SAM SYSTEM DESIGN NOTE

SAM-AD-02-2201

SAM optical design

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Applicable documents

1. SOAR AO optical design, by A.Tokovinin. Delta-CoDR document, Jan. 20, 2004
2. Changes in the SAM optical design, by S. Thomas. April 3, 2004.
3. Tolerancing for SAM's optical design. By S. Thomas, August 13, 2004.
4. SAM-AD-02-2203, Centering requirements on Camera and Collimator in AO module, by B. Gregory. December 22, 2004.
5. Optics specifications for SAM, by S. Thomas, A. Tokovinin, B. Gregory. March 4, 2005.
6. SAM-AD-02-2202, WFS Optics With Collimated Beam. By A. Tokovinin, March 14, 2005
7. SAM-AD-02-2204, High-resolution camera for SAM. By A. Tokovinin, March 15, 2005
8. SAM-AD-02-2205, Optical concept of tip-tilt sensor. By A. Tokovinin, October 26, 2005
9. SAM-AD-02-2206, Notes on SAM Optical Layout. By R. Tighe, S. Thomas, P. Schurter. August 18, 2005
10. SAM-AD-02-2207, Notes on SAM Alignment. By R. Tighe, October 10, 2005

1 Historical notes and overview of the documents

The optical design of the SOAR Adaptive Module (SAM) has not been changed significantly since the incremental conceptual design review of the project in February 2004 [1]. However, some adjustment to the basic re-imaging elements (off-axis parabolae) has been made, increasing the opening angle of the beam [2]. Tolerancing analysis of the SAM optics (fabrication and alignment) has been performed [3,4] and final specifications have been prepared [5]. More details of the wave-front sensor optics [6], HR camera [7], and tip-tilt probes [8] are now fleshed out.

A yet undocumented decision has been taken in the fall of 2004 to eliminate the first flat fold mirror. In this configuration, SAM is no longer transmitting the telescope beam on the same axis, but turns it by 90°, resulting in a somewhat more compact layout with both visitor instrument and CCD imager perpendicular to the input beam. However, the layout (i.e. angles of the DM and folding mirror) has not been optimized to fit space constraints in the best possible way. This task has been accomplished only in June 2005, when a minor oversight (conjugation of the DM to some 100m ahead of the telescope pupil) has been corrected as well [9].

This document gives an overall description of the final SAM optical design (as of July 2005) and serves as an update of [1].

2 Main re-imaging channel and layout

The OAP 1:1 design is relatively straightforward. Pupil size of 50 mm calls for the OAP focal length of 810 mm (taking into account the SOAR focal distance and the useful primary mirror diameter of 4.1 m). To separate the incoming beam from the collimated beam, we need sufficient off-axis shift of the OAP. An even stronger constraint comes from the need to place a bulky element (Fabry-Perot etalon) in the collimated space. This leads to selecting the angle of beam deflection at OAP of 15° [2], or a center offset of 213 mm. The "parent" diameter of the OAPs is then 540 mm.

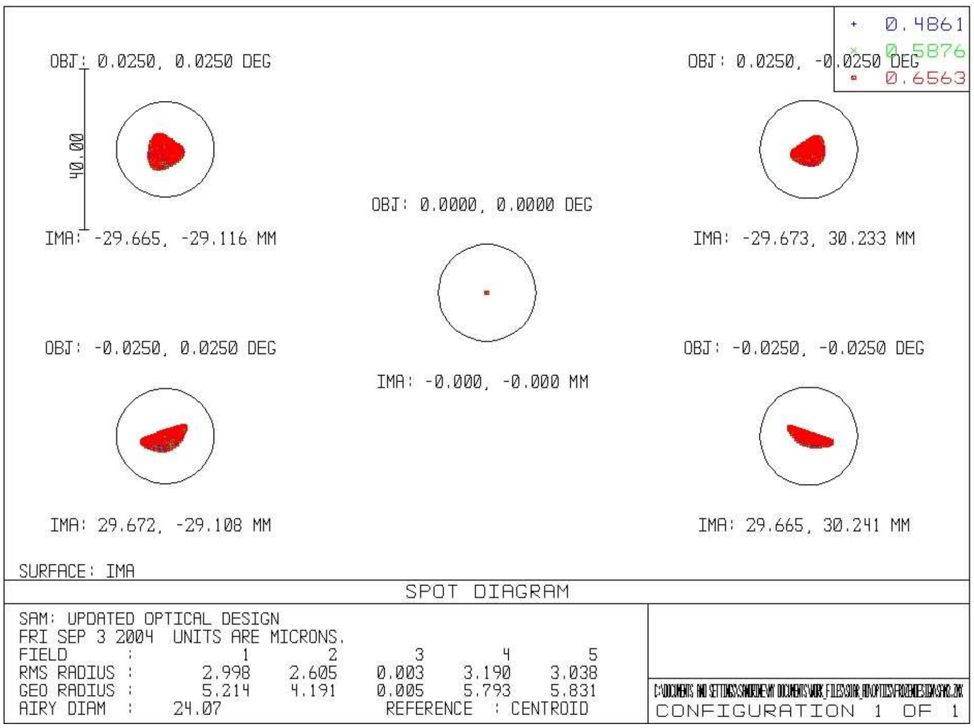

Figure 1: Spot diagrams of the science channel (curved field). The diameter of the reference circle is equal to the Airy disc.

The image quality is diffraction-limited over the whole 3-arcmin. field, with 30nm residual aberration (Fig. 1). The field is curved, however (radius −821 mm). If the field curvature is neglected, image defocus at the periphery of the field is below 0.2″, spots are round and this distortion can be safely neglected. We may want to correct curvature using a detector window with some optical power.

The layout of the optics have been optimized for a best fit to the space constraints [8]. Moreover, the layout has been chosen to match some "reference plane" parallel to the input beam. This plane can be physically implemented as an optical table. The beam reflected from the DM and the beams in the WFS channel are all parallel to the table, leading to some simplification of the mechanical design.

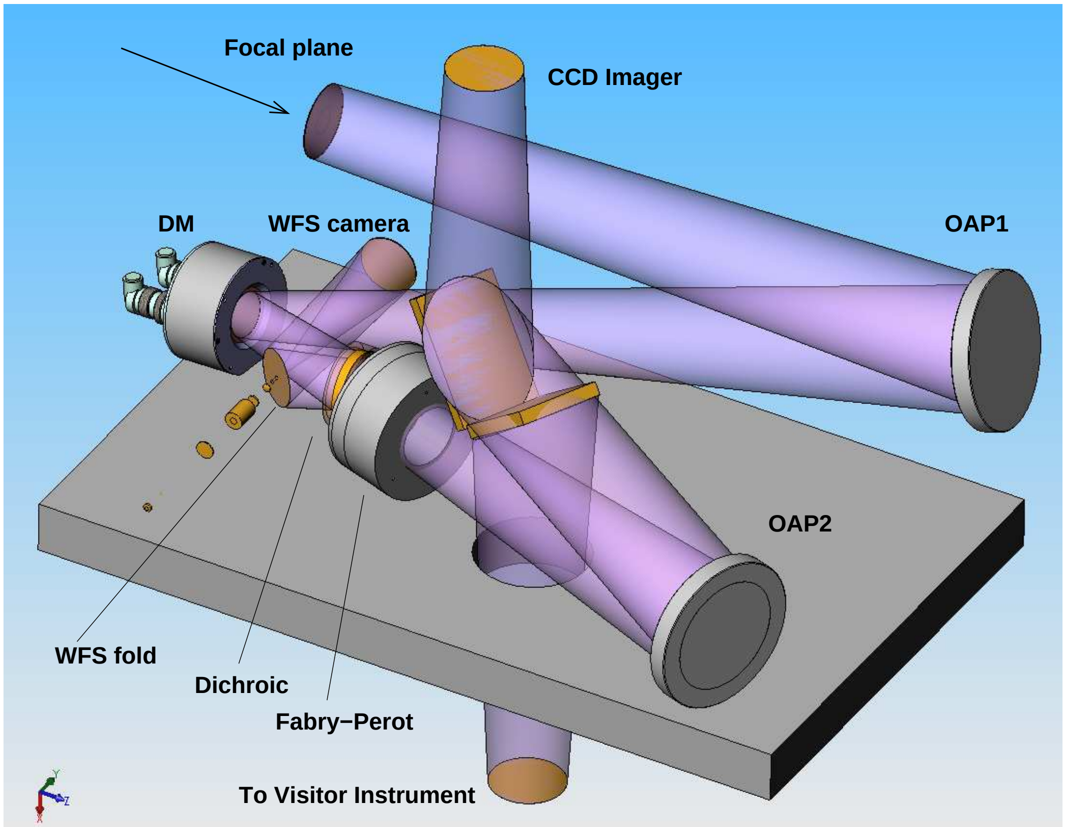

Figure 2: A 3-dimensional rendering of the SAM optical layout.

The layout with a notional table is shown in Fig. 2.

The light beam of SOAR is reflected to SAM by the fold mirror M4 inside the ISB. The beam is nominally centered with respect to the ISB port and the nominal focus position is at 150 mm from the ISB mounting surface. As can be seen in Fig. 2, the DM is in front of the focal plane and would in fact "crush" into the ISB, unless the instrument is placed further away. This, in turn, implies some re-focusing of the SOAR telescope and would lead to some (correctable) spherical aberration.[1] It was decided to displace the input axis of the SAM beam by 67.5 mm towards the Nasmyth bearing by displacing the M4 fold (this fold is not built yet). The location of the SAM becomes more favorable mechanically, and the nominal telescope focus now corresponds to the distance of 217.5mm from the ISB. The guide field of $5'$ diameter is still transmitted without vignetting by the ISB. As a downside, SAM will not be able to work at other focal positions without adaptation.

Two guide probes will pick off guide stars around (or inside) the science field. It is essential to locate the probes close to the focal plane and to make them small, in order to reduce the vignetting by the probes.

The diverging beam hits the collimator OAP1 and is then directed to the deformable mirror (DM) where a pupil image is formed. The quality of the pupil image is not perfect (because of the OAP aberrations), but very good ($<$ 1mm blur) compared to the DM electrode size ($\sim$5mm). Useful DM

[1] Even at a nominal focus of 150 mm there is need to correct spherical aberration because the conic constant of the "as-built" SOAR M2 is different from its design value. This correction is acceptable in regular SOAR operation.

surface has a diameter of 60 mm, hence there will be no vignetting at the DM. The collimator is turned by 65° in the "clocking" direction to optimize the layout.

The parallel beam is deflected by the DM by 25°. A larger deflection angle is possible, but it would increase the overall size of the instrument. Smaller angles, on the other hand, reduce the collimated space.

The beam after DM is split by a flat dichroic: long wavelengths go to the science instruments, while the UV laser light goes to the WFS channel. In case of the natural guide star (NGS) the dichroic will be neutral, splitting all wavelengths in approximately the same proportion. Thus, the dichroic will be changed when switching from LGS to NGS mode and back.

Part of the collimated beam after the dichroic can be used to install spectral filters or grisms. The largest filter considered in the SAM design is the Fabry-Perot etalon with 70 mm aperture [give dimensions of F-P and coll. space].

Corrected image with the same scale as the original SOAR is formed by the camera OAP2. The distance from DM to OAP2 is selected in such way as to form the virtual DM image at some 10 m before focus, thus reproducing the original SOAR pupil position. OAP1 and OAP2 are identical and mutually compensate their aberrations, as in other AO systems using this design.

The beam after OAP2 is deflected either to the internal CCD imager (SAMI) or to the visitor instrument (VI) by a fold mirror (fold-2 in the original notation). We opted for using two physically distinct fold mirrors. The SAMI fold is fixed, while the VI fold is put into the beam when VI is used. Thus, only the "in" position of the VI fold is critical. Selection of either one common fold or two separate folds is driven by mechanical considerations, optically these options are equivalent. The shape of the folds should be rectangular to ensure no vignetting in a $3' \times 3'$ square science field. The "spill-over" of the beam outside folds in Fig. 2 is an artifact of selecting a $5'$ circular field instead of $3'$ square.

3 WFS channel

The parallel beam reflected by the dichroic has to be focused by some optics before it can be fed to the wave-front sensor (WFS). In fact, this beam is divergent for an LGS. Hence the WFS camera has to be as close to the dichroic as possible, and its focal distance has to be short in order to permit easy refocusing between LGS at different altitudes or NGS. The choice of a fast concave mirror with an additional flat fold mirror is thus almost inevitable.

Originally, a slow WFS beam was required, leading to a Gregorian design of the WFS camera. It was recognized later [6] that a better and more versatile option would be to collimate the beam inside the WFS by lenses. Hence the fast converging beam formed by the WFS camera can be fed directly to the WFS optics.

We select the focal length of the WFS camera to be 225 mm. The surface shape of this mirror should be parabolic for imaging the NGS. On the other hand, a conic constant less than 1 is required for a good imagery of the LGS, otherwise a spherical aberration appears. The optimal conic constant changes depending on the distance to the LGS, H_{LGS}. Given the requirement of a free choice of this distance in the range from 6.2km to 15km, we opted for using the same parabolic mirror in both NGS and LGS cases. The spherical aberration of the LGS channel will be corrected by a combination of standard lenses, as described in [6]. At the same time these lenses assure a constant pupil size, on the lenslet array, irrespective of the H_{LGS}.

Yet another aberration in the LGS mode is astigmatism, originating in the OAP1. The amount of the astigmatism is variable, depending again on H_{LGS}. This aberration is correctable by a small tilt of the WFS camera mirror. The tilt is zero for NGS, it is largest (0.1°) for $H_{LGS} = 15$ km and decreases again to zero when H_{LGS} goes to 6.2km. This latter condition corresponds to the LGS image at the surface of the OAP1, when all OAP1 aberrations vanish completely.

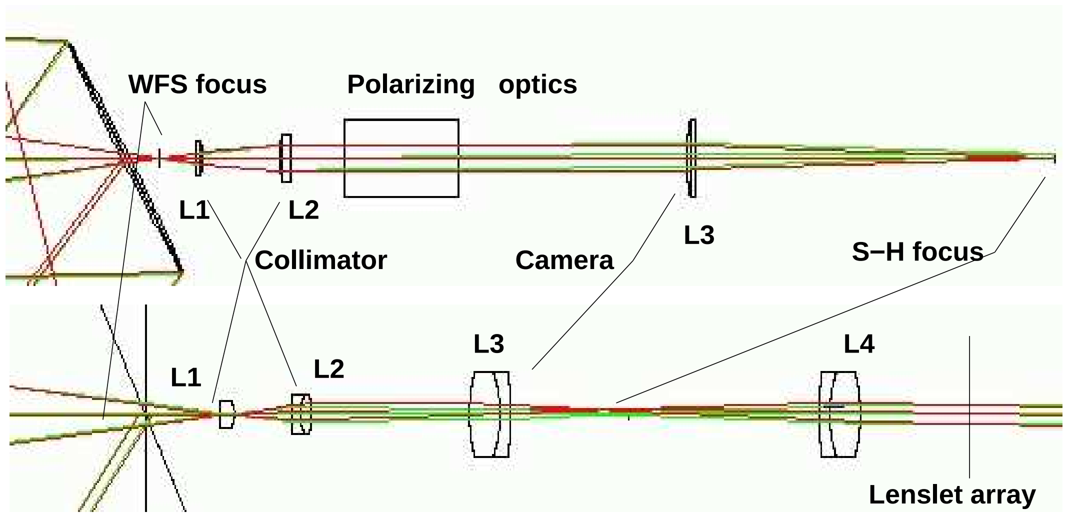

Figure 3: Optical layout of the WFS optics behind the fold. Top: LGS channel up to the S-H focus. Bottom: NGS channel up to the lenslet array.

The general layout of optics following the focus of the WFS camera is shown in Fig. 3. An aperture in the final focal plane will cut off the sky background and (more importantly) will eliminate any cross-talk between S-H sub-apertures. This aperture will have a reflecting front surface and will direct the light outside aperture to a simple TV camera that will facilitate initial pointing to either NGS or LGS.

4 Guide probes

Guide probes will pick up the tiny images of two natural guide stars in the primary focal plane of SOAR. The curvature radius of the SOAR R-C focal plane is −0.962 m (concave toward secondary). In a FOV of 5.4′ diameter (patrol field for guide probes) the max. deviation from plane is 1.50 mm. The image scale is 330 μm per arcsecond. If the focal curvature is neglected and the guide probes are located at mid-range, the maximum defocus due to field curvature will be ±0.75 mm. For an $f/16$ beam this translates to a defocusing of 0.14″ which can be safely neglected even under good seeing. So, we do not need to move the guide probes on a curved surface and a simple in-plane x,y motion is sufficient. However, focusing of the probes is required in order to accommodate for small deviations of the science instrument's focal plane from its nominal position.

We plan to use avalanche photo-diodes (APDs) SPCM-AQ4C from Perkin Elmer as detectors of the tip-tilt signal. These detectors are coupled to the light beam by multi-mode optical fibers with a maximum core diameter of 0.1 mm (larger core diameter is not possible with these APDs). The geometrical factor (product of surface and solid angle) admitted by the fibers is small enough and restricts the field of the probes to some 3″. Such field is sufficient for SAM, however.

We will split the stellar image into 4 quadrants and to couple it to the fibers by means of a lenslet array (LLA) with a short focal length. Details of the proposed design are given in [8], the concept

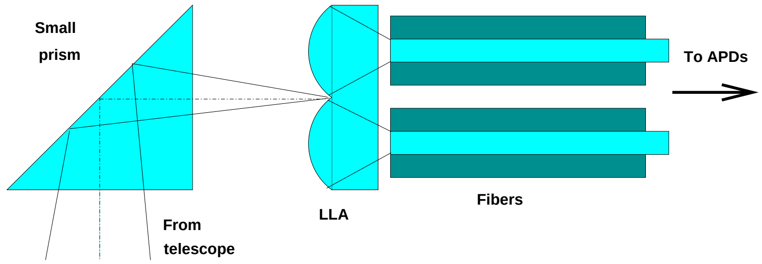

Figure 4: Possible optical layout of the guide probe pick-off (not to scale).

is depicted schematically in Fig. 4. The LLA pith is 0.5 mm, resulting in a total field of 1x1mm or 3″. This LLA from Adaptive Optics Associates is available and has been tested. It is made of acrylic. The fibers will be very close (0.2mm) to the back surface of the LLA, glued by a olptical epoxy into a single solid blok with fibers. Each lenslet forms the image of telescope pupil (73 μm diameter) at the entrance of the fiber with 100 μm core. The SOAR focal plane coincides with the LLA front surface. A small prism in Fig. 4 is added to fold the beam by 90°, so that the fibers are parallel to the guide arm. The design of the guide probe is quite rugged and compact. We successufully produced a prototype of the fiber+LLA assembly, fully aligned and glued.

When not in use, the guide probes will be hidden behind a cover in the "park" position, protecting the optics from dust and protecting APDs from a damage by accidental over-light. We may envision some additional use of the guide probes. For example, a mono-mode fiber can be glued to the probe to shine a point source into the SAM, for alignment and testing purposes. The position of this source will be controlled in x,y,z by the motions of the probe. Similarly, a light beam from TurSim can be, in principle, reflected from the back surface of the prism into SAM, to obviate the need of a fold mirror.

5 Science instruments

5.1 Visitor instrument

The visitor instrument is mounted on the back surface of the SAM that matches the ISB mounting as far as focus and exit pupil positions are concerned. The unvignetted field is 3′ square. Additional vignetting may be caused by elements installed by the user in the collimated space if those elements are not wide enough.

5.2 CCD imager

The CCD imager is the main "internal" science channel of the SAM. Two detector options are considered.

Our main choice is the mosaic of two CCDs from Lincoln Labs, 2Kx4K with 15μ pixels. This CCD mosaic will be identical to the SOAR Imager and SIFS detectors, adding to the modularity of SOAR instrumentation. The pixel size is 0.045″, the field is 3.1′ across. A 2x2 binning will be used most of the time, except when working under very good conditions at long wavelengths.

As a back-up or provisional solution, we plan to use old SIT CCDs with 24 μm pixels recuperated from some de-commissioned CTIO instrument, as a substitute for dedicated CCD at early stages or if money is lacking. The pixel scale and field of those 2Kx2K CCDs will be adequate (0.073″ and 2.5′, respectively).

It would be ideal to find a 2Kx2K CCD with 24 μm pixels. Unfortunately, virtually all modern astronomical CCDs are produced with 15μ pixels. Using a CCD with 15μ pixels and some focal reducer is an option which has not been considered.

The dewar window (10 mm) and filter (10 mm) were included in the optical design to demonstrate that they do not degrade the image quality (not included in the latest Zemax files). We plan that the filter wheel and shutter will be copies of the SOAR imager designs. All filters must have the same optical thickness to ensure confocality.

5.3 Technical HR camera

We plan to include a small-format technical HR camera into the AO module for technical work (analysis of the non-common-path aberrations in the laboratory and at the telescope, detailed image analysis, and limited science use with NGS). This camera need not be LN2-cooled and low-noise, as science CCD, so it can be quite cheap. The HR camera will be mounted at the VI port. The concept of the HR including image magnification to a suitable scale is given in [7].

6 Miscellaneous

6.1 Coatings

We plant to deposit protected sliver coatings on the reflective elements (collimator, camera and folds). A very good reflectivity of this coating ensures small light losses in the science path. The DM has a protected silver coating provided by its manufacturer (98% reflectivity in the visible, 88% at 355 nm).

6.2 TurSim – turbulence simulator

TurSim is described in a separate document.[2] It will substitute the on-axis telescope beam with $f/16.5$ simulated beam, optionally distorted by simulated turbulence. The flip mirror that injects the TurSim beam will be located at different positions depending on the mode (NGS/LGS) and on the selected LGS nominal height. In the NGS mode the flip mirror will be either behind or in front of the SOAR focal plane. In the LGS mode, vignetting by the flip mirror becomes an issue, especially at the lowest LGS altitude of 6.2 km.

6.3 Alignment tools

Focal-plane simulator (FPS) is a mechanical surface that can be installed at the nominal position of the SOAR focal plane. Several single-mode fibers simulate point sources at the center of the field and at various locations, out to the $2.5'$ radius. The fibers are illuminated by a single red diode laser. The simulator will be used at alignment stage for tuning various optical channels (science, WFS) and assuring their confocality. It is also essential in determining the non-common-path errors in the LGS mode. Fiber sources in the guide probe may fulfill most functions of the focal-plane simulator.

Laser alignment tool permits to project a narow collimated beam into SAM, adjustable in angle and position.

Flat mirror diam. 100 mm, $\lambda/20$, is used to substitute the DM for OAP alignment and for the test of high-order aberrations (ripple) in the SAM optical train.

[2]SAM-AD-02-1201 Tursim: Concept. By S. Thomas and P. Schurter, January 2004

Wave-front sensing device is needed to measure quantitatively the aberrations (mostly of low orders) in the process of alignment. We plan to use a software for extracting aberrations from defocused images (donut) and/or the Wavescope device.

6.4 Alignment plan

An outline of the SAM alignment plan [10] developed by R. Tighe is given below. The alignment will consist in 5 major operations:

1. Align the M4 mirror in the ISB
2. SAM bench alignment, science channel.
3. SAM bench alignment, WFS channel.
4. SAM bench to SAM frame alignment.
5. SAM support frame to ISB alignment.

Items 1 and 5 are done at the telescope, the rest in the lab. The alignment procedure is based on the "built-to-print" philosphy: the optical elements will be produced very close to the design specifications, and placed almost where we want them to be. The alignment will consist in correcting small errors only.

Most alignment operations are straightforward. The alignment of the OAPs is not, and it has been given much consideration by the project team. Various alternative methods are possible and viable. Below we list one such method for aligning the OAP1, step-by-step. This method relies on double-pass imaging in auto-collimation. The source is a single-mode fiber in the FPS, offset by 21 mm from the FoV center. The DM is replaced by a flat mirror which reflects the beam back, into a symmetric location on the other side of the center. When the OAP1 is aligned (to within 1 mm), its optical axis passes through the center of the field, and the aberrations in this setup are small (almost the same as in the nominal SAM configuration).

1. Illuminate the fiber at the center of the FPS. Verify that the beam reflected by the OAP1 is collimated (with the help of the shearing interferometer), adjust the OAP1 focus if necessary.
2. Adjust the tilts of the flat mirror to direct the beam back into the fiber.
3. Illuminate the fiber at 21 mm offset and examine the astigmatism of the return beam with the wavefront-sensing device. The errors in the OAP tilt in one direction influence one astigmatism coefficient, and in the perpendicular direction – another coefficient. By measuring the coefficients Z5 and Z6 and knowing the expected dependence from the Zemax model of this setup (10.26λ of astigmatism per degree of OAP tilt), we calculate the required corrections to the OAP1 tilts.
4. After correcting the OAP1 tilts, re-adjust the flat mirror and repeat the previous step iteratively, until the astigmatism is nulled.

This process will end up with the OAP1 focal point centered in the SAM field. If the offset and clocking of OAP1 are correct, the axial collimated beam will be centered on the DM. If not, the beam will be displaced. A displacement of < 1 mm is tolerable. If the displacement is larger, we can calculate the required corrections to the clocking and shift of OAP1. The tilt of OAP1 will be then re-adjusted, to bring back the focal point to the FoV center.

For the OAP2 alignment, we prefer to use the central source and check the image quality in the final (output) focal plane, with the OAP1, DM, and fold mirror pre-aligned. Again, the astigmatism coefficients will indicate tilt errors and their magnitude. The sensitivity is 2 times less than in auto-collimation, 5.14λ per degree.

Appendices

A1 List of Zemax files

Valid optical design files are located in the SAM/optics/Final_design_050720 directory of the SAM web server.

Table 1: List of Zemax files

File	Comment
Soar+Sam_vi_050720_down_65d.ZMX	SAMI channel
Soar+Sam_vi_050720_up_65d.ZMX	VI channel
Soar+Sam_vi_050720_wfsngs_65d.ZMX	WFS channel, NGS mode
Soar+Sam_vi_050720_wfs6km_65d.ZMX	LGS channel, $H_{LGS} = 6$km
Soar+Sam_vi_050720_wfs8km_65d.ZMX	LGS channel, $H_{LGS} = 8$km
Soar+Sam_vi_050720_wfs10km_65d.ZMX	LGS channel, $H_{LGS} = 10$km

A2 Specification of the optical elements

Table 2: Optics specification of main elements

Element	R, mm	D, mm	CC	Thick., mm	Comment
Collimator	810	165	-1	> 20	Off-axis shift 213.3 mm
Camera	810	165	-1	> 20	Off-axis shift 213.3 mm
Folds	INF	125	0	15	Rectanguler 105x130mm
DM	INF	50	0	-	Full diameter 100mm
Dichroic	INF	80	0	10	BK7. Three dichroics: LGS, NGS, spare
WFS fold	INF	90	0	10	Central hole 8 mm diam. at 32.2°
WFS camera	225	80	-1	10	Parabolic

Elements not included: WFS optics beyond the focus, Tursim and its fold, SAMI filters, HR camera optics, alignment tools, LGS projection optics.