# Opto-Mechanical Design of Altair, the Gemini Adaptive Optics System

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## ABSTRACT

Altair[b], the Gemini Adaptive Optics System, is currently being developed for use at the Cassegrain focus of the northern Gemini 8-Metre Telescope, located on Mauna Kea, Hawaii. The Altair mechanical design must meet strict mass, centre of gravity and volume constraints while providing a highly stable optical bench assembly, and housing and thermally controlling a large set of electronics. The optical bench design for Altair has been developed in tandem with the optical tolerance analysis to ensure that the structure could support the most sensitive optics within specification over the full range of gravity vector and temperature encountered. In turn, the optical tolerance budget was reallocated to better match the predicted mechanical performance of each optical element in the system. Although the system will initially be implemented with a natural guide star wavefront sensor, an upgrade path for a laser guide star wavefront sensor is being incorporated in the system design.

**Keywords:** adaptive optics, mechanical design, telescope instrumentation, Altair

## 1. INTRODUCTION

Altair, the Gemini North Adaptive Optics Sytem[1], is a Cassegrain mounted instrument that intercepts light from the telescope, corrects image aberrations, and passes it on to one of three other instruments mounted on the instrument support structure.

The top level design specifications for Altair require the instrument to have a mass of 900 kg and a centre of gravity 1.2 metres from the mounting face. The allowable instrument volume is 1300 x 1300 x 2300 mm. The optical error budget for Altair is 79 nm rms. This allowance includes optical design and manufacturing, and mechanical positioning, flexure and thermal effects. The error budget does not include instrument induced tip-tilt and focus errors, which will be monitored with On-Instrument Wavefront Sensors located on each instrument and fed back to the telescope control system for correction.

Altair is divided into two separate mechanical assemblies: the optical bench and the electronics enclosure. The optical design[2] for Altair utilizes the upper part of the available instrument volume, leaving space in the lower half for electronics racks. The optical bench assembly carries all the optics, mounting cells, and mechanisms that implement the optical design. It is designed to minimize optical errors due to flexure, thermal effects and enable set-up and servicing. The enclosure assembly provides a thermally insulated and cooled electronics enclosure to house the system electronics. It also provides a cover for the instrument and has load points for handling Altair off the telescope. By placing the heavy electronics and the instrument cover on a separate structure, the performance of the optical bench assembly can be maximized. The optical bench assembly and the enclosure assembly are connected only at the instrument mounting face plate to decouple their flexure characteristics. For handling off the telescope, the optical bench assembly and enclosure assembly are bolted together. Once on the telescope, the assemblies are disconnected. In order to determine whether the optical bench assembly mechanics meet the optical design error budget, a bottoms up analysis was performed to estimate the tolerances for the optical components. Flexures were estimated for the optical bench truss and plates and thermal expansion effects over the working temperature range were added. Finally, mechanical decentre and alignment errors were estimated.

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[b] The Gemini 8-m Telescopes Project is managed by the Association of Universities for Research in Astronomy, for the National Science Foundation, under an international partnership agreement.

These numbers were fed into the optical design tolerance analysis to determine whether the system could be built to perform within specification.

It is a goal of the Altair design to be able to upgrade the system for laser guide stars[3]. An optical design and conceptual mechanical packaging have been developed to show how a laser wavefront sensor can be implemented.

The Altair instrument recently passed the preliminary design review. The critical design review will occur in early 1999 and construction will commence soon after. Altair is scheduled to be commissioned in 2000.

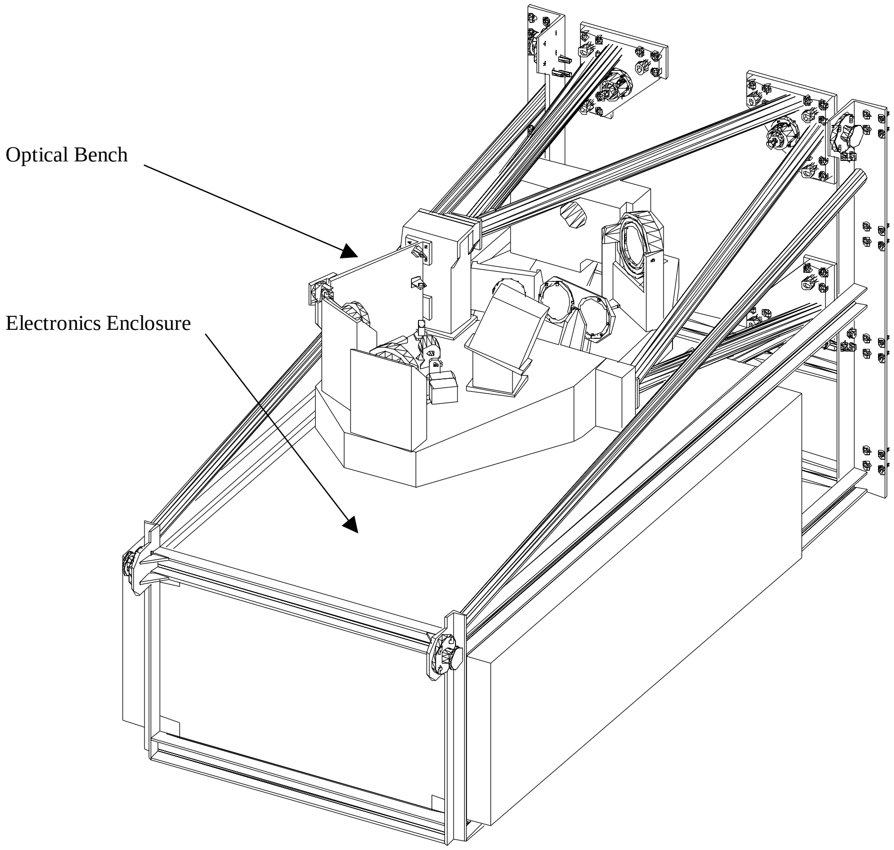


**Figure 1 - Altair, Gemini Adaptive Optics System**

## 2. OPTICAL BENCH MECHANICAL DESIGN

The main structure of the optical bench assembly consists of a welded structural steel truss and a monolithic aluminum optical bench. The truss supports the optical bench at its centre of gravity, minimizing any tendency for the optical bench to rotate as it deflects under gravity. Since the ISS is made from steel, the truss also provides a transition to the different thermal expansion coefficient of the aluminum optical bench. Initial FEA analysis has been used to determine the performance of the truss and optical bench structure. Since the centre of gravity of the optical bench is not perfectly balanced in the vertical direction and the top truss member is offset to clear optical beams, the system does not behave as a true Serrurier truss. FEA analysis was also necessary to model the top and bottom truss connections to the optical bench to determine the overall flexure of the system. The top truss connection is integrated with a vertical plate that is used to support part of the wavefront sensor path optics. This plate also behaves as a structural member to support the truss connection. The worst case flexure of the truss is 70 µm when the telescope is zenith pointing. The maximum optical bench flexure amounts to 27 µm in the same orientation. These figures are within the values used in the optical tolerance analysis in Table 1. As a more detailed analysis of each subcomponent is performed, the results for flexure will be compared with the optical tolerance table to ensure the design will meet the optical error budget.

The optical design places the Collimator, first wavefront sensor mirror (M1), Gimbal 1 and Gimbal 2 mirrors close to the top of the instrument volume. The remaining optics occupy the top half of the instrument space envelope. Space envelopes and mass allocations have been assigned for mounting cells and mechanisms.

The mechanisms on the optical bench consist of a calibration unit at the telescope focus that provides artificial stars, a two position beamsplitter changer, science and wavefront sensor path atmospheric dispersion compensators, and two gimbal mirrors, the second with piston motion, to steer the guide star beam onto the lenslet array.

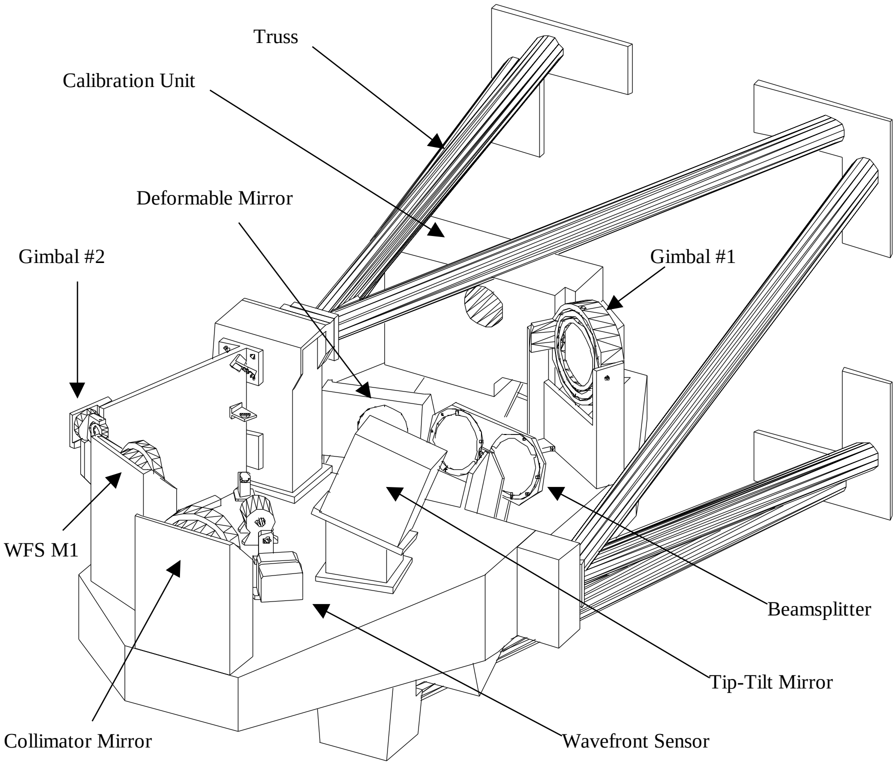


**Figure 2 - Altair Optical Bench**

## 3. SCIENCE PATH OPTICS

The science path optics consist of 5 reflections plus a beamsplitter and remotely deployable atmospheric dispersion compensator. Three of the mirrors are off-axis conics: the science collimator, convex and camera mirrors. The deformable mirror, and tip-tilt mirror are flat. The beamsplitter has a 0.6 arcminute wedge angle between the two flat surfaces. The science atmospheric dispersion compensator (ADC) is removable from the optical path for observations in the infrared.

The optical tolerance analysis was derived by first performing a sensitivity analysis for each optical element. These figures were used in the initial mechanical design to try to minimize the motions of sensitive elements. Bottom up estimates were then made of the mechanical structure to determine the likely motion of each optical surface. By feeding these figures back and forth to the optical designer, the error budget for each surface was determined. The optical tolerance analysis, summarized in Table 1 with units of millimetres and degrees, shows that the relative positions of the camera and convex mirrors must be highly stable in axial separation, tip-tilt and decenter.  An Invar structure is being designed to maintain the alignment of these last two mirrors for ranges of temperature and gravity direction.

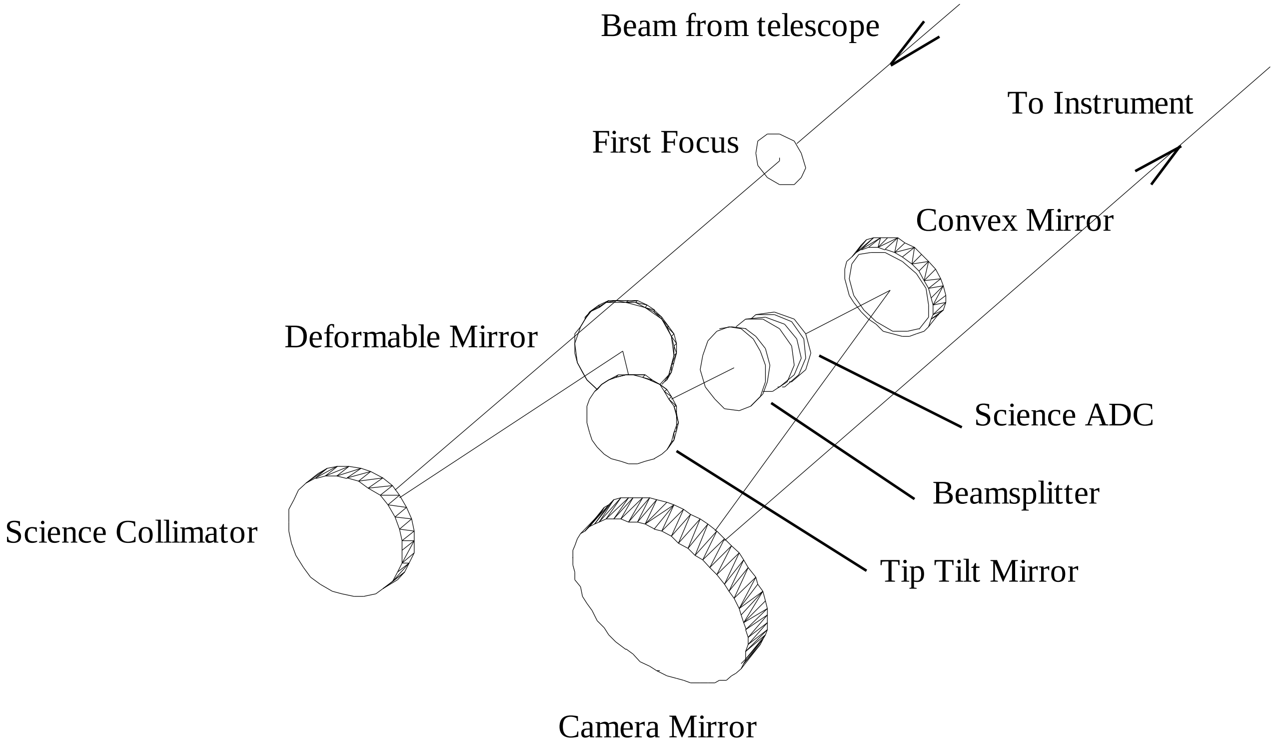


**Figure 3 - Science path optics with laser pencil**

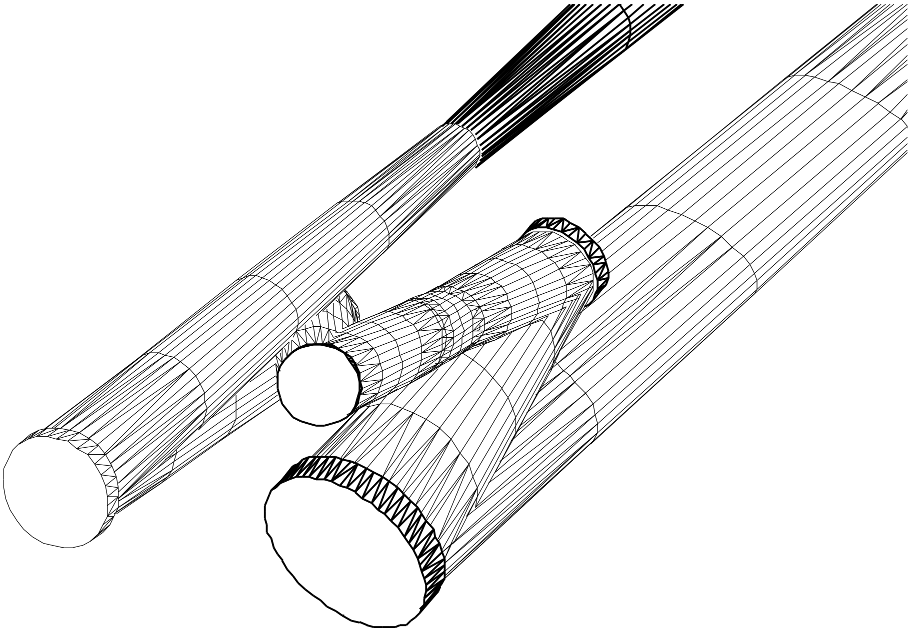
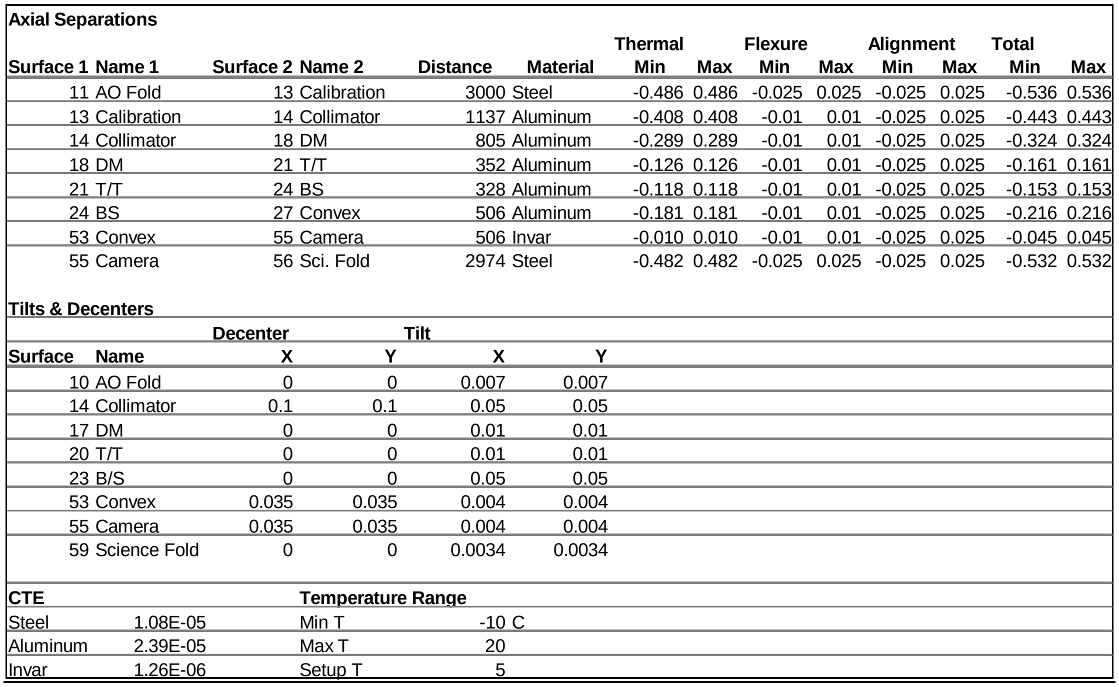


**Figure 4 - Science path optics with 2 arcminute beam size**



**Axial Separations**

| Surface 1 | Name 1 | Surface 2 | Name 2 | Distance | Material | Thermal Min | Thermal Max | Flexure Min | Flexure Max | Alignment Min | Alignment Max | Total Min | Total Max |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11 | AO Fold | 13 | Calibration | 3000 | Steel | -0.486 | 0.486 | -0.025 | 0.025 | -0.025 | 0.025 | -0.536 | 0.536 |
| 13 | Calibration | 14 | Collimator | 1137 | Aluminum | -0.408 | 0.408 | -0.01 | 0.01 | -0.025 | 0.025 | -0.443 | 0.443 |
| 14 | Collimator | 18 | DM | 805 | Aluminum | -0.289 | 0.289 | -0.01 | 0.01 | -0.025 | 0.025 | -0.324 | 0.324 |
| 18 | DM | 21 | T/T | 352 | Aluminum | -0.126 | 0.126 | -0.01 | 0.01 | -0.025 | 0.025 | -0.161 | 0.161 |
| 21 | T/T | 24 | BS | 328 | Aluminum | -0.118 | 0.118 | -0.01 | 0.01 | -0.025 | 0.025 | -0.153 | 0.153 |
| 24 | BS | 27 | Convex | 506 | Aluminum | -0.181 | 0.181 | -0.01 | 0.01 | -0.025 | 0.025 | -0.216 | 0.216 |
| 53 | Convex | 55 | Camera | 506 | Invar | -0.010 | 0.010 | -0.01 | 0.01 | -0.025 | 0.025 | -0.045 | 0.045 |
| 55 | Camera | 56 | Sci. Fold | 2974 | Steel | -0.482 | 0.482 | -0.025 | 0.025 | -0.025 | 0.025 | -0.532 | 0.532 |

**Tilts & Decenters**

| Surface | Name | Decenter X | Decenter Y | Tilt X | Tilt Y |
|---|---|---|---|---|---|
| 10 | AO Fold | 0 | 0 | 0.007 | 0.007 |
| 14 | Collimator | 0.1 | 0.1 | 0.05 | 0.05 |
| 17 | DM | 0 | 0 | 0.01 | 0.01 |
| 20 | T/T | 0 | 0 | 0.01 | 0.01 |
| 23 | B/S | 0 | 0 | 0.05 | 0.05 |
| 53 | Convex | 0.035 | 0.035 | 0.004 | 0.004 |
| 55 | Camera | 0.035 | 0.035 | 0.004 | 0.004 |
| 59 | Science Fold | 0 | 0 | 0.0034 | 0.0034 |

| CTE | | Temperature Range | | |
|---|---|---|---|---|
| Steel | 1.08E-05 | Min T | -10 | C |
| Aluminum | 2.39E-05 | Max T | 20 | |
| Invar | 1.26E-06 | Setup T | 5 | |

**Table 1 - Science path optical alignment error budget**

The error budget for image degradation due to internal optics manufacturing, surface quality, flexure, positioning and thermal distortion is 79 nm rms. The optical tolerance analysis performed by Chris Morbey shows that the actual wavefront degradation most likely be less than 55 nm rms (3 sigma).

## 4. WAVEFRONT SENSOR NATURAL GUIDE STAR OPTICS

Figure 2 shows how the wavefront sensor optical packaging takes advantage of a vertical plate attached to the truss support for an optical bench. The wavefront sensor path passes between two gimbal mirrors, along the vertical plate through two folds to the surface of the optical bench where the ADC, lenslets and CCD are located. The gimbal mirrors are used to steer the guide star light through the centre of the field stop, and onto the lenslets and CCD of the wavefront sensor. The second gimbal mirror is mounted on a linear stage to provide focus capability for the wavefront sensor path. Having the lenslets and CCD on the optical bench is beneficial in maintaining the precise micron level alignment between the lenslets and CCD. Murray Fletcher has analysed the wavefront sensor optical train and determined the following requirements for the alignment and motion control of the optics:

| Element | Requirement |
|---|---|
| WFS ADC | Full 360° rotation for each prism, setting resolution of 0.05° |
| Gimbal Mirrors | Tilt resolution of 0.8 arcseconds, rotation of ±1.5°. Piston range on second gimbal is ±2mm. |

**Table 2 - WFS path optical alignment and motion tolerances**

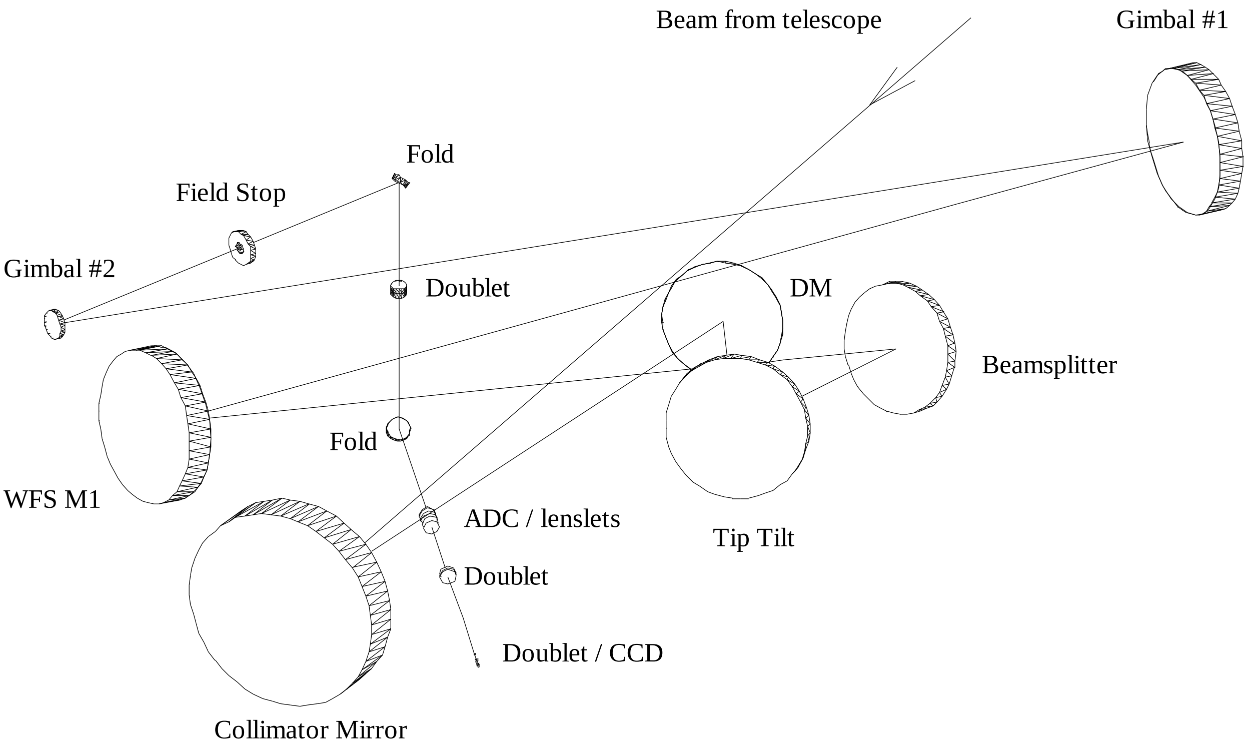


**Figure 5 - NGS WFS optics**

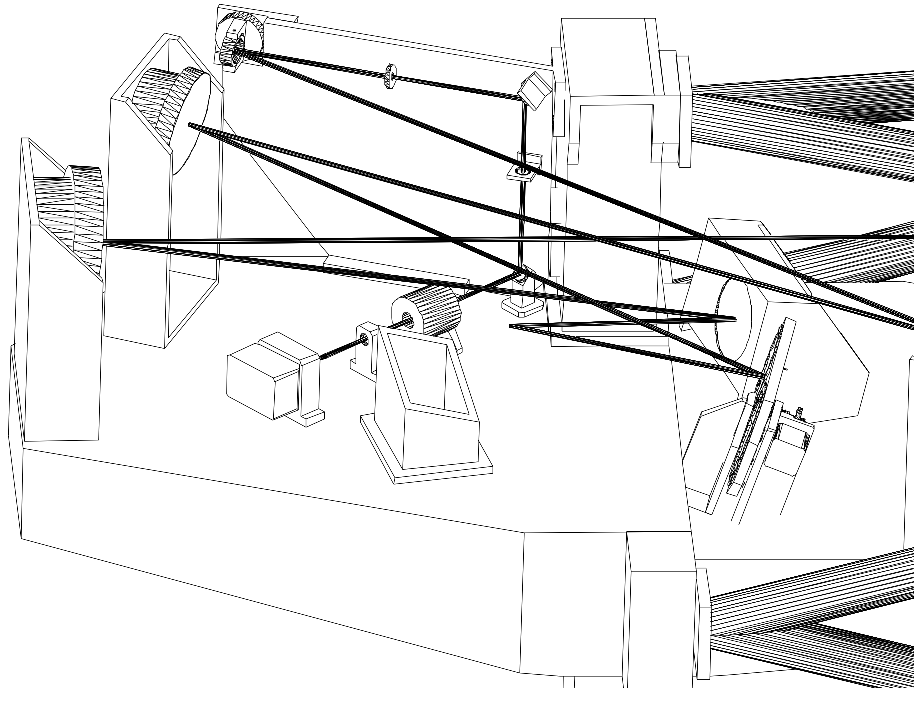


**Figure 6 – Mechanical layout of NGS wavefront sensor**

## 5. WAVEFRONT SENSOR LASER GUIDE STAR OPTICS

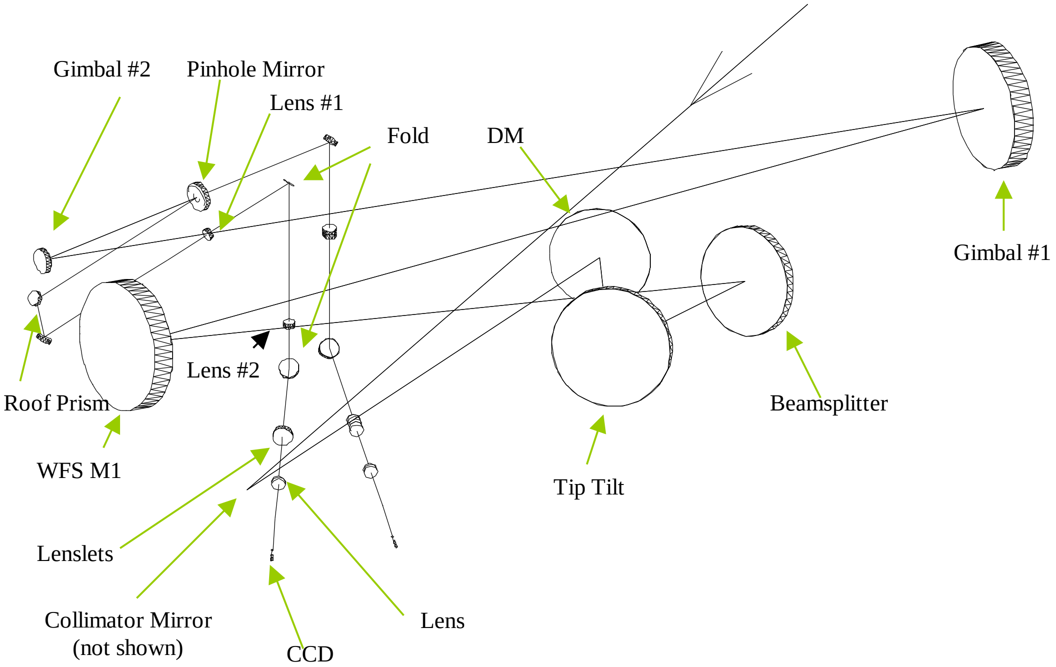


**Figure 7 - LGS and NGS WFS optics**

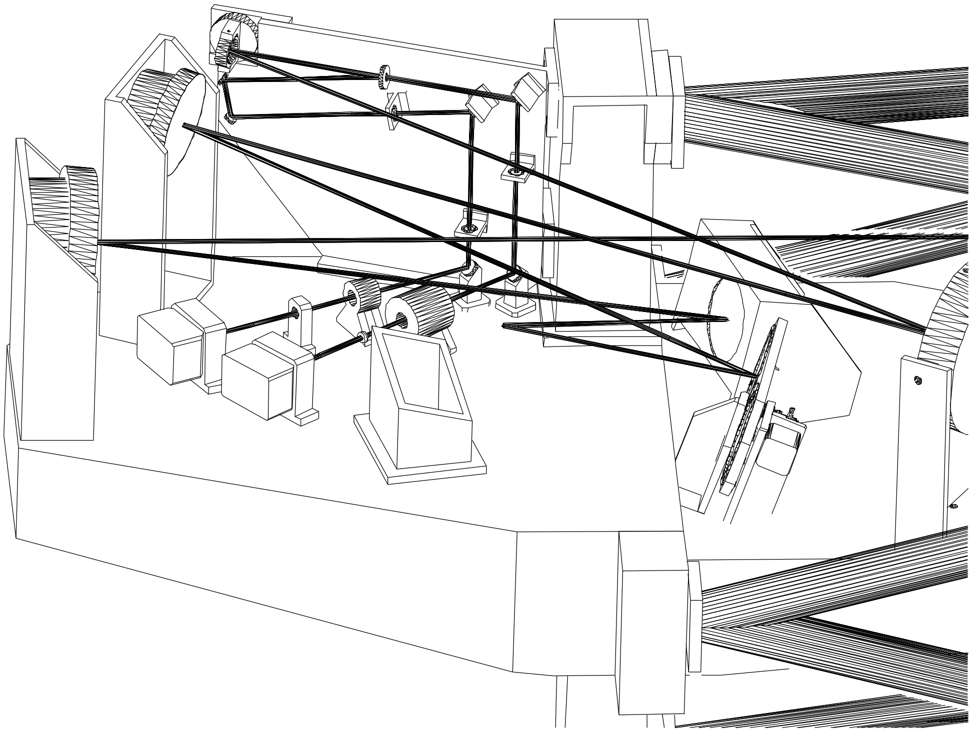


**Figure 8 - Mechanical layout of LGS upgrade**

The optical design layout for the laser guide star (LGS) upgrade is shown in Figure 7. Since the laser guide star distance is 85-95 km at zenith, there is not an image at the field stop as there is for the NGS design. In fact, the patch formed by the LGS system falls entirely outside the field stop diameter due to the central obscuration formed by the secondary mirror. By replacing the field stop with a perforated mirror, called the pinhole mirror, the light from the LGS and NGS systems can be separated and fed to different paths. The roof prism and lens #1 are mounted on translation stages to provide zoom capability for the varying laser guide star elevation as the telescope points off zenith.

Figure 8 shows the mechanical packaging of the LGS upgrade. In order to show the wavefront sensor paths, the tip-tilt mirror is removed from the system.

## 6. ELECTRONIC ENCLOSURE

Various design constraints including the overall mass budget, the centre of gravity (CofG) requirement, and restricted space envelope, have forced us to design a customized enclosure for housing the Altair electronics. The Altair electronics dissipate approximately 1.7 kW inside the electronic enclosure. In order to limit the heat released from the electronic enclosure to less than 100 watts, the enclosure is actively cooled by using air-to-liquid heat exchangers, and is thermally insulated from the surroundings by using flame retardant foam panels. The liquid coolant (40%/60% glycol/water mixture) for the heat exchanger is circulated through remote off-telescope chillers. The chillers exhaust the heat into the telescope exhaust duct tunnel. In order to further minimize the heat loss to the sensitive optics, cold air is sent through air plenums built around the electronics. An exploded view of the electronic enclosure is shown in the Figure 7.

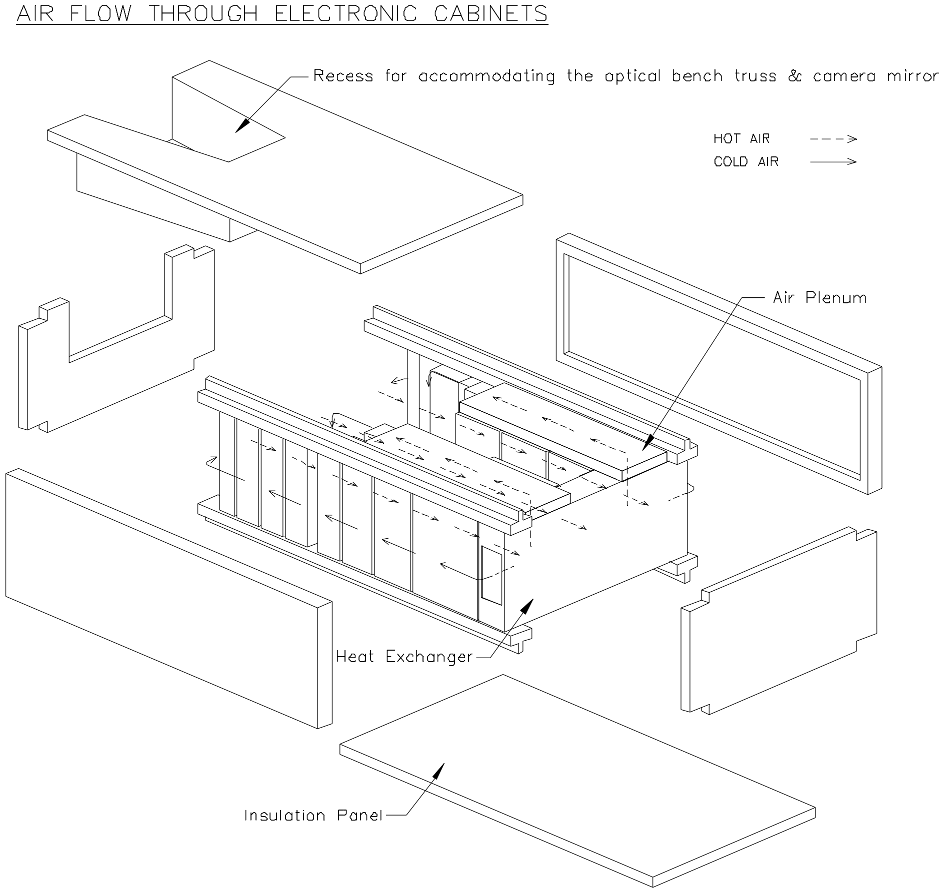


Figure 9 - Altair Electronic Enclosure

# 7. MASS AND BALANCE

The mass and balance of Altair is summarized in Table 3. The instrument enclosure and optical bench are tabulated separately and summed at the bottom of the table. The second through fifth columns tabulate the CofG and mass of each component and the sixth through ninth columns are a running total. The last row shows that the Altair CofG is at the correct location, 1200 mm from the mounting face and the mass is 900 kg. Included in the table are 20 kg of balance mass to achieve the correct CofG for the optical bench and an additional 40 kg to balance the instrument.

**Altair Mass and CofG Estimate**

| **Part Characteristics** | | | | | **Overall CofG, Mass** | | | |
|---|---|---|---|---|---|---|---|---|
| **Part** (material) | **X** | **Y** | **Z** | **Mass (Kg)** | **X** | **Y** | **Z** | **Mass** |
| **CofG of Electronics and Instrument Enclosure** | | | | | | | | |
| Enclosure Structure | 0 | -62.6085 | -886.3144 | 60.0 | 0 | -62.6085 | -886.3144 | 60 |
| Heat Exchanger Box + M_Rails | 0 | -357.5 | -2413.13 | 12.5 | 0 | -113.4519 | -1149.558 | 72.5 |
| Heat Exchanger | 0 | -357.5 | -2367.5 | 18.0 | 0 | -161.9918 | -1391.801 | 90.5 |
| Air Plenum | 0 | -402.8 | -1826.15 | 2.5 | 0 | -168.4652 | -1403.477 | 93 |
| Plumbing, Cables etc. | 0 | -550 | -1600 | 15.0 | 0 | -221.4561 | -1430.772 | 108 |
| Insulation plus Cover | 0 | -290.6 | -1421.28 | 20.0 | 0 | -232.2598 | -1429.289 | 128 |
| Optical Bench/ISS Interface | 0 | 264.27 | -68.038 | 60.0 | 0 | -73.79287 | -994.847 | 188 |
| Controller Chassis #1 | -350 | -357.5 | -2146.5 | 17.0 | -29.02439 | -97.3198 | -1090.35 | 205 |
| Controller Chassis #2 | -350 | -357.5 | -1864.5 | 17.0 | -53.6036 | -117.2435 | -1149.632 | 222 |
| Controller Chassis #3 | -350 | -357.5 | -1582.5 | 17.0 | -74.68619 | -134.3329 | -1180.422 | 239 |
| Power Supply Chassis | 331 | -357.5 | -1753.5 | 50.0 | -4.49827 | -172.9431 | -1279.57 | 289 |
| Elma VME Enclosure | 310 | -357.5 | -2080 | 24.0 | 19.61661 | -187.0944 | -1340.945 | 313 |
| Signal Conditioning Rack | -510 | -357.5 | -974.5 | 3.0 | 14.58861 | -188.7122 | -1337.466 | 316 |
| Solid State Relay Rack | 510 | -357.5 | -1016.5 | 5.0 | 22.3053 | -191.3413 | -1332.466 | 321 |
| Tip/Tilt Mirror Controller | 407.5 | -357.5 | -1538 | 10.0 | 33.9426 | -196.3612 | -1338.676 | 331 |
| Digiplan SC60 Stepper Chassis | 450 | -357.5 | -1366.5 | 2.2 | 36.68968 | -197.4252 | -1338.86 | 333.2 |
| Digiplan SC60 Stepper Chassis | -450 | -357.5 | 1367 | 2.2 | 33.49732 | -198.4751 | -1321.111 | 335.4 |
| Oregon Micro Stepper Chassis | -547.5 | -357.5 | -824.5 | 5.2 | 24.62713 | -200.903 | -1313.529 | 340.6 |
| Power Supply Compartment | -463.5 | -357.5 | -1146 | 17.5 | 0.772829 | -208.5557 | -1305.342 | 358.1 |
| LGS Upgrade-2nd WFS X-Y-Z | 547.5 | -357.5 | -866.5 | 6.7 | 10.81414 | -211.2913 | -1297.282 | 364.8 |
| LGS Upgrade-Power Supply | 463.5 | -357.5 | -1166.5 | 10.0 | 22.89221 | -215.1923 | -1293.793 | 374.8 |
| Overall Instrument Cover | 0 | -75 | -1500 | 35.0 | 20.93704 | -203.2188 | -1311.405 | 409.8 |
| Balance Mass | -100.1 | -326.8 | -1535.2 | 40.0 | 10.17119 | -214.2063 | -1331.303 | 449.8 |
| **Sub-Total Electronics / Enclosure** | | | | | 10.17119 | -214.2063 | -1331.303 | 449.8 |
| **CofG of Optics and Optical Bench** | | | | | | | | |
| *Optical Bench* | 6.0 | 224.0 | -1313.0 | 100.0 | 6.00 | 224.00 | -1313.00 | 100.0 |
| *Truss Connect - Top* | 222.0 | 475.0 | -1303.0 | 10.0 | 25.64 | 246.82 | -1312.09 | 110.0 |
| *Truss Connect - Bottom* | 0.0 | -56.0 | -1297.0 | 10.0 | 23.50 | 221.58 | -1310.83 | 120.0 |
| *Truss Connect +x* | 400.0 | 200.0 | -1275.0 | 3.0 | 32.68 | 221.06 | -1309.96 | 123.0 |
| *Truss Connect -x* | -400.0 | 200.0 | -1275.0 | 3.0 | 22.38 | 220.56 | -1309.13 | 126.0 |
| *Calibration Unit* | 24.0 | 454.0 | -763.0 | 15.0 | 22.55 | 245.39 | -1251.03 | 141.0 |
| *ADC - Science* | -100.0 | 350.0 | -1020.0 | 10.0 | 14.44 | 252.32 | -1235.73 | 151.0 |
| *ADC - Science Stage* | -100.0 | 250.0 | -1020.0 | 5.0 | 10.77 | 252.24 | -1228.81 | 156.0 |
| *Beamsplitter Changer* | -200.0 | 300.0 | -1150.0 | 8.0 | 0.49 | 254.57 | -1224.97 | 164.0 |
| *D/M* | 80.0 | 360.0 | -1135.0 | 10.0 | 5.06 | 260.63 | -1219.80 | 174.0 |
| *T/T* | -150.0 | 475.0 | -1500.0 | 10.0 | -3.37 | 272.28 | -1235.03 | 184.0 |
| *Mirror - Collimator* | 0.0 | 478.0 | -1998.0 | 9.0 | -3.21 | 281.88 | -1270.61 | 193.0 |
| *Mirror - Convex* | -75.0 | 250.0 | -650.0 | 3.0 | -4.31 | 281.39 | -1261.11 | 196.0 |
| *Mirror - Camera* | 0.0 | -5.0 | -1110.0 | 15.0 | -4.00 | 261.03 | -1250.36 | 211.0 |
| *Convex/Camera Cell* | 4.0 | 110.0 | -935.0 | 50.0 | -2.47 | 232.10 | -1189.95 | 261.0 |
| *WFS M1* | 221.0 | 490.0 | -1860.0 | 6.0 | 2.55 | 237.89 | -1205.01 | 267.0 |
| *WFS Gimbal 1* | -258.0 | 447.0 | -890.0 | 8.0 | -5.03 | 243.97 | -1195.84 | 275.0 |
| *WFS Gimbal 2* | 386.0 | 590.0 | -1756.0 | 2.0 | -2.21 | 246.47 | -1199.89 | 277.0 |
| *WFS Optical Bench* | 298.0 | 461.0 | -1535.0 | 7.0 | 5.19 | 251.76 | -1208.15 | 284.0 |
| *WFS Sub-assy* | 20.0 | 350.0 | -1650.0 | 5.0 | 5.45 | 253.46 | -1215.79 | 289.0 |
| *LGS Upgrade* | 20.0 | 350.0 | -1650.0 | 5.0 | 5.70 | 255.10 | -1223.18 | 294.0 |
| *Balancing Mass* | -83.8 | -250.0 | -1330.3 | 20.0 | 0.00 | 222.93 | -1230.00 | 314.0 |
| *CCD Controller (NGS)* | -315.0 | 247.0 | -1870.0 | 10.0 | -9.72 | 223.67 | -1249.75 | 324.0 |
| *CCD Controller (LGS)* | -315.0 | 88.0 | -1870.0 | 10.0 | -18.86 | 219.61 | -1268.32 | 334.0 |
| *Truss* | 15.0 | 200.0 | -488.0 | 115.0 | -10.19 | 214.59 | -1068.46 | 449.0 |
| ***Sub-Total Optics*** | | | | | **-10.19** | **214.59** | **-1068.46** | **449.0** |
| ***Sub-Total Electronics / Enclosure*** | | | | | **10.17** | **-214.21** | **-1331.30** | **449.80** |
| ***Total Instrument*** | | | | | **0.00** | **0.00** | **-1200.00** | **898.8** |

Table 3 - Altair Mass and Balance

## 8. CONCLUSIONS

The opto-mechanical design for Altair has been presented, showing that the system design meets the mass and balance requirements and falls within the optical tolerance limits. Packaging the system with the optical bench occupying the top half of the available instrument space envelope allowed room for the electronic enclosure in the bottom half of the instrument. The method of using optical design sensitivities to drive the mechanical design and then feeding back mechanical flexure and thermal expansion estimates to the optical tolerance analysis has proved valuable in optimizing the performance of the optical bench. An upgrade path for laser guide star adaptive optics has been presented.

## 9. REFERENCES

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