Adaptive Optics for the SALT

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ABSTRACT

We present a cost-effective solution for adaptive optics (AO) correction on the Southern African Large Telescope (SALT), where each primary mirror segment has compensation for tip-tilt atmospheric errors and a slower, active optic loop for sensing piston and correcting for focus drift. By treating the telescope as 91 independent tip-tilt corrected units, we compute the encircled energy gains for different seeing conditions at the SALT. Finally, the optical design for a simple AO demonstrator camera is presented, using seven tip-tilt correctors to directly measure and compare closed loop and open loop performances, which will help lead a full SALT AO system design.

Keywords: adaptive optics, tip-tilt, SALT, segmented primary mirror, active optics

1. INTRODUCTION

The Southern African Large Telescope (SALT)[1,2] is a fixed elevation telescope (based on the Hobberly Ebberly Telescope[3] (HET)) whose aperture is formed from 91 hexagonal mirrors in a close packed hexagonal array, generating an 11 meter diameter telescope. The aperture has a spherical figure with radius of $26165mm$, and a Spherical Aberration Corrector[4] (SAC) that provides a field flattened, aberration corrected 10 arcminute diameter field of view.

Optical path differences introduced by the atmosphere prevent many ground based telescopes from reaching their diffraction limited performance, as the plane wavefront from a distant celestial object is distorted by its propagation through temperature-induced changes in the index of refraction to the telescope aperture. These peturbations vary on a timescale of milliseconds at the wind moves across the telescope's line of sight. Many large telescopes use adaptive optic (AO) systems to improve the delivered image quality to the final science instruments by using a deformable mirror to provide path length compensation at a rate of up to 1kHz.

A standard measure of the optical strength of the turbulence is Fried's parameter, r_0, which is defined as the diameter over which the optical phase distortion has a mean-square value of 1 rad^2 at a wavelength of $0.5\mu m$. The Fried parameter is a function of wavelength λ, varying as $\lambda^{6/5}$. Longer wavelengths have larger Fried parameters, with typical values of $r_0 = 20cm$ for 1 arcsecond seeing in the visible, up to $r_{0(2\mu m)} = 2m$ in the infrared - furthermore, the Fried parameter can rapidly vary (up to a factor of 2) over several seconds.

An adaptive optic system provides partial correction for the aberrations introduced by the atmosphere. The atmospheric aberrations are measured with a wavefront sensor (WFS) camera and a set of deformable optical elements are subsequently supplied with corrective signals from the WFS camera, forming a closed loop whose rate of correction varies between different systems, but is typically 500Hz to 2kHz. The reference wavefront is either supplied by an astrophysical object, either a nearby bright astrophysical source or the science target of interest itself, or from a projected laser beam which produces an artificial guide star. The former systems are called Natural Guide Star[5,6] (NGS) AO systems, whilst the latter are Laser Guide Star[7,8] (LGS) AO systems.

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Many of these systems are designed to provide high-contrast, high Strehl ratio images of bright stars and galaxies that utilise the full spatial resolution of the telescope. SALT is optimized for spectroscopy and NIR imaging, but with a limited payload space near prime focus area, achieving high Strehl, whole aperture correction and Extreme AO is expensive to implement.

We propose an AO system for the SALT that reaches an *intermediate* level of correction. Instead of attempting to provide a diffraction-limited image from the whole SALT aperture, we investigated what gains could be made if one provided tip tilt correction for each individual hexagonal primary mirror segment. No attempt is made to provide coherent combination of the wavefront across the whole aperture.

The proposed SALT AO system is thus composed of 91 tip-tilt NGS AO systems that function independently of each other, which naturally leads to several advantages:

- The components in this design use as many off the shelf, standard optical components as is possible, so that the system can be maintained without significant extra cost.

- If any of the tip-tilt units fail, they do not impact the performance of any of the other units.

- A full AO design using only reflective optics will preserve the achromatic performance and field of view of the telescope.

- The loop can be slowed down and act as an *active optics* system that can accomodate primary mirror segment focus drift and send periodic corrections to the primary mirror support system.

2. SIMULATIONS OF TIP-TILT CORRECTION

We modeled turbulence degraded image profiles using the semi-empirical models from the book on adaptive optics by Hardy,[9] more specifically Eqns. 4.63 and 4.64 on p. 121. Estimates for the root mean squared error on the incoming wavefronts for atmospheric turbulence and for a tip tilt corrected wavefront were taken from Noll's approximations, and each hexagonal aperture was assumed to have a diameter of 1.0 meters.

The seeing at the SALT site was taken from the SALT site characterization report.[10] Figures 2,3, and 4 show the expected gain in encircled energy for seeing at the first quartile, median, and third quartile conditions. The Fried length, r_0, was estimated for each of these conditions using the equation $r_0 \sim 1.22\lambda/D$ with D set to 1m and $\lambda = 0.5\mu m$. Each line on these figures represents a given diameter of optical fiber, ranging from 0.2 arcseconds to 1.0 arcseconds. The upper panel shows the encircled energy gain factor of a tip-tilt corrected beam versus a beam with no atmospheric correction. The lower panel shows the total tip-tilt corrected transmission efficiency for a given diameter fiber as a function of wavelength.

A significant conclusion is that there are very large gains in encircled energy available beyond 1 micron. This is consistent from Ao correction theory, which contains the result that tip-tilt only correction is most optimum when the diameter of the corrected aperture divided by the Fried length for a given wavelength is approximately 4. The values of D/r_0 for diffferent cases are listed in Table 1.

Table 1. The variation of D/r_0 as a function of different wavelengths for median seeing (0.92") at the SALT. At longer wavelengths, D/r_0 approaches a value of 4, equal to the conditions for optimum gain for tip-tilt correction.

Wavelength (nm)	r_0 (cm)	D/r_0
500nm	12.0	8.3
800nm	18.8	5.3
1000nm	27.5	3.6

Tip-Tilt Encircled Energy gain with 0.74 seeing

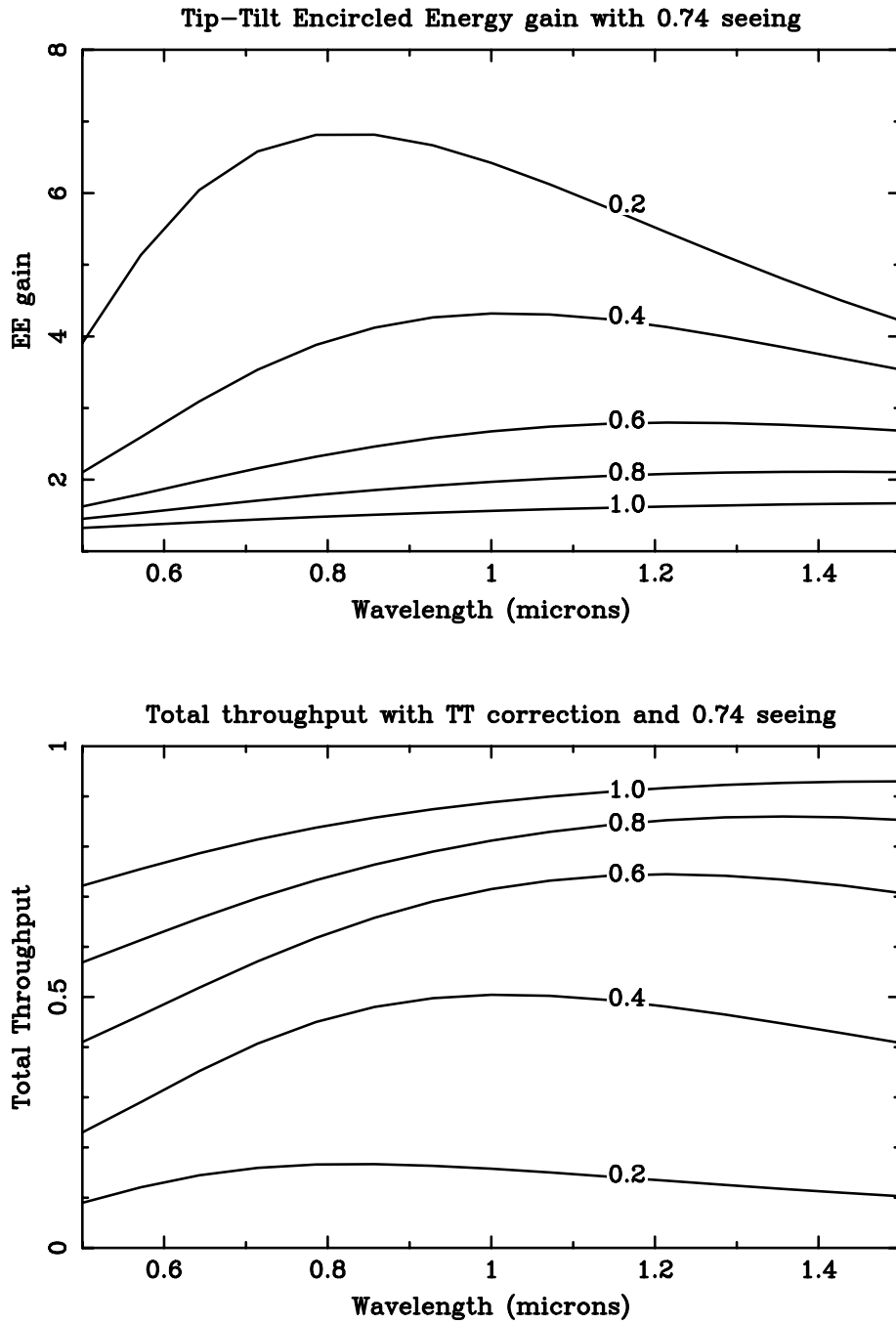## Total throughput with TT correction and 0.74 seeing

Figure 1. Gain in encircled energy and total fibre throughput for a variety of aperture diameters (0.2 to 1.0 arcsec) as a function of wavelength for first quartile seeing.
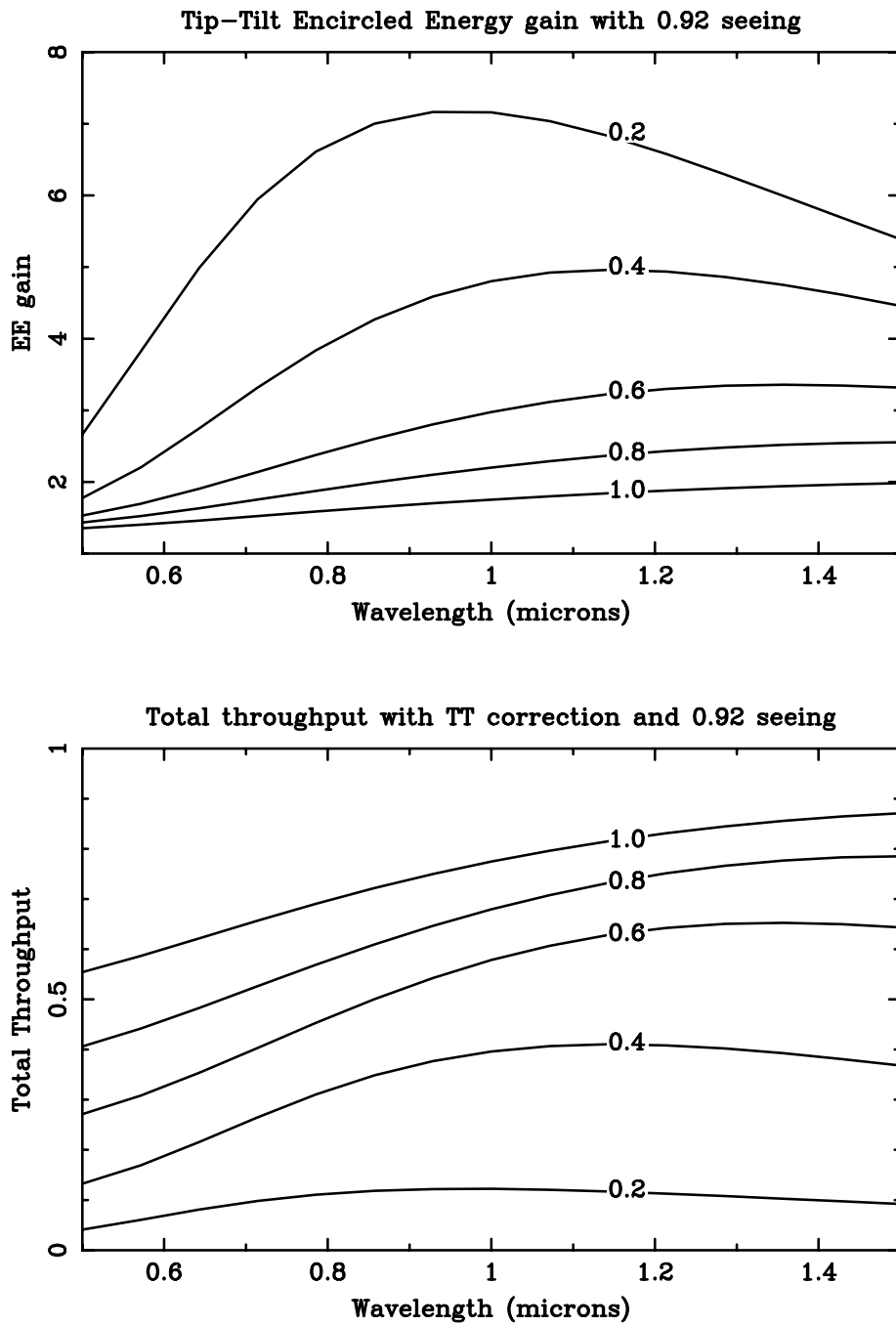
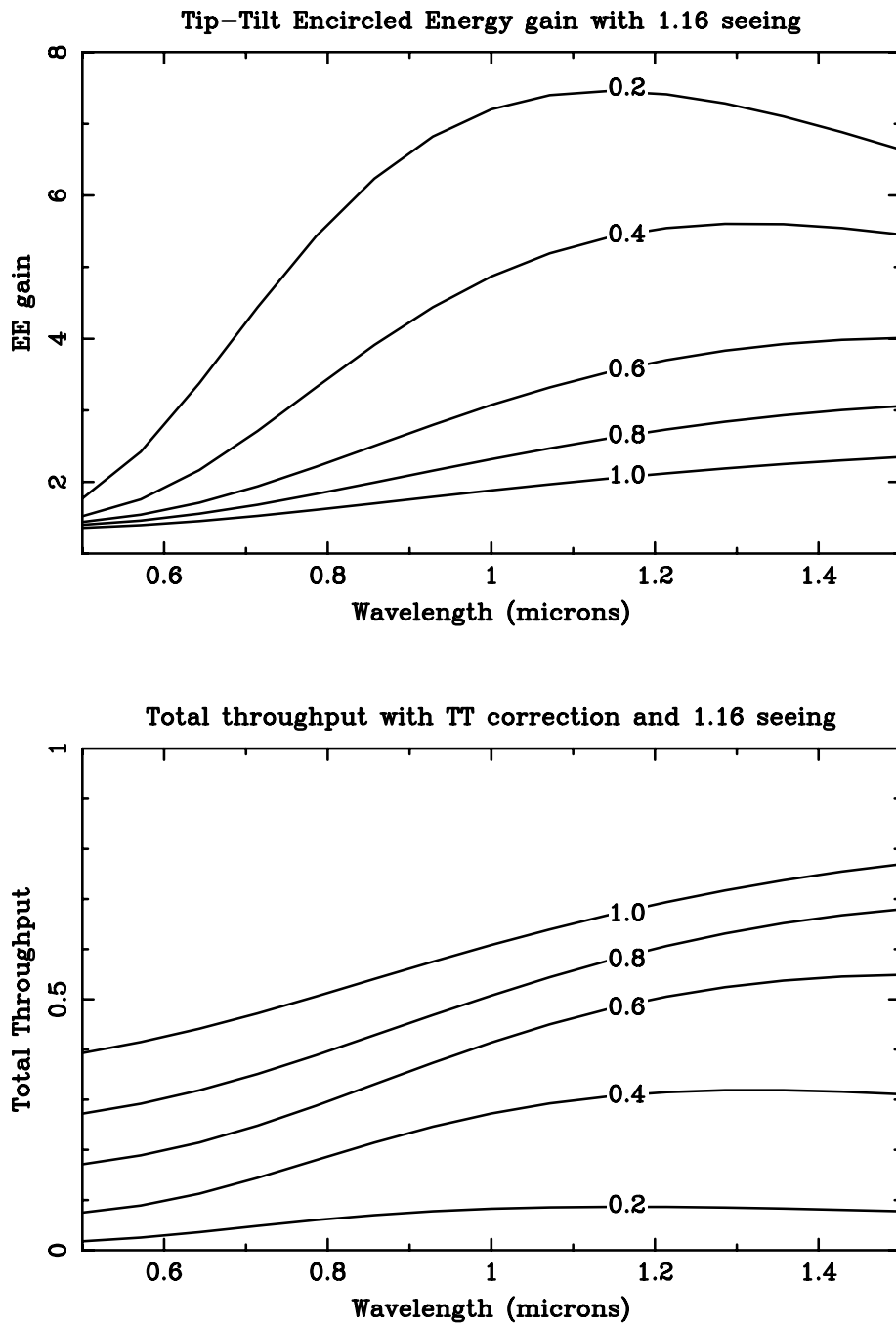Figure 2. Gain in encircled energy and total throughput as a function of wavelength for median seeing.

Tip−Tilt Encircled Energy gain with 1.16 seeing

Total throughput with TT correction and 1.16 seeing

Figure 3. Gain in encircled energy and total throughput as a function of wavelength for third quartile seeing.

2.1 Estimate of Isoplanatic Angle

If the science target is separated from the natural guide star by an angle θ, then the WFS camera will see a different atmospheric beam compared to the science beam. The difference in the wavefronts integrated along the two separate beams is expressed as the anisoplanatic tilt error variance, σ_T^2, and is approximated using a power series expressed in Eqn. 7.58 and 7.59 from Hardy.[9]

The coincident beams at the telescope will have decreasing overlap with increasing altitude and eventually separate at a height $h_c = D\cos(z)/\theta$, where D is the telescope diameter and z the zenith angle of 37°. The dominant turbulence at the SALT site is at 3km and at 12km,[10] so for telescope apertures of 1.0m, the two beams separate at $\theta = 13 arcsec$ for the turbulence layer at 12km. Since some of the dominant turbulence is located above the beam separation height, the full expansion of the power series is required to estimate the single axis root mean squared motion of the science target, and it is dependent on the outer scale of the atmosphere's turbulence, which is a poorly defined quantity for many sites but has been found to be on the order of 10m to 100m. When the anisoplanatic tilt error is normalised to the Airy disk size, the wavelength dependence is removed - the isoplanatic patch is similiar in size at all scientific wavelengths.

Estimating from the graphs of single axis root mean squared motion in Hardy (1998) for $D = 1m$ and $\lambda = 0.55\mu m$, the isoplanatic patch is well over $2'$ in diameter. This is borne out in measurements from the MMTO telescope in 1993[5] and with estimates from the Keck AO systems,[7] who typically quote isoplantic diameters on the order of $2'$.

2.2 Estimate of Sky Coverage

If we assume an effective corrected patch diameter of 2 arcmin, we can calculate the sky coverage using NGS and tip tilt correction. Using an estimate of a limiting magnitude of $m_v = 18$ and the isoplanatic size stated above, there is a 20% sky coverage for the SALT AO.

This number is of course dependent on the atmospheric conditions for a given night, and is expected to vary. What will not vary, however, is *the SALT AO system will always provide active closed loop for the primary mirror system.*

3. SADCAM: THE SALT AO DEMONSTRATOR CAMERA

The simulations in the previous section suggest that modest improvements in encircled enegry are possible over a variety of seeing conditions, typically increasing for longer wavelengths. In order to confirm these simulations, we have designed a simple AO system that can be used at the guest port in the SALT top box. The system, which we have called SADCAM (short for SALT AO Demonstrator Camera), uses two lenses and two fast readout cameras to measure the atmospheric distortions of the incoming wavefront, and seven fast tip-tilt mirrors to provide AO correction which is then measured and compared to the open loop images.

The goal of the camera is to determine encircled energy gain achievable for a variety of seeing conditions at the SALT, and to determine the Fried parameter, r_0, the typical atmospheric time constant, τ_0 and, if possible, determine the isoplanatic angle for the SALT site at visible and IR wavelengths. The results from this camera will determine whether a full size AO system is feasible or not.

In order to keep the budget to a low cost, we are proposing to use off the shelf fast tip-tilt actuators, which can potentially be reused in the larger final SALT AO design, and so require a magnification of the pupil by a factor of two to accomodate the center to center distance of these actuators. We also use video frame rate cameras, but may move to more expensive fast readout CCDs if required to close the AO tip tilt loop.

The optical design is shown in Figure 4. A field lens is placed at the f/4.2 telescope focus, reimaging the telescope pupil and magnifying it by a factor of 2 onto the array of flat, hexagonal shaped tip-tilt mirrors, selected to be mirrors that are continuously illuminated and are not vignetted by the payload assembly.

The seven hexagonal tip-tilt mirrors form a close-packed array, with 25mm center to center spacing. The mirrors are fixed to seven Piezo Instrument fast tip-tilt-piston F325 actuators, which are fed control signals from the SADCAM computer. These mirrors are fixed onto an x-y translation stage which allows tracking of the
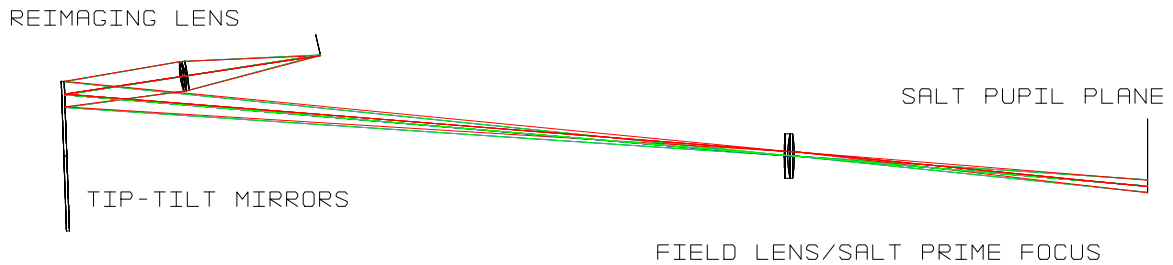
SADCAM BASELINE DESIGN

REIMAGING LENS

SALT PUPIL PLANE

TIP-TILT MIRRORS

FIELD LENS/SALT PRIME FOCUS

Figure 4. SADCAM Optical Design. Shown is the SALT pupil, reimaged at the right hand side of the image. The light moves from right to left, and forma a focal plane image, where a field lens is placed. This lens then forms an enlarged pupil image with a magnification of two. The pupil image is incident on a set of tip-tilt mirrors, and the light is reflected to a second lens that then reimages the star on the detectors. Plate scale is $36\mu m$/arcsrcond.
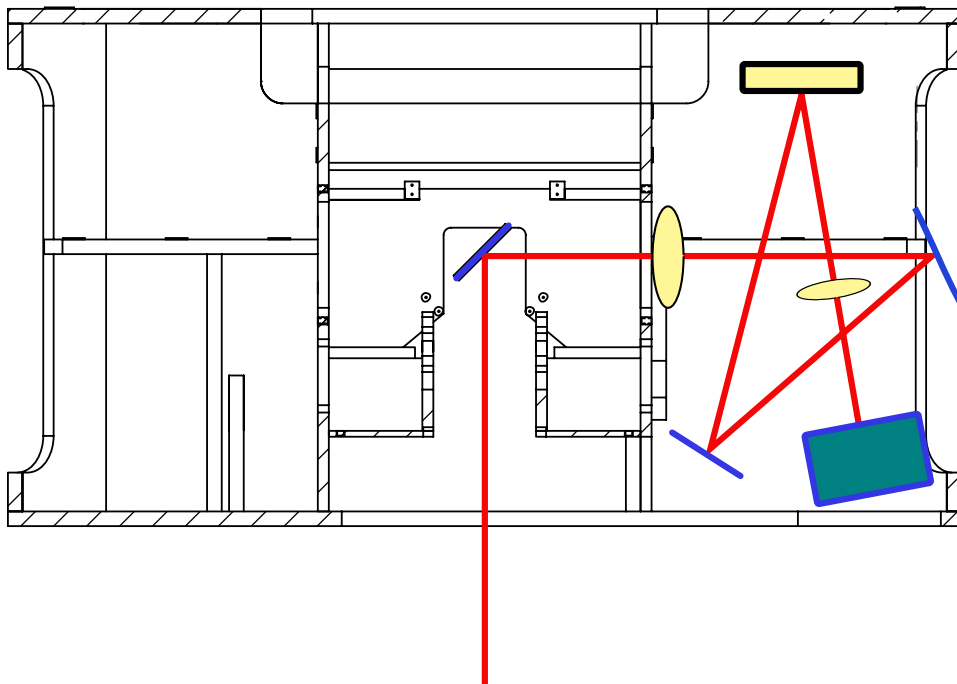
Figure 5. SADCAM Schematic layout in the Auxiliary Port. This shows one possible configuration for folding the optics into the given engineering space.

OBJ: 0.0000, 0.0000 DEG

200.00

IMA: 0.000, -16.851 MM

OBJ: 0.0000, 0.0003 DEG

IMA: 0.000, -16.888 MM

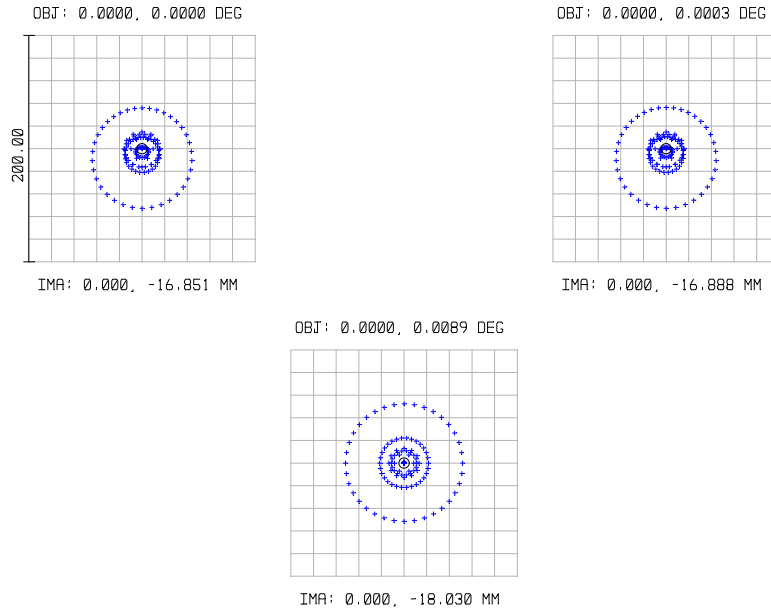OBJ: 0.0000, 0.0089 DEG

IMA: 0.000, -18.030 MM

Figure 6. SADCAM Spot diagrams at 800nm for rays at the edge of the telescope pupil and for field angles of 0, 1 arcsecond and 1 arcminute.

telescope pupil. The corrected beam then passes through a second lens which forms the focus of the telescope at a visible light CCD, and infra-red wavelengths are split off using a dichroic to an infra-red video rate camera.

Wavefront sensing is performed by adding a small tilt offset to each mirror segment, so that a separate star image is formed from each mirror. The rapid read-out cameras then record the image motion from each of the stars, the SADCAM computer calcuates the tip-tilt correction from the location of the centroids, and sends an appropriate corrective signal to the tip-tilt mirrors.

Our goal is to characterize the gains achievable from applying tip-tilt correction at the SALT and to confirm the simulation estimates from the previous section. This simple demonstrator camera will then lead the design and development for any future AO system for the SALT.

By using the same mirrors and tip-tilt actuators that we envision using in the final design, we also test and confirm that the PI actuators are suitable for the full SALT AO system. One potential layout of the camera optics in the Auxiliary port is shown in Figure 5.

3.1 Active Optic Capability for the SALT Primary Mirror

The sky coverage is dependent on both the isoplanatic angle and the limiting magnitude for the wavefront sensor camera. Without a suitable bright guide star, the camera rate can be slowed down and the AO system performs as an active optics system, sending primary mirror offset corrections every 10 to 30 seconds.

4. A TOP-LEVEL DESIGN FOR THE SALT AO

We have not carried out an extensive study for the full concept SALT AO system, but we are considering using an Offner relay to take the prime focus corrected image, perform tip tilt correction, and then sends th light back to the prime focus. The intermediate forms a curved pupil image at the intermediate focus. A spherical curved surface is formed from 91 tip-tilt mirrors driven by actuators, and a hexapod is used to provide six-axis motion of the tip-tilt mirrors to track the motion of the telescope pupil.

The SALT AO system then provides a corrected beam to the whole suite of instruments at the prime focus, with the addition of 6 reflecting surfaces to the delivered beam (three for the Offner relay, and three for folding the beam into the same optical location as the original feed).

5. CONCLUSIONS

We have performed simple simulations that demonstrate the utility of adding an intermediate level of adaptive optics on the SALT telescope. By building a simple tip-tilt system with seven tip-tilt elements we can directly measure the atmospheric parameters we need to determine, and then go forward with a complete design study for a full SALT AO system.

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