Baseline Optical Chassis Work Package Description

wht-naomi-56

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1. Optical Chassis Functional Requirements

1.1 Introduction and General Requirements

This document should be read in conjunction with the AOW/GEN/AJL/6.8/07/96/WP Cover Document which references several other relevant documents and the AOW/SYS/RMM/6.2/01/97/NAOMI S & O Requirements document. Together these documents constitute the current requirements for NAOMI (Nasmyth AO system for Multiple-Purpose Instrumentation). (These documents are from time to time updated by their authors; readers can ensure they have the latest versions by checking with the Project Manager.)

1.1.1 Definition

The optical chassis is defined as the entire adaptive-optics optical train with the exception of the wavefront sensor (WFS) and the WHT. It includes the optical components, their mounts, adjustment mechanisms, calibration sources and the support structures (i.e. baseplates or equivalent) for the optics. The baseline design will have the capability to be readily upgraded to accommodate additional features, e.g. a tip/tilt sensor, turbulent-layer conjugation, when funds become available.

1.1.2 Primary Functions

The optical train may be divided into several optical paths. The functions of these paths are summarised below. More detailed information is provided later in the document.

a. The *common-path optics* must perform at least the following functions:

Interface with the WHT Nasmyth focus and the calibration/alignment source.
Provide optics for imaging the WHT pupil at the deformable mirror and the WFS entrance pupil.
Ensure that the components have sufficient aperture to allow the future implementation of turbulent-layer conjugation.
Include and accommodate the adaptive optics components, i.e. the deformable mirror (DM) and the fast steering mirror.
Provide access for a simple interferometer to monitor the DM surface.
Provide an AO-corrected focal plane where light may be directed to the science instrument, the WFS and an optical science port as required.

b. The *science-path optics* will select the wavelength region used by the science instrument and provide a corrected image at the appropriate plate scale over the instrument's field of view (FOV). (Wavelength selection should be performed with a dichroic beamsplitter.) The science optics must provide a well defined and accessible pupil image and focal plane to which an IR science instrument can be coupled.

c. The *WFS pick-off optics* will allow guide stars to be selected within the available FOV and direct the light from the guide star to the WFS. Note that the selection of the design concept for the pick-off optics is the responsibility of the optical-chassis supplier but implementation is the responsibility of the WFS WP supplier. The guide stars may be within or outside the science FOV. Provision must be made for future operation of the wavefront sensor with a laser guide star in the sodium layer. The optics must also maintain the registration of the deformable mirror with WFS lenslet array independent of the guide-star position. The WFS pick-off must function to specification in the presence of dithering as required by Science Clause 4. Provision must be made to accommodate a separate tip/tilt sensor needed when the system is upgraded to operate with laser guide stars.

d. The *optical science path* will provide a partially corrected FOV for use by visible science instrumentation. The initial applications will be for testing the AO correction at optical wavelengths compared to the image from the pre-correction camera and as an additional acquisition camera. The optics will utilise that section of the FOV not obscured by the pick-off to the WFS. Note that the AO system is not primarily intended to provide high image quality in the visible spectral region and the utility of this port may be limited (see Clause 10).

e. The *calibration and alignment optics* will provide sources conjugate to the Nasmyth focal plane for calibration and alignment purposes. The calibration optics will include provision for a WHT-pupil simulator. Provision must be made for distortion mapping of the AO optical train; off-axis positioning of the calibration source is required to accomplish this function. A calibration source is also required for calibration of the wavefront sensor; this source will be injected at the system's AO-corrected f/16.8 focus although this is the responsibility of the WFS WP supplier.

1.1.3 General Requirements

The optical path to the science instrumentation port shall follow good design practice for infrared operation, e.g. minimum number of surfaces, low emissivity components (see Clause 24). The design should be configured to allow adequate space for existing and future science instrumentation. The space requirements for optical mounts, mechanisms to move components, bench-mounted electronics, cameras and cables should be taken into account.

Consideration shall be given to the use of materials and techniques to reduce the effects of temperature changes within the GHRIL. The minimum supporting analysis shall include a first-order study to assess the system's temperature sensitivity. The analysis should demonstrate that the system performance will satisfy all specifications when operating within the GHRIL temperature limits. No direct control of optical surface temperatures (other than those already cooled in the science instrumentation) should be considered. Local heat sources should be controlled and there will provision to remove heat from the GHRIL.

A modular-build approach should be followed to provide a maximum of four independent but accurately relocatable modules on the existing optical bench (size 1.35 m x 2.5 m) with a maximum of four electronics racks. (Note that the wavefront-sensor module and its electronics are not included in these numbers.) Power and other supplies, e.g. liquid coolant, should be connected through well-designed umbilicals.

As a goal, removal of all equipment by hand is desired but use of a hoist is acceptable. The modules should require only the simplest possible handling trolley for safe transport. In accordance with Clause 13, it shall be possible to install and align the equipment within 8 hours and to remove it to a WHT storage point in 4 hours. A maximum of two people shall be needed to carry out these operations.

The design must allow certain upgrades to be readily incorporated. In particular the system shall be designed to permit an upgrade to Na laser beacon operation. This upgrade will allow high Strehl ratios to be obtained at K band with the sky coverage limited only by the availability of tip-tilt guide stars. The main consequence of this requirement is that sufficient space be left to install a separate tip-tilt sensor with its pick-off. Note that the WFS for the baseline system may later be used as a tip/tilt sensor and a new WFS will be constructed for use with laser guide stars.

The detailed specifications which follow contain references to the applicable science clauses where appropriate.

1.1.4 Guide Star Selection

The design shall allow selection of either of the two operating modes defined below. These modes are referred to by number elsewhere in the specifications. Note that the centre of the science field will always lie on the system's optical axis.

1. The WFS uses the science object or a guide star in the science field.
2. The WFS uses a guide star outside the science field.

1.1.5 Spectral Bandwidths

The common path optics shall transmit radiation from 0.4 µm to ? 4.1 µm wavelength. The science path shall transmit radiation from 0.8 µm to ? 4.1 µm wavelength. The WFS path shall transmit wavelengths from 0.4 µm to ? 1 µm. Note that when the guide star is within the science field (Mode 1) the upper wavelength limit for the WFS is nominally 0.8 µm although Clause 3 (see Section 1.1.6 below) requires some transmission of longer wavelength radiation to the WFS.

1.1.6 Transmission

Table 1 specifies the minimum transmission required from the Nasmyth focus to the input to the WFS. The mode numbers are those given in Section 1.1.4 above. Transmission values refer to the average over the specified spectral band. Specific requirements are not given for wavelengths in the 0.4 µm to 0.5 µm region where the transmission shall be on a "best effort" basis without requiring new coating development or extensive study.

Table 1

Mode	Bandwidth (µm)	Transmission
1	0.50 to 0.8	0.58
2	0.50 to 1.0	0.83

Mode 1 is in accordance with Clause 9. In accordance with Clause 3, the NAOMI system alone shall have a throughput of > 70% to the infrared science port at wavelengths > 1 µm and a throughput to the WFS > 25% at wavelengths from 0.9 µm to 1 µm.

These specifications are independent of the polarisation.

All optical coatings must be such that the transmission specifications are satisfied for a minimum period of one year. The use of approved cleaning procedures, as specified below in Section 1.3.3, is acceptable.

1.1.7 Emissivity

All mirror coatings beyond the Nasmyth focus shall be selected for maximum reflectivity above 500 nm wavelength. An upper limit to the emissivity at 2.2 µm and longer wavelengths of the total optical path to the science instrument's cryostat window excluding the telescope shall be 20% with a goal of ?16% Clause 24). Note that this requirement has implications for maintaining a clean GHRIL room and protecting surfaces from dust and oil.

1.1.8 Optical Surface Quality

Within the clear aperture of each optical component, the cosmetic surface quality shall be 5/3 x 0.40; K2 x 0.06 in accordance with DIN 3140. The surface roughness shall be ? 1 nm rms.(Note that this specification may be relaxed for components that are particularly difficult to manufacture provided analysis indicates no significant effect on the scattered light. Project approval is required for any such changes.)

1.1.9 Pupil and Turbulent-Layer Conjugation

For the baseline design the WHT pupil will be imaged at the deformable mirror. The size of the pupil at the deformable mirror shall be 56 mm diameter. The exit pupil of the telescope has a diameter of 1.17 m at a distance of 12.84 m from the Nasmyth focus.

The limited turbulence profiles currently available for the La Palma site indicate that measures to reduce angular anisoplanatic effects are required to satisfy sky coverage specification of Clause 2. Assuming that a dominant turbulent layer exists, one measure is to make corrections at a conjugate of this layer. Preliminary analysis indicates that this approach may offer a significant performance advantage but further analysis and expansion of the JOSE data base are required. No optics intended solely for turbulent-layer conjugation are to be included in the baseline design. Sufficient space must be set aside to allow installation of these optics and associated mechanisms as part of a system upgrade. These optics are likely to be lenses that are remotely inserted at or near the Nasmyth focus. In addition, the common-path optics excluding the deformable mirror and fast steering mirror shall have sufficient clear aperture to allow conjugation over the 2.9 arcminute field without vignetting to a turbulent layer at 3 km above the telescope. (Note that in practice this may require increasing the aperture of only one component.) The specified clear aperture of 120 mm diameter for the fast steering mirror (see Section 2.2.2) is at least sufficient to allow conjugation (when implemented) over at least a 102 arcsecond field without vignetting for a dominant turbulent layer at 3 km above the telescope.

1.1.10 Dithering

The design shall maintain the closed loop performance to specification while dithering in accordance with Science Clause 4. There shall be no shift of the pupil image relayed to the science instrument during dithering. The design concept for dithering shall be the responsibility of the optical chassis supplier. Dithering will make use of the WFS pick-off translation stages which is the responsibility of the wavefront sensor supplier. More information is given in the Baseline Wavefront Sensor WPD (AOW/SUB/RAH/6.6/03/97).

1.1.11 Wavefront Errors

The need to keep the number of optical surfaces in the science-instrumentation path to a minimum will probably place constraints on the optical performance. The wavefront specifications take into account both these design difficulties and the anticipated science needs within the projected operating period of NAOMI.

The uncorrected wavefront error introduced by the optics over the path from the Nasmyth focus to the science instrumentation port shall be ? 150 nm rms over the central 1-arcminute diameter field. The baseline AO system will usually operate with 7.35 square subapertures across the WHT pupil. Within any subaperture the on-axis common/science-path wavefront error shall be ? 30 nm rms; this high spatial frequency error will not be corrected by the AO system. The off-axis uncorrectable error over this field shall be < 50 nm rms for any subaperture within the pupil. These specifications include design, fabrication and alignment errors <u>except</u> for those introduced by the WHT optics, the deformable mirror and fast steering mirror. Note in particular that the atmospheric-turbulence fitting error is not covered by these specifications. This error is addressed in Section 2.1.4.

Within a 2-arcminute diameter field the design goal for the pupil wavefront error shall be ? 170 nm rms with a maximum of 200 nm rms. At the edge of the field (2.9-arcminute diameter) the goal shall be ? 265 nm rms with a maximum of 300 nm rms. The same exceptions given in the preceding paragraph apply.

Performance predictions over the field shall be supplied with the proposed design. The results should be presented as rms and peak-to-valley wavefront errors and in the form of spot diagrams shown relative to the Airy disc size at 2.2 µm wavelength.

Non-common path wavefront errors between the science path and the WFS should not exceed 100 nm rms. The ray trace results should show spot diagrams for representative WFS subapertures which fall within the Airy disc diameter at 0.6-µm wavelength. Note that reduction of chromatic aberrations below 0.5-µm wavelength is not critical and, as a design goal, the aberrations should not produce a spot more than 10% larger than the diffraction-limited diameter. The optical design results should indicate the variation in non-common path wavefront error over the field; these results are needed to assess the difficulty of calibrating out the errors.

Refocusing of the WFS, e.g. to remove field curvature, is acceptable for guide stars located outside of the science field.

The optical system aberrations can introduce undesirable offsets of the Hartmann spots at the WFS detector. Using nominal design data for the WFS optics, the optical chassis supplier shall determine the predicted magnitude of the spot offsets due to the common path optics and the WFS optics respectively. The offsets should be determined at least at field angles of 0.5, 1.0 and 1.4 arcminutes off axis. These results shall be used to determine an allotment for the WFS optical aberrations in accordance with Section 2.1 of the

Baseline Wavefront Sensor WPD (Document AOW/SUB/RAH/6.6/03/97). The allotment is subject to project review and approval.

1.1.12 Beamsplitters

Any proposed use of conventional beamsplitters, i.e. glass plates or cube beamsplitters, must be supported by evidence that adequate measures will be taken to minimise aberrations and significantly attenuate second surface reflections In particular the dichroic beamsplitter design should provide optimimum on-axis performance to the optical science path.with negligible degradation of off-axis performance compared to that without the beamsplitter. Thus the design approach should provide minimum non-common path errors between the IR and optical science ports, thus allowing good AO correction to be simultaneously achieved at these ports. The primary candidate for the dichroic beamsplitter design shall be a wedge-shaped dichroic . Pellicles are acceptable as beamsplitters provided measures are taken to guard against dust, damage and microphonic effects.

1.1.13 Scattered Light and Ghosting Effects

Measures shall be taken to reduce scattered light to a minimum in the science instrumentation, the calibration optics and WFS paths. Baffles should be used where appropriate and optical mounts should be black anodised or painted with non-flaking flat black paint. All optical surfaces should have a low surface roughness, preferably < 1 nm rms. The optical design should include a first order estimate of the signal/scattered light ratio at the tip/tilt sensor and WFS when operating with a visual magnitude 16 star near the galactic equator. An explanation shall be given if a scattered light analysis is not practical.

The design should follow general good optical practice in the elimination of ghosting effects and a first order estimate of the effects of ghosting within the system to be delivered should be given. This should be done in collaboration within the WFS work package.

1.1.14 Line of Sight and Access to Nasmyth Focus

A direct line of sight along the length of bench for access to the Nasmyth focus by an alignment telescope and He-Ne laser shall be provided. The space required for these components is indicated in Figure 3. If the removal of optical components or modules is required to obtain the line of sight, the component or module must be either kinematically mounted or mounted on a slide. Ease of removal and replacement without requiring realignment are essential.

1.1.15 Correction of Atmospheric Dispersion

No correction for atmospheric dispersion in the science path is required for the baseline design. The design shall not preclude the addition of a science-path atmospheric dispersion corrector (ADC) as a system upgrade. An ADC will be provided with the WFS but this component is the responsibility of the WFS supplier.

1.1.16 Beam Height

The height of the Nasmyth-focus optical axis shall be 150 mm above the mounting surface of the GHRIL optical table.

1.1.17 Mechanism Control

ING standard methods will be used for the control of all standard mechanised functions
Clause 19 requires that VxWorks should be used as the operating system for non-specialised (i.e. AO-specific) local control processors.

Engineering and operational control and status methods will conform to ING standards.

1.1.18 Health and Safety

Potential safety hazards shall be identified and measures taken to protect personnel, e.g. warning notices, covers with interlocks. Handling procedures and lifting aids, e.g. eye bolts, shall be provided for heavy items.

1.2 Space Allocation

The existing GHRIL optical table will support the optical chassis and accommodate electronics that must be mounted on or over the table. Figure 1 indicates the size and

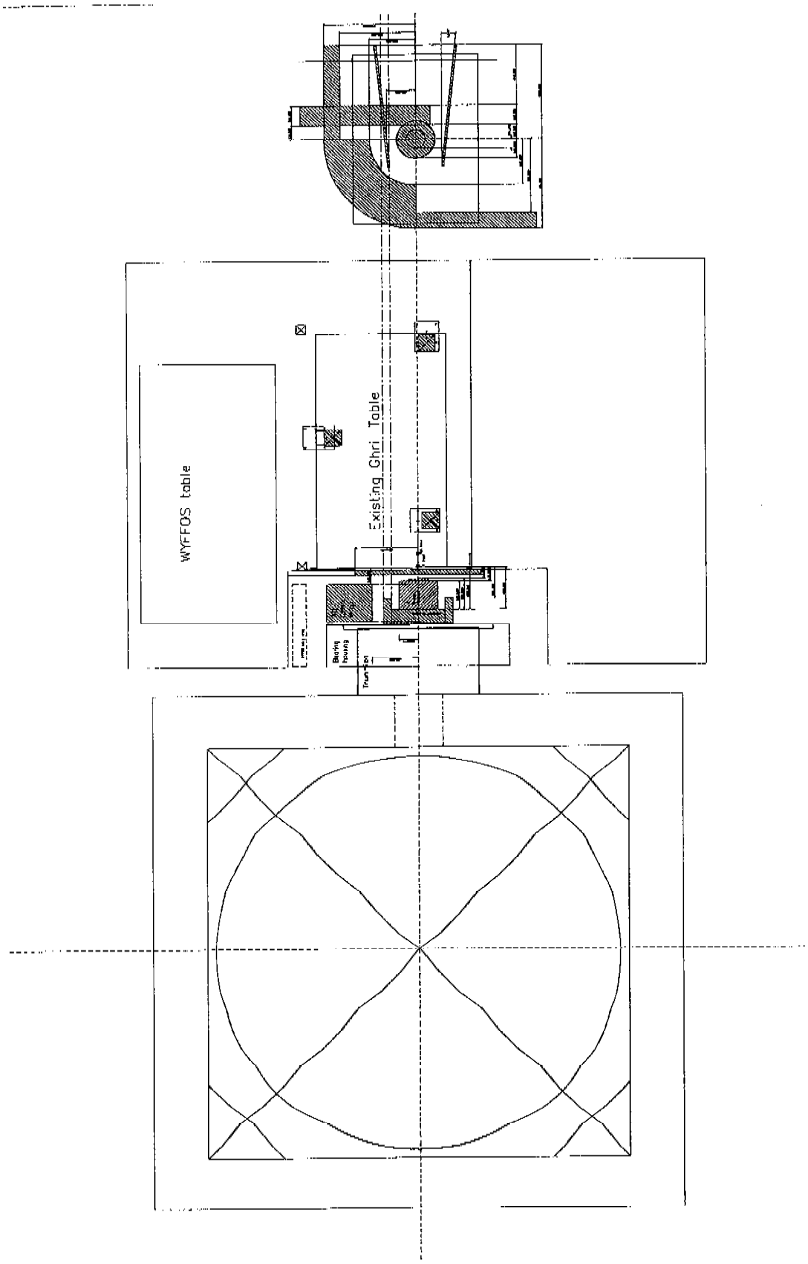

Figure 1. General layout of the GHRIL showing the existing GHRIL table and components at the front of the bench..

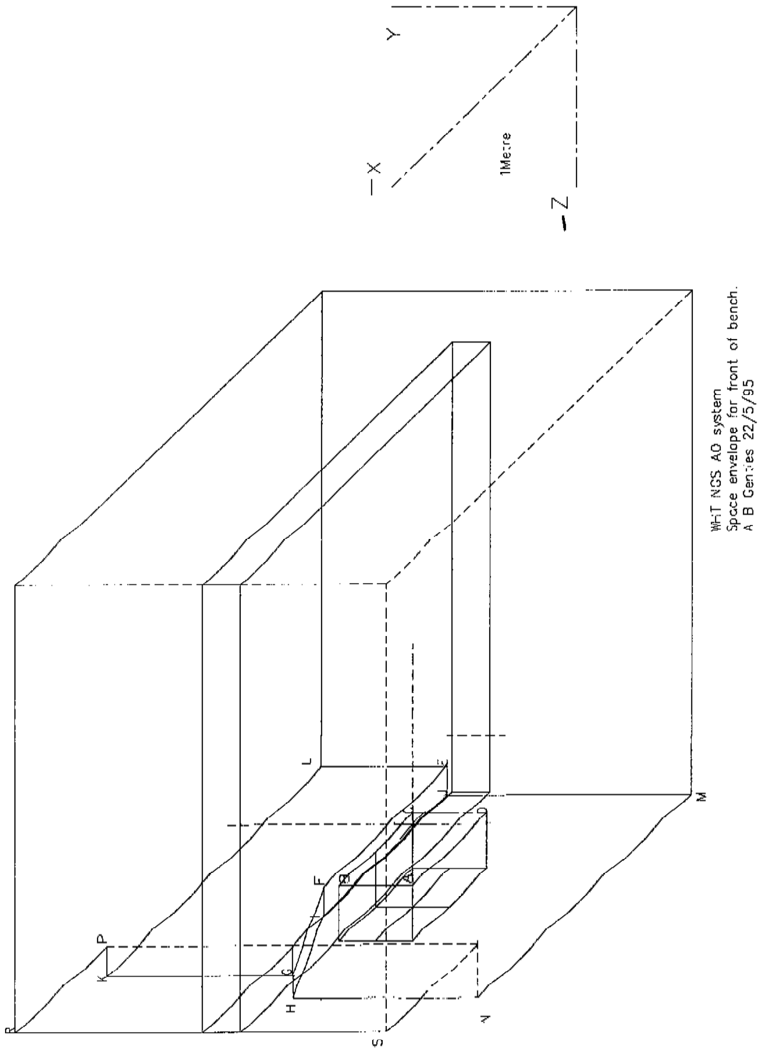

Figure 2. Space envelope for the front of the existing GHRIL table.

(View rotated clockwise by 90 degrees).

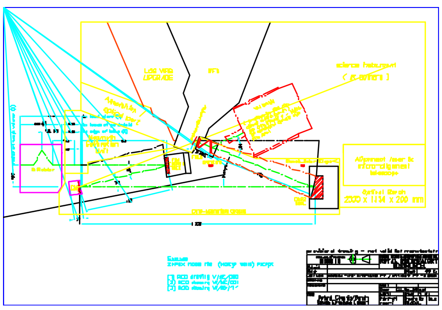

Figure 3. Allocation of space on the GHRIL table.

location of this table. Some optical components may need to be mounted beyond the front edge of the existing table where the space is limited, particularly in the region of the WHT image derotator. The project will investigate the possibility of moving the table towards the derotator although the maximum movement is expected to be only a few cm. Figure 2 shows the space envelope for the front of the bench. Sufficient space must be provided for the wavefront sensor (WFS), the upgrade to laser-guide-star operation, WHIRCAM and future instrumentation as required by Clause 7. Figure 3 shows the space allocations for the WFS, future science instrumentation and the laser-guide-star upgrade. Figure 3 is also available as an AutoCAD file from Tully Peacock at ROE and in the Drawings area of the NAOMI BSCW facility. The drawing date is 19 December 1996. Detailed dimensions are contained in this file and the file shall be treated as part of the WPD.

Although the tip/tilt sensor is planned as part of the system upgrade for laser-guide-star operation, there is a remote possibility that a tip/tilt sensor may also be required in the near term system.The WFS supplier is required to establish the feasibility of incorporating a simple tip/tilt sensor such as fibre-coupled APDs in a quad-cell configuration in the NAOMI optical train, e.g. at the optical science port. The optical-chassis supplier follow any work in this area.

Equipment should extend no more than 1 metre above the table surface. The optical-chassis supplier will be expected to work closely with the project, the suppliers of the wavefront sensor, the Real-Time Control System and the appropriate WHT staff.

1.3 Environmental Requirements

1.3.1 Overall Requirements

The overall requirements are driven by Clauses 17 and 21.

That part of the AO system installed in the GHRIL shall operate within specification over a temperature range of -10^{o}C to 25^{o}C in relative humidity from 10% to 90%. Any prediction of failure to satisfy this requirement shall be briefly documented and submitted to the AO project manager. (Note that the University of Durham intends to characterise the performance of the ELECTRA deformable mirror as a function of temperature.) An environmentally conditioned enclosure for the optical chassis will not be part of the baseline system. Note that whilecertain components, e.g. rack-mounted electronic components, may be housed in environments with temperature excursions less extreme than specified above in normal operation, the system must be able to cope with a start-up from a lengthy powered-down state within the GHRIL environment. For example the heat generated by electronic components in normal operation may keep the interior of a rack well above -10^{o}C when powered up and therefore apparently allow components specified to 0 ^{o}C to be used, but these components could fail on a cold start. Any special measures to control the temperature of components must not only comply with Clause 21 but also require project approval. The maximum free atmosphere temperature variation expected within the GHRIL is TBD ^{o}C / hour; this variation is important when designing the optical chassis to meet the requirements of Clause 5. The system shall be able to survive relative humidity of 100%. Protective measures may be employed, subject to project approval, to guard against such extreme conditions when the equipment is not operating.

All equipment must operate to specification at an altitude of 2500 m.

Equipment shall be designed to an EMC specification to be defined by consultation between the WP supplier and the ING.

The baseline optical chassis will have only covers over the modules that can be sealed for dust protection when the system is not in use. The number and shape will be chosen to fit the final layout with a goal of not more than four.

Equipment in the GHRIL control room will be cooled by recirculating chilled air through a roof-mounted heat exchanger which will be designed to handle a maximum load of 4 kW. The heat will be taken to the global GHRIL environment heat removal system. Global control of the GHRIL environment is the responsibility of ING. The optical-chassis supplier will be expected to work closely with ING and the NAOMI project in this area. All electronic heat sources not associated with motors or drivers which must be on the bench should be above or away from the bench. In accordance with Clause 21, optical-chassis thermal sources must not degrade the uncorrected local seeing by more than 0.1 arcsecond with a goal of no detectable degradation.

Equipment installed in the WHT control room must operate to specification over a temperature range of 10^{o}C to 30^{o}C.

1.3.2 Vibration and Stability

All AO components and their mounts shall exhibit good stability consistent with the optical and environmental requirements. In particular the system shall be designed such that the performance specified in Clauses 1, 2 and 3 is achieved for integrations up to 1 hour without recalibration, provided the telescope alignment and focus stability does not limit the system performance. This requirement is driven by Clause 5.

Uncorrectable tip/tilt jitter induced by vibration sources both internal and external to the GHRIL shall not exceed 30 nrad rms (0.006 arcsecond rms) in WHT object space. (Vibration data for the GHRIL are obtainable from the RGO.) Note that the 30 nrad rms includes an allotment of 17 nrad rms for the WFS on the assumption that the vibrations are independent and may be root sum squared. Uncorrectable tip/tilt jitter includes jitter beyond the response of the AO system and jitter at any frequency within the non-common-path regions between the science port and the AO components. Microphonic effects are also included in this specification.

1.3.3 Cleaning Procedures

Cleaning procedures must be developed for all optical components and successfully demonstrated on witness samples of all coatings prior to use on the AO optical system.

All such procedures must be adequately documented for use by optical technicians or engineers.

2. Common-Path Optics

The primary functions of the common path optics were specified in Section 1.1.2 above. These optics must cover a 2.9 arcminute field of view which is set by the new WHT image derotator. The common path optics are essentially a relay stage operating at a magnification of 1.5 with a collimated region to accommodate the deformable mirror and fast steering mirror. Note that the latter may be a collimating optic. Any proposal to use a relay stage operating at a different magnification requires project approval. The common path optics must provide for an upgrade to a variable conjugation capability as specified in Section 1.1.9 above. Sections 2.1 and 2.2 specifically address the deformable mirror and fast steering mirror respectively. The common-path optics must produce a pupil size of 56 mm diameter at the deformable mirror.

Note that several other specifications given above apply to the common-path optics and other sections of the optical train.

2.1 Deformable Mirror and Drivers

This section contains information primarily intended to aid the optical chassis design.

2.1.1 General Description

The deformable mirror to be used in the baseline design is the ELECTRA deformable mirror. The 76-element segmented mirror and its drivers will be supplied to the project by the University of Durham. The mirror segments are arranged in a 10 x 10 matrix with each of the 6 corner segments removed. The centre-to-centre spacing of the mirror segments is 7.62 mm. The nominal gap between the segments is 0.08 mm.

Each segment is controlled by 3 PZT actuators which provide tip, tilt and piston motion. The mirror segments are coated with aluminium.

2.1.2 *Clear Aperture and Active Area*

The specified pupil diameter of 56 mm gives an AO system with 7.35 subapertures across the pupil diameter. System modelling indicates that this configuration provides satisfactory performance. The 56-mm pupil size was chosen to accommodate an exchange with a “standard” commercially available mirror with a 7-mm actuator spacing. The ELECTRA mirror segments beyond the 56 mm pupil diameter will be used to perform turbulent layer conjugation when the system is upgraded.

2.1.3 *Actuator Stroke and Hysteresis*

The total stroke of each PZT actuator is 6 µm. Up to 2 µm of stroke is required to flatten the mirror surface, thus the available stroke after flattening is 4 µm. The mirror has built-in strain gauges to determine the actuators’ positions and provide signals to the electronics that will correct for actuator hysteresis. These electronics are the responsibility of the University of Durham. Hysteresis will be reduced to ? 0.7% with a goal of ?0.2%.

2.1.4 *Fitting-Error Coefficient* (For information purposes only)

The atmospheric-turbulence fitting-error coefficient, µ, provides a simple means of defining how well a deformable mirror can compensate a wavefront degraded by atmospheric turbulence. The coefficient is given by the following equation:

$$?^2 = \mu \, (d / r_0)^{5/3}$$

where $?^2$ = variance of the residual wavefront error

d = actuator spacing (57 cm projected at WHT pupil)

r_0 = atmospheric turbulence coherence length (³ 8 cm)

With reference to the baseline-system error budgets for Clauses 1 and 2 we have:

µ = 0.18 (representative of the ELECTRA mirror)

d = 0.57 m

r_0 = 1.05 m (20-cm visible r_0 scaled to 2.2 µm).

Substituting these values in the above equation gives $?^2$ = 0.065 rad^2 which is consistent with the error budgets.

2.1.5 *Mirror Resonant Frequency*

Preliminary measurements made by the University of Durham indicate that the first resonant frequency of the mirror segments is > 2 kHz.

2.1.6 *Settling Time*

The University of Durham expects the mirror settling time to be < 400 µs.

2.1.7 DM Incident Angle

The incident angle at the deformable mirror should be ? 10 degrees. The small incidence angle is required to keep the one-dimensional misregistration between the actuators and the WFS to within the error-budget allotment

2.1.8 Interferometer

Sufficient space shall be provided to view the DM clear aperture with a simple interferometer that would not exceed a Zygo interferometer in size. Normal incidence viewing of the mirror surface is preferred but viewing at another angle may be acceptable if justification is given. The configuration need not be confined to a horizontal plane and it may occlude the main beam. The interferometer will be used for alignment purposes only.

2.1.9 Operational Lifetime

In accordance with Clause 16 the mirror shall have an operational lifetime of > 3000 hours subject to one actuator failure and replacement.

2.1.10 Mirror Removal

The deformable mirror and its electronics shall be supplied with its own carrying and transport case (see Clause 23). It shall be possible to remove and re-install the DM safely, including its electronics, in less than one hour and without dismantling the rest of the NAOMI system. Only minor further optical alignment should be required after re-installation, i.e. by using the remotely controlled x-y stage described in the next section.

2.1.11 X-Y Stage

The deformable mirror shall be mounted on a motorised stage with sufficient travel along horizontal and vertical axes parallel to the mirror surface to accommodate initial alignment to the WHT pupil image and provide fine adjustment to the WFS lenslet array. The range requirement for the former, i.e. initial alignment to the WHT pupil image, shall be determined as part of the development of the Interface Control Documentation to be provided by ROE. The range requirement for the latter shall be determined by analysis and discussions with the WFS WP supplier. The stage axes shall be position encoded and repeatable to an accuracy of ? 0.1 mm.

2.2 Fast Steering Mirror

2.2.1 General Requirements

The WFS (or a tip/tilt sensor in a future upgrade) will provide information on overall (or common mode) tilt. This is the tilt present over the entire WHT pupil and it will be corrected by the fast steering mirror and to a limited extent by the TCS. There are four sources of tip/tilt error as listed below.

1. Atmospheric turbulence
2. Pointing jitter of the WHT
3. Component vibrations
4. WHT long-term pointing drift

The FSM will use the WFS tip/tilt data to primarily correct for the first three sources. The tip/tilt mirror significantly reduces the stroke requirements that would otherwise be placed on the deformable mirror. DC and large low-frequency tip/tilt errors will be passed on to the TCS to avoid an excessive range requirement for the FSM.

The FSM and its associated drive circuits should be based on existing technology that has been demonstrated to provide high reliability. The FSM may perform two optical functions, e.g. it may provide tip/tilt correction and also serve as a collimating optic. This dual function approach has the advantage of reducing emissivity and increasing transmission. Analysis is required to demonstrate that a dual-function mirror has no adverse effect on system performance.

2.2.2 Clear Aperture

Cost considerations and the availability of suitable existing mirrors require that the mirror clear aperture be limited to 120 mm diameter. Note that this diameter is at least sufficient to allow conjugation over a 102-arcsecond field without vignetting for a dominant turbulent layer at 3 km above the telescope. Note also that turbulent-conjugation will not be implemented in the baseline design.

2.2.3 Tip/Tilt Range

The mirror surface shall cover an angular range of ? 500 ?rad over two orthogonal axes with a design goal of 1 mrad. A smaller range is acceptable at frequencies above 20 Hz as specified in Section 2.2.4 below.

Provision shall be made to protect the FSM from being driven to the limits of its operational range, e.g. as the result of excessive WHT pointing drift. When the FSM has reached a critical point in its range, a signal shall be sent to the telescope control system to remove the undesired offset. Determination of the critical point will depend on the rate of drift and the response of the telescope control system. The WFS and FSM must maintain a stable loop closure during this mode. As mentioned in Section 2.2.1 above, DC offsets will also be offloaded to the TCS.

2.2.4 Frequency Response and Related Characteristics

Note that all angular specifications in this section refer to the angle of the mirror surface and apply to both axes.

Full stroke response:	0 to 20 Hz
Tilt range given by:	A lower bound for the total tilt range in both axes over 20 – 250 Hz is given by R= ?0.41 log(frequency) + 1.033 where R is in milliradians, frequency in Hertz.
Resolution:	? 1.5 ?rad
Static (open loop) jitter:	? 1 ?rad rms
Repeatability:	? 4 ?rad
Reactionless to:	250 Hz (Goal: the supplier should indicate what is realistically achievable).
Resonance:	> 250 Hz (>500 Hz goal)
Linearity error:	<1%
Pivot stability:	Better than ? 0.05mm

2.2.5 Optical Coating

The mirror surface shall be provided with a durable coating providing ? 95 percent reflectance (goal) in the 0.4 µm to 0.5 µm spectral region and ? 97 percent reflectance from 0.5 µm to 0.8 µm. Beyond this region the reflectance shall ? 98 percent to ? 4 µm.

2.2.6 Surface Quality and Accuracy

Within the specified clear aperture the cosmetic surface quality shall be 5/3 x 0.40; K2 x 0.06 in accordance with DIN 3140 and the surface shall be plane (or parabolic) to within 25 nm rms. Within any 1-cm diameter area inside the clear aperture the surface shall be plane (or parabolic) to < 10 nm rms. The surface roughness shall be ? 1 nm rms.

2.2.7 Mirror Orientation

As a design goal the mirror shall operate to specification in any orientation. The intent is to allow for possible future use in other AO systems, e.g. with a Cassegrain mount.

2.2.8 Mounting

The mirror assembly shall have a flat surface with three threaded holes for mounting purposes. Drawings shall be supplied in the design stage to indicate the mounting configuration.

2.2.9 Mirror Cover

A mirror cover shall be provided to protect the mirror surface when not in use.

2.2.10 Operational Lifetime

In accordance with Clause 16, the mirror should have an operational lifetime > 10,000 hours. It is appreciated that a supplier is unlikely to give a firm guarantee of the operational lifetime, but some assurance of the durability of the unit should be given and the design should allow for rapid and reasonably priced repair.

3. Science Path

Clause 7 requires that the science field of view shall be sufficient to illuminate all of a 1024 x 1024 imaging array fully sampled at the 1.65 micron diffraction limit with no vignetting. The instrument with this detector array size is the new infrared camera (INGRID) that has been under development at RGO.At the time of writing the goal is that INGRID should be completed at RGO.
Clause 16 further requires that the system shall have a well-defined and accessible science port around which other instruments such as spectrographs and a coronograph can be designed.

A single dichroic beamsplitter should be provided to reflect radiation to INGRID. Any adjustments required for the dichroic beamsplitter shall be manually controlled. The optical design shall provide sufficient space to allow the installation of a remotely-controlled assembly with 3 dichroic beamsplitters as part of the system upgrade.

The system science path without turbulence effects should provide a diffraction-limited PSF at 1.2 µm (J - band) over a minimum field diameter of 1 arcminute.

The plate scale should be 335±15 µm/arcsecond (Clause 9).

The image of the telescope pupil should be a distance of 1100 mm beyond the focus with a diameter of 66.7 mm. (These dimensions are subject to change. Any change requires project approval.)

The optical layout should provide for future science instruments a space envelope as shown in Figure 3.

4. WFS and Tip/tilt sensor Optical Paths

The design concept for the WFS and future tip/tilt sensor optical pick-offs is the responsibility of the optical-chassis supplier. Note that the tip/tilt sensor and its pick-off will not be constructed as part of the baseline design. Note that, as mentioned in Section 1.1.3, the approach of using the the baseline WFS as a tip/tilt sensor and constructing a new WFS for the laser-guide-star upgrade is considered acceptable by the project. Sufficient space must be left to add the tip/tilt sensor and its pick-off as a system upgrade. Detailed design and implementation of the WFS pick-off is the responsibility of the WFS supplier.

The pick-offs for the WFS and a tip/tilt sensor should be located at or near the corrected focal plane of the common-path optics. The pick-off approach should be such that its aberrations are independent of the field position. The tip/tilt sensor pick-off should be located before the WFS pick-off to allow the latter to be refocused when operating with laser guide stars. The pick-offs will direct f/16.8 beams from the selected guide stars to the WFS and tip/tilt sensor respectively. Note that the f/16.8 beam assumes that the common-path relay optics operate at a magnification of 1.5. Any proposed departure from this magnification must be justified as it affects the interfaces with other components.

The pick-off optics and their supporting stages will be the responsibility of the WFS supplier. The optical-chassis supplier will however be expected to follow the design of these optics and the mechanical components to ensure a correct interface with the optical chassis. Note that the WFS module must register against a reference on the adjacent optical-chassis module with a registration repeatability of < 50 µm in all three axes. The design of this interface should be the result of collaboration between the optical-chassis and WFS suppliers. The optical requirements for the pick-offs given in this section are provided mainly for information purposes.

Mapping of the DM image at the WFS lenslet array must be maintained over the full field. A field lens should be used to image the deformable mirror at infinity. Provision of this field lens and its mount is the responsibility of the optical-chassis supplier. The separation between the field lens and the AO-corrected focus shall be chosen initially to optimise performance. Sufficient separation must be provided between the last element in the OMC optical train and the AO-corrected focus to accommodate the WFS pickoff. A non-optimal separation may be used only if there is a significant advantage, e.g.extra space, with negligible performance loss.

Any obscuration of the optical science port by the pick-offs shall be kept to a minimum but the IR science must not be compromised (Clause 10). An obscuration of < 4 x 4 arcseconds is a design goal. There shall also be provision to insert a calibration source for the WFS (see Baseline Sensor WPD, Document AOW/SUB/RAH/6.6/03/97); this source is the responsibility of the WFS supplier. The optical-chassis supplier must work with the WFS supplier to determine the interface requirements.

5. Optical Science Port

In accordance with Clause 10, the region of the field not used by the WFS sensor pick-off shall be made available for use as an optical acquisition field and possibly by optical science instrumentation provided this does not in any way compromise infrared science. Note that the AO system is not designed to provide a high degree of correction at wavelengths below 0.8 µm.

In accordance with Clause 9, the throughput to the optical science port shall be > 58% averaged over the 0.5 µm to 0.8 µm spectral band; the transmission of the WHT optics is not included in this specification. The f-number of the beam to this port shall be f/16.8.

An acquisition camera will be provided at the optical science port. At the time of writing the ING is investigating the possibility of obtaining a high-performance acquisition camera. Further information will be provided when available.

In the event that the high performance camera is unavailable, a low cost CCD video camera will be used. The camera will have a nominal pixel scale of 0.45 arcsecond/pixel. The video camera should be able to detect stars with V?8. The choice of camera will be driven by cost and availability. It will cover the full 2.9 arcminute field in at least one axis.

As part of a system upgrade, the low-cost video camera(if used) may be replaced by a copy of the Gemini acquisition and HRWFS camera, most probably using the 1024 x 1024 pixel EEV47 CCD. This camera will operate with a smaller pixel scale (0.17 arcsecond/pixel), view fainter stars (V>26) and allow detailed inspection of a limited area (?256 x 256 pixels) at ?10 frames/second

The space envelope shown in Figure 3 is available for use by the acquisition camera.

6. Alignment and Calibration

6.1 General Requirements

The design approach to the alignment and calibration functions shall satisfy the applicable sections of Clauses 6 and 13. In summary Clause 6 requires that the astronomer shall be able to spend at least 50% of the night integrating on science targets or astronomical standards. Once installed and aligned the system shall require no more than 30 minutes to optimise/confirm the alignment in any 24 hour period. Clause 13 requires that the on-island staff shall be able to install and align the equipment within 8 hours using no more than two people. Furthermore it should be possible to carry out pre-use alignment, calibration and testing off the telescope. A suitable off-telescope mounting base shall be supplied with NAOMI. Requirements for various alignment and calibration optics are given in Sections 6.2 to 6.4. Note also the requirement for a line of sight to the Nasmyth focus as specified previously in Section 1.1.14.

6.2 Nasmyth Calibration Unit

6.2.1 Overview

The Nasmyth calibration unit shall be designed as a module to be mounted on the edge of the GHRIL table close to the Nasmyth focus. The general requirements are to provide:

1. an on-axis diffraction-limited (in visible region over full aperture) point source
2 a fast low-amplitude tip/tilt motion of the above source
3. an on-axis non-diffraction-limited source (approximately 1 arcsecond)
4. a diffraction-limited (at K band) point source close (2 -3 arcsec) to the axis for science instrument use
5. an upgrade capability for a 40-arcsecond diameter flat-field source for IR and optical science instrument calibration
6. an on-axis f/11 laser beam for initial alignment
7. a laser pencil beam if readily implemented
8 a WHT pupil simulator using a mask
9. a feed for a pre-correction camera
10. an array of off-axis sources for mapping the AO optical system distortion and wavefront aberrations over the field of view
11. a means of generating a known static aberration
12. an upgrade capability for the future installation of a turbulence generator for use during laboratory tests
13. neutral density and spectral filters for controlling the intensity and colour of all broad band sources listed above.

All of these sources will effectively propagate from the Nasmyth focus. Further information on the characteristics and function of these sources is given below.

6.2.2 On-Axis Sources

Provision shall be made to insert remotely a point source on axis at the f/11 Nasmyth focus. The source shall be sized to appear as a diffraction-limited point source in the visible region when the entire f/11 beam is observed. Four other sources, namely a non-diffraction-limited source, a source which is diffraction limited at K band, an extended white-light source and a He-Ne laser, will be used less frequently and these are specified later in this section. The point source will perform several functions:

a. Provide radiation over at least the 0.5µm to 2.5µm spectral region for use by the WFS, the acquisition camera and science instrumentation, e.g. to boresight these components; to calibrate the common-path and non-common-path wavefront errors.

b. Simulate the WHT exit pupil, e.g. as an alignment aid for determining the deformable mirror position and for minimising the difference between laboratory calibrations and sky.
c. Introduce small (variable to 2.6 arcsecond, frequency 0.1 Hz to 150 Hz) motions of the source for functional checks of the AO control system.
d. Uniformly illuminate the f/11 beam so that when a pupil of the system is imaged on to the WFS detector each pixel receives the same signal. This requirement follows from the need to flat-field the WFS detector.(Note that the WFS supplier is required to provide a separate flat-field source that bypasses the intervening optics.)

A design using reflecting optical components is expected. Provision shall be made to replace the source with a sodium lamp emitting at 589 nm for possible future operation with a sodium-layer laser guide star. Note that there is no requirement for a detailed design or procurement of the sodium source.

The point source shall have a uniform radiant intensity over the f/11 beam equal or exceeding the values shown in Table 2 below. The maximum radiant intensity shall not exceed the specified minimum values by more than a factor of 5. The spectral distribution (integrated over each spectral band) shall match that of a star in the spectral class range G0 to K0 weighted by the zenith atmospheric transmittance and the WHT transmission to the Nasmyth focus.

Table 2. Point Source Spectral Characteristics

Spectral Band (µm)	Radiant Intensity (W $ster^{-1}$)
0.5 to 1.0	1.6×10^{-8}
1.0 to 1.5	4.0×10^{-9}
1.5 to 2.0	9.0×10^{-10}
2.0 to 2.5	2.5×10^{-10}

Filter holders are required to hold up to three spectral and three neutral density filters (TBD) to simulate different stellar types and magnitudes. These filters will be used with all broad band sources in the calibration unit. The optical-chassis supplier may advise the project on the choice of these filters. Procurement of the filters is subject to project approval. The decision to change the filters either manually or remotely will be based on a review of the operational scenarios to be undertaken by the project; the optical-chassis supplier is expected to participate in this review. Note that there should be no focus shift when changing from visible to IR operation. A larger source which appears diffraction limited at K band shall be located 2 to 3 arcseconds away from the on-axis point source; this source is intended for use with the IR science instrumentation. The IR irradiance at the source shall be the same as for the on-axis source.There shall also be provision to replace the on-axis point source with a larger source to simulate the time-averaged size of turbulence-degraded spots for calibration of the WFS under strong turbulence conditions. A nominal diameter of 1 arcsecond in object space is considered acceptable for this purpose.

Provision shall be made for an upgrade to an extended broad-band source for flat-fielding IR and optical science instrumentation. This source may be a modified version of the point source if desired, e.g. an integrating sphere with different exit apertures that may be changed manually. The relative spectral distribution specifications are the same as for the point source. The specified minimum radiance is given in Table 3; these values shall not be exceeded by more than a factor of 5. The illuminated area at the Nasmyth focus shall be at least nominally10 mm diameter (40 arcsecond)with a uniformity < 0.5%. The project shall be notified if the size of this area presents serious design difficulties. The use of this source will be infrequent, i.e. for the initial checkout of some science instruments and as an auxiliary source for WFS calibration.

Table 3. Uniform Source Spectral Characteristics

Spectral Band (µm)	Radiance (W $ster^{-1}$ cm^{-2})
0.5 to 1.0	1.6×10^{-3}
1.0 to 1.5	5.8×10^{-4}
1.5 to 2.0	1.6×10^{-4}
2.0 to 2.5	1.9×10^{-4}

In addition to the broad-band sources there shall also be an on-axis He-Ne laser to be used for the initial system alignment. The laser beam may be inserted manually. The laser should provide a monochromatic (0.633 µm wavelength) point source at the Nasmyth focus with an f/11 output cone. Its brightness shall be such that the laser beam is clearly visible on a white card anywhere within the optical train with the GHRIL room lights turned off. If easily implemented, e.g. by manual removal of a component, a pencil laser beam should also be provided.

It is desirable that the calibration unit should provide as an upgrade a wavelength calibration capability for an IR spectrometer with a slit length of at least 10 arcseconds. An indication of a plug-in concept shall be given. The project should be informed if this is not feasible. The effort should not be allowed to be a cost driver.

Further specifications relating to calibration operations at the Nasmyth focus are given in Sections 6.2.4 to 6.2.6 below.

6.2.3 WHT Pupil Simulator

The optical system associated with the on-axis point source specified shall have a location conjugate to the WHT exit pupil which has a diameter of 1.17 m at a distance of 12.84 m from the Nasmyth focus. As a design goal, a slot shall be provided for the manual insertion of a mask simulating the WHT pupil at this location. As a minimum requirement a simple mask may be used only on axis and in this mode it need not be located at a pupil image. The mask must simulate the central obscuration of the WHT. The choice of a mask location other than at a pupil image is subject to project approval. Analysis shall be performed to determine the required uniformity of the pupil illumination.

6.2.4 Provision for Pre-correction Camera

Space shall be left for a camera to view the Nasmyth focus, preferably using the same optic that inserts the light from the calibration source. The OMC design shall include the design of a mount for this camera and take into account the cabling requirements. A Cohu Model 6400 camera is the preferred candidate (see http:/www.cohu.com/cctv/4800.htm); if sufficient funds are not available an inexpensive video camera may be used. The selected camera will be project furnished with the choice subject to project approval.

6.2.5 Distortion Calibration and Aberration Measurement

Provision shall be made to map the AO optical-system distortion and wavefront aberration over the full field of view. The former information is required for astrometry purposes. To perform these operations the preferred implementation is a mask with an array of point sources, i.e.illuminated pinholes, which can be manually inserted at the Nasmyth focus.(The project anticipates that these operations will be infrequent and therefore manual insertion is acceptable.) The radiant intensity of each point source shall be as specified in Table 2. The optical chassis supplier shall determine the optimum illumination scheme and the size(s) of the pinholes. The number of calibration points within the field should be determined as part of the optical design process but it should not be less than 7 across the field.The position of each point source relative to the central point source shall be known to an accuracy better than ?2 µm (0.01 arcsecond in object space). The repeatability of the mask position using manual insertion shall be better than ? 25 µm in the x and y axes.

The z-axis (focus) repeatability shall be better than ? 50 µm. An additional source, which is diffraction limited at K band over the full aperture, shall be located 2 to 3 arcsecond from the axis for use with the IR science instrumentation.

6.2.6 Aberration Generation

The on-axis point source design shall include a technique for introducing a known amount of low-order aberration, e.g. coma, astigmatism. Sufficient aberration shall be introduced to fully exercise the DM and WFS. The aberration generator may be inserted manually. If necessary, the aberration generator may be positioned in the collimated beam before the deformable mirror. A suggested approach is to use pairs of lenses with zero overall power that can be tilted to introduce aberration. The aberration could be calibrated using an interferometer. The technique should be clearly defined and costed prior to submission for the project for evaluation. Implementation of the approach will be subject to project approval and the availability of funds.

6.2.7 Simulation of Atmospheric Turbulence

Provision shall be made for the future installation of an atmospheric-turbulence simulator during laboratory testing. The turbulence simulator should be based on an inexpensive design used by Durham University. The simulator would be manually inserted just beyond the Nasmyth focus, possibly in place of the He-Ne laser although the optimum location should be determined as part of the design process. Further information may be obtained from Dr. Richard Myers at Durham University.

6.3 Wavefront-Sensor Calibration Source

This source is the responsibility of the WFS supplier and the following paragraph is provided primarily for information and space-allocation purposes.

Provision shall be made to inject a reference plane wavefront from a light source for the WFS phase-gradient calibration. The wavefront shall be produced by inserting the light from the source at a point close to the AO-corrected f/16.8 focus but before the WFS collimating lens. Light from this source will pass through the WFS collimating lens to produce a plane wavefront. The tilt of this plane wavefront shall be remotely and independently variable in the x and y axes over the maximum operational phase gradient range of the wavefront sensor. This function may be provided by the WFS pick-off stage. Further information on the WFS calibration is provided in the Baseline Wavefront Sensor WPD (AOW/SUB/RAH/6.6/03/97).

6.4 Calibration of Non-Common Path wavefront Errors

Provision shall be made for the calibration of non-common path errors between the science path and the WFS path. The optical chassis supplier is expected to devise an approach which will be subject to approval by the project. It is expected that the wavefront error will need to be measured at several points across the field to generate a catalogue of look-up tables for use in the wavefront reconstruction. The number of points selected will depend on the magnitude and rate of change of the non-common path aberrations over the field.

7. Additional Support and Interface Requirements

This section covers support and interface requirements not addressed above.

The document AOW/SYS/RMM/6.0/01/97/NAOMI Electronics and software interfaces is a preliminary guide to the system interface requirements.

Documentation shall be supplied in accordance with Clause 14.

Where appropriate, the same type of electronic components should be used as are already in use at the ING. Where other components are used a minimum of one spare for each type shall be supplied in accordance with Clause 19.

As required by Clause 20, NAOMI software shall be written to standards agreed with the ING. A draft software standards document has been prepared by Paul Rees. See the latest version for guidance.

In accordance with Clause 11, any NAOMI interface to the telescope or any instrument control system shall be via DRAMA and shall conform to ING networking standards.

Any limitations on cable lengths that may severely restrict the location of components on or around the GHRIL table should be reported to the project.

8. Error Budgets

Figures 4 and 5 show the system error budgets for Clauses 1 and 2 respectively. For consistency all errors have been expressed as phase variances in radian^2 at a wavelength of 2.2 µm. In parts of some work packages the errors have been converted to units that are more appropriate and easier to interpret. The error budgets are similar to those shown and discussed in earlier documents except that the ELECTRA DM's smaller fitting error and the effect of the larger subaperture size (57 x 57 cm^2) have been taken into account.

STREHL RATIO = 0.75 (• 0.65 Required)

(Wavefront-Error Variances in radian^2)

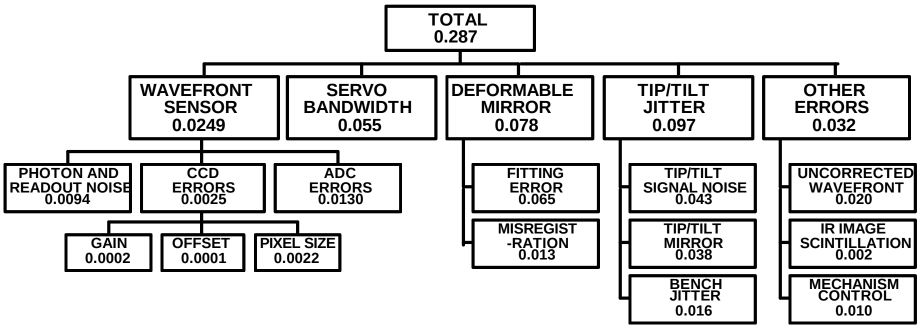

Figure 4. Clause 1 error budget.

Figure 4 shows the Clause 1 error budget. With the change from a continuous facesheet DM to the segmented ELECTRA DM, fitting error is no longer the dominant effect (see Section 2.1.4 above). Because the light level is high, i.e. magnitude 8 star, the wavefront sensor errors are small. The budget assumes that the wavefront sensor CCD has been calibrated to specification and the pixel size errors do not exceed 1 µm rms. A conventional centroiding algorithm was used in determining the budget for the CCD errors. The tip/tilt jitter includes an allowance of 30 nrad (0.006 arcsec) rms for jitter on the optical bench induced by telescope motion and moving bench components; this jitter is in addition to the 70-nrad (0.015 arcsec) rms residual jitter from the WFS-FSM subsystem. The "misregistration" box refers to errors associated with the incorrect mapping of the mirror actuators at the wavefront-sensor lenslet array, e.g. due to a non-zero incident angle at the deformable mirror. The optical design is such that the deformable mirror is imaged at the lenslet array. The allowance for the uncorrected wavefront error includes only those errors specified for the AO system. The contribution from the WHT optics was not known at the time of writing but this information is being sought.

The error budget in Figure 4 gives a Strehl ratio of 0.75 which is comfortably above the specified value of 0.65 for Clause 1.

The ability to satisfy Clause 2 requires that the system operate with faint stars, e.g. visual magnitude of at least 15 or 16. The error budget shown in Figure 5 is for an

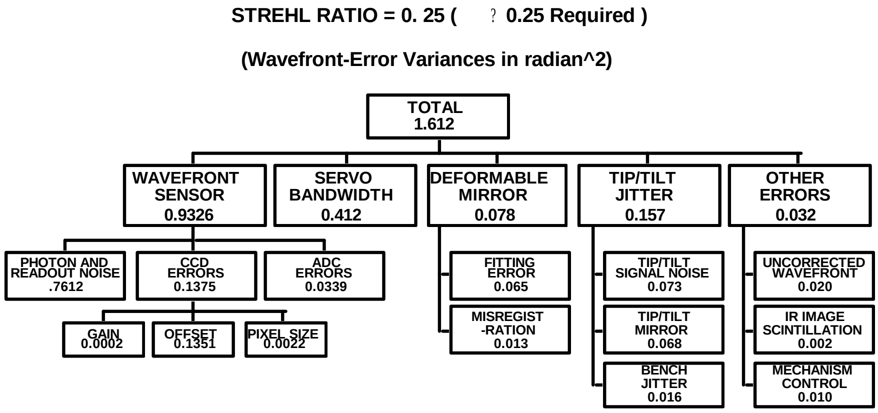

Figure 5. Clause 2 error budget.

on-axis visual magnitude 16 guide star; operation with a dichroic beamsplitter that allows the WFS to be used over its maximum spectral bandwidth was assumed. Section 5.4.2 of the NAOMI technical description document (AOW/GEN/AJL/7.0/07/96) presents the expected number of detected photons for various spectral classes of 16th magnitude stars; several classes exceed the error-budget number. An integration time close to the assumed atmospheric time constant was used. In accordance with Clause 2, the time constant assumed atmospheric conditions equivalent to a single turbulent layer moving at 10 m/sec at 3 km above the telescope. The error budget assumed that two benefits of the long integration time were a slower CCD readout rate and reduced readout noise. Specifications on readout rates and noise are covered in Section 3.0 of the Baseline Wavefront Sensor WPD (AOW/SUB/RAH/6.6/03/97). The Clause 2 error budget takes into account the increase in sources of error such as photon noise expected at these low light levels. Note that this version of the error budget takes into account a small increase in readout noise predicted by the WFS WP supplier.

Note that several simplifying assumptions were made in deriving the error budgets and there are some small sources of error that have been omitted. However, preliminary propagation code results appear to support the overall performance predictions of the error-budget analyses.

9. Reviews and procedures

The work package will be subject to Preliminary Design and Critical Design Reviews. The document AOW/MAN/AJL/8.0/07/96 CoDR, PDR and CDR Definitions gives some guidelines as to what levels of design, modelling and costing are expected at each of these stages. It also gives guidelines on the preparation of procedures, e.g. for alignment and calibration, and the level of detail required.

Further PDR and CDR information is given in AOW/OCH/AJL/1.1/01/97 /Optical Chassis PDR Requirements and AOW/OCH/AJL/2.0/01/97/Optical Chassis CDR Requirements respectively. In addition to the PDR and CDR, the optical chassis supplier will also be expected to participate in the System Design Reviews. These are also covered in the document AOW/MAN/AJL/8.0/07/96. The first System Design Review is addressed in AOW/SYS/AJL/6.0/01/97/1st Design Review Requirements.

10. Deliverable items

In addition to the optical chassis and all associated hardware, other deliverables include software and licenses, review documents, test procedures and reports, reports on analyses and simulations, user manuals, and test equipment paid for by the programme. Also see Section 25 of the NAOMI technical description document (AOW/GEN/AJL/7.0/07/96) for further information.

The final delivery location is the WHT, La Palma. Intermediate delivery to the location for system integration (University of Durham) is also required.