Optical design of Gemini “Altair”

E. H. Richardson[a*], J. M. Fletcher[b*], C. L. Morbey[b], J. M. Oschmann[c], J. S. Pazder[a,d]

[a]University of Victoria, Victoria, B.C. V8W 3P6
[b]Dominion Astrophysical Observatory, Victoria, B.C. V8X 4M6
[c]International Gemini Project Office, Hilo, Hawaii
[d]3876 Pine Street, Burnaby, B.C. V5G 1Z2

ABSTRACT

The 8-meter Gemini telescope’s adaptive optics (AO) module, Altair, is “transparent” in that it does not change the focal ratio, being f/16 in and f/16 out; it has the same focal position as the bare telescope, with insignificant change in the exit pupil. However, Altair has a flat focal surface, unlike other AO designs which have focal surfaces curved more than the focal surface of the bare telescope and in the opposite direction. An unusual requirement for Altair is that the atmospheric layer 6.5 km above the telescope should be imaged onto the deformable mirror. Other requirements are minimization of distortion in the wavefront sensor module for both the imaging of the deformable mirror onto the lenslet array and for the reimaging of the ~230 lenslets’ images onto a CCD, (~106 lenslets are illuminated by a single star) for a natural guide star, and also for a Sodium laser guide star ranging in object distance from 85 km to 156 km. The separation of natural and laser star beams is done with minimum light loss by passing the in-focus natural star image through a pinhole which is smaller than the shadow of the secondary mirror of the telescope in the out-of-focus laser beam which is reflected by the tilted pinhole mirror.

Keywords: adaptive optics, flat focal plane, wavefront sensor, atmospheric dispersion, pinhole, laser star, distortion

1. INTRODUCTION

Experiments[1,2] conducted on Mauna Kea in 1982 and 1983 demonstrated that with feasible correction the resolution could be comparable with that of Space Telescope. This inspired an optical design[3] which was not built, but meanwhile an experimental adaptive optics instrument[4] , “Come-on” was put into operation on the ESO 3.6-m telescope. Later, optical designs for the Laguna[5] and CFHT[6,7] telescopes were unusual in that the paraboloidal collimator and camera mirrors were off-axis by distances proportional to the square of their focal ratios, resulting in a larger field of good definition. The CFHT design was confocal with the f/8 Cassegrain focus but the focal ratio changed from f/8 to f/20 thus supplying the extra optical path required for the light to pass through the adaptive optics module, called AOBonnette, or PUEO[9], to the fixed Cassegrain focus. By comparison, the Gemini requirement was for unit magnification at f/16. The first Gemini AO design[7,8] was unique in having the first of its two powered mirrors located before the folded focus of the telescope. It had ample back focal distance but had mirrors on both sides of the telescope’s axis. Later, it was required that the Gemini AO module should be restricted to one side of the central instrument support structure. An initial design by Pazder using 3 powered mirrors had improved resolution and less curvature of the focal surface, later refined to have a flat focal surface and, to eliminate two extra folding mirrors, the optical system was tilted to fit within the vertical space permitted for the AO module, later named Altair meaning “altitude-conjugate adaptive optics for the infrared”.

2. MAIN PATH LAYOUT

The main path has 3 off-axis conic mirrors in the order concave-convex-concave[10]. Compared with 1994-5 designs, there is now only one DM (deformable mirror) and it is now fixed at the conjugate to the 6.5 km atmospheric layer. The unvignetted field of view has been reduced to 2 arcmin diameter from 3 arcmin. There is no longer a DM at the pupil but instead a beamsplitter followed by an ADC (atmospheric dispersion corrector) are in that region. The layout is shown in Figure 1, side and top views. When activated, two flat diagonal mirrors are inserted, one at M1 which turns the beam into the adaptive optics module, and a second, M7, which directs the beam back onto the axis and down to the location of the focus of the bare telescope in the drawing, but M7 could also direct the beam to other instruments or be removed which allows the beam to cross the axis to feed the instrument on the opposite side.

Altair is unique among AO modules on other telescopes in that its location on a side of the Instrument Support Structure is so far from the focal surface that the diameter of the beam at the exit of the module exceeds that of the DM (deformable mirror).

---

[*] Contacts: harveyr@me.uvic.ca; murray.fletcher@hia.nrc.ca

It has unit magnification, being f/16 in and f/16 out, and the output focus is at the same location as that of the bare telescope. In the current design this is done by the addition of a powered mirror to act as a reverse telephoto, i.e., beam expander, to make the distance to the focus longer than the effective focal length (instead of shorter in the standard, unreversed telephoto). The distance from the module to the focus is 1.9 metres, the last powered mirror being located an even larger distance: 3 metres. An additional advantage to having 3 powered mirrors is that the focal surface can be flat.

Even with the ADC prisms in the beam, Altair is diffraction limited: at 850 nm, the Strehl ratio ranges from 1.00 to 0.94 around the 2 arcminute field.

In Figure 1, the camera mirrors, M5 and M6, are sensitive to alignment errors and will be mounted on invar. However, the collimator mirror, M2, and the flat mirror, M4, are less sensitive to alignment errors and either one could be used as a tip-tilt correcting mirror.

AO systems on other, smaller telescopes such as CFHT and MPIA need only 2 powered mirrors for packaging, both off-axis paraboloids, because they magnify thus push the focus further from the module, and the modules themselves are also closer to the focus. For example, CFHT is F/8 in and F/20 out. The Subaru AO[11] has unit magnification with only 2 powered mirrors but its back focal distance is less than half of that of Gemini; it has an additional flat mirror, compared with CFHT and MPIA, and it has elements on both sides of the telescope axis.

In Figure 1, M2 partially collimates the beam, and M5 + M6 constitute a reverse telephoto camera. One reason that M2 has a longer focal length than that required to perfectly collimate the beam is to increase the distance to the image of the 6.5 km atmospheric layer where the deformable mirror (DM) is located (at M3 on the drawing) thus increasing the clearance around the DM for its cell. Consequently, the single-star beam between M2 and M5 is slightly diverging. Another requirement for Gemini is that the exit pupil should be at the same location as that of the bare telescope: at the secondary mirror, 16.5 metres above the final focus. It can be seen in Figure 1 that the beam from M6 (the last powered mirror) is from a distant exit pupil, thus near-telecentric. The exit pupil is not very sharp but good enough to have, when not preceded by an ADC, a blur of less than 1% over a 1 arcminute field when imaged onto a Lyot stop in an instrument designed for use with the bare telescope.

3. VIGNETTING

The clear diameter of M6, the largest mirror, is 244 mm; M2, the collimator, is 150 mm, and the convex mirror, M5, is 120 mm. The upper fold mirror is elliptical, 240 by 170 mm. The lower fold mirror is larger than needed for GAOS. Vignetting begins beyond the 2 arcmin field. For a 3.0 arcmin diameter field, 46% of rays are blocked for stars around the edge of the field; for a 3.5 arcmin field the vignetting is 70%; for a 4 arcmin field it is 94%. In practice the vignetting would be a little less because the cells would be made a few millimetres larger than the minimum clear diameters.

4. MAIN OPTICS ADC

The design includes an ADC (atmospheric dispersion corrector) which is in a beam which is not exactly collimated. However, its design is such that when it is inserted or removed no refocusing of the telescope is required. Thus no refocusing of the WFS (wavefront sensor) is required. The reason for this unusual feature is that, unlike most older telescopes, Gemini will have very little focus adjustment: only ± 1 mm (by moving the secondary mirror). The ADC is currently optimized for the near-IR, 850 to 1800 nm, but an ADC to 2500 nm will be evaluated.

5. MAIN PATH BEAMSPLITTER

The beamsplitter (BS on Figures 1, 2) transmits the IR science beam and reflects visible light, 834 to 414 nm, to the WFS (wavefront sensor), for both NGS (natural guide star) and LGS (laser guide star). It is unusual in being located between the collimator and camera mirrors instead of in the exit beam. Because of the beam expansion needed for Gemini, a beamsplitter in the exit beam would be larger than that required for the internal beamsplitter. Other advantages of the internal beamsplitter are that the visible guide star light does not pass through the IR coated ADC in the science beam and that it is in a near-collimated beam, thus producing less optical aberration than if in the converging exit beam. Insertion of the tilted beamsplitter produces no change in resolution if given a small, 0.6 arcminute, wedge. Fortuitously, this wedge also moves the ghost images produced by internal reflection in the beamsplitter substrate by 2.5 arcseconds from the parent images at the focus which helps with flat fielding and with the identification of ghost images. A disadvantage of the internal beamsplitter is that the WFS needs its own camera because it does not use the main optics camera.

6. WAVEFRONT SENSOR LAYOUT

For the main optics, the off-axis camera mirror pair corrects aberrations introduced by the off-axis collimator mirror, but at the BS these aberrations have not yet been corrected and the reflected NGS and LGS beams require corrections by the camera in the WFS path. In early designs this camera mirror in the WFS path had 2 mirrors that produced very sharp images of natural guide stars with Strehls better that 0.99 at 550 nm throughout the 2 arcminute field, but, as predicted by Jim Oschmann, a single-mirror camera produces adequate resolution, the worst Strehl being 0.78, which increases when the beam is segmented by the lenslet array (because the smaller apertures have larger diffraction patterns).

Unlike the 1994 and 1995 designs, the current design details the complete wavefront sensor (WFS) from beamsplitter to WFS CCD detectors. It also includes changes needed to focus laser guide stars ranging in height above the telescope from 85 km to 156 km. The Altair WFS foreoptics must reimage a natural guide star anywhere in a 2 arcminute field, and a laser guide star anywhere in a 1 arcminute field and at an object distance ranging from 85 to 156 km. A 1997 design used a single gimbal mirror to permit the CCD to be stationary, but the optics before the gimbal mirror were required to handle the full field and were large and complicated. On the advice of Peter Wizinowich[12] two gimbal mirrors are now used, shown in Figure 2, where a guide star is imaged at the same point regardless of the field angle. The first, larger gimabal mirror, G1 in Figure 2, has x and y tilt motions, as does G2 which also has a focus adjustment. At the focus of the NGS, a field stop, in the form of a pinhole mirror, is followed by a collimator lens and a small zero-deviating ADC in front of a lenslet array.

7. GIMBAL MIRRORS

The two gimbal mirrors must not only be adjusted in angle, and the second also in axial position, so that the natural guide star is focused on the pinhole, but also so that its beam passes through the pinhole at a slight tilt which depends on the field angle of the star so that the beam from an off-axis star is displaced on the lenslet array by the same proportional amount as on the DM. For an on-axis star, the angles of the 2 gimbal mirrors were selected to provide clearance of the reflected beam from other components, such as the beamsplitter, and also to avoid rotation of the pupil when the gimbal angles are changed to center an off-axis star. (The single-gimbal design had a larger ADC followed by relay optics but Jim Oschmann demonstrated that the ADC could perform adequately even if made much smaller so that it could be placed close to the lenslet array permitting the elimination of a set of reimaging lenses. The earliest WFS designs had fewer optical elements and a simplified ADC consisting of only one glass type, but the trade-off was complications in the mechanical design requiring that the CCD and foreoptics to be on multistage movable mountings.)

8. SEPARATION OF LGS AND NGS LIGHT

The laser light is imaged onto the Sodium layer in the atmosphere by a 400 mm telescope located behind the 1022 mm diameter secondary mirror. Sometimes both a LGS (laser guide star) and NGS (natural guide star) will be sensed simultaneously in Altair, in which case the LGS is pointed at the NGS at the center of the field. In this case, the separation of light is done with exceptionally high efficiency by locating a pinhole mirror at the focus of the NGS which passes the NGS without loss through the hole in the glass which is smaller than the central obstruction (caused by the secondary mirror of the telescope) in the out-of-focus LGS beams which are reflected by the tilted pinhole mirror which can have a narrow-band coating with virtually 100% reflectivity of the 589 nm laser light. In other words, the field stop which would in any case be at the location of the NGS is simply made reflective instead of black, and tilted. A pinhole diameter of 1 arcsec is adequate for the NGS, which is smaller than the 2.5 arcsec diameter of the central shadow in the beam from an 85 km LGS, or of the 1.38 arcsec shadow from the extreme 156 km LGS. Fortunately, the edge of the central shadow is sharper than the outer edge of the beam which is blurred by several tenths of an arcsecond because the cylindrical shape of the LGS makes it bigger when viewed from the edge of the telescope. The blurring of the 156 km LGS beam would cause some of the light to enter the hole but it would illuminate only the central lenslets. All of the NGS lenslets would be illuminated by stray LGS light scattered by mirrors or by the atmosphere. An option is to deliberately offset the LGS so that the shadow moves off the pinhole thus transmitting up to 0.9% of the LGS light onto a selected lenslet in the NGS path which might be useful for analysis.

The biggest disadvantage of a dichroic beamsplitter is decrease of NGS thruput by transmission of NGS light into the LGS path which, in addition to the needed band centered on 589 nm which transmits an average of 50% of the NGS light in the 25 nm band width, would transmit about 80% of the NGS light in the 400 to 450 nm region through sidebands there, and at the long wavelength end where an average of 25% of the NGS light would be transmitted in the 750 to 850 nm region. By comparison, with a pinhole mirror beam separator, which would replace a black pinhole field stop, there would be no decrease in the amount of NGS light reaching the lenslets. Most of the NGS light exceeding the 1 arcsec diameter or being scattered on preceding surfaces thus entering the LGS path would be blocked at the black field stop located at the LGS focus (Figure 4).

9. PATTERN DISTORTION AND NGS WFS ADC

The optical design of the WFS path, Figure 2, is optimized not only to produce sharp stellar images and to image the 6.5 km layer (which is imaged onto the deformable mirror) onto the lenslet array, but also to minimize distortion of the DM actuator pattern. Some asymmetrical distortion is caused by the off-axis foreoptics mirrors. Also, the lenses following the lenslet array are optimized to minimize the distortion of the pattern of sub-aperture stellar images on the CCD. These distortions are separate: DM onto lenslets, and stellar images onto the CCD. (In the case of the MPIA WFS, no attempt is made to optically match DM actuators to lenslets, one-to-one, but computer time at the telescope is needed to determine the defacto match.)

Because the ADC is conjugate to the DM, which is conjugate to the 6.5 km layer, the post-gimbal beams are displaced depending on the field angle by being directed by the gimbal mirrors through the pinhole at the appropriate angle. (In other AO systems the primary mirror is conjugate to DM and there is no lateral displacement of beams there or on the lenslet array.) Because the ADC is as close as possible to the lenslet array its diameter is not much larger than that of the of the lenslet array where the lenslet spacing is 1.061 mm and there are about 12 lenslets across a NGS beam, with a total of 18 across the full diameter. The focusing of the DM onto the ADC is done through a tiny aperture, the hole in the pinhole mirror, and thus has great depth of focus. For Figure 3, the pinhole (Figure 2 and 4) is made 3 times larger than reality so that some beam divergence and convergence is seen in Figure 3 where the field angle is ±1.5 arcsec.

The WFS ADC, Figure 3, is exceptionally small, having a clear diameter of only 18.5 mm, only 13 mm of which is illuminated by a beam from a NGS (the extra diameter serving to cover the 2 arcmin NGS field). Atmospheric dispersion produces color on the DM which should be retained when it is imaged onto the lenslet array (which was not done in earlier GAOS designs), but the atmospheric dispersion in the stellar images focused by the lenslet array should be removed. In order to prevent the ADC from changing the color on the DM, the DM is imaged at the middle of the ADC, as indicated in Figure 3. Another requirement is to minimize decentering of the DM pattern on the lenslet array which is done by imaging the tip-tilt mirror, M4 in Figure 1, onto the lenslet array.

Because the ADC is small its wedge angles are proportionally large which requires a different selection of glass types than for the main beam ADC which uses the Mt. Wilson KF9 and LAF21 but has a diameter of 100 mm and is not followed by a lenslet array requiring very low field distortion which is less than 2% per lenslet spacing, thus less than 0.2% for a beam width. For each of the two cemented prism pairs in the ADC, each of which is zero-deviating, it is the difference in angle between the input and output faces that causes distortion by making the exit pattern elliptical instead of circular. The net distortion would depend on the rotation of the two prism pairs, thus vary on the lenslets both in amount and direction. If the two glass types have the same index of refraction, ideally at the central wavelength, there would be no angle between the input and output surfaces, thus no distortion, but there is a very limited selection of such glass types with appropriate differences in dispersion to produce the required net dispersion. Unfortunately the glass pair KF9 and LAF21 which has such a good match to the atmosphere have about the same dispersion but different indices of refraction which is the opposite of what is required and produces the maximum pattern distortion. If the difference in dispersion between the two glass types is very large, then there can be a substantial difference in index of refraction without producing much distortion. However, use of a very high dispersion glass absorbs the shorter NGS wavelengths and also has a poor match to atmospheric dispersion. An option for this small ADC is LLF6 and calcium fluoride (which is now readily available at low cost), used for the design in Figure 3.

Finally, a slight cylindrical curvature on the prism surfaces, in Figure 3, corrects for the elliptical pattern distortion caused by the slight net wedge, resulting in less than 1% distortion per lenslet spacing , thus less than 0.1% distortion of the full beam diameter, on the lenslet array caused by the ADC.

The distortion in the pattern of stellar images on the CCD is well within a pixel, being at worst 2% of a quad-cell (4-pixel) spacing.

10. FOCUS OF LASER GUIDE STARS

The light from a Sodium laser guide star, LGS, whose distance from the telescope ranges from 85 to 156 km, depending on the zenith angle of the telescope, follows the same path as the light from the natural guide star down to the pinhole mirror which reflects the out-of-focus laser beam and transmits the in-focus NGS light through the pinhole. The laser light is then reflected back over the pinhole mirror by a right angle prism retroreflector which is zoomed to bring the laser light to focus at the same place in a stop for a star ranging in distance from 85 to 156 km. However, the rate of divergence of the beam is slightly different depending on the distance of the star, which requires that the 2-element collimator lens have a slight zoom to preserve the scale of the DM pattern on the lenslet array despite the change in distance between the DM and the lenslet array caused by the zoomed retroreflector.

If it were required to sense both NGS and LGS for other than at the center of the field, it would be necessary to replace the retroreflecting prism with two moveable mirrors and also make the pinhole mirror tiltable, otherwise the laser star would be off axis at its stop. However, this complication is not necessary when the LGS is used without a NGS in which case the gimbal mirrors, G1 and G2, would be set to get the LGS centered and in focus. In this case, the tip-tilt of the NGS would be measured in the telescope's guider, or by a WFS on an instrument.

The field for the laser guide stars is 1 arcmin diameter, but if the laser guide star is not at the center of the field its beam would move on the pinhole mirror and from 0.5 to 1 percent of its light would pass through the pinhole, in which case the mirror could be replaced with one without a pinhole.

11. RELAY LENSES

Because of the required number of lenslets and the required field scale on the CCD, which is 0.4 arcsec/0.024 mm pixel, and because of the minimum distance that a lenslet can be from the CCD imposed by the dewar window, it is necessary to reimage and demagnify the sub-aperture stellar images produced by the lenslet array and focus them on the CCD, with a 0.096 mm (4-pixel) spacing. This is done by the small reimaging lenses shown in Figure 5 for the NGS, and Figure 6 for the LGS where the field scale on the CCD is 1 arcsec/pixel. The lenslets for the NGS and LGS beams have the same diameter but the radius of curvature in the epoxy is 109.6 for the NGS and 43.7 mm for the LGS lenslets. The used aperture of the lenslet array can be smaller for the LGS because it ranges over only a 1 arcminute diameter field whereas the NGS must be selectable over a 2 arcminute field.

12. REFERENCES

1. L. A. Thompson, "An active mirror image stabilizing instrument system (ISIS) for use on Mauna Kea", *SPIE Volume 480,* page 560, 1983
2. C. A. Christian, P. G. Waddell, R. Racine, "Very high resolution camera for the 3.6m on Mauna Kea", *SPIE V445,* 1983
3. E. H. Richardson, C.L. Morbey, "Optical Design of an All-Reflecting High Resolution Camera with Adaptive Optics for Ground Based Telescopes", *Adaptive Optics, SPIE V551,* pp.26-31, 1985
4. Rousset, G., Fontanella, J.C., Kern, P., Gigan, P., Rigaut, F., Léna, P., Boyer, C., Jagourel, P., Gaffard, J.P., Merkle, F., "First diffraction-limited astronomical images with adaptive optics'', *Astron. Astrophys., 230,* 1991
5. E. H. Richardson, "Optical Design of an Adaptive Optics Coude Imaging Selectable Atmospheric Layers", *Laser Guide Star Optics Workshop: Proceedings, Vol 1,* Albuquerque, New Mexico, p. 278, 1992
6. W. A. Grundmann, E. H. Richardson, "Design of the Adaptive Optics System for the CFHT Cassegrain Focus", *ESO Conf. On Progress in Telescope and Instrumentation Technologies,* Garching, p. 547, 1992
7. J. S. Pazder, E. H. Richardson, G. Barrick, "Optical designs of adaptive optics modules for the Canada-France-Hawaii and Gemini telescopes", *Proceedings of the ICO-16 Satellite Conference on Active and Adaptive Optics, Garching,* pp. 59-64, 1993
8. E. H. Richardson, "Integrated adaptive optics systems", *Proceedings of the NATO Advanced Study Institute on Adaptive optics for astronomy, Cargese 1993,* pp. 227-236, 1994
9. F. Rigaut, D. Salmon, R. Arsenault, J. Thomas, O. Lai, D. Rouan, J.-P. Véran, P. Gigan, D. Crampton, J. M. Fletcher, J. Stilburn, C. Boyer, and P. Jagourel, "Performance of the Canada-France-Hawaii Telescope Adaptive Optics Bonnette", *Pub. Astronomical. Soc. Pacific,* Vol. 110, No.744, February 1998
10. John Stanley Pazder, "The Optical Design of an Adaptive Optics System Imaging Two Selectable Atmospheric Layers", Thesis, University of Victoria, p. 61, 1996
11. H. Takami, N. Takato, M. Ostubo, T. Kanzawa, Y. Kamata, K. Nakashima, M. Iye, "Adaptive optics system for Cassegrain focus of Subaru 8.2-m telescope", *SPIE Conference 3353,* Kona, 1998
12. Peter Wizinowich, Skip Radau, "Wavefront Sensor Optical Design", *Keck Adaptive Optics Note No.137,* 1997

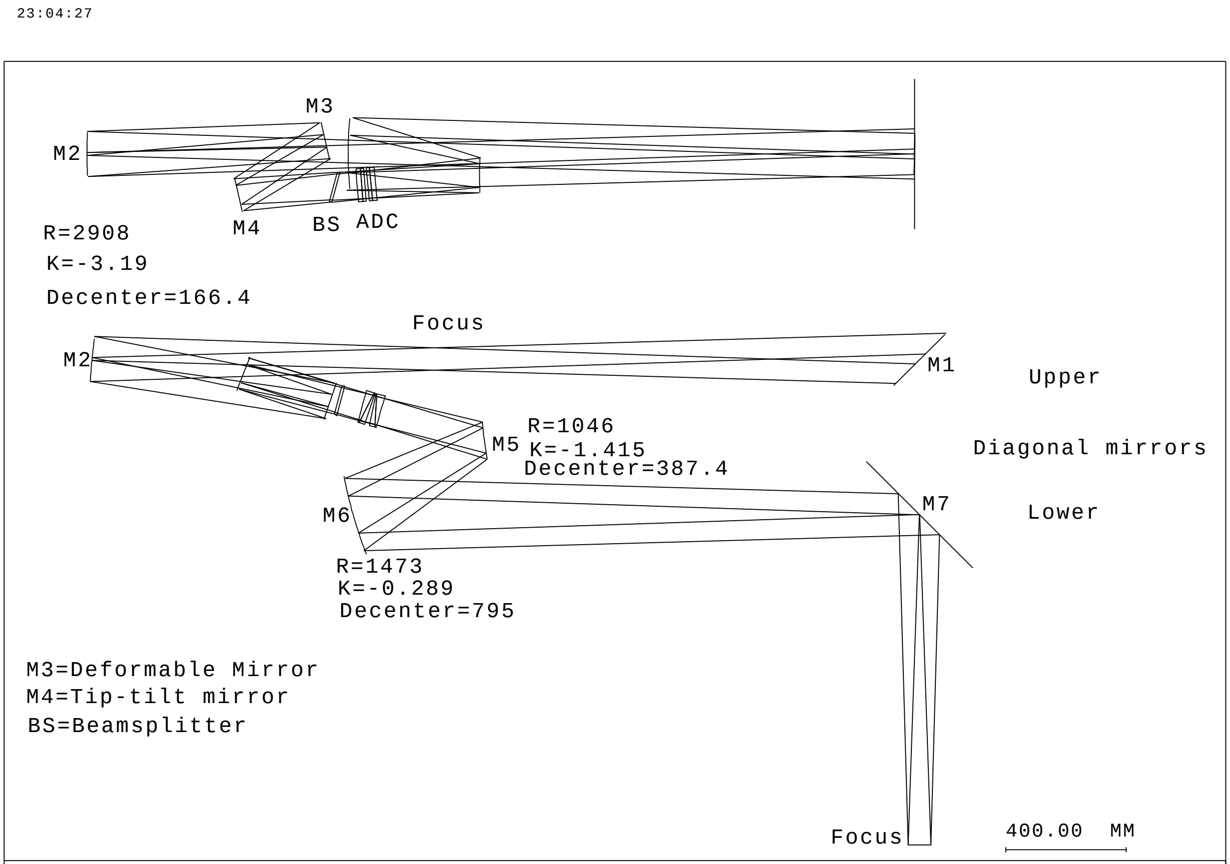

Figure 1. Altair main path, top & side views

19-Apr-98

11:59:02

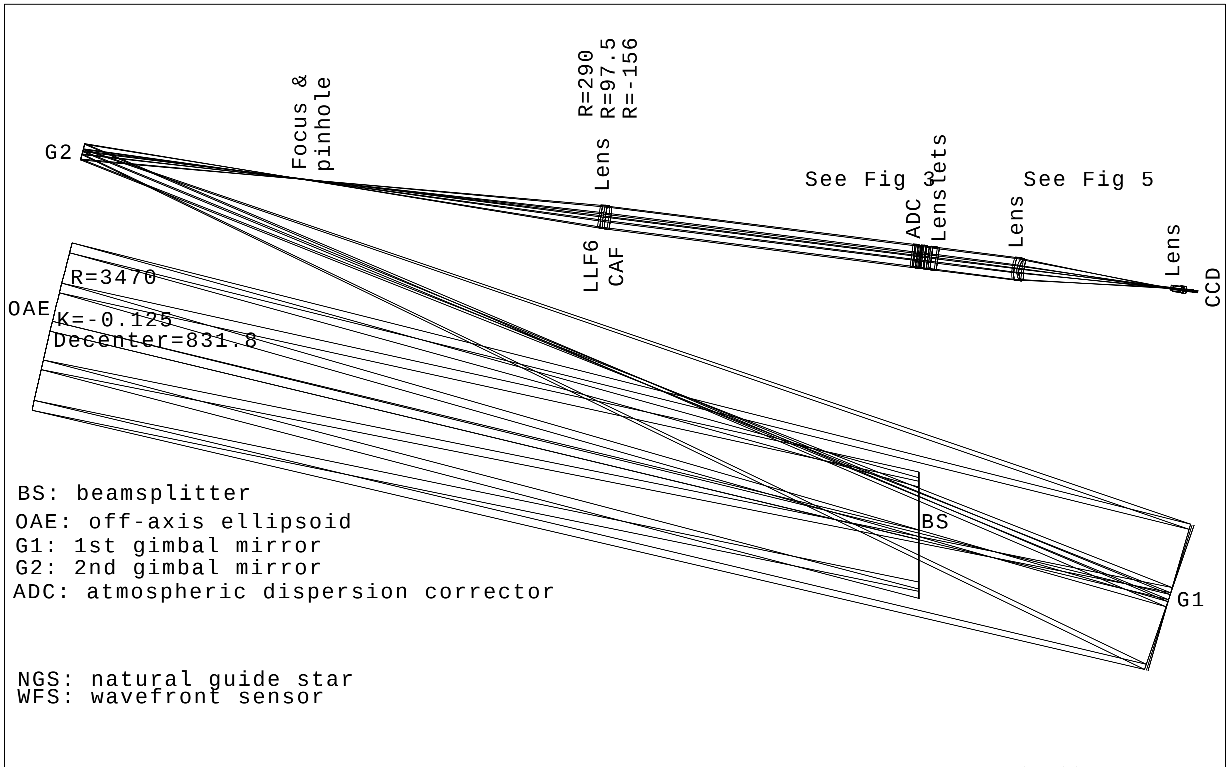

Figure 2. NGS WFS path, BS to CCD

WFS, NGS, BS to CCD

Positions: 1-2,5-7 20-Mar-98

23:06:47

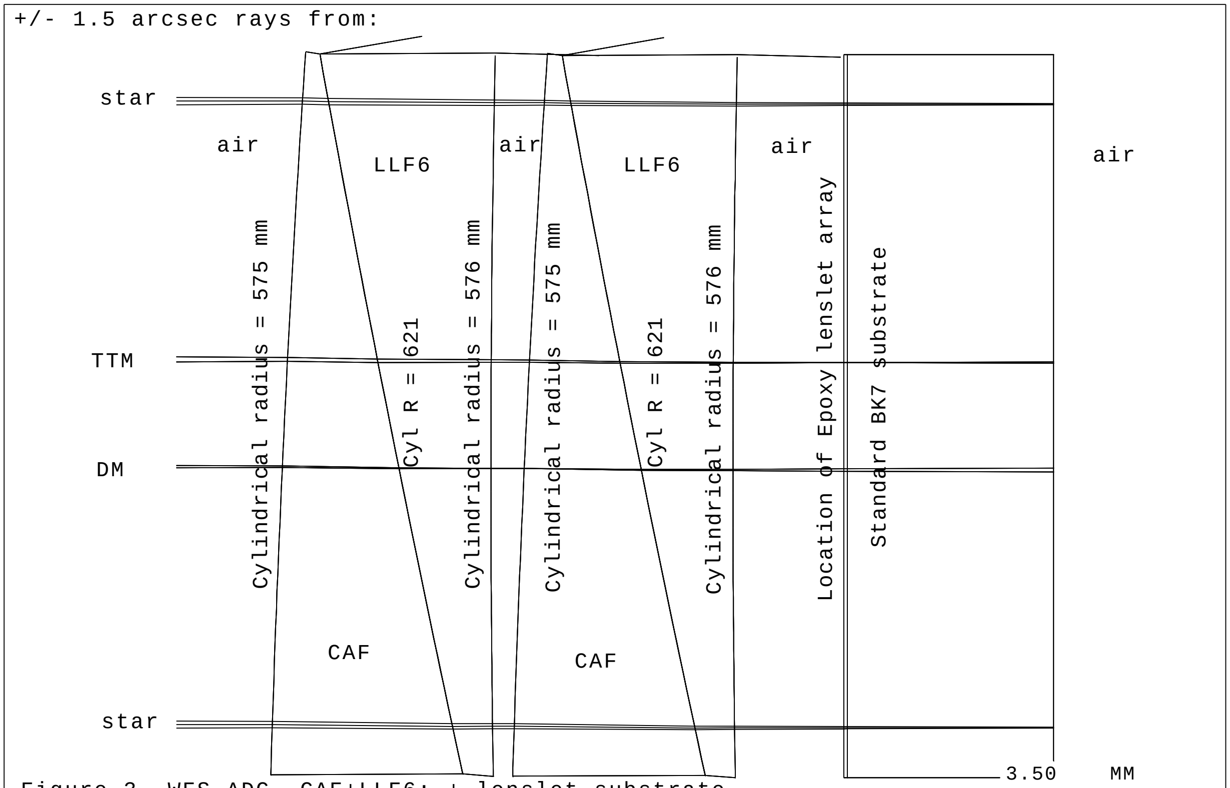

Figure 3. WFS ADC, CAF+LLF6; + lenslet substrate

WFS ADC CAF+LLF6 Positions: 1-3ehr 7-Jan-98

08:32:32

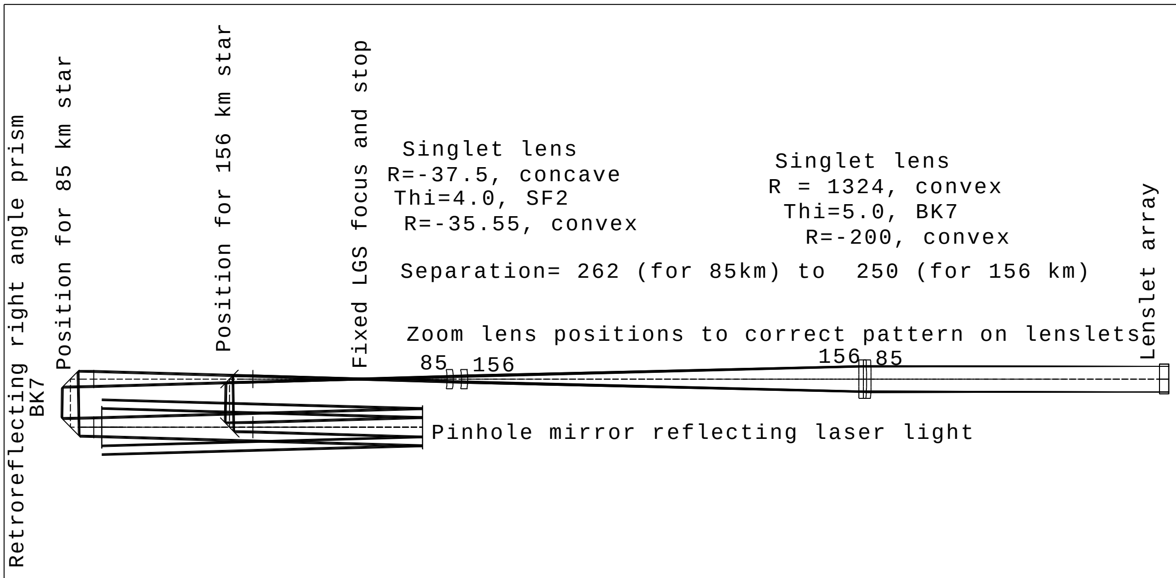

Figure 4. LGS path from pinhole mirror to lenslet array, 85 & 156 km retroprism zoom

75.00 MM

XZ

LGS Prism

Positions: 1,5ehr 17-Mar-98

11:58:19

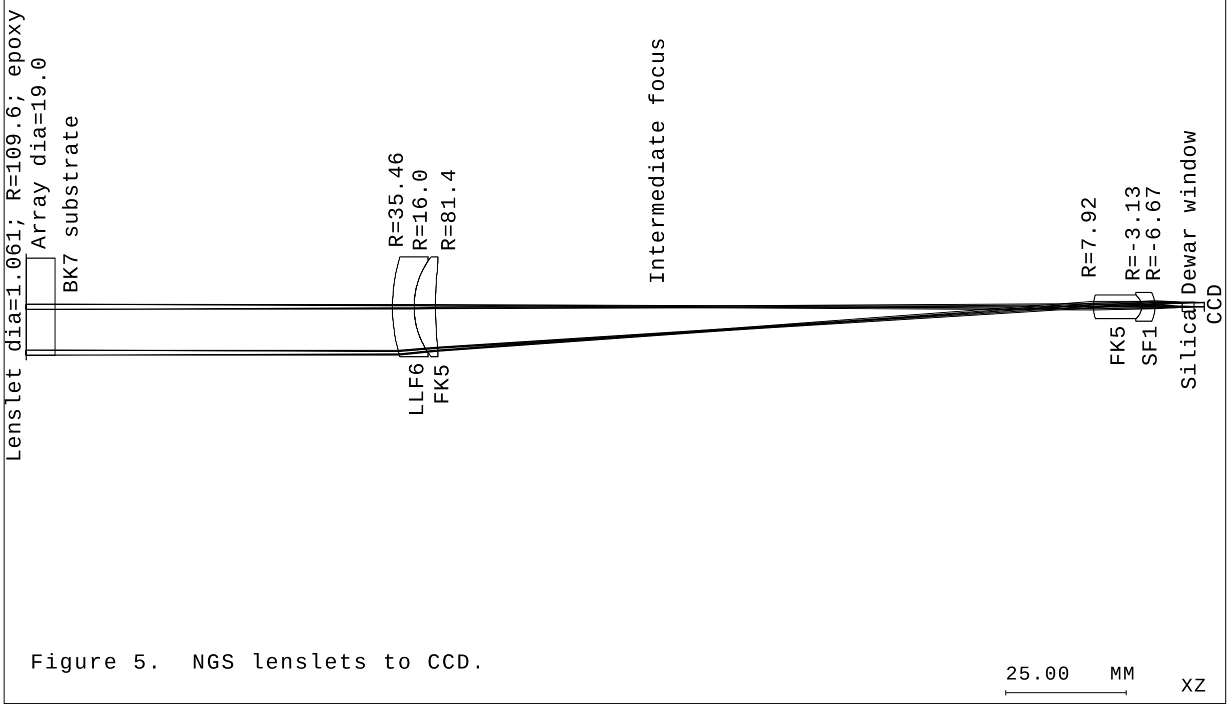

Figure 5. NGS lenslets to CCD.

Custom lenslets: R=109, dia 1.061 Positions: 1,5ehr 20-Mar-98

13:01:39

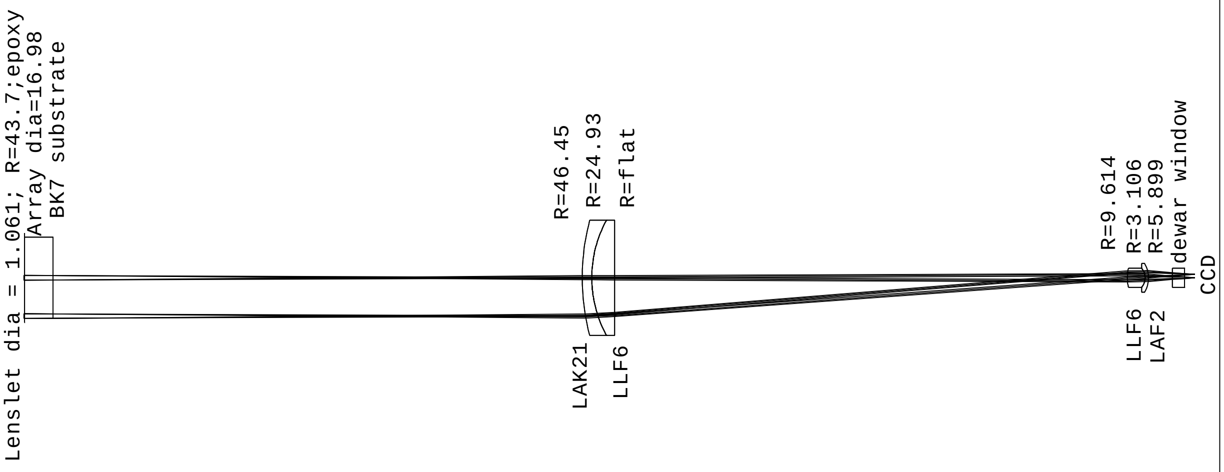

Figure 6. Lenslet-array to CCD for Sodium Laser star

25.00 MM

XZ

85 km LGS to CCD

Positions: 1,5ehr 22-Jan-98