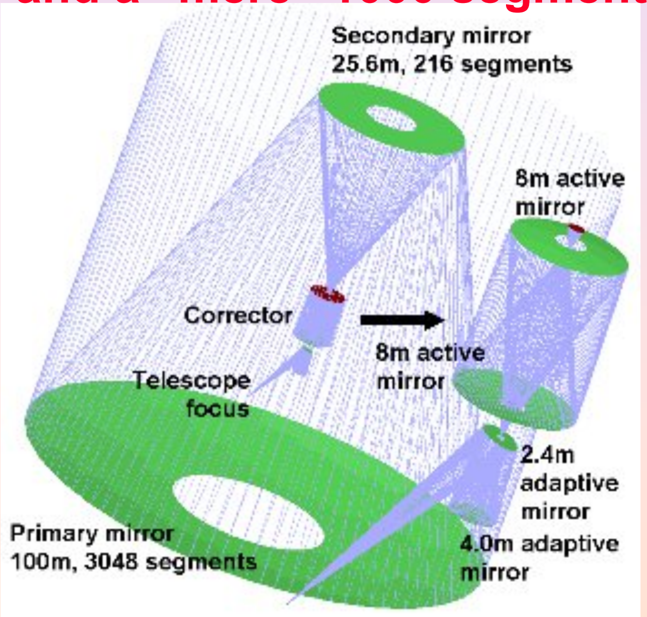
Figure 9. A matter of perspective ...

A fore-runner of much bigger telescopes

- Highly segmented
  - Serial production
- Spherical primary
  - "small" correcting optics

Owl: European 100m, 3000-segment telescope ➔ downgraded to a ~42m and a "mere" 1000 segments

- Fixed elevation
- Rotation in azimuth
- Tracking prime-focus
  - ➢ These last 3 have additional major cost savings



The Arecibo Concept:

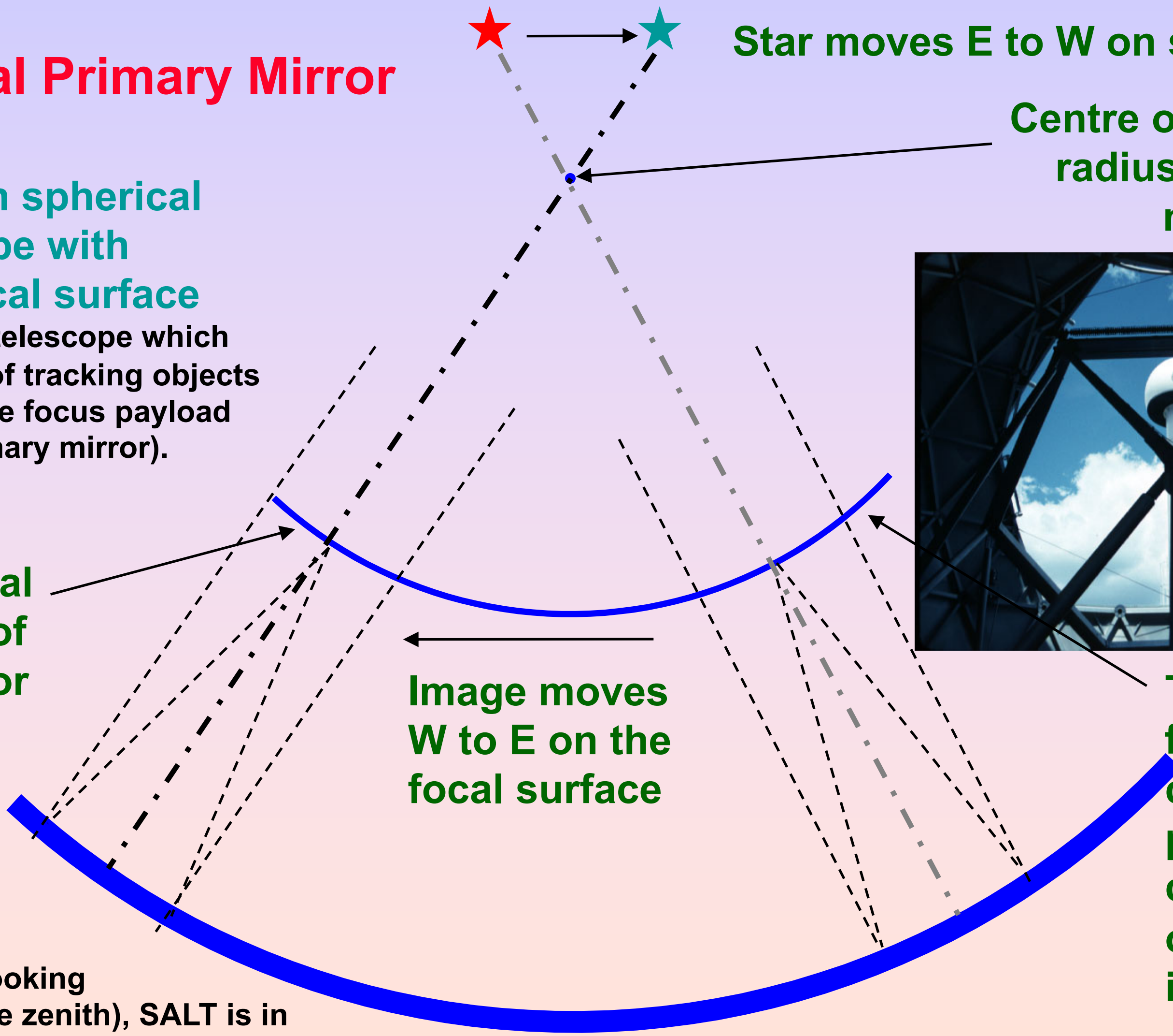
Spherical Primary Mirror

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

(Arecibo is a radio telescope which first used the idea of tracking objects by moving the prime focus payload rather than the primary mirror).



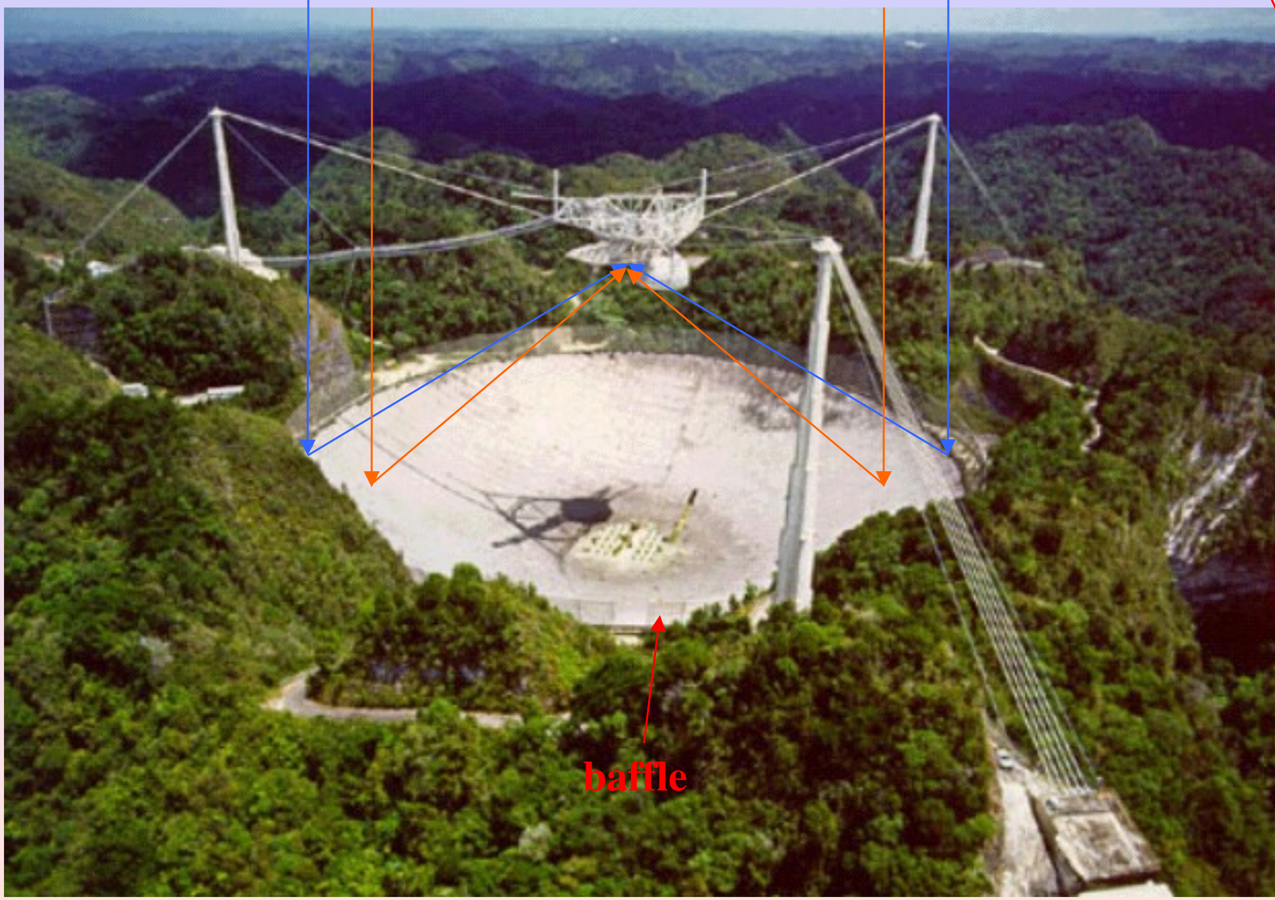
Spherical focal surface: 1/2 of primary mirror radius

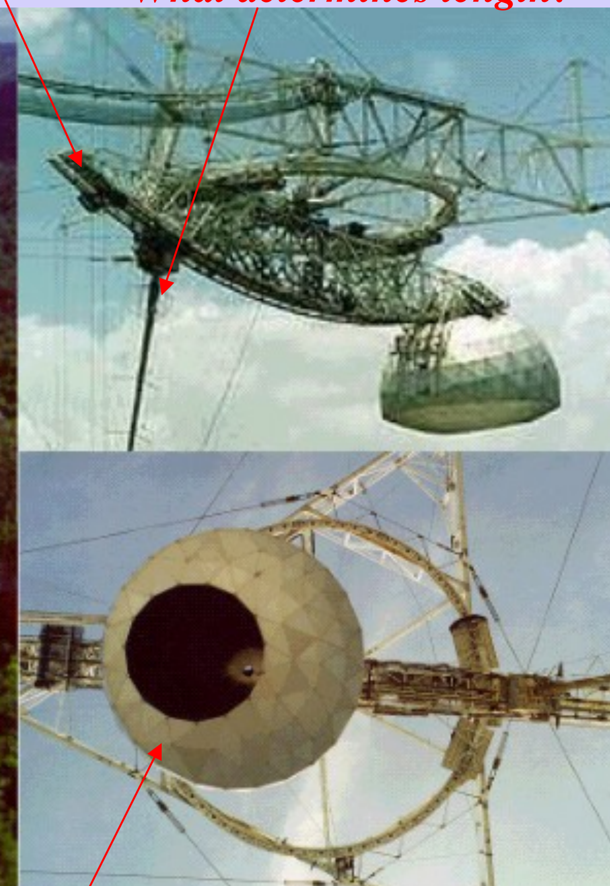
Image moves W to E on the focal surface

Tracker follows focus of star. It carries a payload consisting of optics and instruments.

Although pictured looking straight up (i.e. at the zenith), SALT is in fact tilted 37° from the zenith.

SALT is the optical analogue of the Arecibo radio telescope

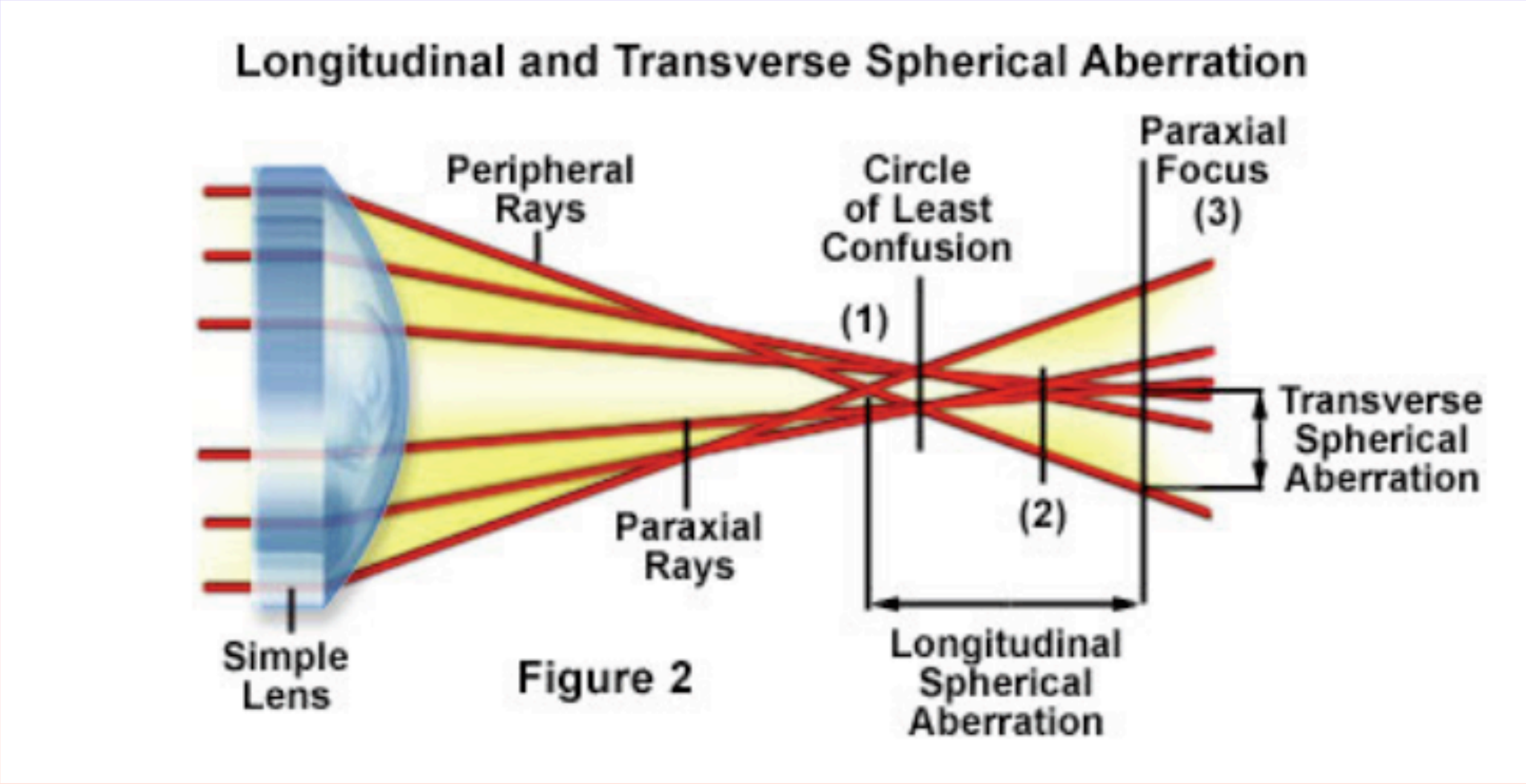




304.8m primary diameter, 265m radius of curvature

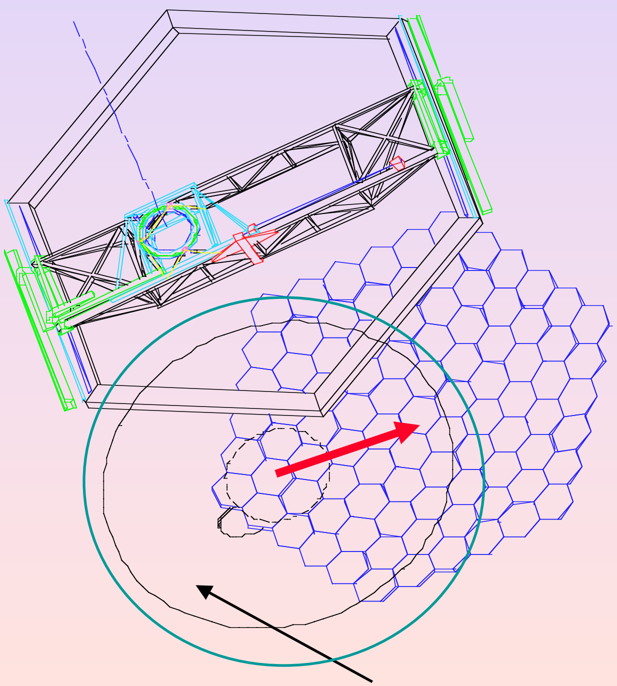
2-element off-axis Gregorian corrector; elliptical entrance aperture 210 x 240m

Spherical Aberration-2

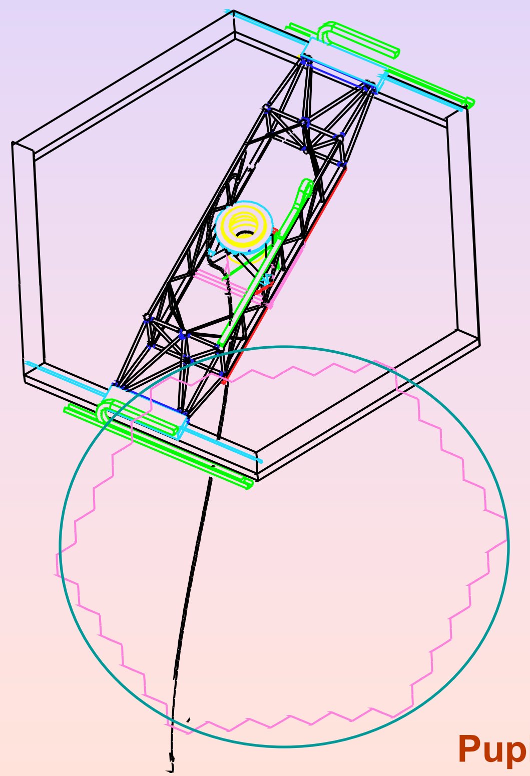


How the telescope tracking works

Tracker off-centre
and pupil partially on primary
mirror array. At worst extreme,
still a 7.9 meter telescope!



With tracker and 11-m pupil centered on primary mirror array and central obstruction (from SAC optics), equivalent to a 9.2 meter telescope.



Part of pupil off mirror is baffled at exit pupil position

(SALT has 11-m diameter pupil compared to 9.1-m for HET)

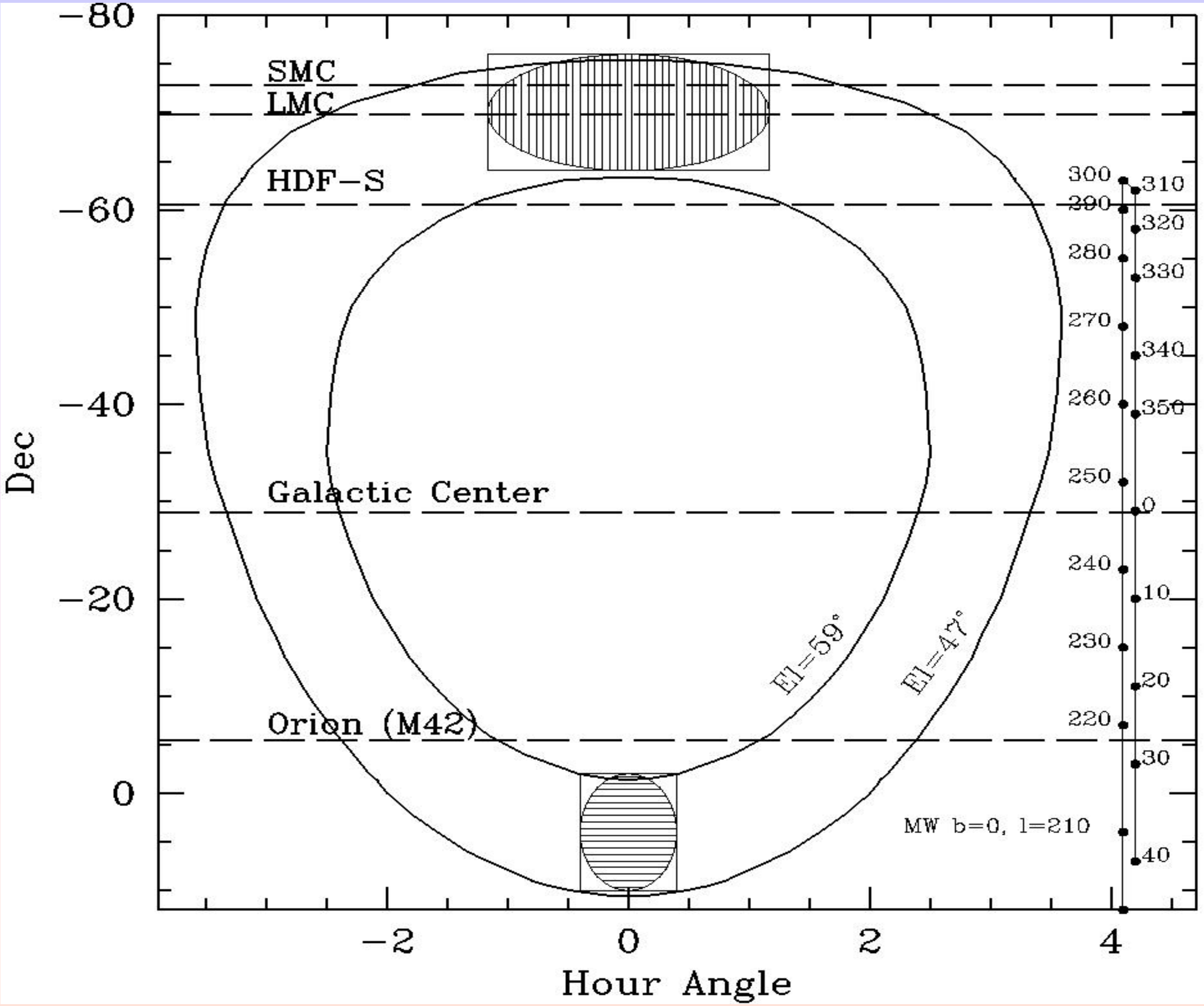
Pupil is underfilled

SALT annulus of visibility

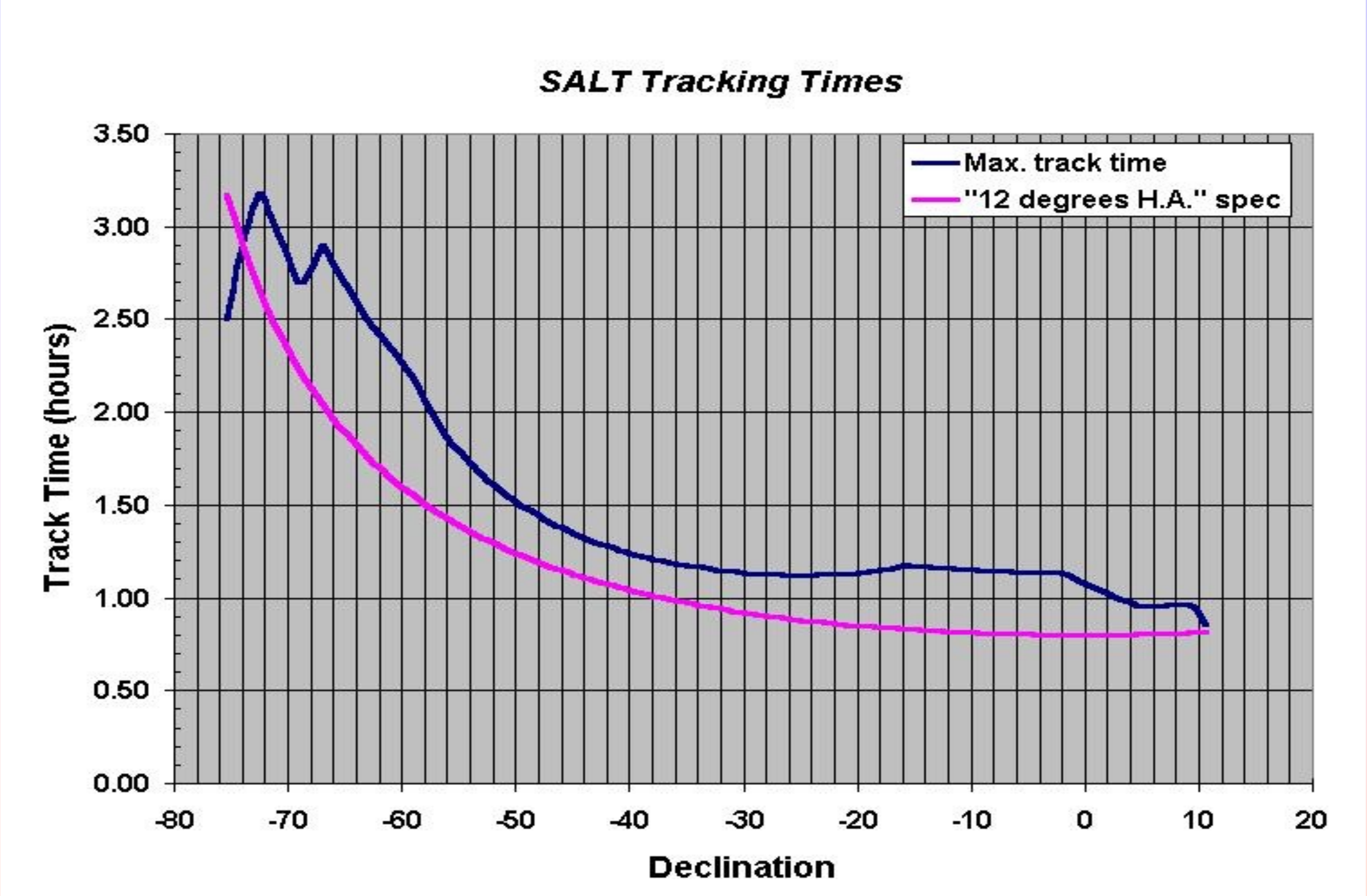
As SALT rotates in azimuth, different areas of the sky fall within the tracker's field of view.

Annulus represents 12.5% of visible sky

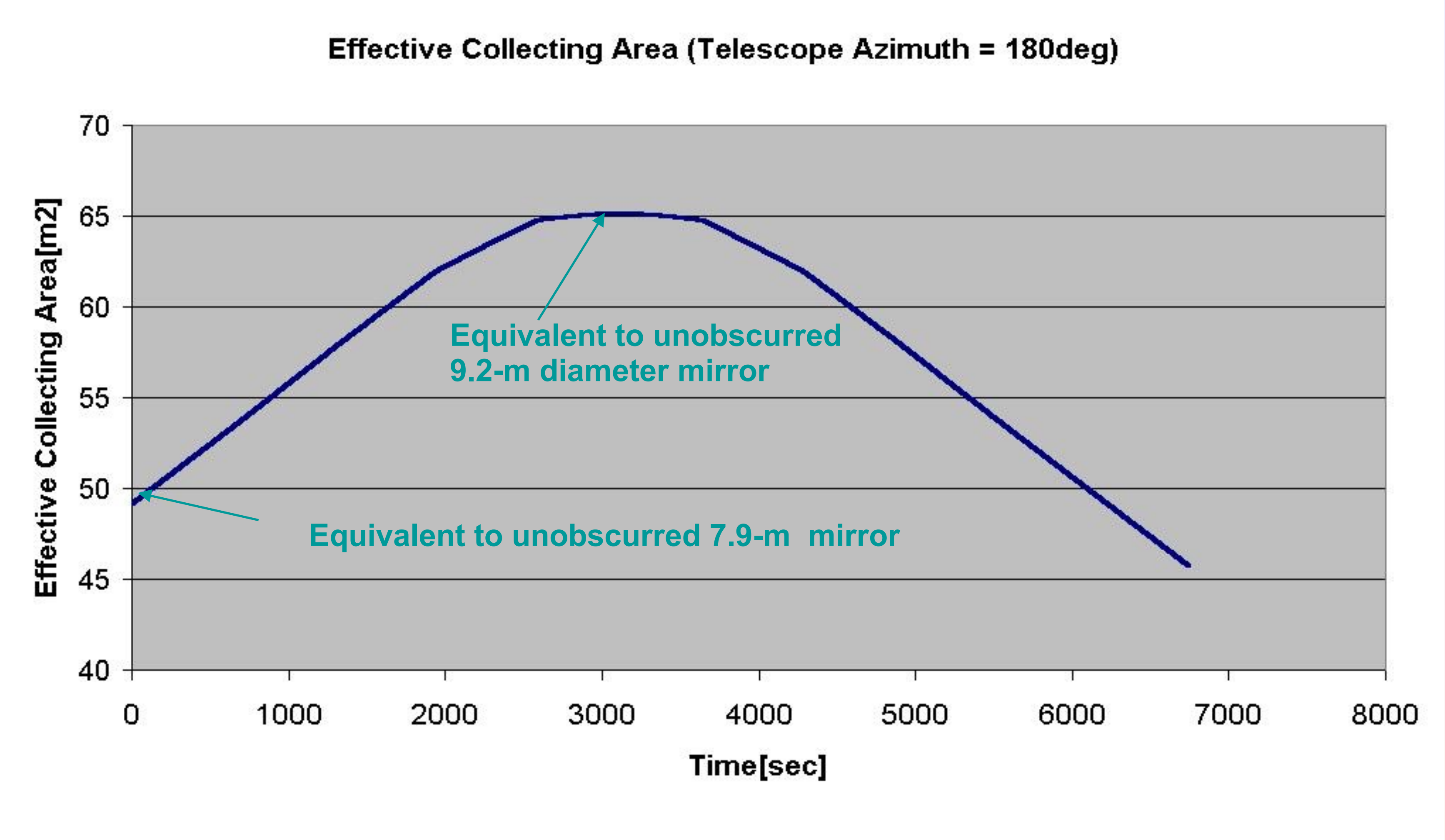
Shaded regions show continuous visibility for extreme North/South declinations



Track characteristics-1



Track characteristics-2



Design enhancements for SALT

SALT has greatly improved performance compared to HET:

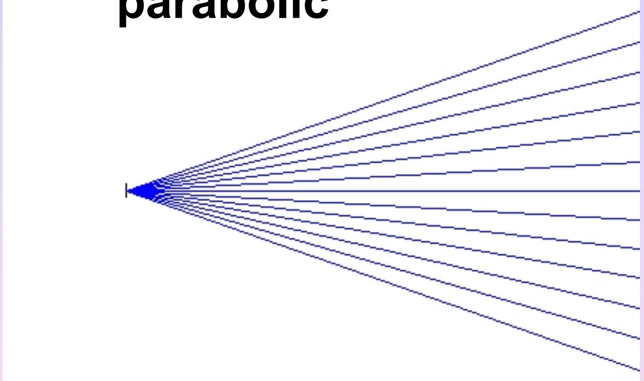
- **lessons learned**
- **a systems-engineering approach**
- **technological advances and global sourcing**

- **Improved optical corrector:** ***Larger field, better image quality.***
- **Larger entrance pupil:** ***15% more collecting power.***
- **Higher-efficiency coatings:** ***High blue/UV performance (320-450 nm).***
- **Integrated payload design, increased mass budget (~1000 kg) and use of carbon composites:** ***Enhanced capabilities, 4 foci, relatively easy access.***
- **Large prime focus instruments:** ***Versatile instruments delivering unique science (UV, polarimetry, Fabry-Perot, high time resolution, VPH gratings).***
- **Superior primary mirror segment alignment system (e.g. Shack-Hartmann camera) and use of capacitive edge sensors on the mirror segments:** ***More stable, sharper, images.***
- **Active thermal control: use of natural ventilation (e.g. louvres) and aggressive removal of heat sources:** ***better image quality.***

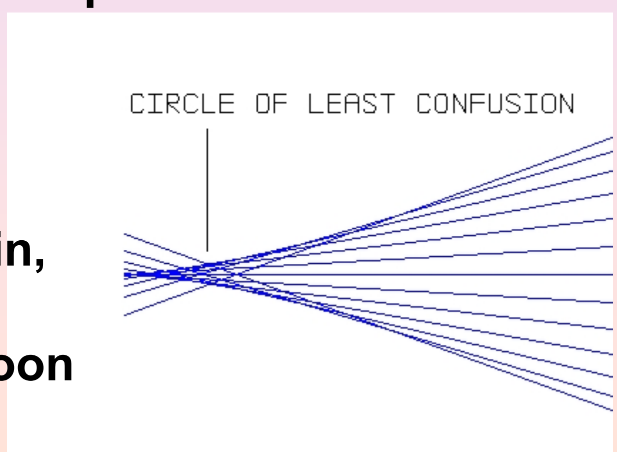
Spherical Aberration in HET & SALT

If the primary were parabolic

Perfect image

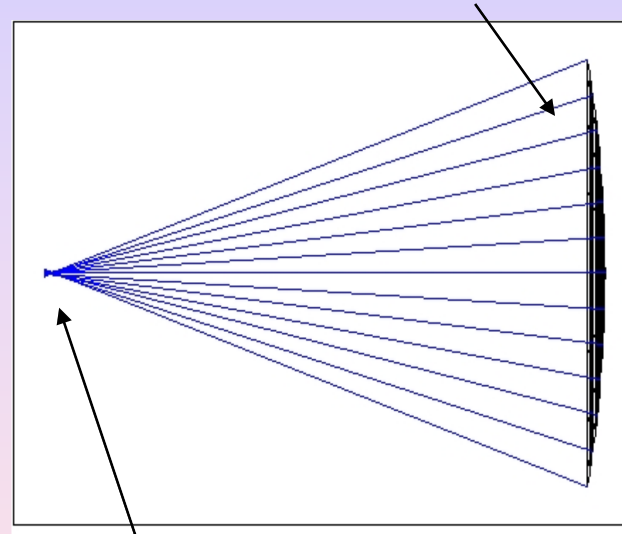


… BUT the primary is spherical



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

Primary Mirror array

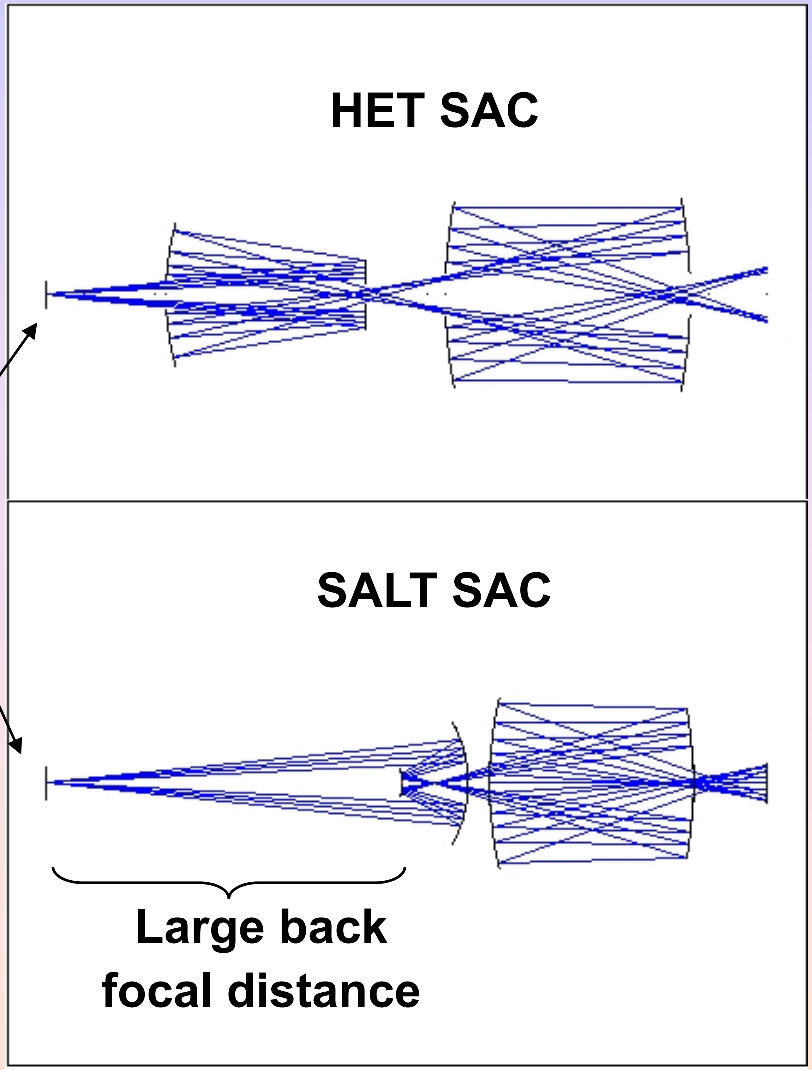


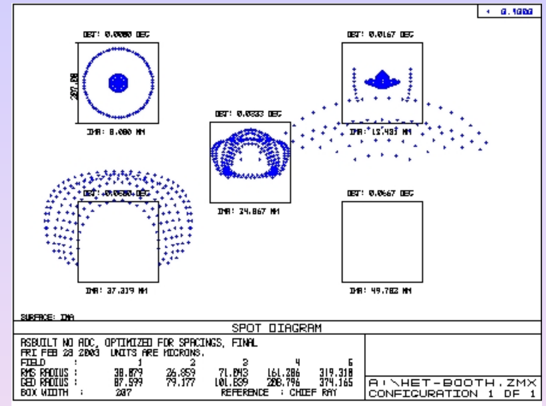
Prime Focus

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

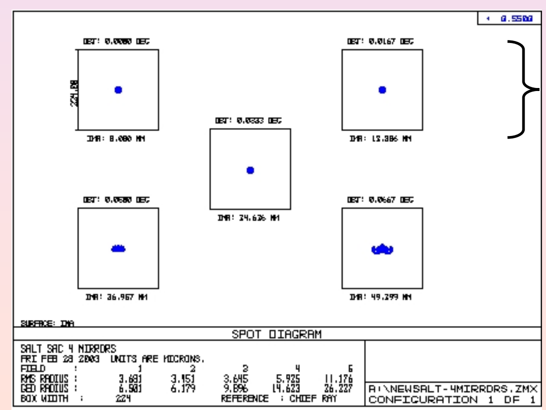
Spherical aberration corrector

Focal Plane

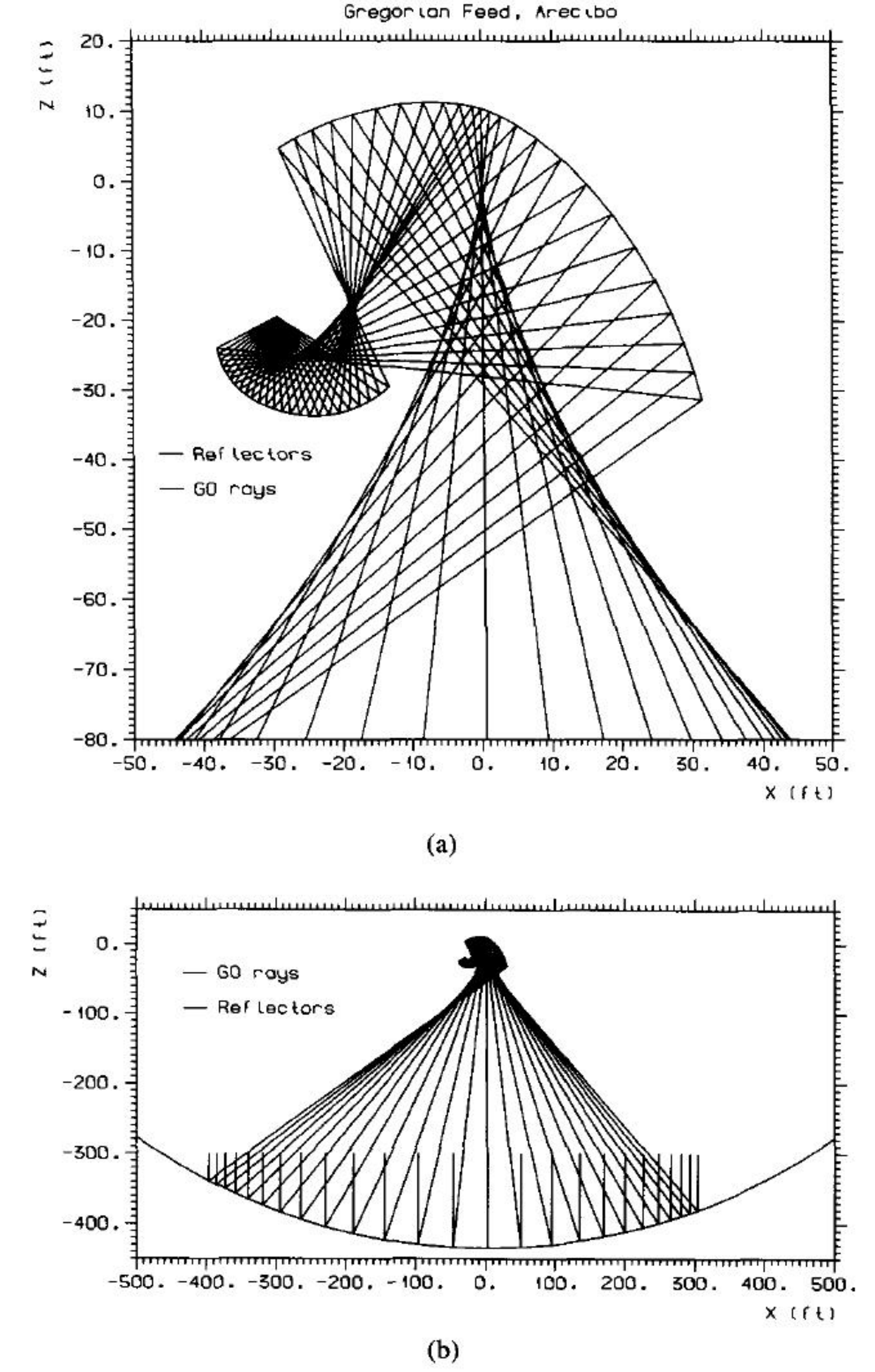




Spot diagrams



One arcsec boxes

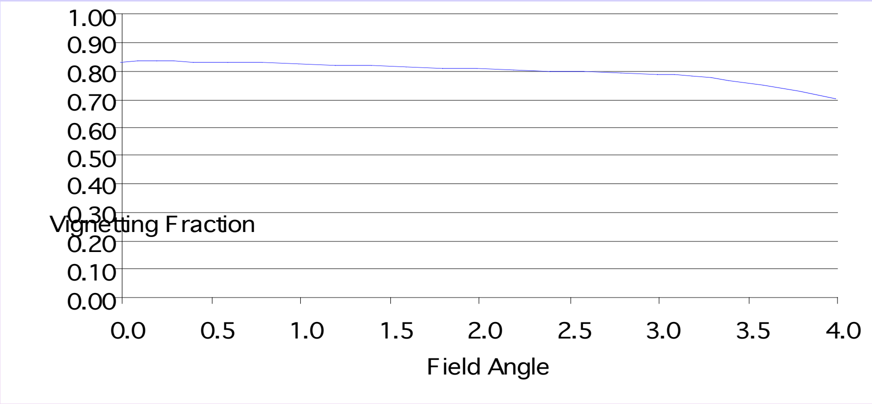


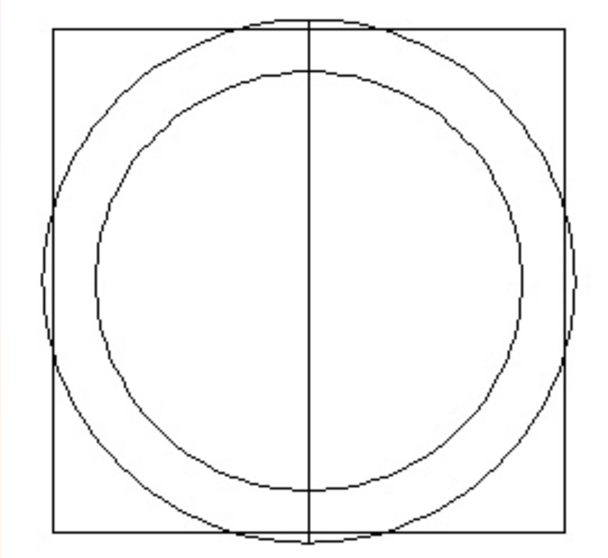
Comparison:

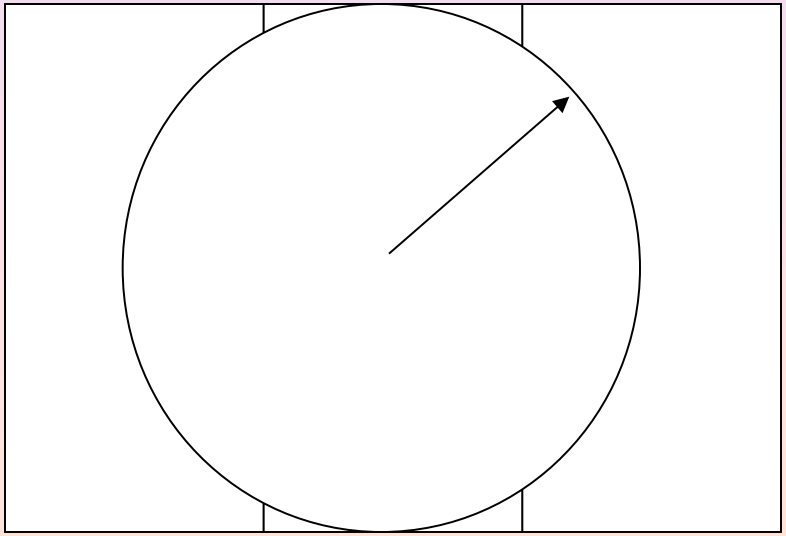
Spherical Aberration Corrector for Arecibo

SALT's Field of View

- **Vignetting from SAC**
  - ➢ **Image quality also degrades significantly beyond 4 arcmin radius**
  - ➢ **Science FoV chosen to be 8' diameter**
- **SALTICAM** has an 8' science FoV and up to 10' for guidance.
  - ➢ **Guide/focus probes access either entire 10 arcmin circle or the annular region**







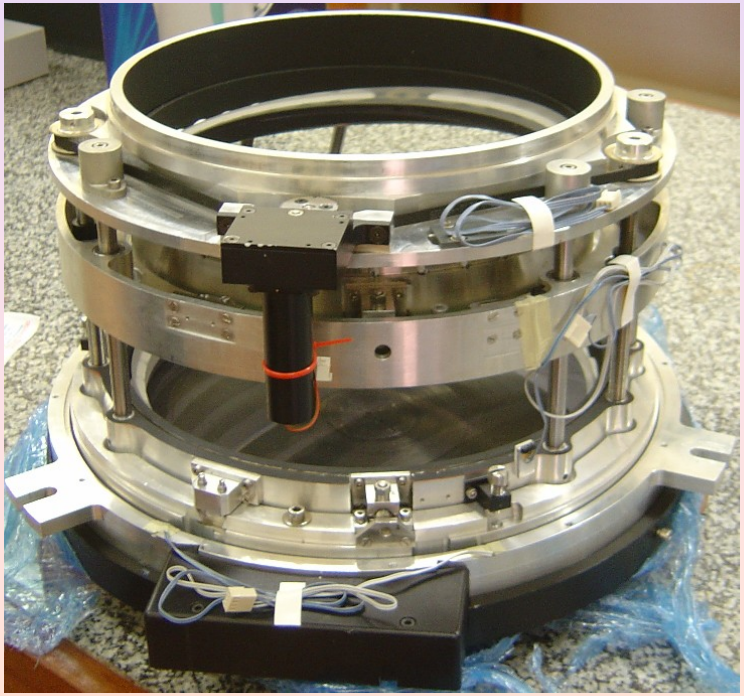
PFIS:

Also 8 arcmin FoV

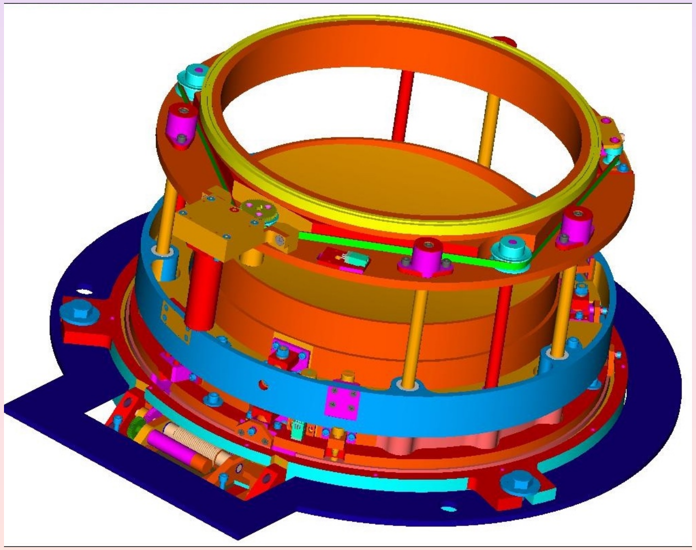
Atmospheric Dispersion Compensator

Corrects dispersion
- **over 320-1700 nm**
- **amounting to 3.5 arcsec**
- **zenith distance 31-43º**
- **residual <0.15 arcsec in 320 – 900nm range**

Uses fused silica translating prisms (280 mm diameter)

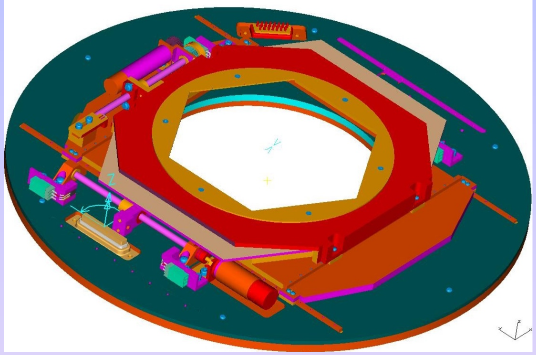


Payload subsystems designed in-house (SALT/SAAO), prisms from *Optical Surfaces,* and mechanism manufactured locally.

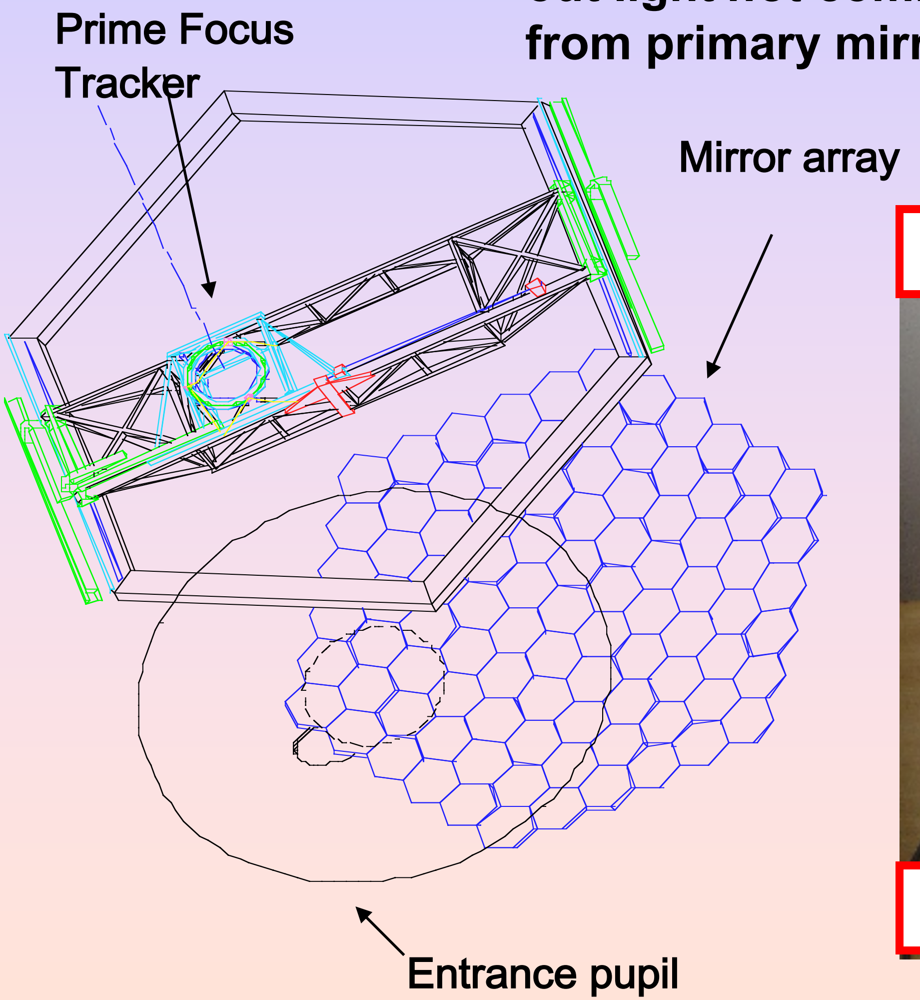


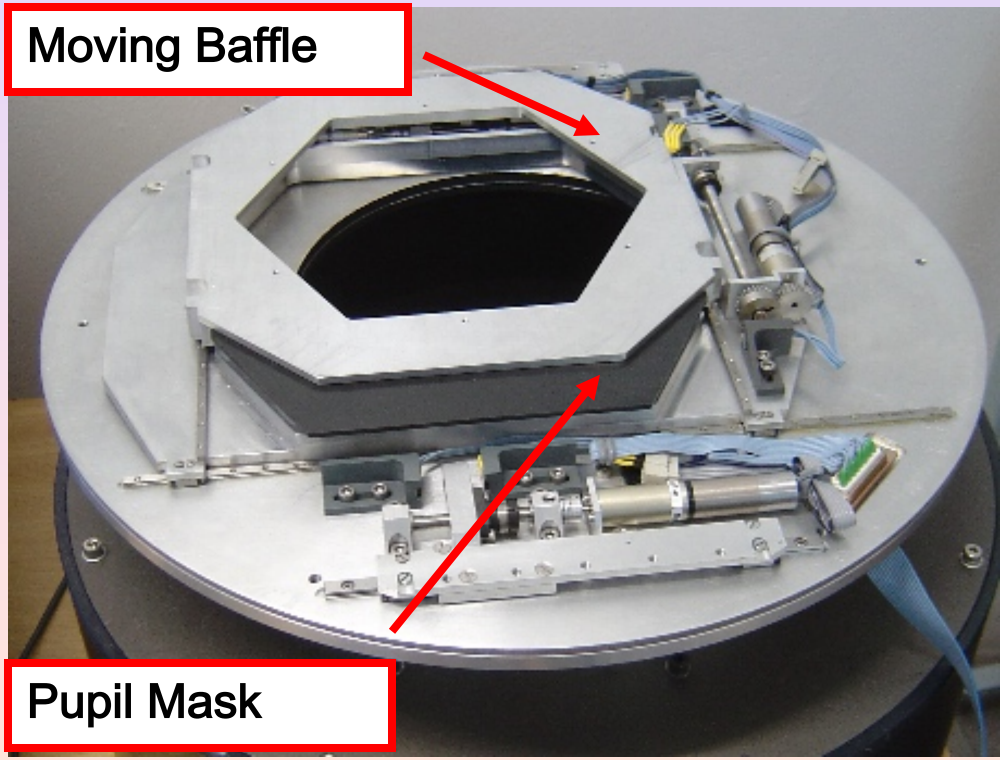
ADC mechanism design

Moving Baffle



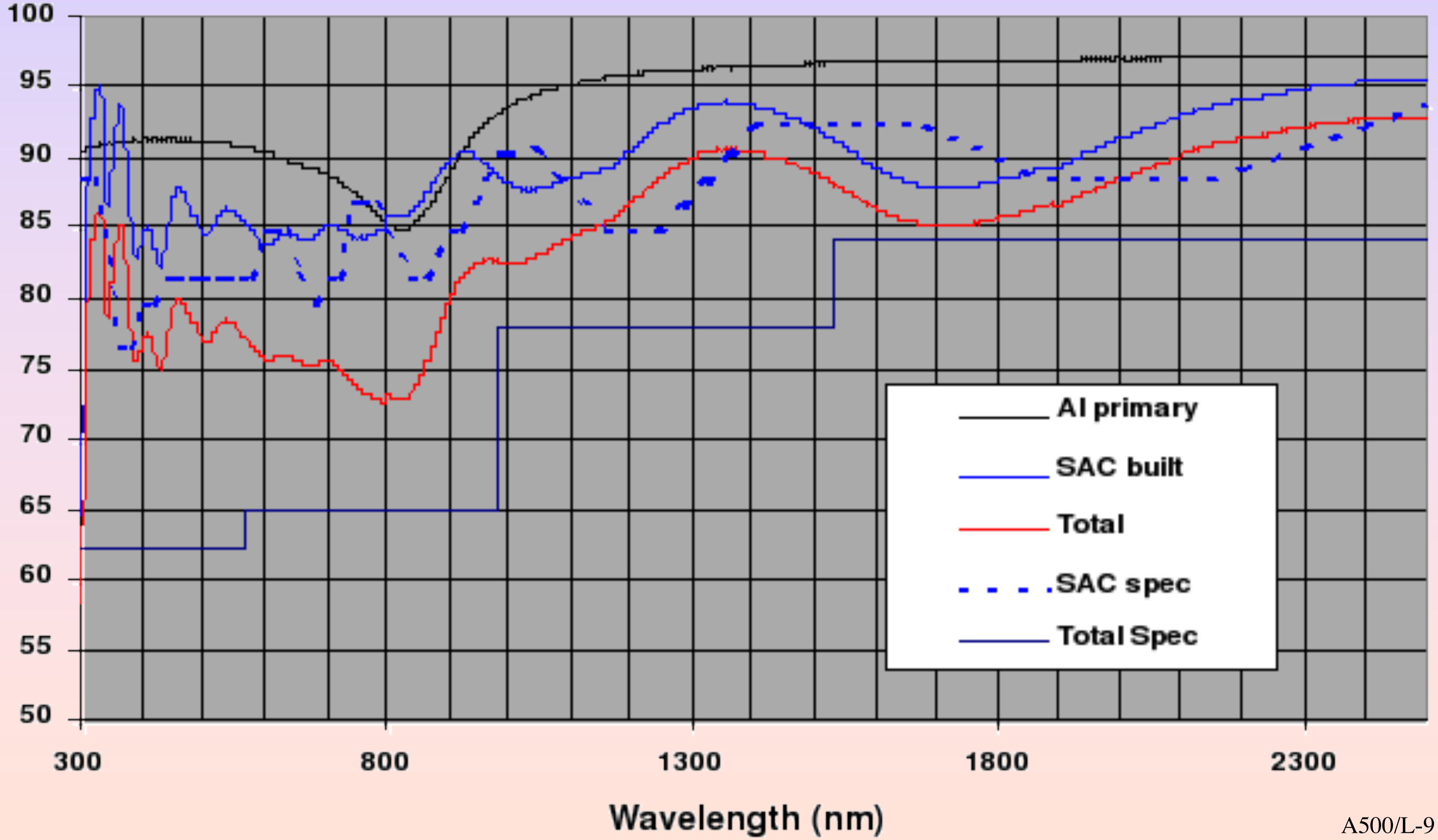
Moving baffle at exit pupil cuts out light *not* coming directly from primary mirror segments





Gains from High-Efficiency Coatings

SALT has a minimum of 5 reflections before the focal plane (1 from the Al primary, and 4 from the Ag/Al SAC)



SALT Prime Focus Payload

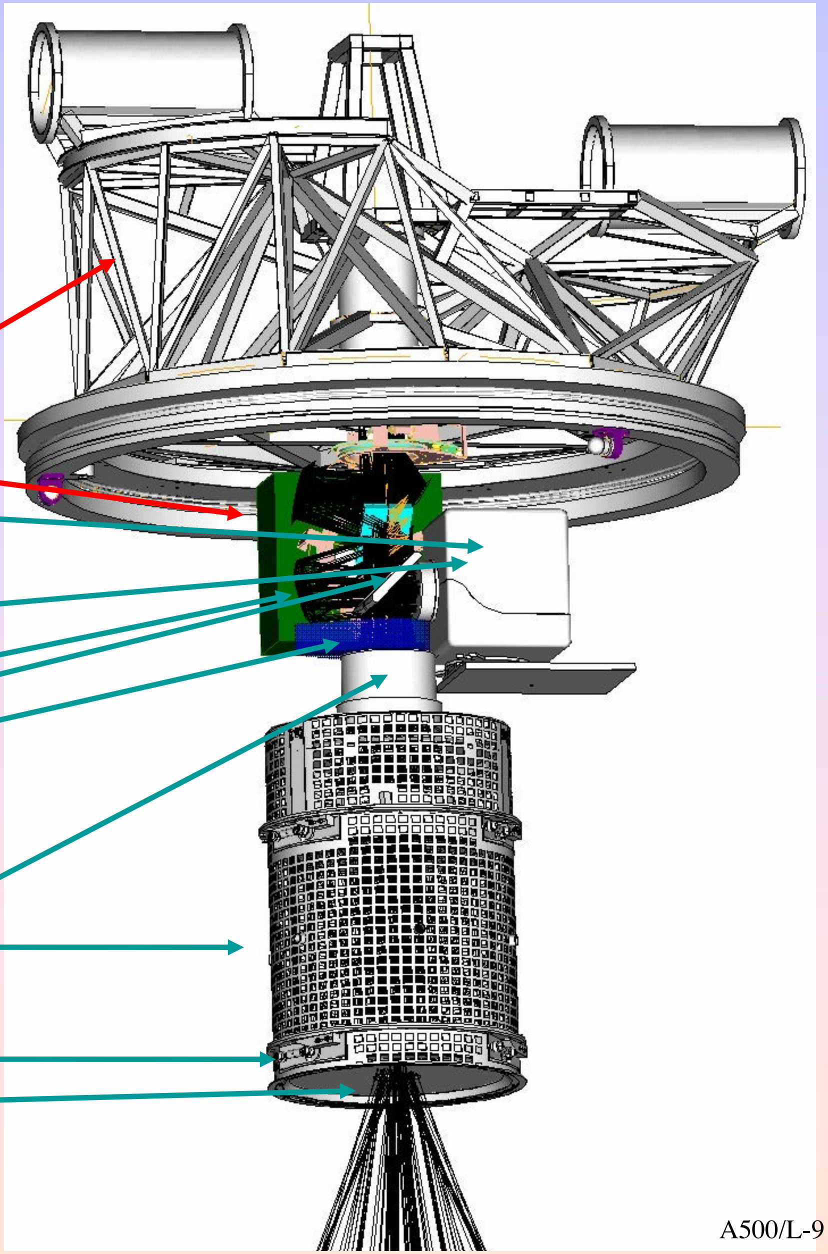
Prime Focus Payload (~1000 kg)
mounts via hexapod to tracker and comprises of:

Science instruments:

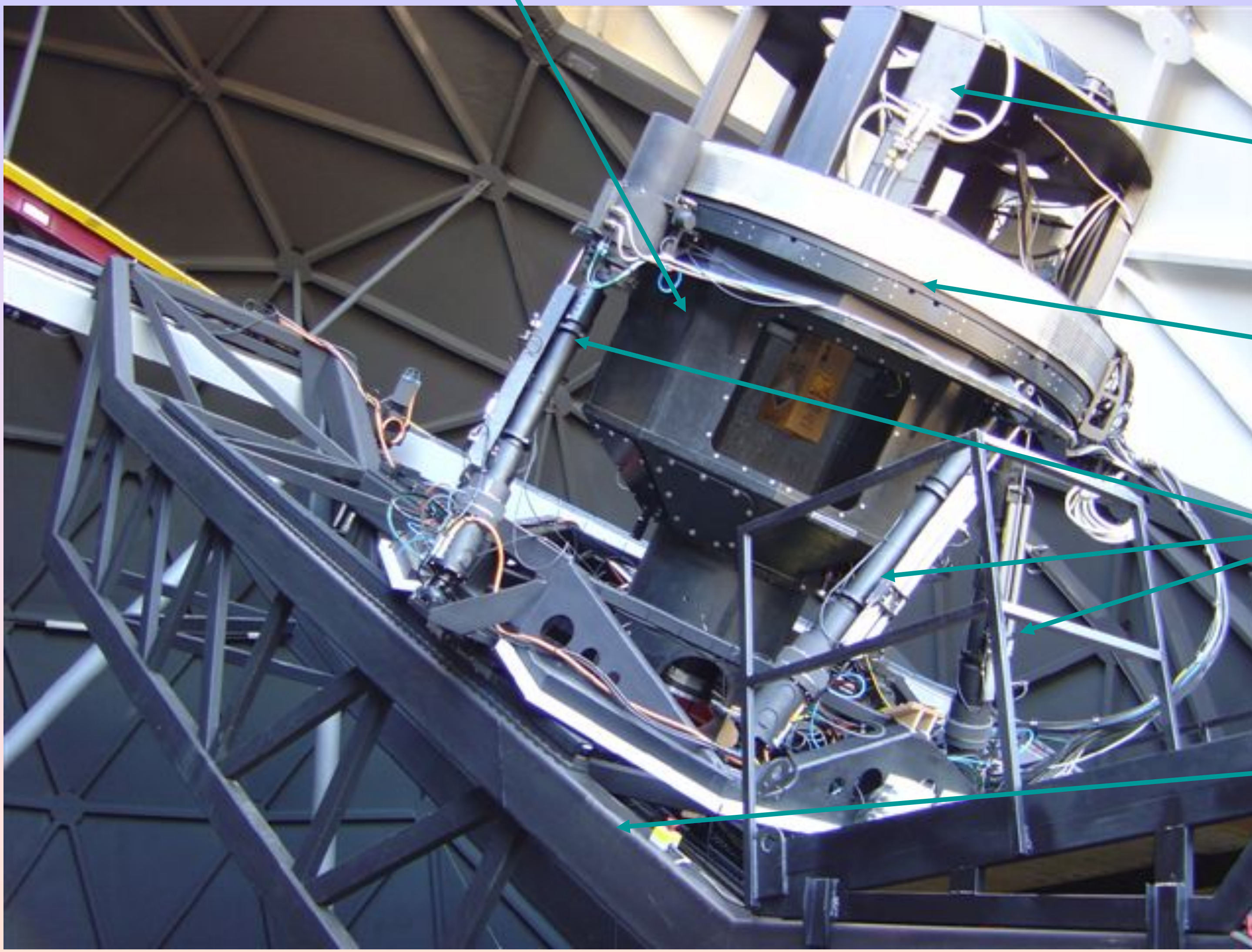
- Prime Focus Imaging Spectrograph (RSS-VIS)
- Fibre Instrument Feed (FIF)
- SALTICAM (optical imager)

Facility instruments:

- Acquisition camera (SALTICAM)
- Guidance & focus system
- PFIS slit-viewing optics
- Fold mirrors (to 3 focii)
- Moving pupil baffle
- Atmospheric Dispersion Compensator (ADC)
- SAC structure
- Payload alignment system (autocollimator and interferometer)
- Calibration system (flats, arcs)



Payload structure (rotating & non-rotating components) made of carbon composite



Dummy RSS-VIS mass

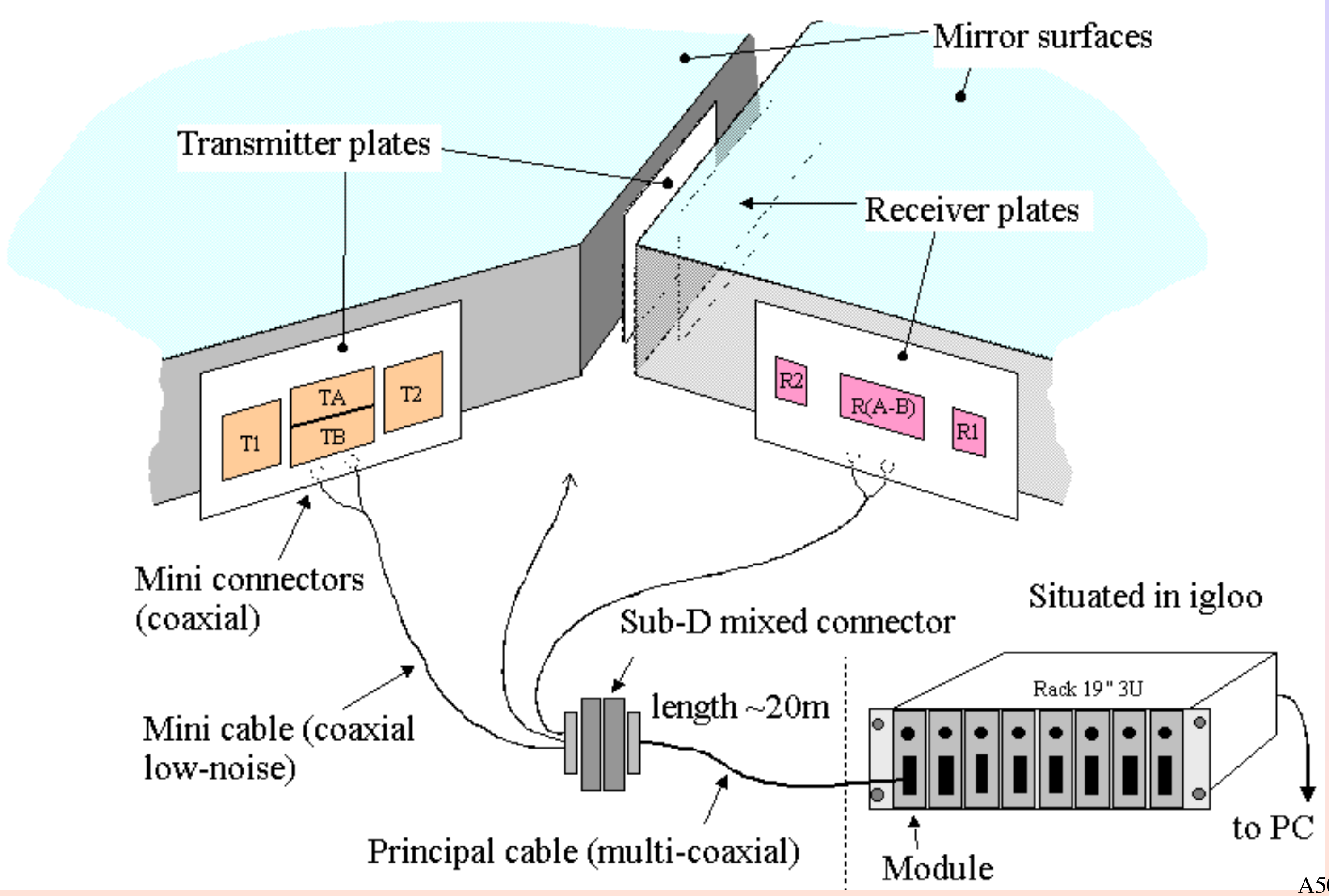
Instrument rotator ring

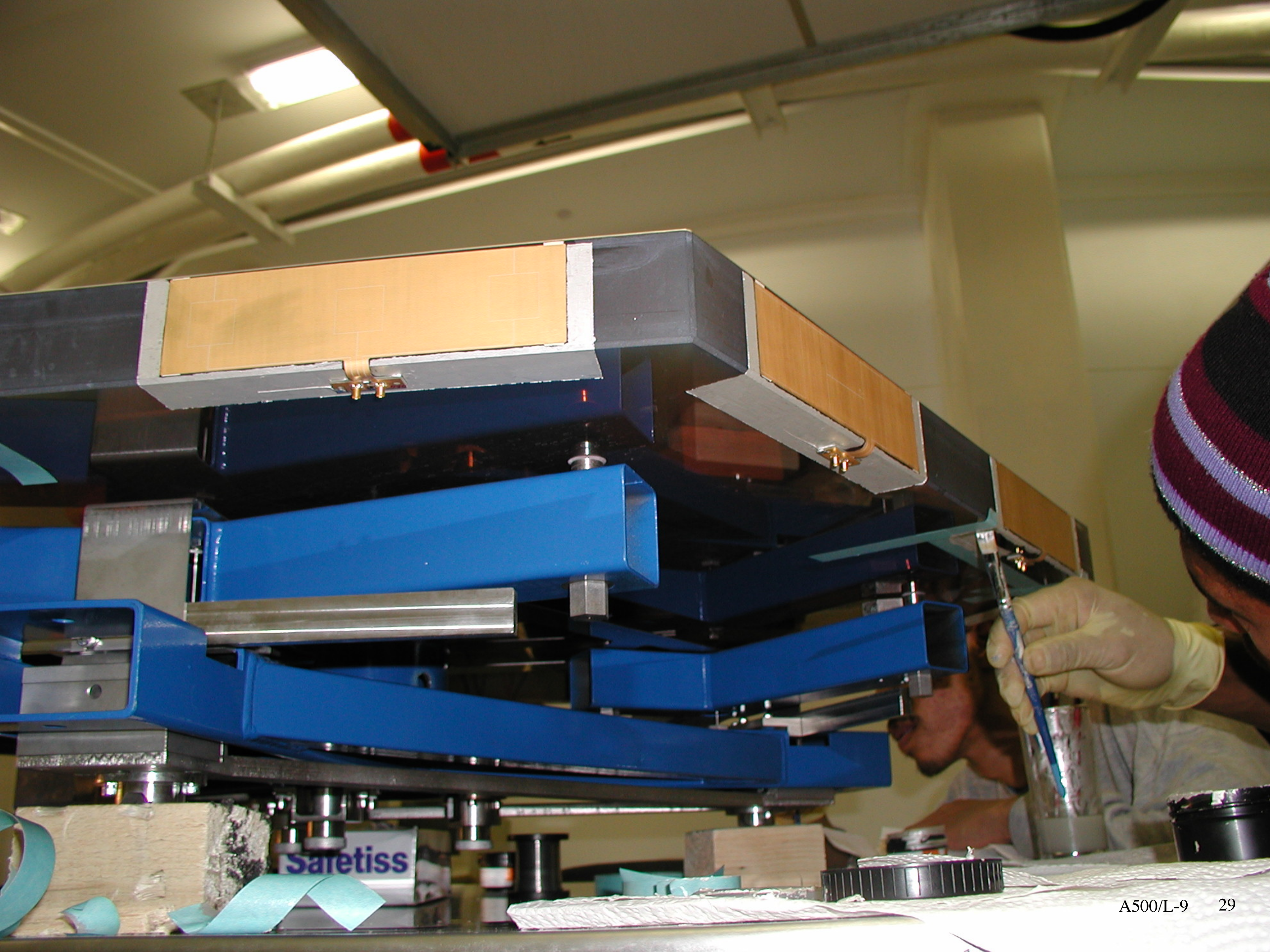
Hexapod legs

Tracker beam

SALT edge sensors

Thin, capacitive edge sensors between all mirrors achieve piston and tip/tilt tolerances. Low-cost design is highly replicable.

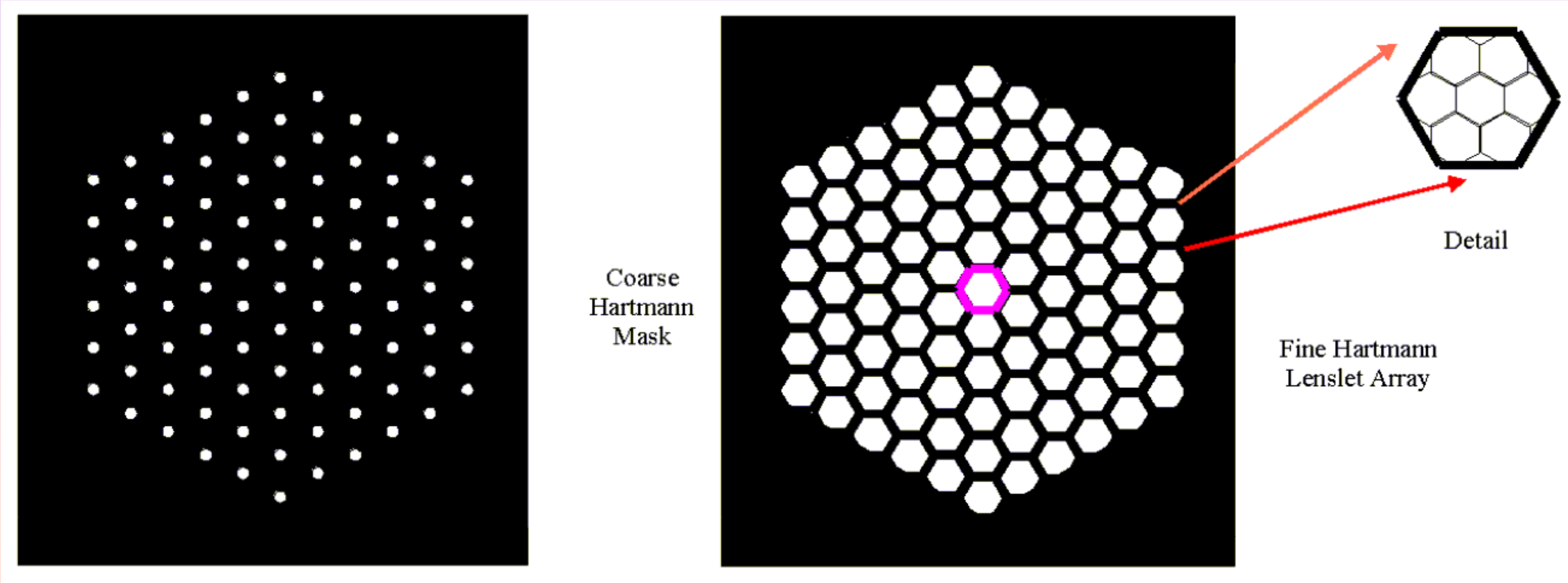



Safetiss

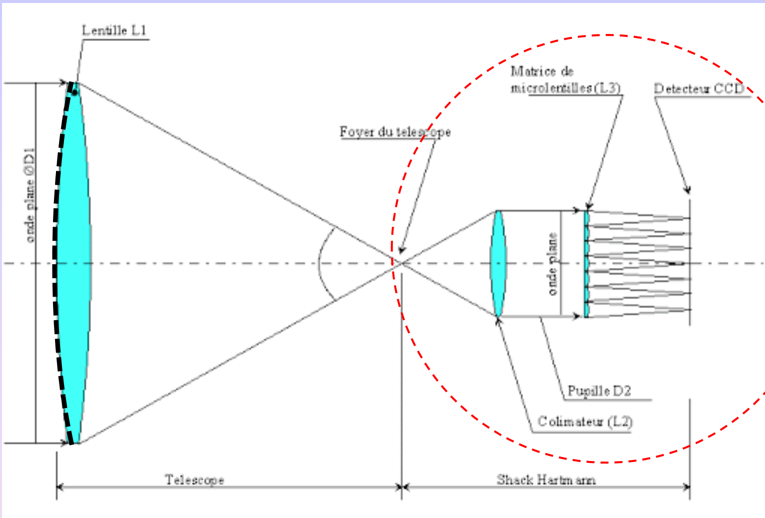
Centre of Curvature Optical Alignment

Custom built Shack-Hartmann wavefront sensor (from AOA).
Course alignment with 91 element lenslet array:
- captures primary in range ± 230 arcsec

Fine alignment with 7 x 91 lenslet array
- capture range ± 3 arcsec
- capable of measuring low-order Zernike terms for individual segments: diagnose mount errors



Shack-Hartmann wavefront sensor



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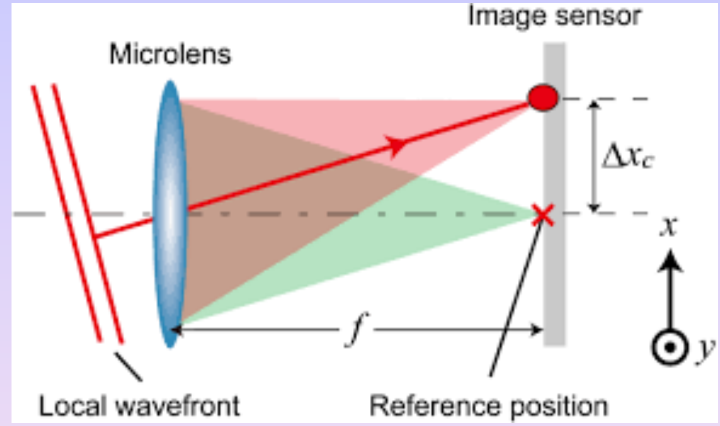
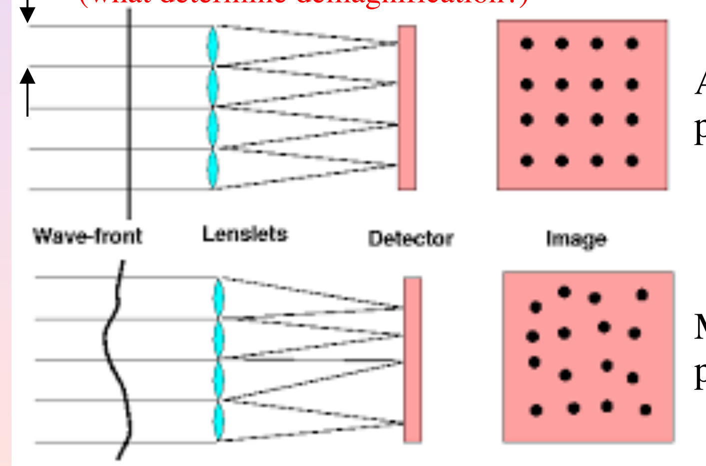


Demagnified mirror element diameter

(what determine demagnification?)



Aligned primary

Misaligned primary

ctio.noao.edu

In the case of SALT the telescope (L1) is an array of 91 spherical segments. The collimator (L2) in the S-H resizes the beam so that each mirror produces a collimated beam of the size of a single lenslet. In fact, you don't even have to collimate.

NB: this example is for AO (adaptive optics) where the wave-front distortions are continuous, but in the case of the SALT primary they are discrete (coarse alignmen) and the continuous in the fine-alignment mode (per mirror).

Comparisons of Operational Efficiency

Telescope	Bad weather	Technical problems	Engineering & Calibrations	Moving & acquisition overhead	Science
Keck I	16%	4%	11%	26%	43%
VLT	12%	2%	5%	15%	63%
Gemini	20%	3%	10%	15%	52%
HET	30%	6%	20%*	18%	26%**
SALT spec	25%	3%	7%	15%	50%**

*Including mirror alignment

**Defined as shutter open plus CCD readout time

SALT First-Generation Science Instruments

Major science niches for SALT in the visible' region (320-900 nm)

- High time resolution photometry and spectroscopy
- Efficient multi-object spectroscopy and Fabry-Perot imaging
- Good near-UV (to 320nm) sensitivity
- Spectropolarimetry (time resolved, all-Stokes)
- High-precision high-resolution spectroscopy (R = □/□□ up to 70,000)
- Rapid mode changes for queue and synoptic scheduling

➢ ***SALTICAM***: **optical imaging camera, of high-speed photometry.**

Status: ***in operation***

➢ ***RSS-VIS***: **optical multi-object spectroscopy, high-speed spectroscopy, spectro-photometry, spectropolarimetry (all-Stokes), narrow-band and Fabry-Perot imaging.**

Status: ***repaired in 2009-11; in operation; further repairs ongoing***

➢ ***NIR spectrograph (NIRWALS)***: **0.8-1.8μm IFU spectroscopy over 20 x 30 arcsec FoV**

Status: ***delivered from Uwisc in 2022; undergoing commissioning***

➢***HRS* (High Resolution Spectrograph)**: **high radial velocity precision (~few m/s), ideal for exoplanet detection.**

Status: ***in operation; upgrades for iodine cell and laser comb underway***

SALT: our 10m-class telescope

Review:

- **First light**
- **Science competitiveness**
- **Current status**

SALT Science - competitiveness

- Survey Science:
  spectroscopic follow-up of wide-field imaging surveys and clusters.
- Time variability studies:
  on scales of 0.05 sec up to a few hours, or > a day
  (photometry, spectroscopy, polarimetry)
- Multi-wavelength studies:
  suite of UV-visible instruments on large telescope with flexible scheduling
- Unique capabilities:
  spectroscopy & polarimetry from UV (320 nm) to 900 nm initially,
  extending eventually to J and H.
  - Wide range of parameter space & multiplex advantage (R = 370 – 10,000);
  - MOS of ~100 objects;
  - F-P spectroscopy of 1000's of objects.

Queue scheduling should give SALT unique ability for flexible scheduling allowing for time sampled programs in the Southern hemisphere

SALT: Current Status

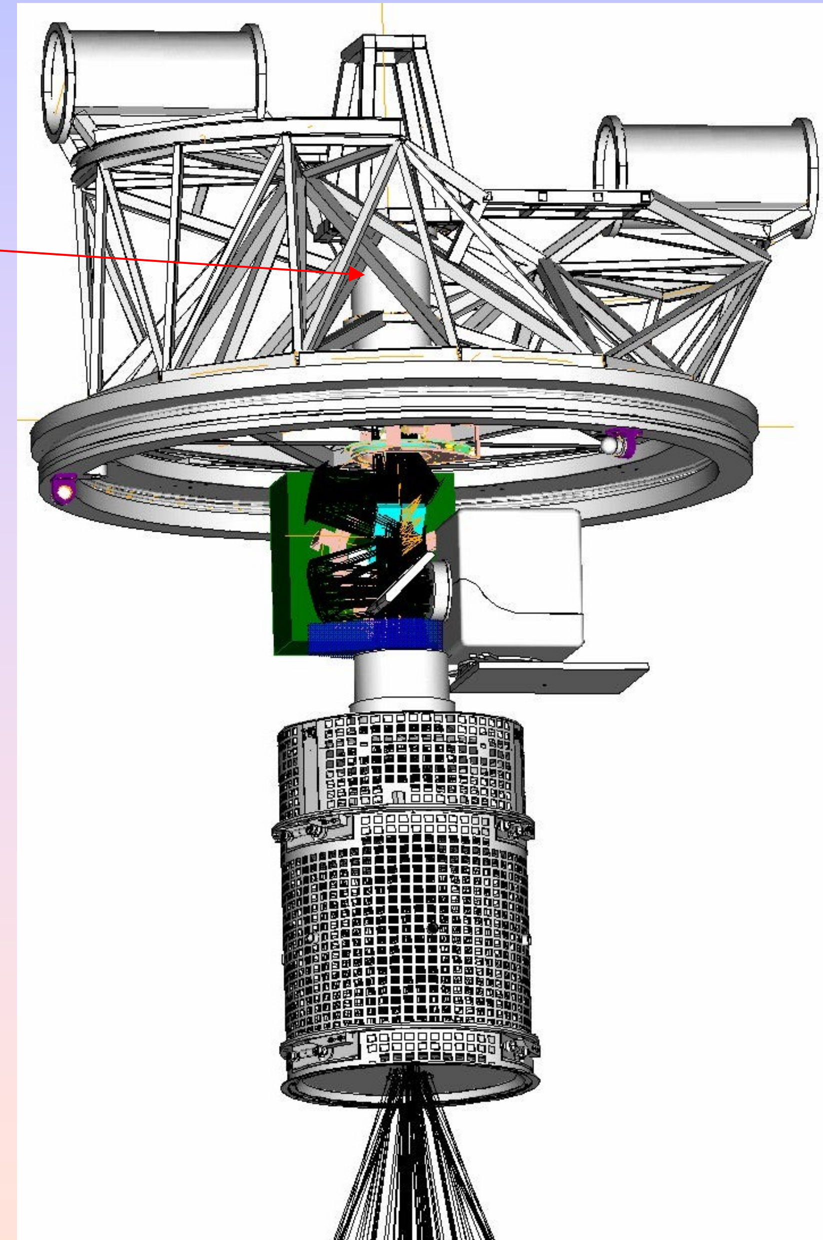
- *Restricted observations underway from 2006-2009*
  - **Limited primarily to time-series imaging data with poor image quality**
- *Three major problems:*
  - **SAC – testing, diagnosis and repair underway; some risks remain (2009-2010)**
  - **RSS-VIS – optical repairs, redelivery and integration (2011-2012)**
  - **Edge-sensors – system redesign. (2015-2016)**
- ***Full-up mode:*** **"anticipated for sometime in 2009"**

  (as reported in 2009…

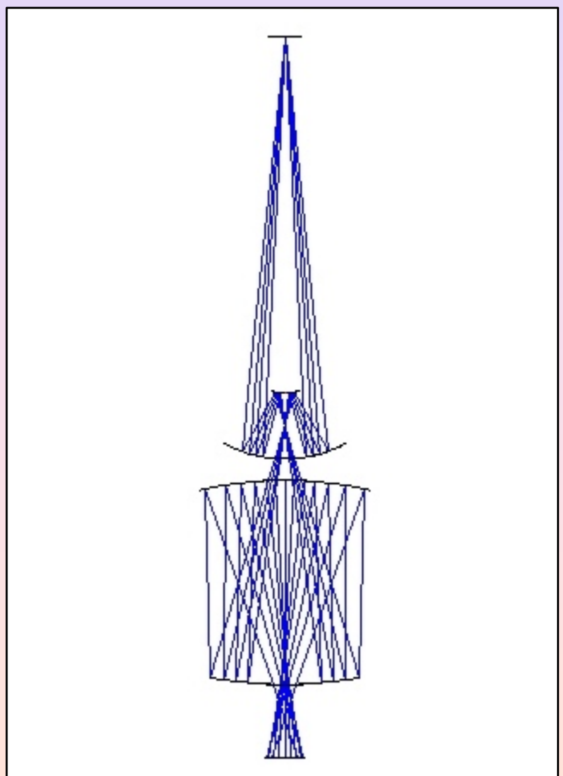
  … approached reality in 2015-2016)
- **Outstanding issues:**
  - **Spectropolarimetry**
  - **Calibration – field-flattening (variable pupil)**
  - **Fabry-Perot modes**
  - **Data reduction pipelines**

SALT Repairs: 1 & 2

1. RSS-VIS:
   - Optical coating-problem repair led to lens damage
   - Partally-fixed system on telescope in late 2011
   - NIR beam under construction; decision in 2015 to move system to fiber-fed IFU system in basement for 2018 delivery.



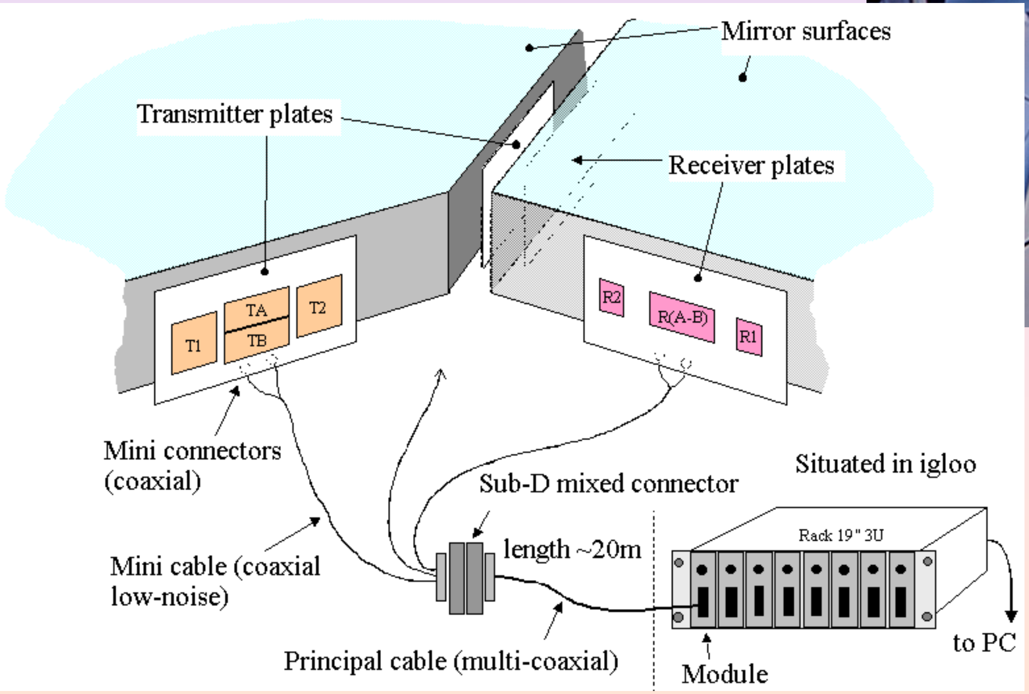
2. SAC:
   - Structural problems with mount
   - Diagnosis, repair and testing *completed* Dec 2010.
   - Coatings an outstanding issue.



3. SALT edge sensors

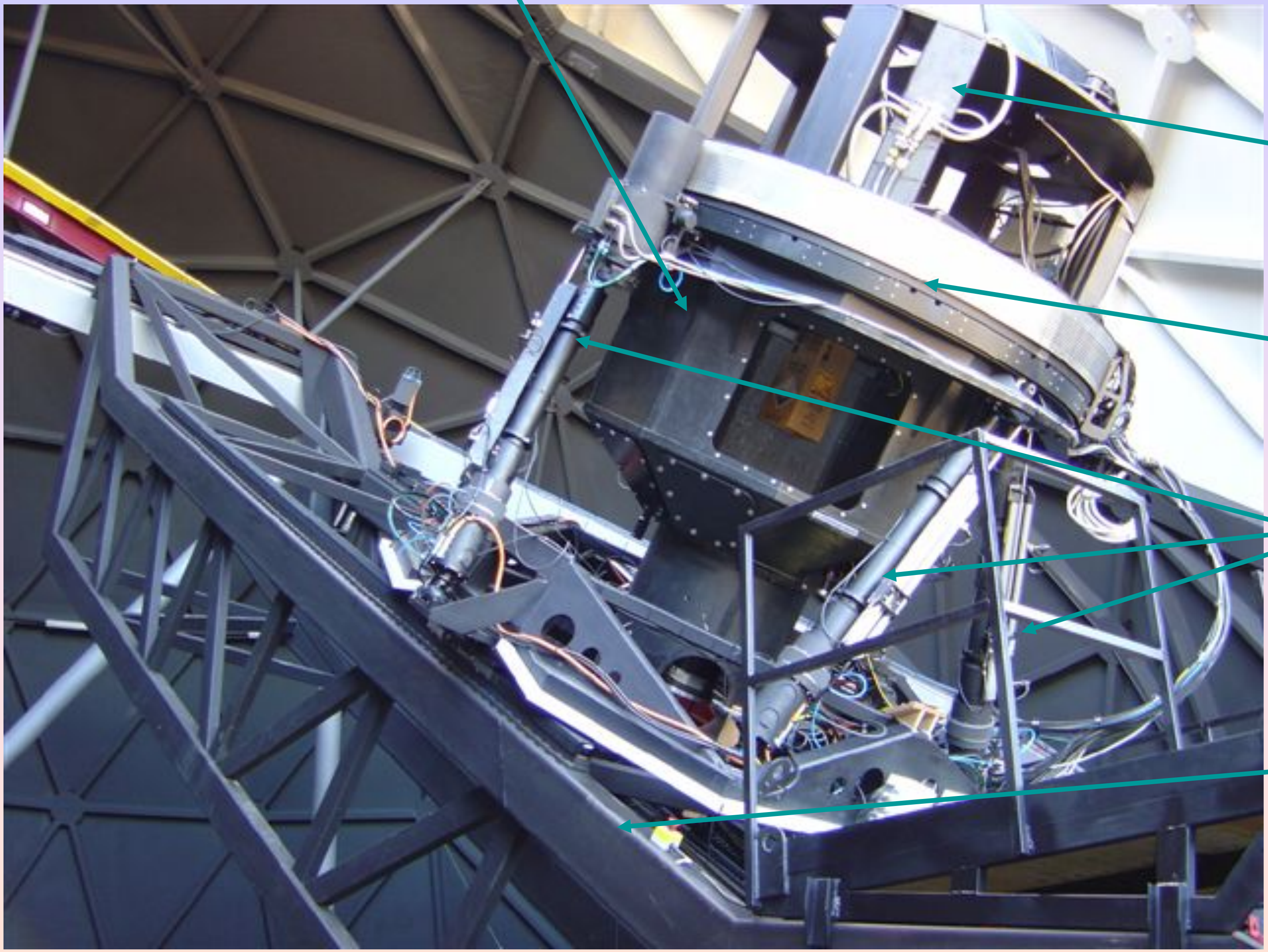
Status for nearly a decade:

- New system under design.
- Implementation 1-2 years from design completion.



Old system finally replaced 2015-2016

And a 4th problem: tracker had to be upgraded to accommodate added mass and moment of RSS-NIR; near critical-failure with current load.



Dummy RSS-VIS mass

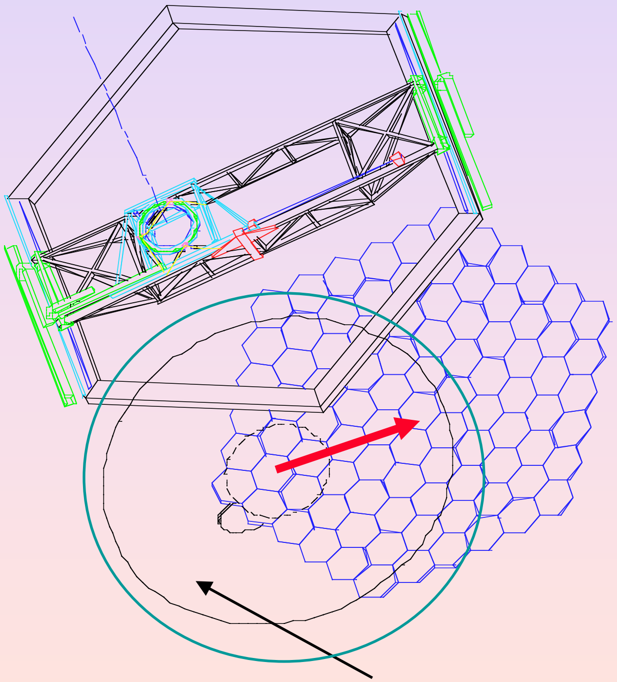
Instrument rotator ring

Hexapod legs

Tracker beam

How the telescope tracking works

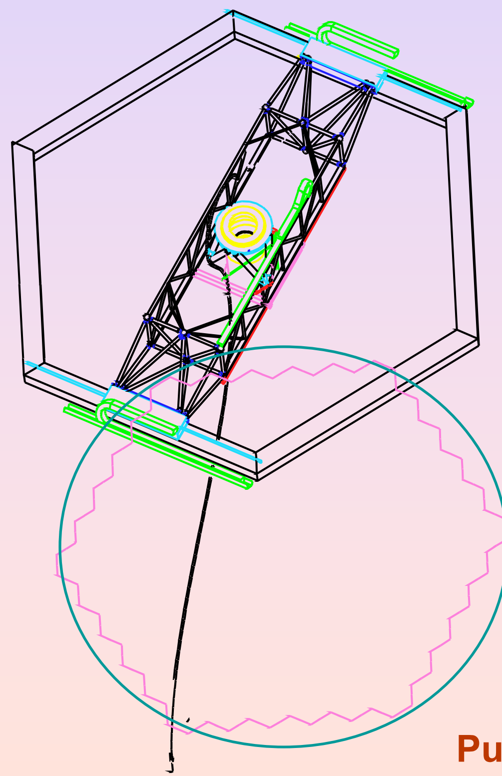
Tracker off-centre and pupil partially on primary mirror array. At worst extreme, still a 7.9 meter telescope!



Part of pupil off mirror is baffled at exit pupil position

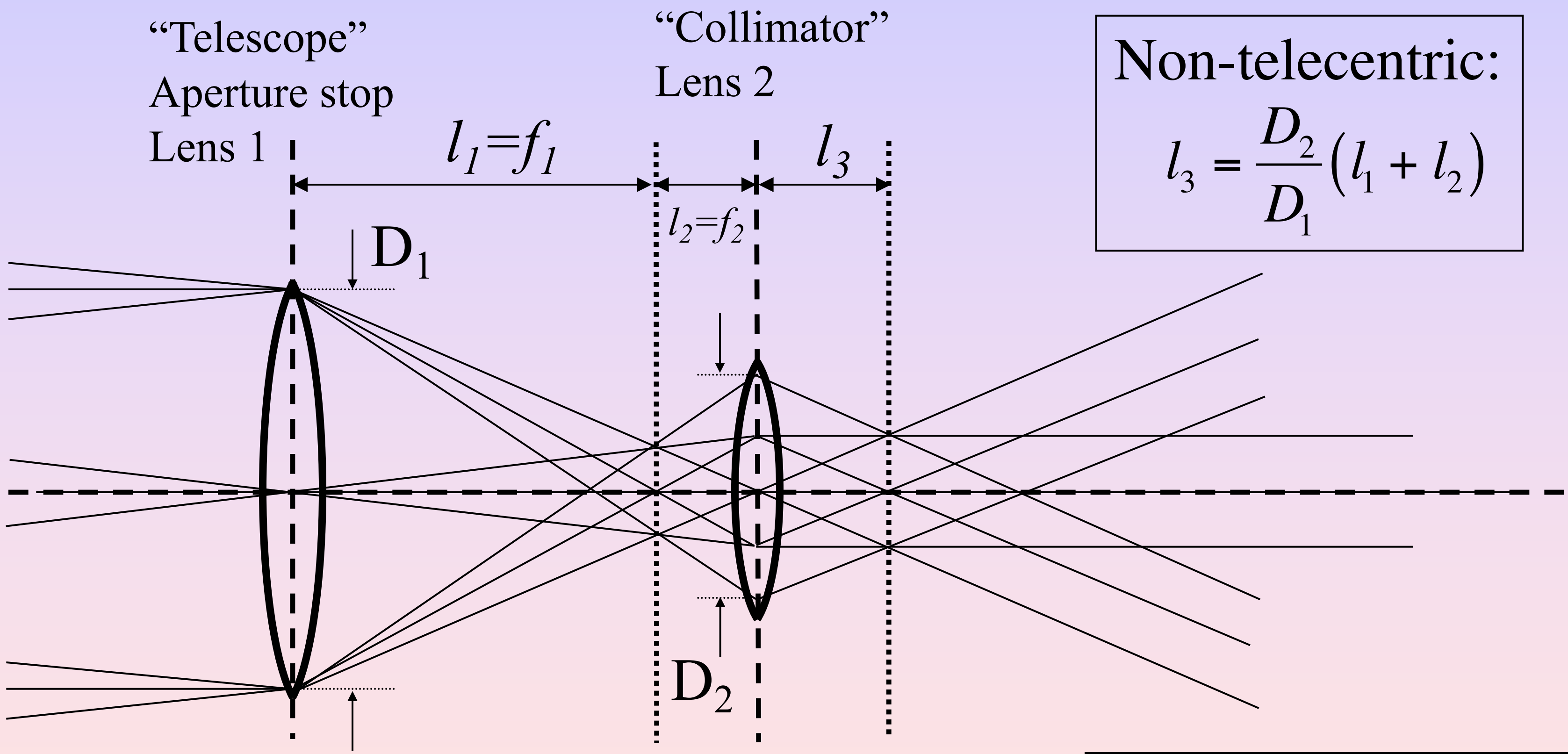
(SALT has 11-m diameter pupil compared to 9.1-m for HET)

With tracker and 11-m pupil centered on primary mirror array and central obstruction (from SAC optics), equivalent to a 9.2 meter telescope.



Pupil is underfilled

Objects, Images, Pupils



Object at ∞

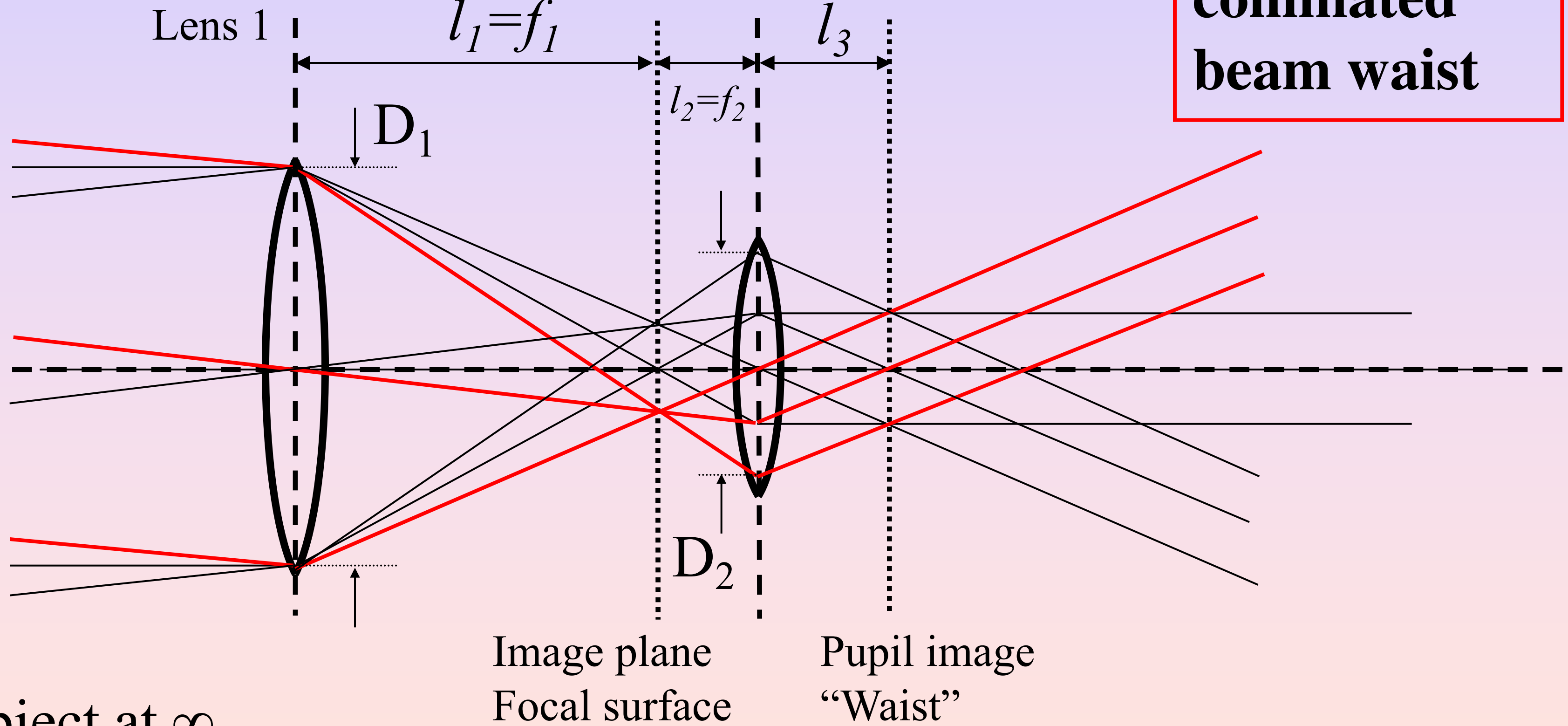
Non-telecentric:

$$l_3 = \frac{D_2}{D_1}\left(l_1 + l_2\right)$$

When does $l_3=l_2$?

$l_1>>l_2$ (telecentric)

Objects, Images, Pupils

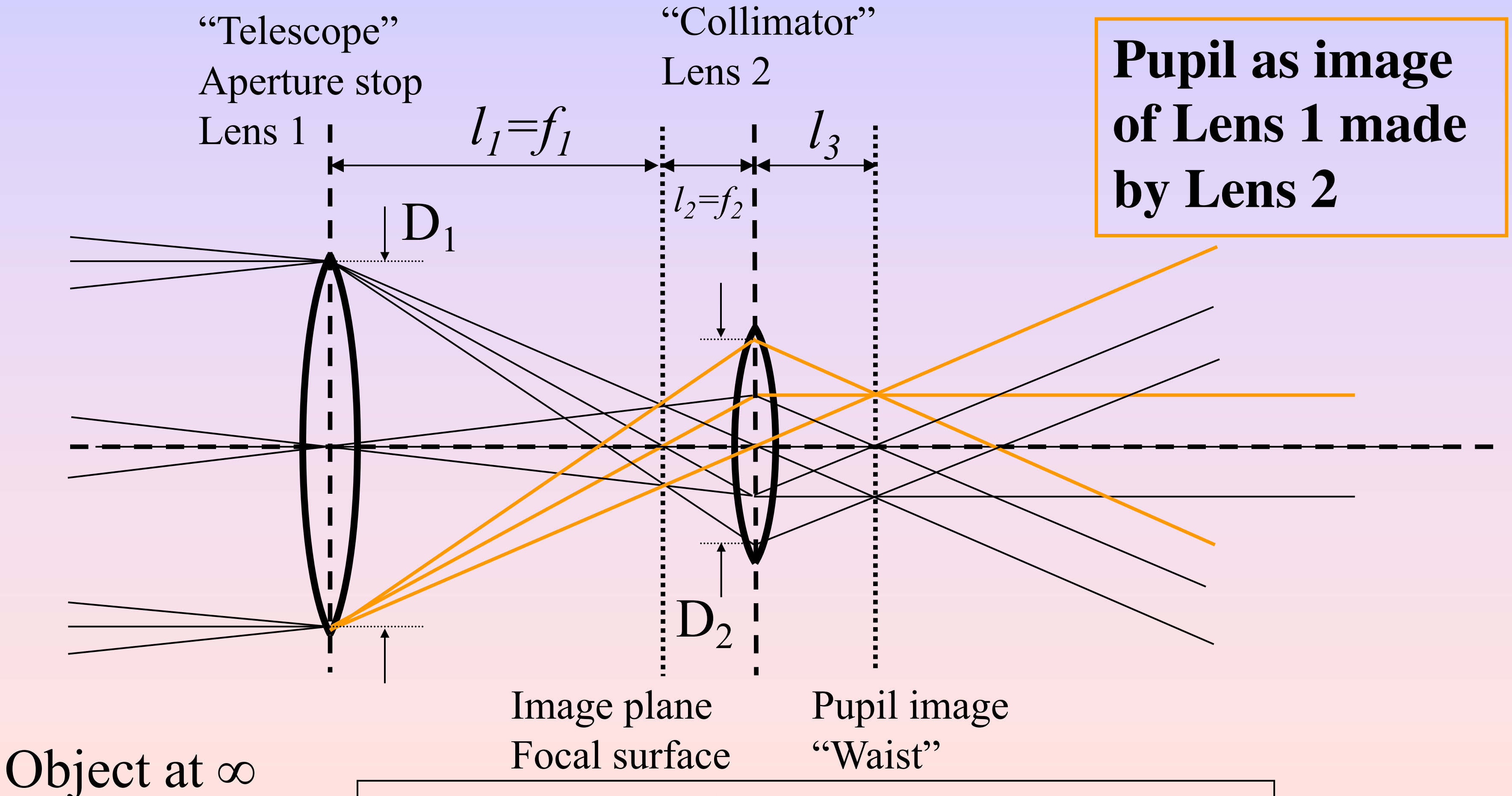


Pupil as collimated beam waist

Object at ∞

Pupil: cross-section of light-bundle where light from all field angles in focal plane completely overlap. This is an image of the telescope primary and its associated stops.

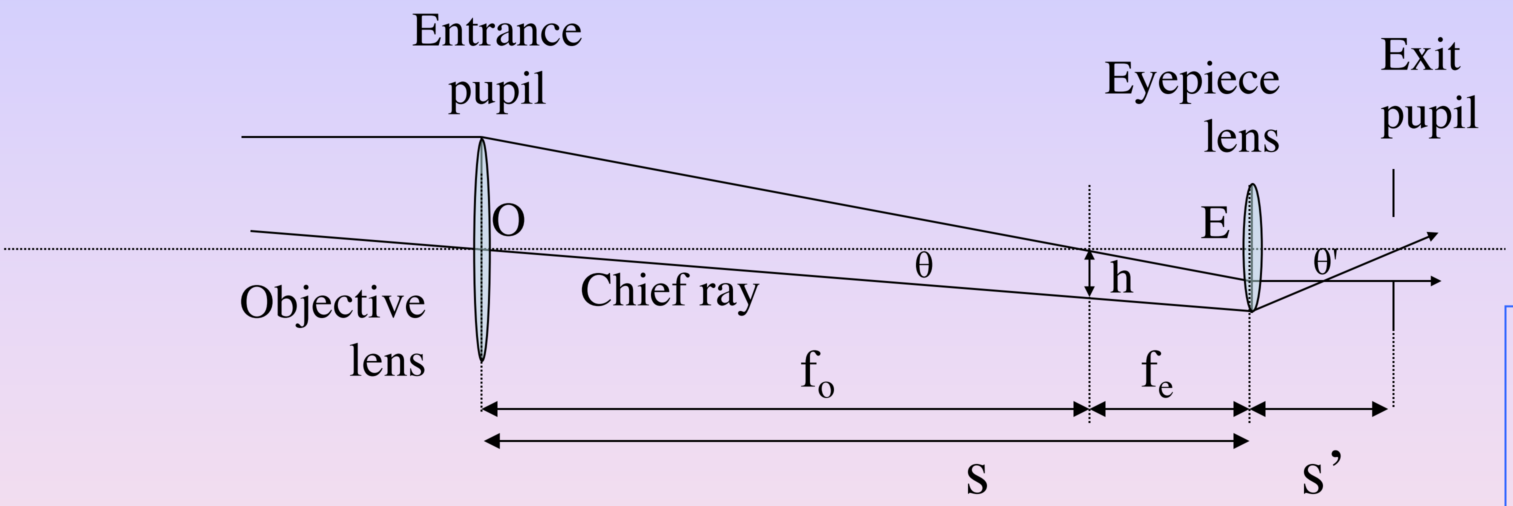
Objects, Images, Pupils



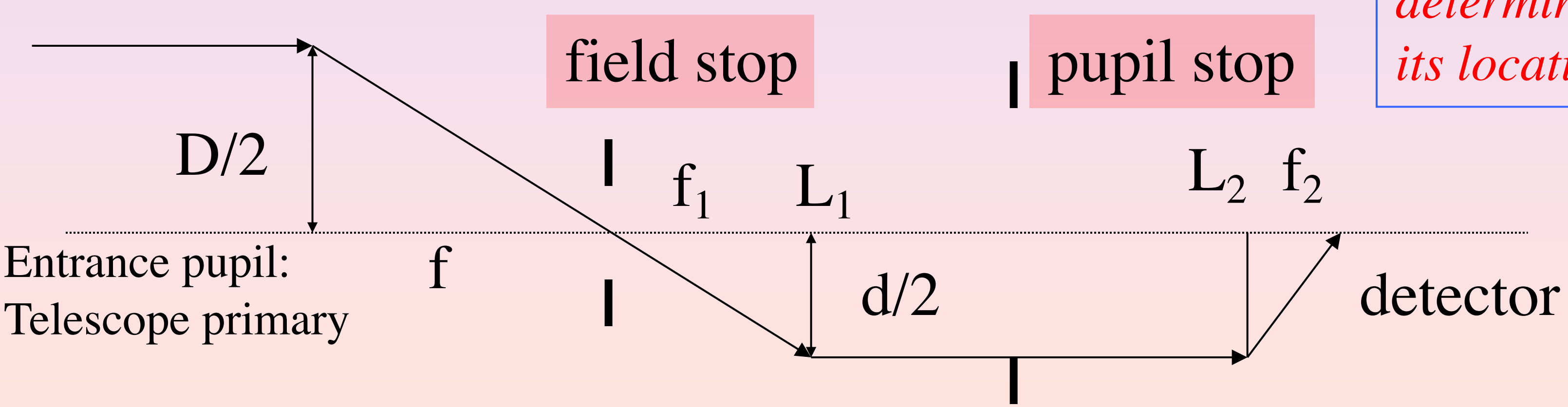
Pupil as image of Lens 1 made by Lens 2

Pupil: cross-section of light-bundle where light from all field angles in focal plane completely overlap. This is an image of the telescope primary and its associated stops.

Pupils and layouts



What is a pupil, and what determines its location?



Supplement

- SALT Construction photos

Before Nov 2000

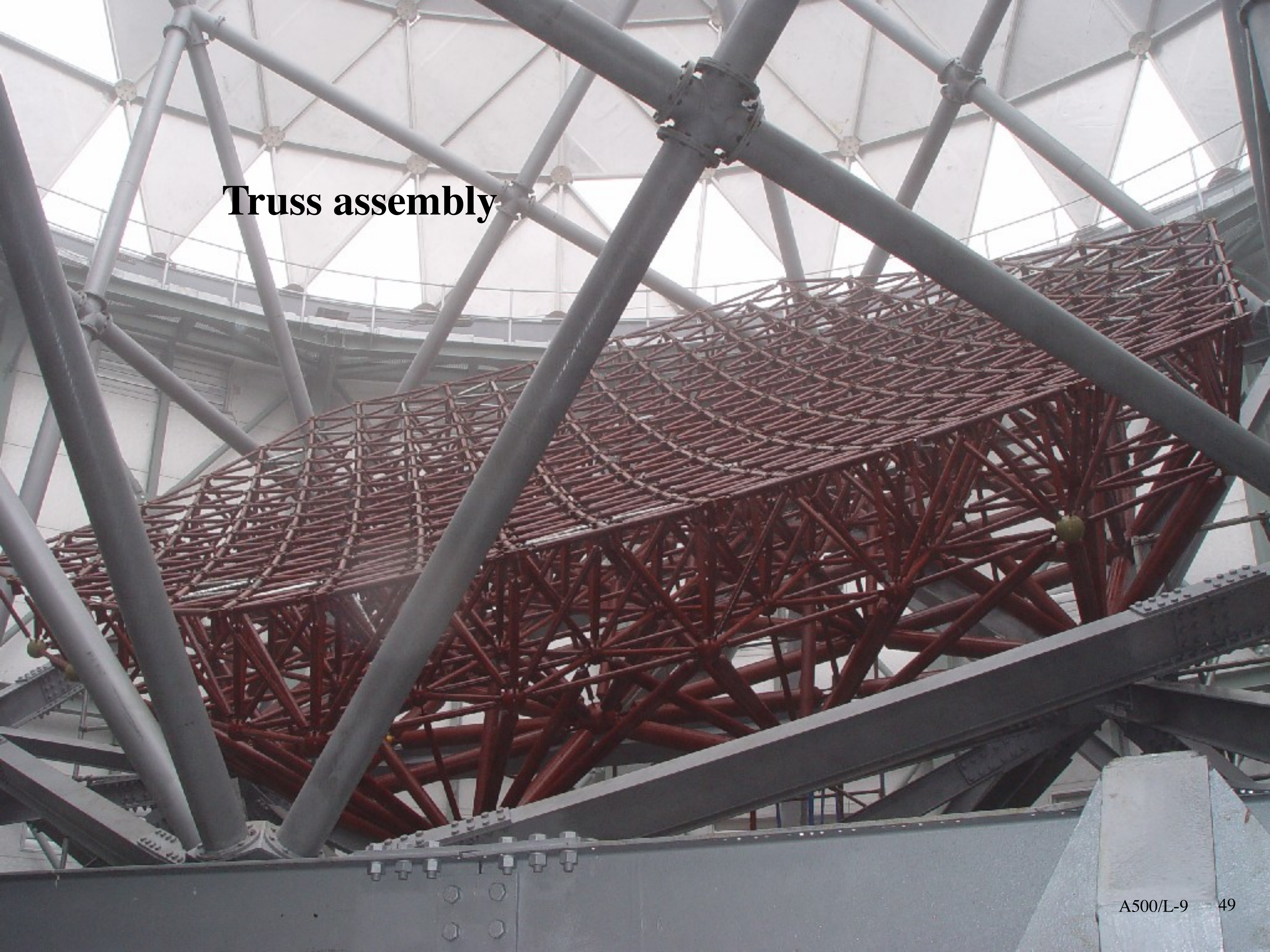
Photographic history of SALT:

In the beginning….
SALT site with existing SAAO telescopes


1 April 2001

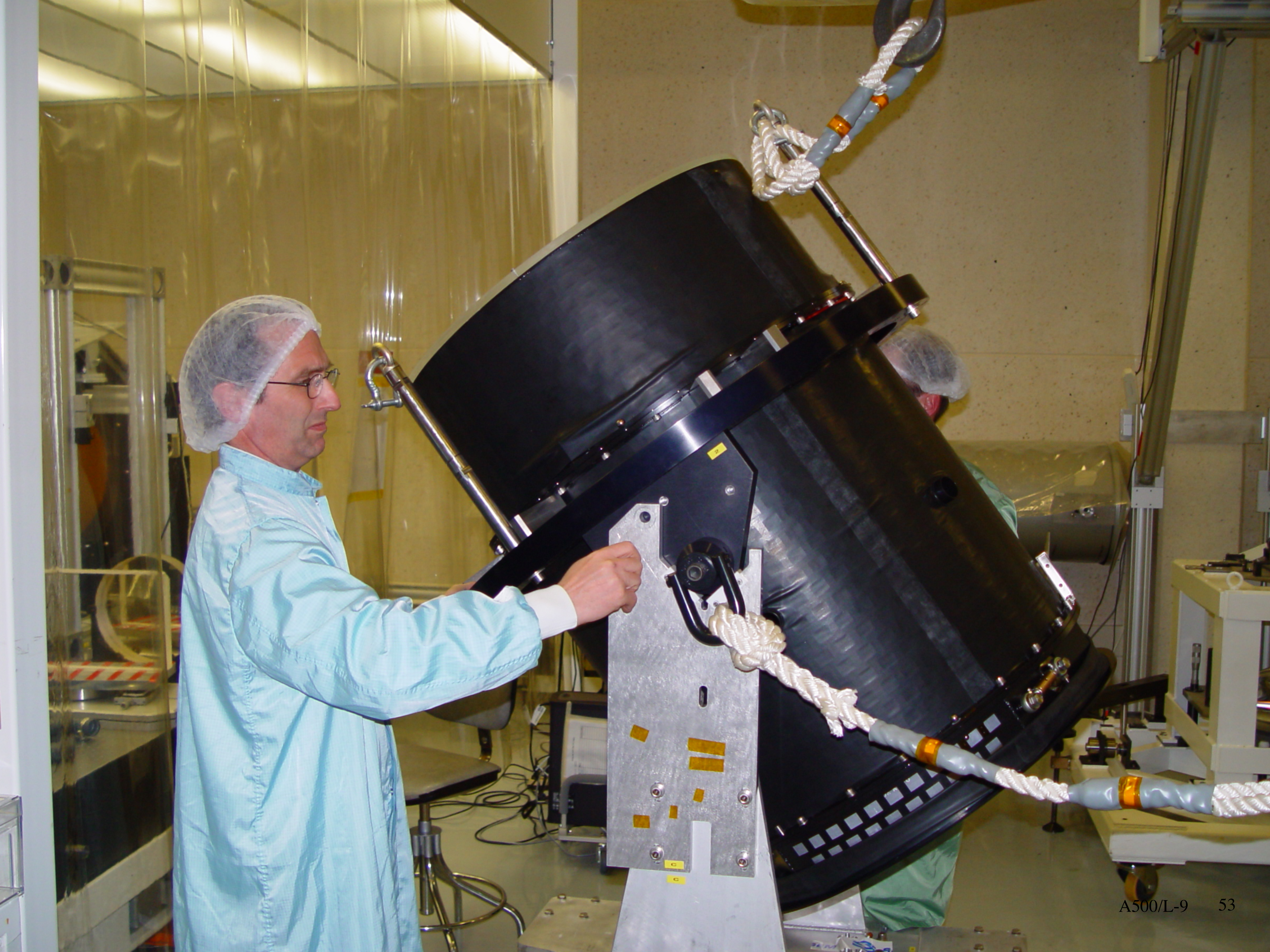
Oct 2002

Truss assembly



Sept 2003

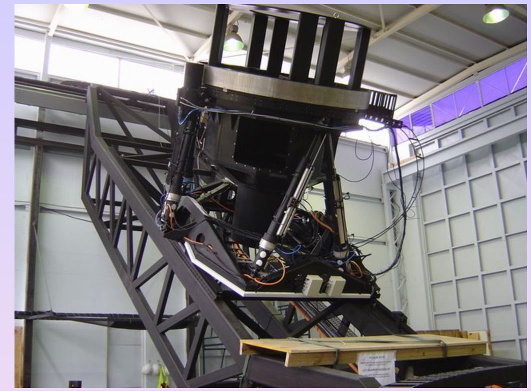
First PM Segment



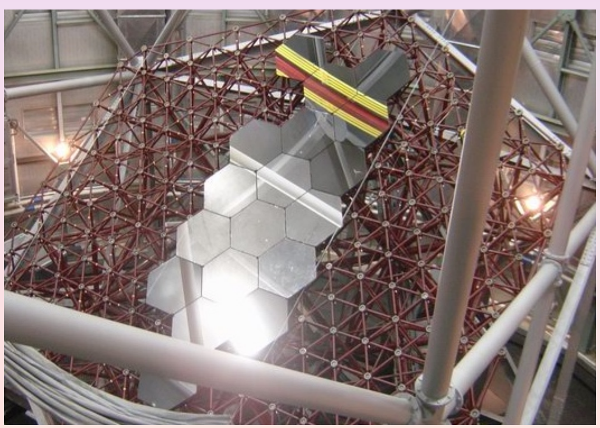
All telescope subsystems nominally complete

Structure & Dome (SDC)

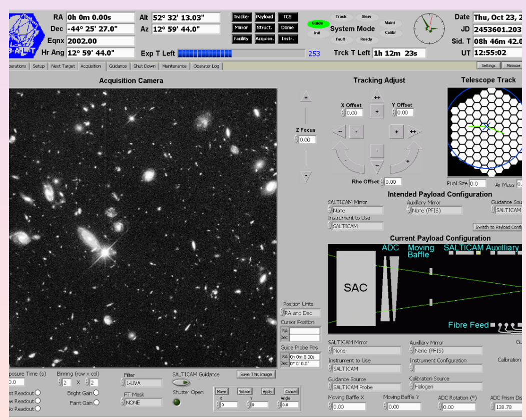
Building/Services (BMS)



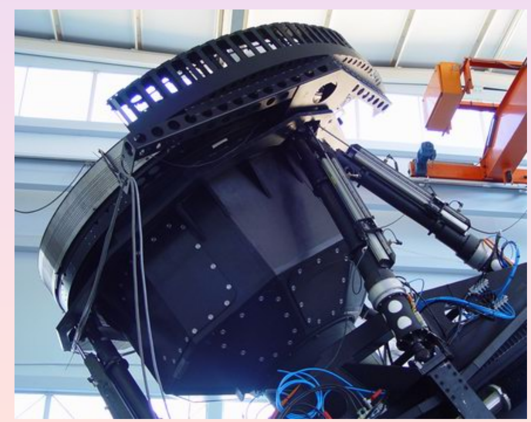
Tracker (TC)



Mirror Control
(MACS, SPS, SAMS, CCAS)



TCS (TCSS, SDB, PIPT,
OPT, SOMMI, SAMMI, ELS)



Payload (TPC)

PFIS delivery (30 Sep 2005)

PFIS = RSS

First Light: Sep 01 2005


47 Tuc
First Light: Sep 01 2005
1” FWHM