TECHNICAL DESCRIPTION OF NAOMI **wht-naomi-67**

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CONTENTS

1. Introduction

This document provides a technical summary of the NAOMI system designed to meet the requirements described in the document *Top Level Scientific and Operational Requirements for NAOMI*. As each major technical feature or specification is introduced the table format illustrated below is used to describe the following connections:

?? connections back to the document *Top Level Scientific and Operational Requirements for NAOMI*, in particular to the driving scientific, instrumentation interface or operational clause which requires the particular technical feature or specification,

?? connections to work package specification documents carrying more detailed technical descriptions of the particular feature or amplifications of the specification,

?? connections to figures or external documents presenting performance modelling which illustrates the relationship between the driving requirement and the technical specification.

	Reference	**Comment**
Driving Science Requirement	Clause *X*	
Detailed Specification	*Y* work package description	
Performance Modelling	Figure *Z*	example showing effect of *Y* on *X*

Upgrade routes available for extending the baseline NAOMI specifications are indicated in the same format as this paragraph. The maintenance of this upgrade potential is to be regarded as part of the baseline NAOMI specification and subject to the same change control.

This document continues with a brief qualitative overview of the overall system concept and purpose and of the remaining sections of this document and then proceeds to a description of the system's key features and components and their respective functions.

2. System Overview

This section provides a brief qualitative overview of the NAOMI system and of the contents of the remaining sections of this document.

2.1 Purpose and Scope of NAOMI

NAOMI is an Adaptive Optics (AO) system to be deployed at the GHRIL (Nasmyth) focus of the William Herschel Telescope (WHT). The acronym NAOMI stands for Natural guide star AO system for Multiple-Purpose Instrumentation. Its purpose is the amelioration of the effects of atmospheric turbulence on GHRIL image quality.

The principle subsystems of NAOMI are illustrated schematically in Figure 1. NAOMI will be a *feed-through* facility providing improved image quality to near-IR imagers and spectrographs deployed at GHRIL. It will also provide partially-corrected light to instruments at a separate optical science port.

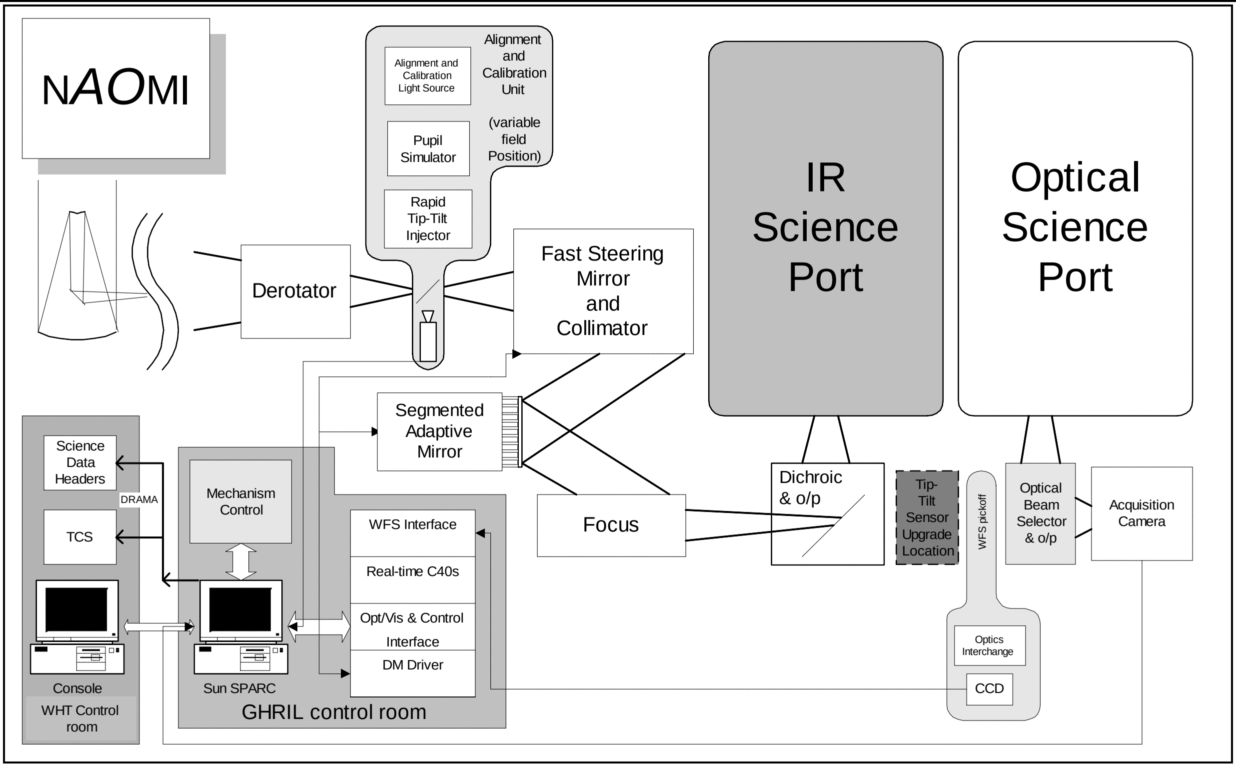


Figure 1: A NAOMI system block diagram.

NAOMI will use natural reference stars rather than a laser-beacon for measurement of the instantaneous turbulence-distorted wavefronts. Guide stars of a certain brightness are required in order to provide a given level of compensation and because this compensation is only effective over a limited angular patch, the sky coverage will be constrained. Using low-noise, high quantum-efficiency wavefront sensing and an accurate compensation element, it will be possible, however, to attain the performances outlined in the attached modelling predictions.

A significant part of the project plan for NAOMI is based on the Durham University *ELECTRA* AO development programme. This will yield early characterisation and testing of key adaptive subsytems: principally the segmented ELECTRA deformable mirror itself . The ELECTRA wavefront sensing and computer systems will also be closely-related to the final NAOMI systems. It will also yield significant components of the real-time, optimisation, visualization and GUI *software*.

NAOMI may be upgraded in the following ways:

?? A full implementation of turbulence conjugation: a method of extending the sky coverage available with natural reference stars (and also of controlling the field-dependence of the adaptively-compensated point spread function).

?? Complete integration into the observatory software and control systems.

?? Full laser-beacon compatibility.

2.2 Adaptive Control System

The ELECTRA mirror is a *linearised, segmented* adaptive mirror and will be used with a Shack-Hartmann wavefront sensor. The segmented mirror technology gives an important gain in fitting error at J and H wavebands when compared to a continuous facesheet deformable mirror. This is particularly important for the WHT which can be most competitive at these wavelengths. The linearisation will also give improved closed loop bandwidth for a given sampling frequency when compared to a deformable mirror with hysteresis.

2.3 Optical Layout, Science Ports and Modularity

The optical layout is illustrated in Figure 2. It enables a modular build of the opto-mechanical chassis, which in turn allows the operational specifications of removal from GHRIL and testing at a different location to be met. Infrared and optical science port space envelopes are located in outer areas of the layout so that constraints on future AO instrument design are minimized.

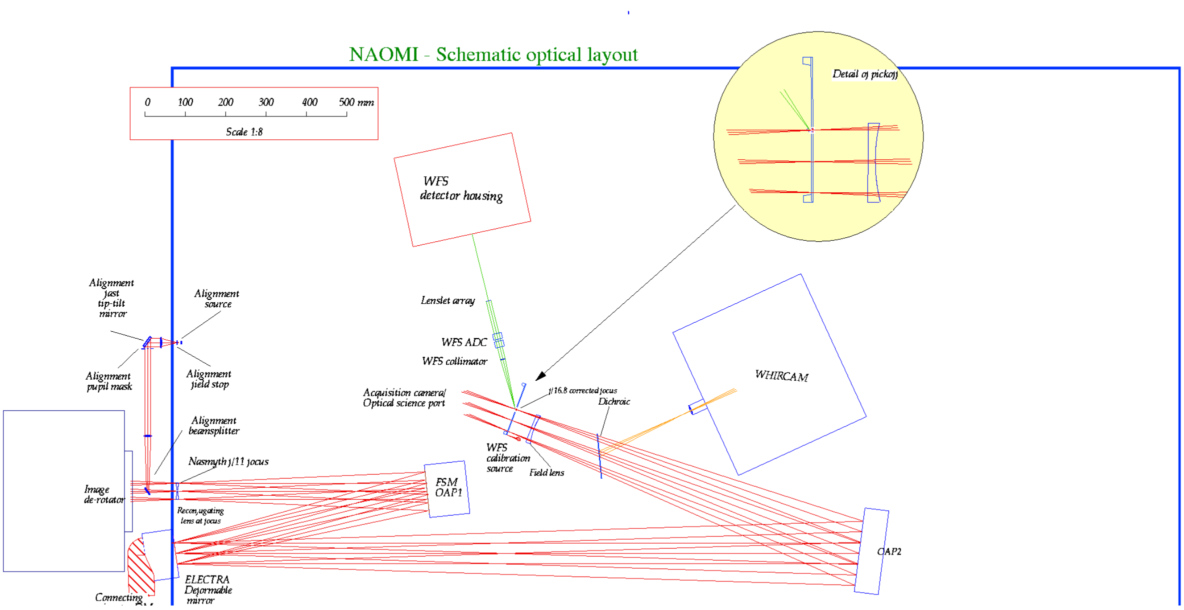


Figure 2: A schematic illustration of the optical layout for NAOMI.

2.4 IR and Optical Throughput

IR throughput is driven by emissivity minimization requirements and will be > 65% to the instrument window, including the telescope. Emissivity due to NAOMI optics alone will be < 20%. Optical throughput depends on the observing mode and is driven by the wavefront sensor (WFS) sensitivity requirement which in turn is driven by the sky coverage requirements. Typically optical throughput to the WFS CCD is 25%.

2.5 Real Time Control System and Visualization

The RTCS is based on a Texas Instrument TMS320C40 ('C40') Digital Signal Processor (DSP) system which is paralellised and expandable. The baseline configuration will be the minimum one which allows the system latency specifications to be met. Visualization tools and hardware will be such that the eye can recognize and follow the detected wavefront shape and the system response using both recorded and averaged live data. The diagnostics and displays will allow the current system performance to be understood so that it can be optimized.

2.6 Observational Capabilities

Observational procedures have been devised which allow calibration and observation of observations using infrared imaging and spectroscopic instruments. It will be possible to acquire bright and faint sources, the latter requiring very accurate absolute positions or offset positions from a bright star. Automation of some desirable procedures, particularly target acquisition and calibration requiring automatic feedback of image information from the instrument, will not be possible in the baseline implementation.

2.7 Telescope, Instrument and User Interfaces

Interfaces will support key functionality such as jitter mode, tip-tilt off-loading (these terms are defined in the document) and will provide necessary data file header information. The User Interface will allow user-friendly operation of NAOMI itself but will not be optimized for simultaneous control of telescope, NAOMI and instrument. It will be a minimal development of ELECTRA's GUI.

2.8 Software Standards.

These will conform with ING requirements. Starlink standards are the guideline, with DRAMA and EPICS adopted for messaging and mechanism control respectively.

2.9 Other Topics

Documentation, maintenance, half-arcsecond programme and JOSE are covered briefly.

2.9.1 Assumptions about the Telescope

System models currently assume that imperfections in the telescope alignment can be taken out by the DM. However it is advisable to use as little as possible of the DM stroke in so doing. Therefore the accuracy and stability of telescope alignment and focus are relevant to performance and NAOMI setup. Also the power in telescope aberrations on pupil scales of < 57cm is unknown: such power is not correctable by the NAOMI system. Experience indicates that that these are not likely to be major issues but for realistic end-to-end modelling of the system they should be included. Provision of the relevant input information would be required from ING.

2.9.2 Environmental Factors

Environmental factors including thermal and temperature control, electromagnetic 'noise' control and vibrational specifications are discussed briefly. It is noted that successful implementation of these will need joint development between the NAOMI project and the ING.

2.10 Summary of System Approach and Future Development.

An astronomical adaptive optics system has certain elements which are indispensable, others which are highly desirable in allowing good observing efficiency and elements which give additional scientific gains but are not essential to allow the system to do worthwhile science. The baseline NAOMI design has the indispensable elements (optics which deliver diffraction limited images, adaptive components and control system which give diffraction limited cores in at least average or better seeing conditions) and some but not all of the highly desirable features which enhance user friendliness and observing efficiency (see Telescope, Instrument and User Interface summary above). NAOMI has no 'frills' implemented which are not essential to doing the basic science. However the design is such that many of these could be added efficiently should additional funds become available.

Throughout this document, potential upgrade paths are indicated with the same textual highlight as this paragraph.

3. System-Level Features

3.1 Introduction

A simple block diagram illustrating the NAOMI system as planned is shown in Figure 1. Before proceeding to the descriptions of the subsystem specifications, which are given in the next section, a number of NAOMI's system-level features are introduced and their requirements traced. In particular, any special optical, control and interface features are described together with the specialization requirements for instruments exploiting NAOMI image quality.

3.2 *Instrument specialization*

3.2.1 Introduction

The requirement to feed AO-corrected images to unspecified instruments with unknown space envelopes demands a layout in which the science port is in a relatively open area of the bench. The image scales (i.e. camera properties either for a spectrometer or direct imaging device) required to fully sample an image at 1.65?m wavelength (~0".04/pxl) mean that any instrument intended for use with NAOMI will need purpose-designed input optics. A significant change in its input optics configuration will be required for it to be used at an alternative focus of the WHT with an image scale suitable for uncorrected seeing. The baseline system has a minimal instrument control interface, via DRAMA, which will allow header information to be written to data files.

3.2.2 Specification

	Reference	Comment
Driving Science Requirement	Clause 7	
Detailed Specification	Optical chassis document	
Performance Modelling	Figure 3	example point source imaging sensitivity

The input beam to the science port will have an f ratio of f/16.5. For optimum performance the instrument will require a cold stop at an image of the telescope pupil.

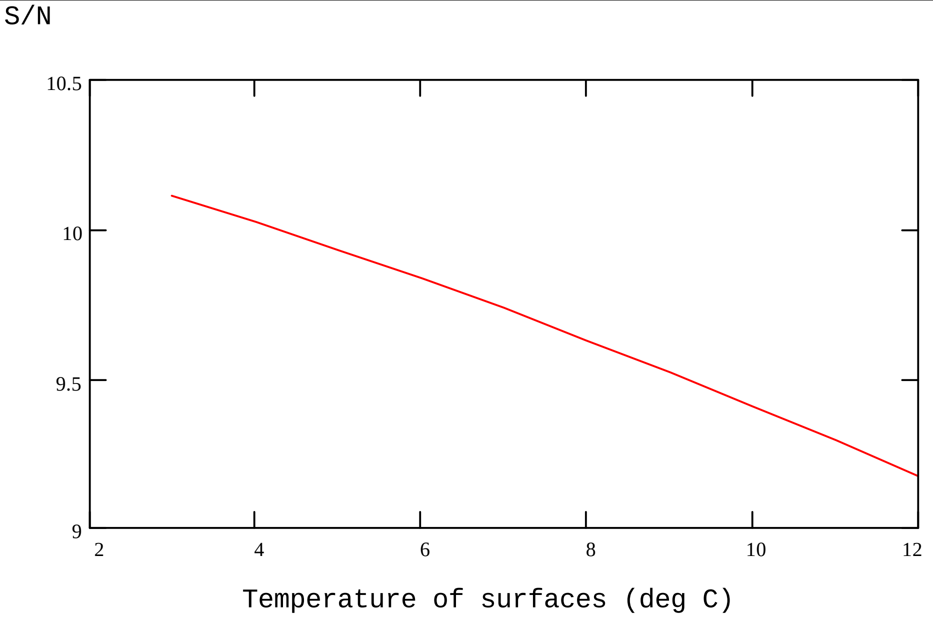


Figure 3: The 2.2? m point source sensitivity for NAOMI as designed plotted against the temperature of the system surfaces. An effective seeing of 0".2 has been assumed.

3.2.3 Upgrade Specification

Greater observing efficiency (Clause 6) will be possible if full image analysis facilities are available to the AO system to allow automated calibration and image size minimization to be carried out in a loop mode.

If a conjugation facility is implemented via a full concave lens (as opposed to a lens with a hole passing the science field unchanged) at the first Nasmyth focus, then the instrument will need a cold stop with adjustable position along the optical path and probably adjustable size.

3.3 Special optical features

3.3.1 Guide Star selection

The star which is used as a reference object for the WFS can be selected from anywhere with in the 2.9 arcmin unvignetted FOV of the Nasmyth focus. (Clause 2). This is done using a small mirror mounted on a thin glass disc at the corrected f/16.5 focus. This mirror, and the rest of the WFS, are moved to the position of a star selected by the user. By making the system telecentric at this focus the alignment of the DM and the lenslet array in the WFS is maintained. The guide star can be the same as the infrared science object.

3.3.2 Conjugation

3.3.2.1 Introduction

The turbulence in the atmosphere can be concentrated in thin layers above the telescope. In this case there is an advantage, in terms of the isoplanatic angle, in conjugating the correcting surface to the turbulence. The gains that can be achieved are demonstrated in Wilson and Jenkins (1996) and the means by which this can be done is described in Wells (Conjugating AO correction to Turbulence in the WHT AO system design, *Proc. OSA topical meeting on Adaptive Optics*, ESO Conference and Workshop Proceedings No. **54**, 1995.) The increase in isoplanatic angle gives science gains in two related areas: sky cover and PSF variation across the image. There is not a conjugation facility in the baseline NAOMI implementation but the choice of 7.3 sub-apertures/pupil for the system order means that the DM is oversized. It can accommodate conjugation up to 3km for stars up to 51” off-axis should such a facility be introduced. See Figure 4 for an illustration of the footprint on the DM and Figure 5 for a graph indicating the science gains.

3.3.2.2 Specification (upgrade)

	Reference	Comment
Driving Science Requirement	Clause 2	Not in baseline specification. Nominally makes a difference of factor two in sky cover.. If it is implemented it involves additional specifications for science instruments.
Detailed Specification	Original Optical Chassis WP	Via concave lens at Nasmyth focus.
Performance Modelling		See Figure 5

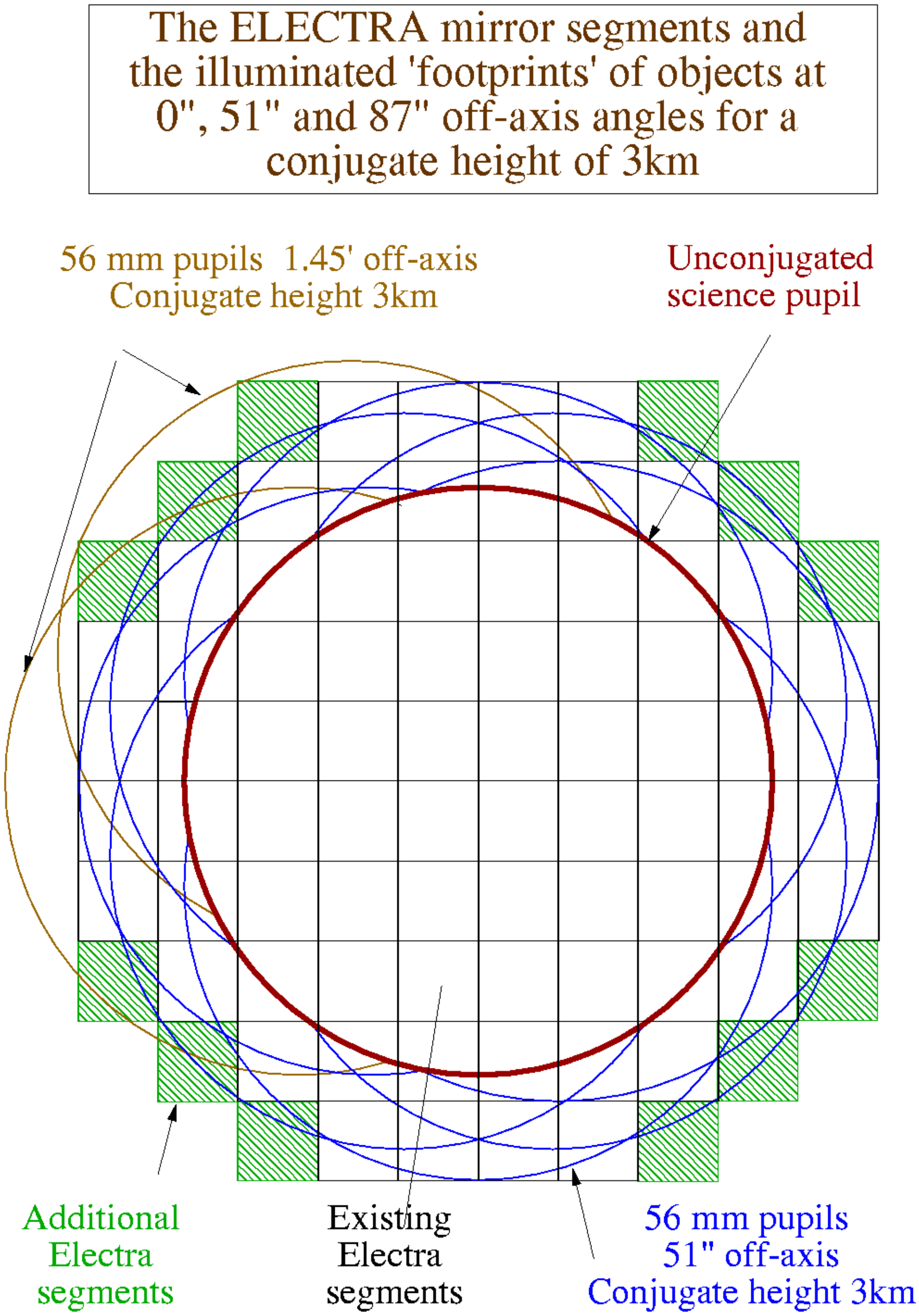


Figure 4: The NAOMI system footprint on the deformable mirror for various off-axis angles and a turbulence layer height of 3km.

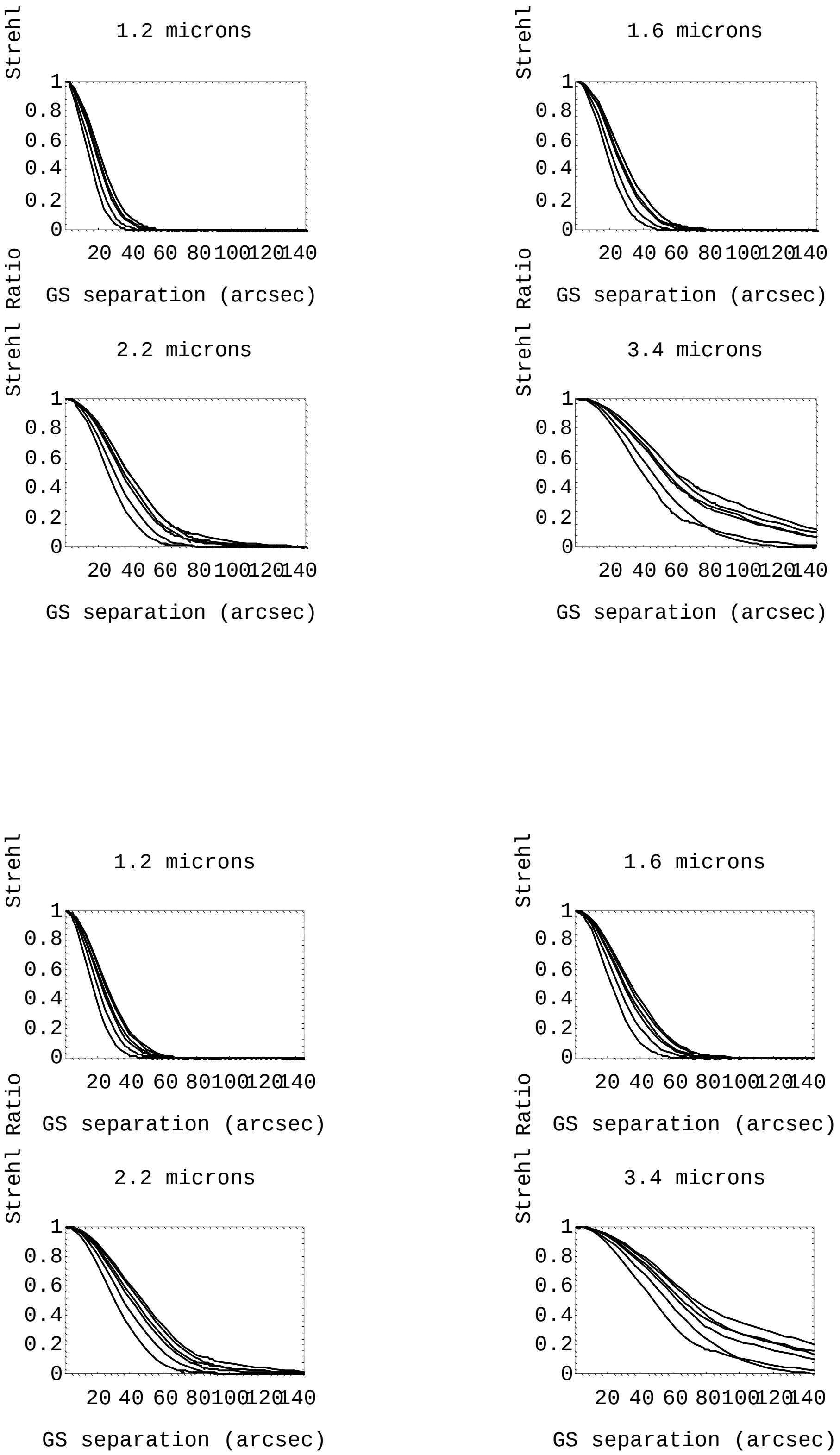


Figure 5: The gains in Strehl ratio for a given off-axis angle which could be obtained by using turbulence conjugation with six La Palma turbulence profiles. The plots show modal angular decorrelation for Vernin et al. Cn^2 profiles with standard pupil (top four) and turbulence layer (lower four) conjugation. The latter assume perfect extrapolation and no vignetting and so are optimistic.

3.3.3 The need for ADC's

Over the wavelength range of the WFS the light from the WFS is dispersed by about 2 arcsec at a zenith angle (?) of 45?. This is larger than the images at the WFS detector and the dispersion therefore has to be corrected using an ADC. The NAOMI design uses an ADC within the WFS optics which is optimized for its (visible) wavelength range.

For the IR science light the dispersion is greatly reduced. For the 3 IR filters J, H and K the atmospheric dispersions, (at ?=45?), are 0.1, 0.05 and 0.015 arcsec respectively. The diffraction limits at these wavelengths and for the WHT are 0.07, 0.1 and 0.13 arcsec. It is clear that at K the dispersion will not degrade the PSF and an ADC is not required. For J and H an ADC in the IR science arm is not in the baseline system and dispersion will start to affect the broad-band PSF's at ??45?

It is very important to note that there will be a change in the apparent separation of the visible object used as a reference for the WFS and the position of the IR object being studied as the Zenith angle changes. This change has to be compensated for during long observations using look-up tables. For exact compensation an effective wavelength, $?_{eff}$, (within the WFS) needs to be assigned to the guide star. $?_{eff}$ will be a function of the stellar spectral type, the overall throughput *vs* ?? of the WFS and the accuracy of compensation achieved by the WFS ADC.

3.3.3.1 Specification

	Reference	Comment
Driving Science Requirement	Clauses 1, 2 and 3	Reduces image broadening away from zenith in both WFS and IR science path Gain in the WFS control loop maintains its value at zenith
Detailed Specification	WFS WP	
Performance Modelling	Not implemented	

3.3.4 Pupil rotation

3.3.4.1 Introduction

The derotator will be used to maintain the required orientation of the science field. Therefore the pupil will rotate. Because the pupil is divided into sub-apertures the vanes *may* affect the slopes measured by the WFS. This will depend on the area the vanes project onto the pupil and, at any given instant, the angle they project.

3.3.4.2 Specification

	Reference	Comment
Driving Science Requirement	Clause 5	
Detailed Specification		
Performance Modelling	APD models	Effect still to be included. Models need to be run with different vane angles relative to the sub-apertures to calculate size and variation of vane effect.

The area which the vanes actually project onto the pupil needs to be provided by ING so that the effects on the wavefront measurement can be calculated

3.4 *Special control features*

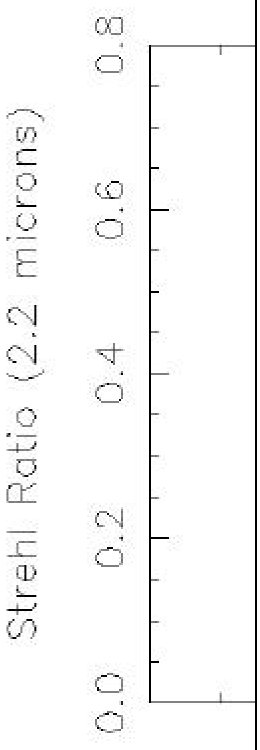
3.4.1 Modal control

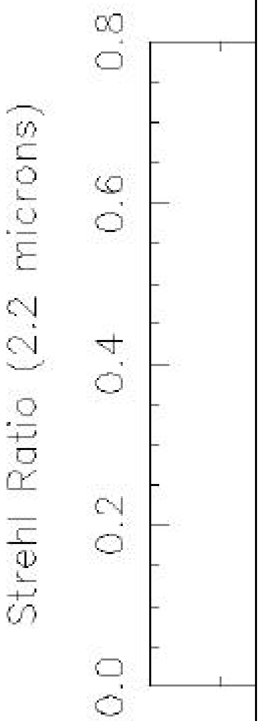
3.4.1.1 Introduction

Modal control refers to a technique where the instantaneous wavefront is fitted using a set of orthogonal functions. A useful set of functions is one which gives a near-optimal fit to the wavefront over the telescope pupil for a given number of functions fitted. When the signal-to-noise ratio of the wavefront measurements is low, because only a faint reference star is available, then the modes which are fitted can be restricted to those which have the slowest spatial (and therefore temporal) variations. These modes also have the best auto-correlation as the guide star position moves away from the science target and therefore provide an excellent means of tuning the level of guide-axis correction to give an optimal science-axis result (see Wilson and Jenkins, 1996).

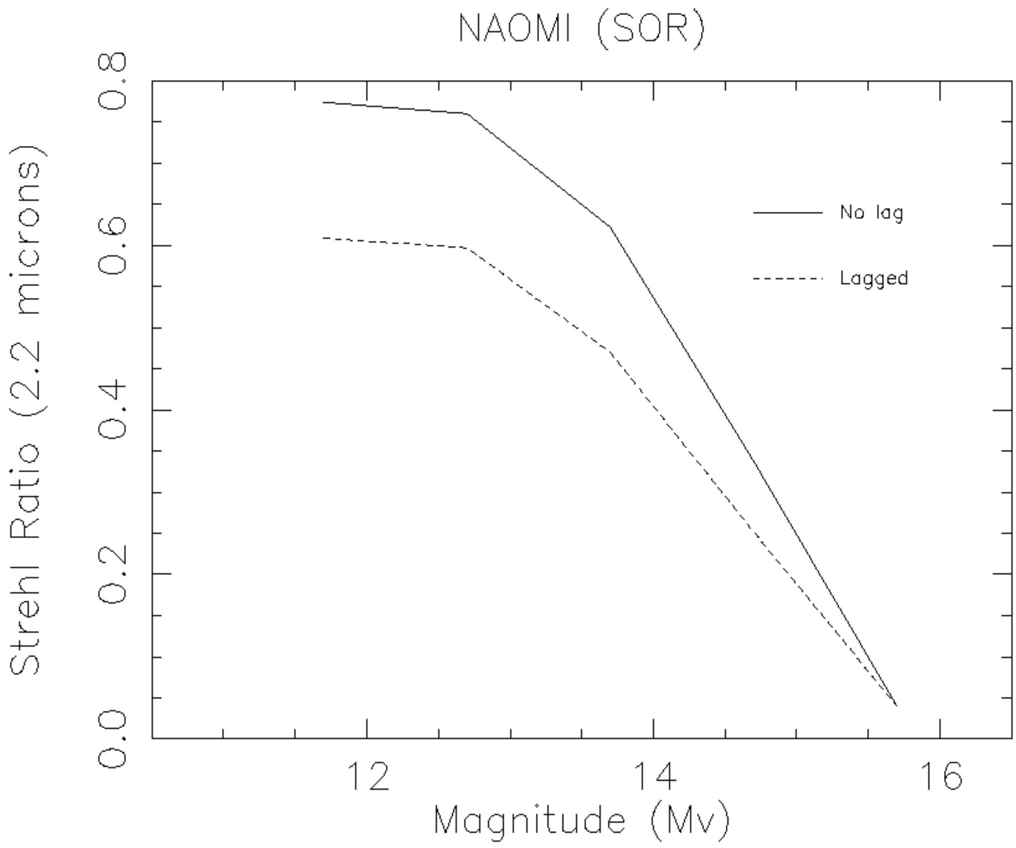
Modal control is in distinction to *zonal control* were the wavefront is fit according to a locally determined optimum. Zonal control is the first level of control which will be implemented during development and will remain available for use in high light level conditions.

3.4.1.2 Specification

	Reference	**Comment**
Driving Science Requirement	Clause 2	Requires use of *faint* guide stars *off-axis*.
Detailed Specification	Software ADD	
Performance Modelling		Compares optimized modal and zonal control of NAOMI on-axis. Improved off-axis performance with optimized modal control. Sky cover vs magnitude vs offset

	 Figure 6 Figure 7, Figure 8 Figure 9	

NAOMI is required to provide zonal and modal control with adjustable modal gains. These gains may be set on-the-fly without opening the control loops. Adjustment of gains is dealt with in the section on *modal optimisation* below.



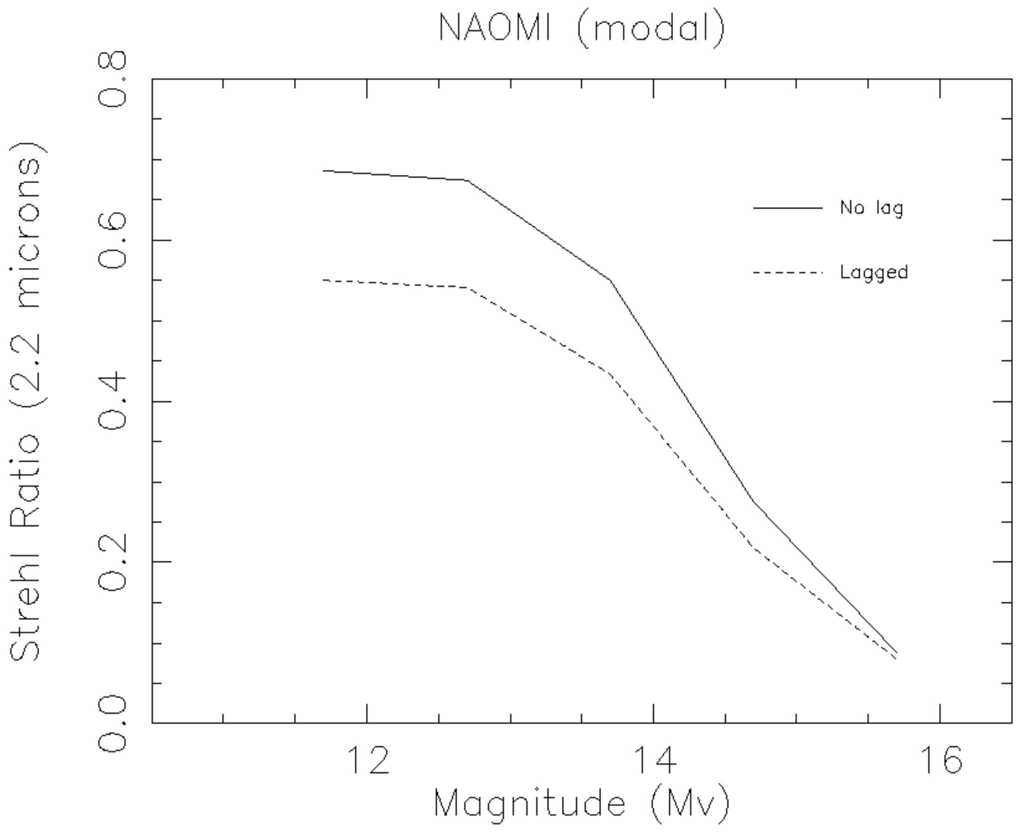


Figure 6: Comparison of on-axis NAOMI performance as a function of reference star magnitude with zonal (SOR) and optimized modal control (A.P.Doel, Durham).

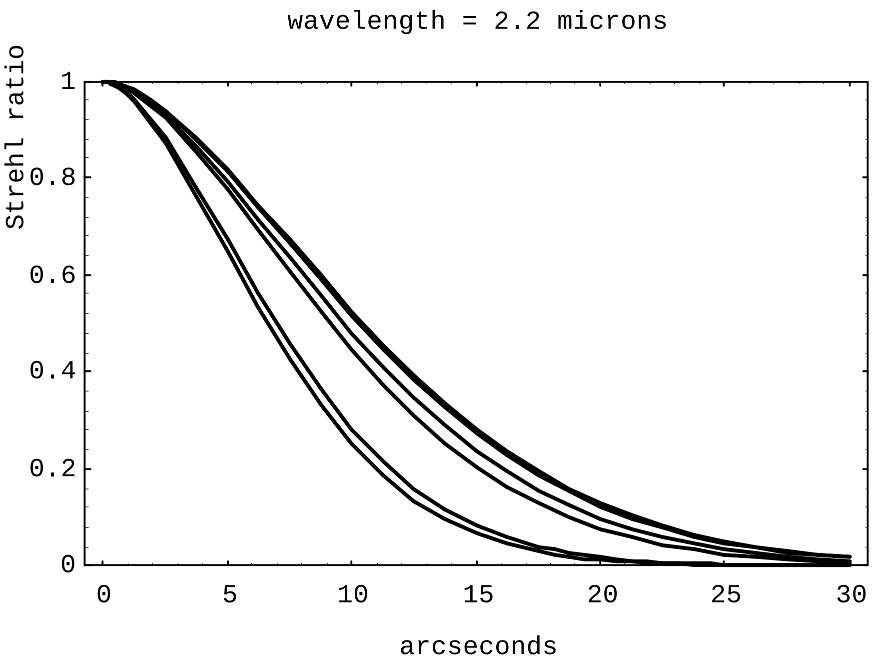


Figure 7: Angular decorrelation for simple zonal correction. The figure shows the 2.2? m Strehl ratio degradation due to off-axis angles for six vertical distributions of turbulence measured by Vernin on La Palma. This is for simple zonal correction where no attempt has been made to optimize for each off-axis angle.

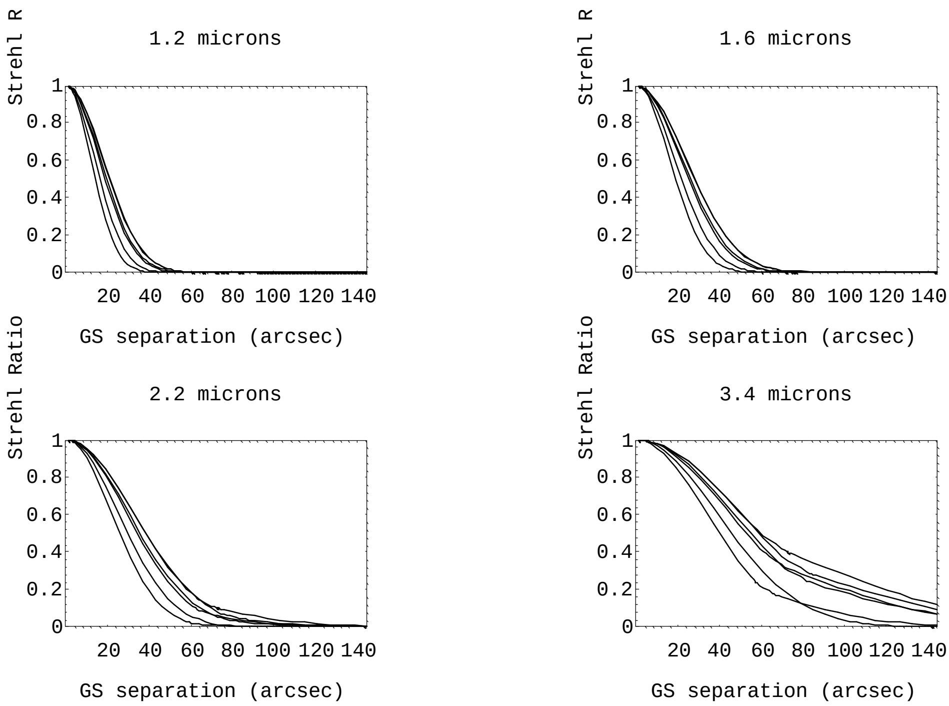
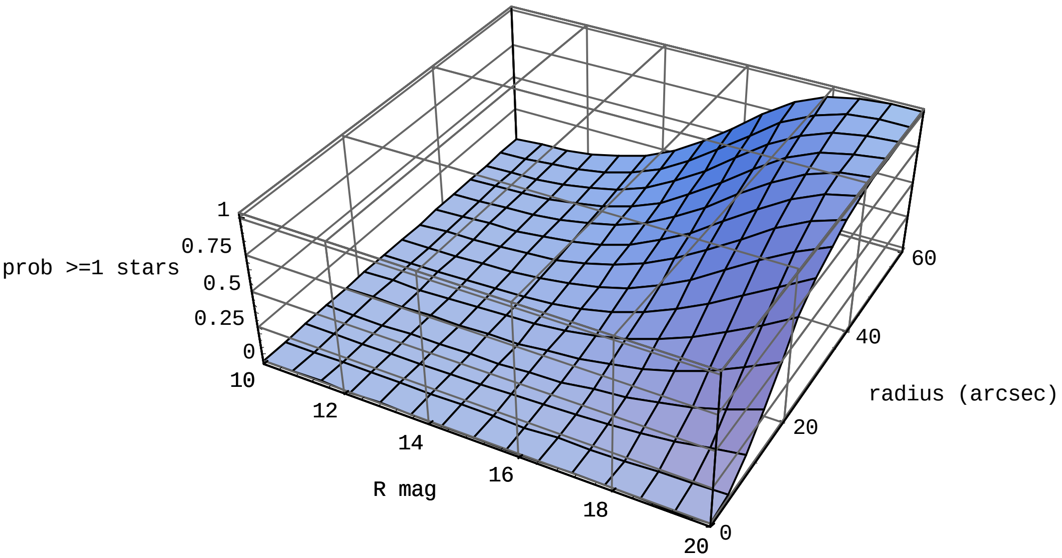


Figure 8: Angular decorrelation for modal correction. This figure shows the Strehl ratio degradation due to off-axis angles for the same turbulence distributions as figure 4. This is for modal correction where the optimum radial degree of Zernike polynomials has been chosen for each off-axis angle. Pupil conjugation is assumed.



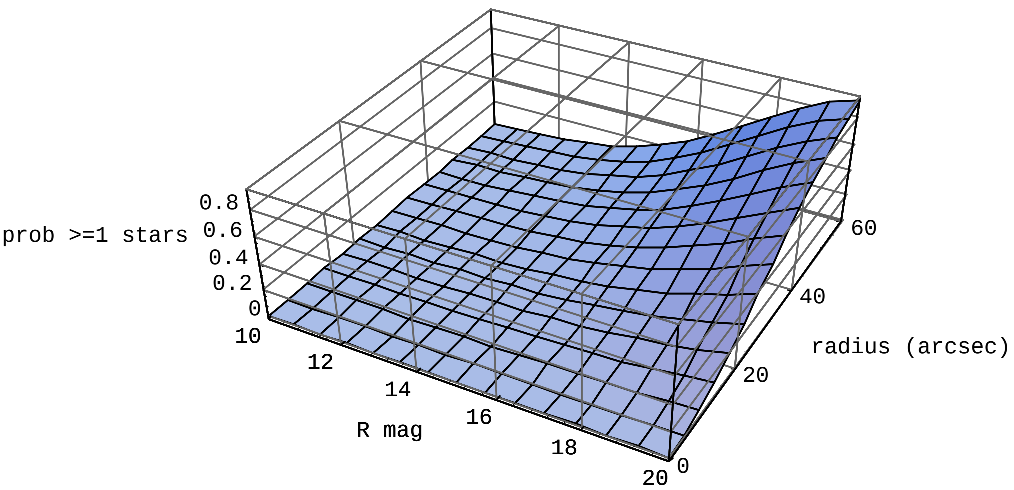


Figure 9: Grid illustrating all-sky (top) and galactic latitude > 30? (lower) probability of finding at least one guide star of a given R magnitude within a circular area of a given radius in arcseconds. (Model: Doug Simons, Gemini-Tucson).

3.4.2 Modal Optimisation

3.4.2.1 Introduction

See the section on *Modal Control* above. *Modal optimisation* is the process of automatically adjusting modal gains to cope with observing conditions. This technique has been successfully demonstrated by the *Adonis* and *PUEO* AO systems both of which use to good effect an optimisation algorithm derived from that described by Gendron and Lena (1995). Modal optimisation is still recognized as having a strong developmental aspect however; particularly in respect of off-axis or field-averaged optimisation or in the use of optimisation selection functions other than minimal wavefront variance over the pupil.

The priorities for NAOMI are the provision of the baseline Gendron-type optimisation and the hooks to allow further extensions. The WHT is well-placed in this respect as the *JOSE* measurements will provide tests for optimisation techniques and on the frequency of mode gain updates required. It should be note that Adonis and PUEO differ in this respect: the former has an off-line open-loop method and the latter can calculate updates concurrently with closed-loop operation.

3.4.2.2 Specification

	Reference	**Comment**
Driving Science Requirement	Clauses 2,6	Maintenance of high system availability during variable seeing. Improves system stability.
Detailed Specification	URD	
Performance Modelling	See Section 3.4.1	on and off-axis benefits of optimized modal control.

NAOMI will provide the ability to update modal gains on-the-fly whilst the adaptive control loops are closed.

Concurrent calculation of loop gains will take place on a NAOMI workstation. The initial algorithm to be implemented will be as Gendron and Lena (1995).

3.4.2.3 Upgrade

Future optimisation algorithms requiring higher processing capacity may be implemented on additional processors in the real-time control computer rather than on the host workstation.

3.4.3 Non-sidereal tracking

3.4.3.1 Introduction

Many solar-system objects will be bright enough for self-referencing. These will be tracked using the tilt off-load capability in which the integrated tip-tilt error is sent to the autoguiding loop. The rate is nominally limited by the autoguiding rate. Faint solar system objects will be followed using the ‘jitter’ facility, which allows motion at up to 4”/sec. This is more than adequate for all known solar system objects (except meteors!).

3.4.3.2 Specification

	Reference	**Comment**
Driving Science Requirement	Science Clause 7	
Detailed Specification	Optical Chassis WP; FSM WP; Software URD.	
Performance Modelling	N/A	

3.5 Interface Features

3.5.1 Telescope interface

3.5.1.1 Introduction

A minimal required interface to the TCS will be implemented, sufficient to allow the integrated tilt error to be off-loaded to the telescope autoguiding system. This will adjust the telescope position via a slow feedback loop to keep the integrated tilt error to zero. Focus will also be offloadable to the telescope in order to provide the capability of keeping the WHT wavefront focus peak-to-valley error <0.2 ?m. The telescope position and derotator settings will also be available to be attached to the saved data files output by the instrument in use. The interface will be handled by the DRAMA messaging system.

3.5.1.2 Specification

	Reference	Comment
Driving Science Requirement	Clause 4, Clause 7	
Detailed Specification	(Software) URD	URD currently describes long term goals. It is being modified to reflect baseline requirements.
Performance Modelling	N/A	

3.5.1.3 Upgrade Specification

The software architecture will be designed such that the long term URD requirements can be implemented within the existing architecture. This upgrade would add the capabilities for the AO system procedures to control and co-ordinate all DRAMA-available functionalitity of the telescope and of other instruments AND for AO system functionality to be available to external process such as instrument control and TAG tasks.

3.5.2 Observing interface

3.5.2.1 Introduction

The detailed long term goals for a GUI are described in the Software User Requirements Document. For the baseline system, a GUI will be available which enables user friendly control of the AO system with only minimal interface to instruments or telescope. A DRAMA-based procedural layer will allow efficient internal calibration and control of the NAOMI components through EPICS. The top-level control will be derived from the ELECTRA GUI with minor add-ons found to be high priority from Electra-1 (first light cophasing test of ELECTRA) experience. Control of the NAOMI optical bench will be via a revision of the (editable) ELECTRA optical bench GUI. The project philosophy is that GUI tools are a rapidly changing area of software technology and therefore a full system GUI will be one of the last items to be written and cannot be specified at the present time. It is also envisaged that there will be developments of GUI standards at ING for running the WHT and its instruments. The specifications of these are not yet available, which again drives the decision to provide a minimal GUI based on ELECTRA for the baseline system.

An integrated telescope control - instrument control - NAOMI control GUI would be part of a software upgrade.

3.5.2.2 Specification

	Reference	Comment
Driving Science Requirement	Clause 3	

Detailed Specification	Software URD, FRD.	URD currently describes long term goals. It will be modified to reflect baseline requirements.
Performance Modelling	N/A	Some aspects testable with E0/E1 GUI.

3.5.2.3 Upgrade Specification

The long term goal is to have a fully integrated NAOMI, Telescope and Instrument interface mitigated by DRAMA.

4. Key Adaptive Subsystems

4.1 Introduction

The overview of implementation commences with the principal adaptive subsytems:

?? Wavefront Sensor

?? Tip-tilt Mirror

?? Deformable Mirror

?? Processing Subsytem

The specifications for each subsytem are introduced and attributed to the driving system-level specifications. References are given to the detailed specification and subsystem workscope documentation. Closely-related ancillary (non-adaptive) features are described briefly for completeness.

4.2 Wavefront sensor subsystem

4.2.1 Introduction

The wavefront sensor (WFS) will use the Shack-Hartmann configuration. In this configuration the input pupil is divided into several subapertures by an array of small lenses. Each lens focuses the light from a guide star on a section of a detector array, e.g. 4 x 4 pixels, and the focused spot's centroid shift is determined by a processor. The average phase gradient for each subaperture is determined by dividing the centroid shift of the focused spot by the effective focal length of the lens. Because the Shack-Hartmann sensor does not provide a direct phase measurement of the turbulence-degraded wavefront, the phase gradients are transmitted to a reconstructor which calculates the phase of the wavefront. Note that both the wavefront processor and reconstructor are part of the RTCS. The conjugate (or reverse) wavefront (with its overall tip/tilt removed) is then applied to the deformable mirror. The tip/tilt information is sent to the tip/tilt mirror discussed in Section 4.3.

The WFS will usually operate with 7.3 subapertures across the WHT pupil. This number defines the system order and it is driven by the science clause 1. System modelling shows that Clause 1 can be satisfied using from 7 to 8 subapertures across the pupil diameter (see

Figure 10 and Figure 11). The segments of the ELECTRA deformable mirror will be optically mapped onto the WFS subapertures. Occasionally the system will operate with a smaller number of subapertures (see section 4.2.2.6).

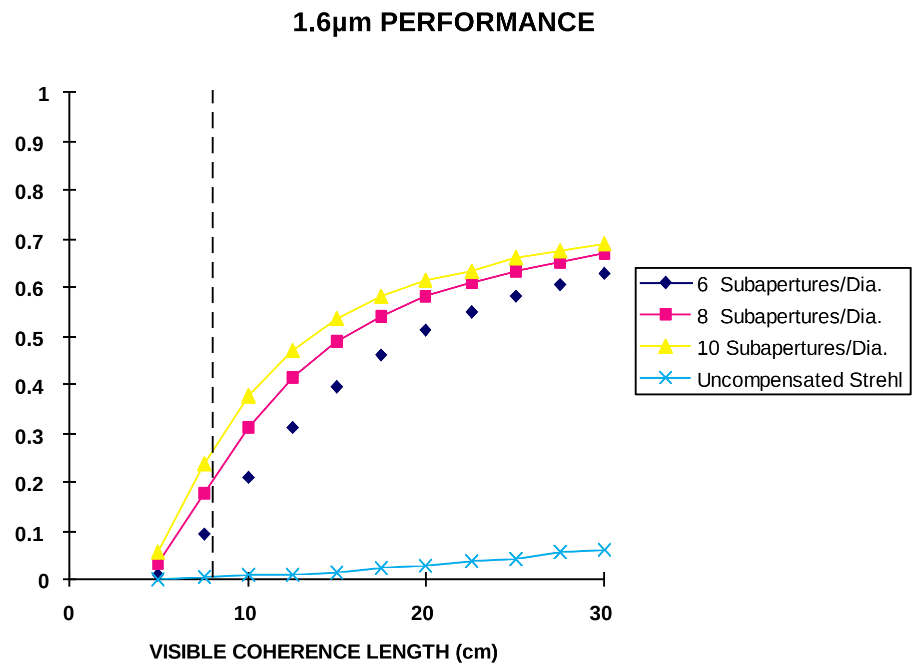


Figure 10: The effect of system order on Strehl ratio at 1.65? m (H-band) for a range of seeing conditions as parameterized by the coherence length r_o. (Continuous facesheet DM)

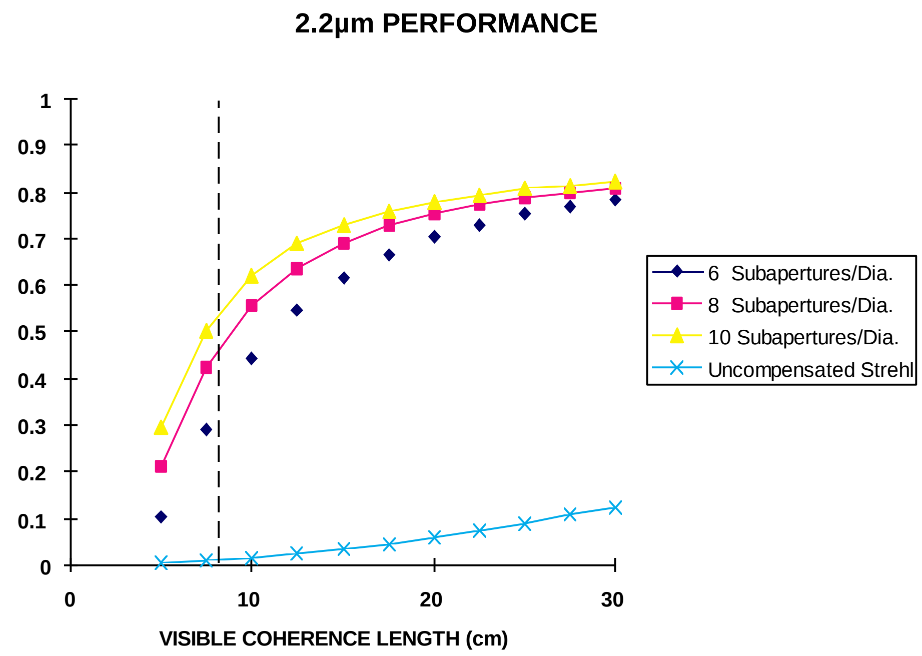


Figure 11: The effect of system order on Strehl ratio at 2.2? m (K-band) for a range of seeing conditions as parameterized by the coherence length r_o. (Continuous facesheet DM)

The main components of the WFS are a pickoff mirror with a field stop, a collimating lens, an atmospheric dispersion corrector (see Section 0), interchangeable lenslet arrays (with ? 10 x 10 lenslets for the largest array), a relay optic and a CCD. The relay optic images the array of focused spots at the appropriate pixel scale on the CCD. All of these components will be mounted on a remotely controllable stage to allow operation with a guide star anywhere within the 2.9 arcminute field. This stage will also allow jittering to be supported in accordance with Clause 4. The WFS will also have its own calibration source.

4.2.2 Specifications

4.2.2.1 Wavelength range

The WFS will operate over a spectral range from 0.4 µm to 1.0 µm.

4.2.2.2 Phase gradient accuracy

The phase-gradient measurement accuracy along any axis will be equal to or better than 0.018 $?_{C}$ rms (where $?_{C}$ = 2.2 µm) over each subaperture when operating with ? 1500 photons per subaperture per measurement incident upon the CCD when using no more than 4 x 4 pixels/subaperture. This performance includes the effects of sensor noise, photon noise and other sources of error. It is derived from system modelling for the Clause 1 conditions, i.e. system performance with bright stars, and it has been included in the Clause 1 error budget.

When operating with faint stars under the conditions for Clause 2, the phase-gradient accuracy is expected to be equal to or better than 0.14 $?_{C}$ rms (where $?_{C}$ = 2.2 µm) over each subaperture when operating in the quad-cell mode with ? 40 photons per subaperture per measurement incident upon the CCD. This lower level of performance takes into account the high photon noise present at such low light levels. This performance has been included in the Clause 2 error budget.

Note that the error budgets referenced here are being updated to the 7.3 actuator pupil geometry at the time of writing.

4.2.2.3 Read noise/ read latency

The WFS CCD will have two readout rates that will be electronically switchable without recabling. There is no need to switch between frames. Under some conditions, e.g. good seeing with low wind speeds, one will be able to use a longer read latency and thus operate the CCD with lower readout noise. At 100 kilopixels/second/port the CCD will have ? 2 noise electrons/pixel and at 1 megapixel/second/port the readout noise will be ? 6 noise electrons/pixel. CCD readout noise and latency have been included in the modelling and the error budgets for Clause 1 and 2.

4.2.2.4 Pickoff

A small (TBD mm diameter) pickoff mirror will direct light from the guide star into the WFS. The pickoff will be an integral part of the WFS and it may be moved anywhere within the 2.9 arcminute field to acquire a guide star. Light passing the pickoff will be directed to the optical science port.

4.2.2.5 Field stop

A field stop will be provided to allow the use of guide stars in crowded fields. The field stop diameter will be 3 arcseconds.

4.2.2.6 Spatial descoping

Under some conditions, e.g. low light levels with modal optimisation, a performance advantage may be gained by using fewer subapertures across the pupil diameter; this is known as spatially descoping. The WFS will have the capability to change lenslets remotely to operate with only 4 subapertures across the pupil diameter. This facility is driven by Clause 2.

4.2.2.7 Auto change of lenslet focal length

A shorter focal length lenslet array will be provided to handle moderate to strong turbulence conditions ($r_0 <$ 13 cm). As the atmospheric turbulence increases, the spot excursions also increase. Changing to a shorter focal length keeps the spots on the CCD. This facility is driven by Clauses 2 and 3 together.

4.3 Tip-tilt mirror

4.3.1 Introduction

As previously stated in Section 4.2, 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 tip/tilt mirror. 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 tip/tilt mirror (a.k.a. the fast steering mirror or 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. Large low-frequency tip/tilt errors will be passed on to the TCS to avoid an excessive range requirement for the tip/tilt mirror. The mirror will also serve as a collimating optic, i.e. an off-axis paraboloid, in the common-path optics. This dual function reduces the number of optical surfaces resulting in higher transmission and lower emissivity.

4.3.2 Specifications

The mirror surface will cover an angular range of ?1 mrad over two orthogonal axes. This range is equivalent to about 5.6 arcseconds in WHT object space. The frequency response of the mirror shall extend to TBD Hz at the - 3 dB point. (Current JOSE data from Richard Wilson indicate that 250Hz will be a safe - this will be confirmed for a wider range of conditions within clause 3) The error budgets for Clause 1 and 2 allow for residual rms closed-loop tilt jitters of 0.016 arcsecond and 0.022 arcsecond respectively in WHT object space.

The mirror’s clear aperture of about 100 mm diameter in the current design is large enough to allow conjugation over a 102” field for a dominant turbulent layer at 3 km above the telescope. This matches the effective over-sizing of the DM introduced by having 7.3 sub-apertures across the pupil. However turbulent-layer conjugation is an upgrade and it will not be employed in the baseline system. 100mm is significant because it is the size supported by two potential commercial suppliers of the tip-tilt mirror.

4.4 Deformable mirror subsystem

4.4.1 Introduction

The deformable-mirror subsystem will correct for the higher-order, i.e. tilt-removed, wavefront errors. Modelling shows that either continuous facesheet or segmented deformable mirrors can satisfy the requirements of Clauses 1, 2 and 3. The baseline system will operate with the 76-segment Electra deformable mirror and its drivers. This mirror has 10 segments across its maximum dimensions and approximately rounded corners. The WHT pupil, as imaged at the mirror, will cover 7.3 segments. The additional segments provide for a future upgrade to a turbulent-layer conjugation capability. Each segment has dimensions of 7.6 x 7.6 mm^2. The segments’ optical surfaces are coated with aluminium. Three actuators are used to move each segment thus providing tip-tilt and piston control. The mirror will be provided with electronics to drive the actuators; these electronics are usually referred to as the drivers.

4.4.2 Specifications

The stroke of each actuator is 6 µm. Modelling indicates that this stroke is adequate to handle the strongest turbulence specified by Clause 3 (r_0 = 8 cm). Strain gauges and electronics will be provided to measure and correct the hysteresis present in the actuators. The hysteresis will be reduced to ? 0.7% (0.2% currently expected) as required by the results of system modelling with a propagation code. Hysteresis affects both the mirror fitting error (defined below) and the servo system response. The mirror settling time, i.e. the time required for the mirror surface to form a specified shape, will be < 400 µs. An allotment for mirror settling time as part of the system latency has been included in the error budgets for Clauses 1 and 2.

The deformable-mirror fitting error coefficient is a simple way of defining how well the mirror surface matches the conjugate of the turbulence-degraded wavefront. The following equation defines the coefficient.

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

where $?^{2}$ = variance of the residual wavefront error (radian^2)

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

r_o = atmospheric turbulence coherence length (? 8 cm)

Clause 1 is the driving science requirement for the deformable-mirror fitting error. It is the dominant source of error when operating with bright stars. The error budgets for Clauses 1 and 2 were based on a fitting error coefficient of 0.4 which is characteristic of a well-designed continuous-facesheet mirror. A segmented deformable mirror has a smaller fitting error coefficient (about 0.18) and thus it provides better performance (see Figure 12). This performance improvement was taken into account in recent propagation code studies.

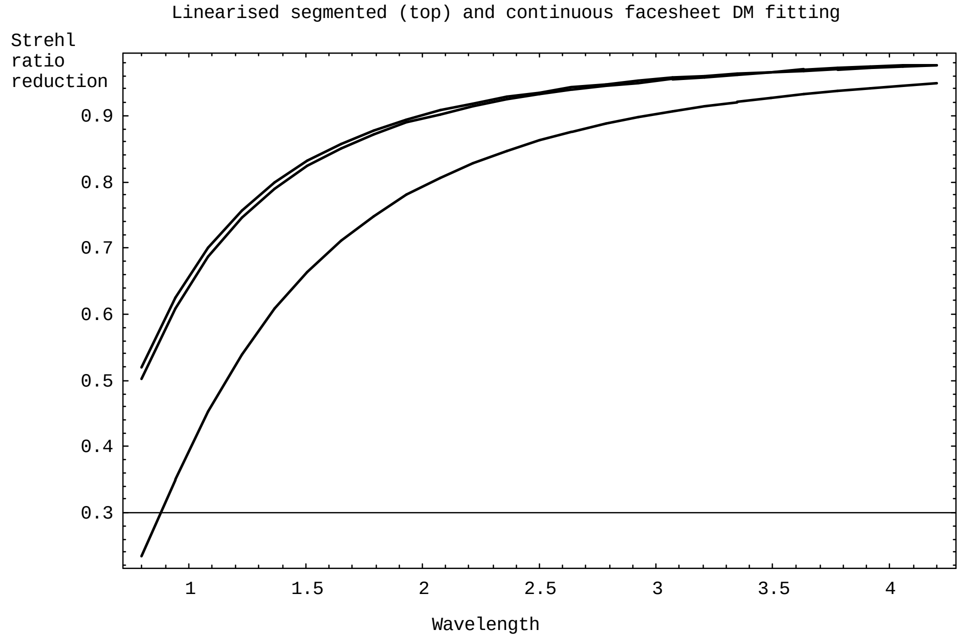
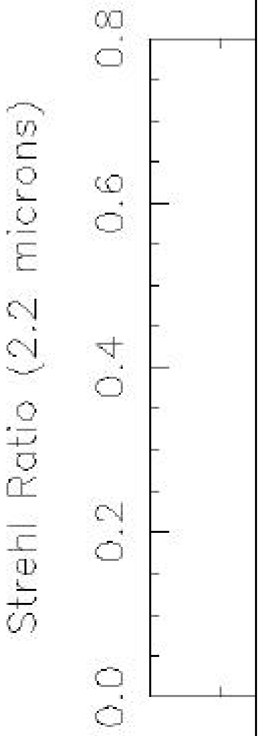
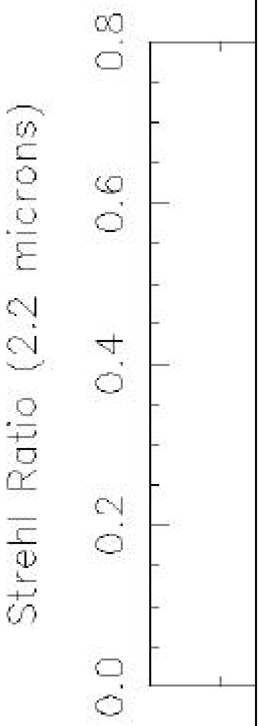


Figure 12: Fitting error gains from linearised segmented adaptive mirror technology.
This figure shows the effects of deformable mirror fitting error on output Strehl ratio in seeing conditions of r_0 = 15cm. Note that these are NOT the final output Strehl ratios but the factors arising from fitting error. With a bright guide star and reasonable seeing conditions, fitting error will dominate at shorter wavelengths. The upper curve is for a segmented mirror with fitting error coefficient ? =0.18 (i.e. with perfect hysteresis removal on pistons) and the lower curve is for a continuous facesheet mirror with ? =0.40. The middle curve shows the effect of adding residual hysteresis to the segmented mirror at the currently measured upper limit for ELECTRA (0.2%).

4.5 Processing subsystem

The NAOMI computer and software systems are illustrated schematically in Figure 1. The overall software architecture is described in section 9.

	Reference	**Comment**
Driving Science Requirement		
Latency	Clause 1	High bandwidth performance
Modal Control	Clauses 2, 6	sky coverage, system availability and stability
Detailed Specification	URD,SRD,ADD	
Performance Modelling		On axis clause 1 and 2 modelling Off axis modelling for zonal and modal control.

	 Figure 6, Figure 7, Figure 8	

4.5.1 Real-time computer

The *real-time computer* will perform the three stages of processing required to transform WFS pixel data into mirror figuring commands:

1. The NAOMI real-time computer will accept pixel data from a 4-port WFS camera at at least the maximum *peak* readout rate and digitization accuracy indicated in the WFS subsystem error budget and specification. These are 1 Mpixel/sec/port and 12 bits/pixel respectively. A peak rather than average readout rate is specified because the WFS will operate in a frame-transfer mode. The first processing stage of the real-time computer will reduce these pixels to subaperture wavefront slope values and will provide for switching its slope estimation algorithm between multi-pixel and quad-cell mode on-the-fly (between one frame and another). The supported WFS readout formats and required phase gradient accuracy are described in the WFS subsystem specification. These are: 6x6 pixels [acquisition-only], 4x4 pixels [WF slope measurement accuracy: 0.018 waves rms at 2.2 microns for clause 1 conditions] and 2x2 pixels [WF slope measurement accuracy: 0.14 waves rms at 2.2 microns for clause 2 conditions]. The algorithm switching will be synchronized with corresponding changes in the WFS camera readout format.
2. The slopes will then be used to derive either a complete set of deformable mirror drive commands directly via a single matrix multiply (zonal control) or a set of instantaneous modal coefficients (modal control).
3. The modal coefficients (if modal control is being used) will then be transformed into mirror drive data. The mirror drive data will then be output via DACs to the mirror power amplifiers.

The elapsed time for all these operations will be ? 250 microseconds between the end of the WFS frame readout and the end of the deformable mirror write operation (but not the DM mechanical settling period). Any relaxation of the overall latency specification (WFS readout + computation + DM settling) will in the first instance be allocated to CCD readout (with a potential read noise gain - see the WFS subsystem specification) rather than to computation.

The real-time computer will provide command and status interfaces which will permit the wavefront correction method (zonal or modal), WFS pixellation and control matrices to be altered and examined. These operations should not cause the control loops to open (in conditions which were otherwise stable).

The real-time computer will make all of its operational data available to an external visualization system where it may be recorded and/or analyzed and subsequently presented. The retrieval of these data for external analysis will in no way compromise the performance of the real-time control computer.

The implementation for the above is described in section 10.

4.5.2 Mechanism control

ING standard methods will be used for the control of all standard mechanized functions (Clause 19).

The baseline is EPICS and VxWorks on a VME-based MVME-167.

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

4.5.3 User Interface

A procedural (scripting) interface and simple graphical user interface will be provided for the control of mechanism, real-time, optimisation and visualization functions. Basic visualization functions will be provided.

4.5.4 Upgrade

An upgrade route is available such that a full function GUI and visualization system may be provided which is fully compliant with ING standards.

5. Optical performance specifications

5.1 Introduction

The optical design of NAOMI aims to fulfil, as nearly as possible, the science clauses in the document *Top Level Scientific and Operational Requirements for NAOMI*. The givens for the design are

?? The WHT optics - diameter, f-ratio, and the position of exit pupil

?? The position of the Nasmyth focus 16mm from the edge of the GHRIL optical table

?? The GHRIL table - size (1.35 x 2.5 m) and space constraints especially the derotator

?? The unvignetted FOV - 2.9 arcmin

?? The pixel scale at the science camera - 0.04 arcsec/pixel so as to nearly fully sample the diffraction core of the J PSF.

?? The need to minimize the number of warm surfaces in the IR science path to maximize the IR sensitivity. The reductions in background gained by using smaller pixels are easily lost if the emissivity of the AO system itself is too high. See section 5.3.

?? The need to maximize throughput to the WFS. The sky coverage of a natural guide star system such as NAOMI is limited by the availability of stars. It is important therefore to make sure that as much *visible* light as possible reaches the WFS detector.

5.2 Wavelength ranges

5.2.1 IR Science

The operating wavelength range of instruments fed by NAOMI is limited at long wavelengths by the emissivity of the telescope and instrument. Measurements longwards of the K band will have a lower sensitivity because the increased background more than offsets the gain from using smaller pixels. The short wavelength limit of the IR science path is set by the reflectivity of the dichroic which in turn is affected by the need to maximize the visible throughput to the WFS. The reflectivity-transmission curve for the dichroic design being used in modelling is shown in Figure 13. This shows that the mean J band reflectivity is >80% and K-band reflectivity >94%.

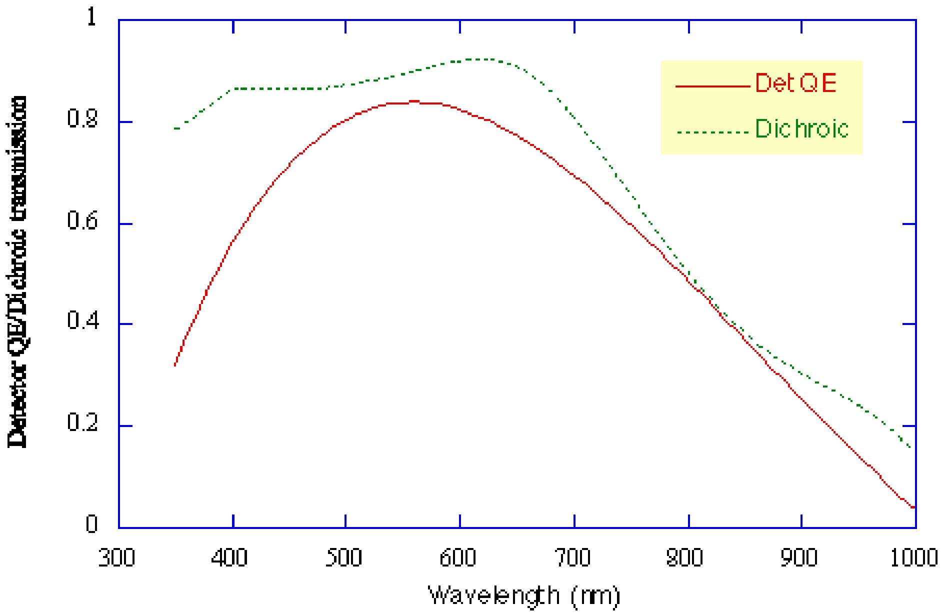


Figure 13: A dichroic mirror transmission/reflectance curve similar to the one proposed for NAOMI.

5.2.2 WFS

The wavelength range of the WFS is fixed by the QE of the CCD's, the transmission curve of the dichroic, atmospheric dispersion and the fact that stars at the faint limit of those that can be used as reference objects will be predominantly red (G and later). Taking these factors into account the wavelength range for the WFS is fixed at 0.4 to 1 µm.

5.2.3 Optical science port

For wavelengths shorter than 1 µm (Science clause 3) a new dichroic with high reflectivity at 0.8 µm could be used. This has the advantage of a FOV with no vignetting due to the WFS pickoff but, because of the lower throughput to the WFS, the limiting magnitude on the stars that can be used as a reference will be brighter. Alternatively the dichroic can be removed in which case all the visible light, apart from an area of ~5 x 5 arcsec used for the WFS pickoff, is available at the optical science port.

5.3 IR throughput and emissivity

5.3.1 Introduction

All broad band IR (J filter and longer wavelengths) will be background limited after several tens of seconds on-chip integration, either by OH airglow (J,H) or thermal emission (K,L, M). Narrow band (?4%) filters at wavelengths < 2.4?m will be detector noise limited for most observations because for on-chip integrations of longer than about 5 minutes array and/or sky stability has usually become an issue. This could change as arrays develop. S/N ratio once on-chip integration times have reached background limited conditions varies as the square root of the total integration time. Keeping the emissivity low is important for two main reasons: (a) it improves S/N ratio and (b) the array wells have limited depth so lower background allows either longer on-chip integration times or gives higher dynamic range. At the longer thermal wavelengths the array can saturate even with the shortest possible integration time unless the emissivity is reasonably low. A high IR throughput is a by-product of a low emissivity goal and cannot sensibly be specified independently.

5.3.2 Specification

	Reference	**Comment**
Driving Science Requirement	Clause 3, 24	
Detailed Specification	Optical Chassis WP doc.	Drives to silvered surface coatings wherever possible; need to define optimum balance between dichroic optical throughput to WFS and K-band emissivity
Performance Modelling	AJL IR simulation. See Figure 3 for an example	Sensitivity to point source simulated by assuming 0”.2 effective seeing. Expected to be accurate to 25%. Simulations using real AO-generated psfs in progress

5.4 Optical throughput

5.4.1 Introduction

The optical throughput driver is therefore to get as many photons to the WFS as possible (Clause 2) and also to meet the optical science port throughput requirement (Clause 9). This is jointly met by minimizing the number of surfaces and making an optimum choice of coatings. The balance of dichroic coating between maximum optical transmission and maximum IR reflectance (minimum emissivity) presents a direct conflict. The NAOMI system philosophy is that sky cover is very important while a change in the emissivity of one surface from 3% to 6% makes negligible difference to the S/N ratio obtainable at IR wavelengths given the overall system emissivity. Therefore Clause 2 becomes the main driver for the optical throughput of the dichroic. The dichroic coating currently assumed (see section 5.2.1) has the 50% transmission/reflectance cross-over at ~0.8?m.

5.4.2 Specification

	Reference	**Comment**
Driving Science Requirement	Clauses 2, 9	
Detailed Specification	Optical chassis WP	
Performance Modelling	MW system throughput	See below

The table below shows the integrated throughput (in percent) from 0.4 to 1?m at the WFS for guide stars of different spectral type. The model includes the reflectivity of all telescope and NAOMI mirrors, all the air-glass interfaces, the expected QE curve for the EEV CCD and the dichroic transmission curve shown in Figure 13

Spectral type	O9	B0	A0	F0	G0	K0	M0	M5
Mean throughput - With dichroic	18	28	27	25	23	23	19	15
Without dichroic	34	34	33	31	30	29	25	22

The next table shows the same information but for a wavelength range from 0.5 to 1?m and includes the expected number of detected photons for a 16th magnitude star. Viewed together with the sky cover figures this demonstrates that the proposed system meets Clause 2 of the specifications.

Spectral type	O9	B0	A0	F0	G0	K0	M0	M5
Integrated detection rate								
With dichroic	29%	29%	27%	25%	23%	22%	18%	15%
Without dichroic	36%	35%	33%	31%	29%	28%	25%	22%
Detected photons†								
With dichroic	40	40	28	32	34	37	70	155
Without dichroic	48	48	34	41	44	49	97	228

† Photons/sub-aperture/25 msec, spectral bandwidth 0.5-1 µm, detected by the WFS CCD for stars of these spectral types with m_V=16

5.4.3 Upgrade Specification

The field delivered to the acquisition TV is the full unvignetted field the telescope passes through the derotator, but with some obstruction of the pupil by the WFS (and possibly TTS) pick-off mechanisms. With an upgraded acquisition camera it will be possible to carry out some simultaneous IR (approx. >1?m) and optical (approx. <0.8?m) scientific experiments with an AO corrected image.

5.5 FOV; Image quality; correctable and uncorrectable errors

The FOV of the IR science port is fixed by the size of the dichroic mirror. In the baseline design the FOV is 15 arcsec diameter which matches to WHIRCAM with 0.04 arcsec/pixel. A 1024^2 instrument (FOV 1 arcmin, Science Clause 7) can be accommodated with a suitably sized dichroic coating area.

The system is diffraction limited at J and longer wavelengths, in the absence of atmospheric and telescope aberrations, over this 1 arcmin FOV.

At the larger off-axis angles used by the reference stars there are significant aberrations introduced by the telescope and AO optics. These aberrations will produce offsets in the WFS which have to be subtracted before the modal decomposition is carried out. The stability requirement (Section 5.6) means that these non common path errors should not change during an observation.

5.6 Stability

The system will 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 is adequate for this. This requirement is driven by Clause 5.

6. Opto-mechanical system design requirements and goals

6.1 Introduction

The constraints and requirements on the optical design of NAOMI are given in section 5.

A diagram of the layout is shown in Figure 2. This shows the principle components and their relationship to the derotator and the GHRIL optical table. A brief 'walk through' description of the system is given in Table 1 and a more detailed list of all the components is given in section 8.

Table 1

The f/11 beam from the derotator reaches a focus 16mm after the edge of the existing GHRIL optical table. The unvignetted FOV is 2.9 arcmin in diameter.	Nasmyth f/11 focus
Light from the alignment system can be injected into the main optical path by inserting the alignment beam splitter in front of the f/11 focus.	Alignment system
A camera is placed opposite (in an optical sense, not necessarily physically opposite) the alignment beam. This allows a comparison to be made between the 'before' and 'after' correction images.	Alignment camera
From the focus the beam is collimated by the off-axis paraboloid (FSM) which also acts as the fast steering mirror of the system used to remove the tip-tilt component of the incoming wavefront. The FSM images the telescope exit pupil on to the DM.	FSM
The full 2.9 arcmin Nasmyth FOV is refocussed by OAP2. The focal length of OAP2=1.5 focal length of FSM giving an f/16.5 corrected focus. In front of the second focus an IR reflecting dichroic beam-splitter spectrally separates the IR/science and optical-WFS paths.	OAP2 Dichroic beamsplitter
The field lens just in front of the optical path focus makes the system at this point telecentric (DM imaged at infinity). This is required so that when selecting off-axis guide stars there is no movement of the image of the DM at the lenslet array.	Field lens
The guide star is selected by moving a small mirror in the focal plane. The mirror directs light from the star towards the WFS. Note that the whole WFS assembly has to move with the pickoff.	Guide star pickoff
The pickoff mirror is mounted on a thin glass disc which allows the rest of the 2.9 arcmin FOV through to the acquisition camera and any optical instrumentation that is to be used with NAOMI	Acquisition camera
A collimating lens in the WFS path images the DM onto the lenslet array. The collimated space between the collimator and the lenslet allows for the insertion of the WFS ADC.	WFS collimator ADC Lenslet array
The array of spots produced by the lenslet array is imaged onto the CCD detector with an focal reducing relay lens (not shown in diagram)	WFS relay lens

6.2 IR Science Port

The IR science port has a FOV limited initially by the dichroic beamsplitter. In principle it can be up to the full 2.9 arcmin available at the Nasmyth focus, but the telescope/instrument PSF will not be diffraction limited beyond about 30 arcsec from the optical axis at 1.2 µm (J-band). The following numbers are nominal values. Actual designs of IR instruments will need to use the as-built values and a full ray-trace.

The f/ratio is 16.5.

The plate scale is 335 µm/arcsec

The image of the telescope pupil is at a distance of 1100mm beyond the focus and has a diameter of 66.7 mm.

The footprint available for IR instrumentation is TBD

6.3 Optical Science Port

The optical science port has a FOV of 2.9 arcmin.

The f/ratio is 16.8

The plate scale is 338 µm/arcsec

The image of the telescope pupil is at infinity. i.e. the system at this focus is telecentric.

The footprint available for optical instrumentation is TBD.

6.3.1 Acquisition Camera

An acquisition camera will be provided at the optical science port. Initially 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. A possible alternative to the video is the use of an ING autoguider CCD. This possibility is currently being investigated.

As part of a system upgrade, it 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.

7. Alignment and Calibration

7.1 Introduction

Two sources are required at different locations for alignment and calibration purposes. Provision will be made to insert remotely a point source at the f/11 Nasmyth focus at any location within the field using an x-y translation stage. A second point source will be located off axis at the corrected f/16.8 focus to provide a diffraction-limited input wavefront for WFS calibration. It will be positioned just outside the 2.9 arcminute field but within the range of the WFS pickoff stage.

7.1.1 Specifications for the Nasmyth calibration source

This source will perform several functions:

a. Provide radiation over at least the 0.5µm to 2.2µm 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 minimizing the difference between laboratory calibrations and sky.

c. Map the AO system distortion over the full field for astrometry purposes. The repeatability of the mapping operation will be ? 0.01 arcsecond.

d. Introduce small (? 2.6 arcsecond, frequency <150Hz) motions of the source for functional checks of the AO control system.

e. 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.

7.1.2 Specifications for WFS source

The source may be positioned anywhere within the WFS field of view to allow generation of WFS transfer curves, i.e. plots of measured phase gradient versus actual phase gradient. The maximum source brightness will be equivalent to at least a magnitude-8 star representative of Clause 1 conditions and the brightness may be decreased by either a factor of 10 or 100, as desired, to simulate fainter stars. The source spectral bandwidth will cover 0.4 µm to 1 µm.

8. Global Opto-Mechanical Components

The following table lists all the opto-mechanical components of NAOMI.

8.1 Global opto-mechanical component table

Component	Type	Purpose	N
Alignment Beam Splitter	Cube beamsplitter	Two position 50/50 beam splitter which can introduce an f/11 alignment beam into the AO system. The f/11 alignment beam is principally used to set up the deformable mirror static state such that an optimal image is obtained at the science focus. The corresponding static values on the wavefront sensor are then taken as the zero values for closed-loop operation.	5 W
Alignment camera	Fast CCD - e.g. DALSA	To monitor the input to the AO system of both the alignment source and uncorrected stellar images. This camera will provide a very useful diagnostic tool for optimisation of the NAOMI control loops	
Alignment field stop	Circular Aperture	To provide a diffraction limited alignment image	
Alignment Source	Light source	To provide uniform illumination of the Alignment field stop with radiation from 0.4-2.5 µm.	W
Alignment pupil mask	Circular Aperture with central obscuration	To simulate the WHT exit pupil	
Alignment Field Position	Two axis slide.	The aberrations vary over the FOV of NAOMI. It must be possible therefore to insert the alignment source anywhere within the 2.9 arcmin FOV	±
Alignment Tip-Tilt injection	Small, fast, plane tip-tilt mirror	So that the tip-tilt control loop can be tested it is necessary to introduce a known fast movement on the alignment source. The movement may be sinusoidal or replayed from measured tip-tilt motions.	± tc
Fast Steering Mirror	Glass off-axis paraboloid, mounted on fast tip-tilt mechanism	Primary tip-tilt correction system. See FSM specification document.	F A B T
Deformable Mirror	Segmented mirror	Primary phase correction system. See Deformable Mirror and Drivers specification.	7

			C
Imaging OAP	Glass off-axis paraboloid	Reimages sky at an f/16.5 focal plane	F A
Dichroic Beamsplitter	IR reflecting beamsplitter	The initial NAOMI design has a dichroic beamsplitter which reflects a 15 arcsec FOV to the IR science port.	
WHIRCAM	IR Camera	256 x 256 IR camera, pixel scale 0.04 arcsec/pixel incorporating a correctly positioned and sized cold stop.	
Field lens	Achromatic lens	To put the image of the DM at infinity. This is required so that the image of the DM on the lenslet does no move on the lenslet when using off-axis guide stars	
Wavefront Sensor pickoff	Small plane mirror	To direct light towards the WFS	
Wavefront sensor field selector	3 axis slide	Moves the entire WFS assembly together with its pick-off. The XY motion is used to select a guide star for the WFS. To perform a dithering operation the pickoff is moved by the required amount with the control loops closed. The tip-tilt error which this produces will move the FSM and subsequently the telescope. This has the desired affect of changing the area on the sky which imaged at the IR science port without shifting the pupils..	± 4
Optical Science Port		This port is not required in the specification but is a by-product of the preservation of the 2.9’ tracking and acquisition field to this point in the optical train. The high bandwidth capabilities of the system mean that partial visible AO should be available here for bright guide stars (say V ~ 10 in good conditions).	S
Par-Align-Source	Point source injected just outside the corrected f/16.8 focus	Visible wavelengths covering the sensitivity of the WFS detector are required. The light is injected as a point source into the WFS pickoff area.	U
WFS Atmospheric Dispersion Corrector	2 pairs rotating prisms	Reduces effects of atmospheric dispersion for WFS star.	A
Wavefront Sensor Lenslet	10 x 10 lenslet array	Lenslets which match one-to-one with the segments on the ELECTRA DM	1 A F
WFS Shutter		Remote control shutter.	R

WFS Alignment Stage	WFS CCD automated stage.	See WFS specification	U
Wavefront Sensor Detector		High-speed, low-noise, frame-transfer CCD. See WFS specification AOW/SUB/RAH/2.8/02/96	

9. Software Architecture

Figure 14 indicates schematically how the software for the baseline NAOMI system is to be developed using the *maximal ELECTRA software re-use* policy.

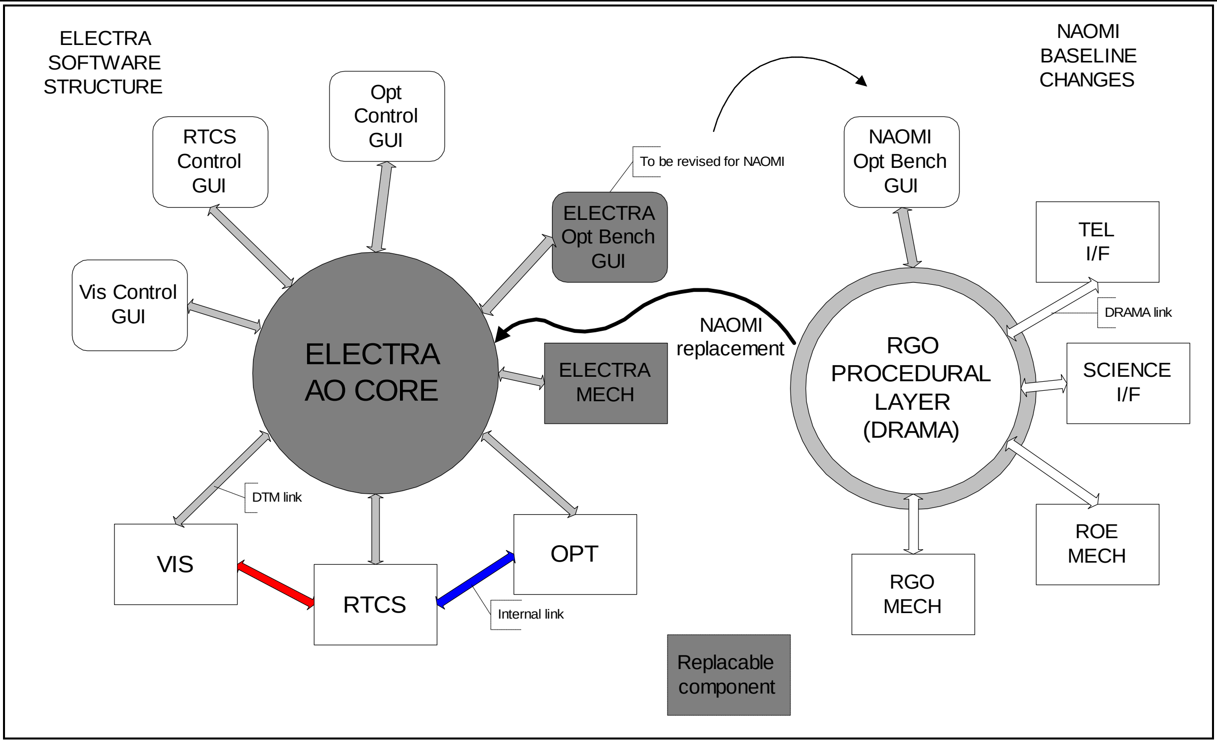


Figure 14: Schematic illustration of NAOMI software architecture showing maximal re-use of ELECTRA software components.

The ELECTRA system software has a number of presentation layer (GUI) processes communicating via DTM (NCSA Data Transfer Mechanism) with application logic located either on the C40s (RTCS) or the host (OPT) or both (VIS). The majority of the presentation layer exists.

The ELECTRA presentation layer also includes an optical bench metaphor GUI. This is an editable tool which has been initially configured for the ELECTRA EPICS mechanisms.

A minimal intervening layer is introduced between presentation and applications.

The maximal re-use of ELECTRA software involves retaining a large proportion of the ELECTRA presentation and application layers, modified as determined by ING, for NAOMI. A new intermediate layer is, however, to be introduced which will be mitigate all communications between presentation layers and application logic. This new PROC layer will introduce a full scripting facility and, as it will be DRAMA-based, it will be capable of communicating with all DRAMA-based telescope systems and instruments. It will therefore be capable of implementing a full interlock system. The initial communications provided from PROC will be concerned with the TCS (offsetting) and the ability to write AO information into the science headers. It will also provide access to the NAOMI mechanisms. The ELECTRA optical bench metaphor GUI will be revised for NAOMI mechanisms.

Sections 10 - 12 describe the software and computing subsystems in more detail.

10. Real-Time Control system

10.1 Architecture

The implementation for the real-time control system is based on an array of TI TMS320C40 parallel Digital Signal Processors (DSP's). Each C40 has the following features:

?? Multiply-accumulate optimisation: the processor can accomplish a floating point multiply, accumulate and 2 data moves in 1 cycle (40ns on a 50MHz processor)

?? local and global (shared) system buses to avoid contention. When the latter is mapped to, say, a 32-bit VME bus backplane it will provide for the “FIFO” data to be DMA-transferred to a workstation at up to 20 MB/sec.

?? 6 x 20MB/s communications ports with DMA engines on-chip. These communicate with other C40s. This provides for scalability and should allow zero or minimal contention monitoring of the wavefront and reconstruction data

?? JTAG scan chain providing an independent parallel debugging path with multiple independent hardware breakpoints.

The specifications in section 4.5.1 can be met by a ring architecture of 8 C40 processors, 2 of which are connected to 2 WFS ports each and one of which is connected to the DM drivers. All these internal and external data interfaces go via the C40 communications ports. An additional C40 with a larger memory buffer (32Mbytes) will be connected to the ring and will perform pre-processing of visualization data. The WFS and DM data input and out data rates will permit pipelining of ring data transport operations and all eight ring processors will have access to all slope and mode data.

Booting and command and status interfaces will be via C40 comm-ports using a connectionless protocol to a DTM (NCSA data transport mechanism) process on a Sun SPARC host which will also support debugging via an XDS/ JTAG interface.

An implementation of the above on Loughborough Sound Images and Sun SPARC station 10 is available for the ELECTRA development and testing stage of the project. NAOMI will be provided with a corresponding implementation on Arial Hydra C40 hardware and a Sun SPARC station host of ING's choice.

The software for NAOMI will include a DRAMA-based procedural system which will provide an interface between the real-time, optimisation and visualization systems and the corresponding GUI elements which will permit all command and status exchanges between these components to go via a procedural layer executed in the ING DRAMA environment and offering an upgrade route to accessing all future ING DRAMA-based instruments and services.

10.1.1 Upgrade

The system is readily upgradable by addition of further processors.

10.2 Real-Time Data Interfaces

10.2.1 Wavefront Sensor input

The real-time control system must have a high bandwidth data interface to the wavefront sensor camera. In the case of 4x4 pixels per subaperture, better than 8-bit digitization (12 is currently specified) and no pre-processing within the WFS camera, then an average of 8MB/sec must be accommodated. This would then deliver a readout latency of 250?s after frame transfer.

Multiport wavefront sensing CCD-devices will not be multiplexed into one input of the real-time control processor. Given a multiprocessor implementation and given also the inherent parallelism of the Shack-Hartmann data pre-processing, then it is in fact advantageous to flow the port data into different processing nodes. The implementation will flow the EEV-39 CCD wavefront data into two processors of the eight processor ring. Ring data distribution can be fully pipelined with data input at the above rate.

10.2.2 Deformable Mirror and FSM output

DM output to the ELECTRA mirror and FSM will be via the C40 comm port to DM DAC card interface developed at Durham.

10.2.3 TTS Upgrade

The real-time processing system can be upgraded to accept tip-tilt sensor data input via either C40 comm port or VME bus. The data can be processed to provide FSM, DM and TTS signals.

10.3 Real-Time Optimisation

The optimisation processing system will be implemented on the host workstation and will have access to all the wavefront and reconstruction data without contention. The initial implementation provided will be that of Gendron and Lena (1995). The requirement for this facility is described in section 0.

The optimisation system will also be capable of providing performance estimation to the science data acquisition system for possible inclusion in science data headers.

10.3.1 Upgrade

The real-time optimisation facility may be upgraded to perform future optimisation algorithms on additional processor attached to the C40 ring rather than on the host workstation.

10.4 Real-time visualization

ISO Open/GL and Motif/X11 based software will be available for visualization on any Unix workstation specified by ING which supports these facilities (at the time of writing this is believed to include all commercially-available new Unix Workstations). Visualization tools are available for displaying live or recorded data selectable from the real-time data flow as moving surfaces, images or traces.

This software is primarily concerned with development and fault-finding rather than observational use.

11. Observing System control interfaces.

Scientific requirements A (image quality) and D (dithering) require a link to the telescope control system to allow NAOMI to offset the telescope as DC tip-tilt components are detected.

11.1.1 TCS offset link specification

	Reference	**Comment**
Driving Science Requirement	Clauses 1,4	Permits AO-locked dithering without pupil shifts. Maintains average zero position on FSM (and, of course, thereby prevents over-ranging)
Detailed Specification	Software URD, ADD	

A method will be provided for writing AO data into science instrument file headers.

11.1.2 Science header data link specification

	Reference	**Comment**
Driving Science Requirement	Clause 6	Permits AO observational data to be included in science data headers. The baseline system will

		be for a programmable selection from all available integrated AO statistics.
Detailed Specification	URD	

12. User interfaces

The specification for user interfaces is driven by clauses 6 and 15.

User interfaces will be provided from the ELECTRA programme which will control all the real-time visualization and optimisation functions. Software will be provided to flow the operational command and status via a DRAMA based procedural system executing in the ING DRAMA environment. The ELECTRA user interface will be modified to cope with the new RGO and ROE mechanisms and will also access these via the DRAMA-based procedural layer.

12.1 GUI Upgrade

A full upgrade path shall be maintained whereby all user interfaces may be re-implemented to future ING GUI standards.

13. Observational capabilities and procedures

13.1 Introduction

Observational capabilities of the system design have been tested against observers requirements for infrared imaging and spectroscopy. Procedures will exist to allow observation of optically bright and optically faint/invisible sources, infrared bright and infrared faint/invisible sources. For sources which are faint at both optical and IR wavelengths methods are clearly more complex and for spectroscopy will rely on either very accurate (< 0".1 error) absolute positions being provided or similarly accurate offset positions from a bright source within 1'.4 radius. The same accuracy will be required for imaging if spatial registration against other images is needed which cannot be determined post-observing. See also the section (3.4.3) on non-sidereal rates.

In the baseline implementation the position registration will be defined by the relative position of the WFS pick-off to the optical axis (or WFS pick-off datum) and acquisition will be by a combination of TCS coordinates and a direct viewing mode of the WFS. A low-cost (video) acquistion camera will be available to carry out TCS calibration and to confirm system functionality. This camera will be able to distinguish objects at least as faint as V = 8.

Automation of acquisition procedures (e.g. using 'drag-and-click' on visible sources to position either the telescope or WFS stages) will be possible with an upgraded implementation of the acquisition software and acquisition camera.

13.1.1 Specification

	Reference	**Comment**
Driving Science Requirement	Clauses 4, 6	
Detailed Specification	software URD	drives necessary and desirable level of telescope, NAOMI and instrument interface, existence and accuracy of jitter mode (i.e. WFS pick-off accuracy and speed if not driven by other requirements), need and specs. for acquisition camera.
Performance Modelling	N/A	

13.2 Procedures covered

All the following procedures will be possible but some will not be optimized because of the minimal implementation of the link between the TCS, Instruments and NAOMI and implementation of the acquisition camera with point-and-drag capabilities.

- ?? system startup
- ?? system configuration
- ?? WFS calibration
- ?? optical alignment
- ?? determine rotation centre and calibrate TCS pointing (may be manual input in baseline system)
- ?? acquire setup star
- ?? set telescope focus
- ?? determine seeing parameters
- ?? set up target parameters
- ?? acquire science object
- ?? align science target/guide stars
- ?? determine closed loop parameters
- ?? make science instrument exposure, including dither operation if necessary
- ?? write data file with necessary headers (position, time, key NAOMI settings)

13.3 Upgrade Specification

Greater observing efficiency (Clause 6) will be possible if full image analysis facilities are available to the AO system to allow automated calibration and image size minimization to be carried out in a loop mode. Improving the functions implemented and extending the number of them is expected to occur as a continuing process driven by what is learned from the initial delivered system. The purchase of an upgraded acquisition camera and more sophisticated software to implement point-and-drag acquisition would significantly improve user efficiency.

14. Telescope, GHRIL and supported instruments

This section details the relevant working assumptions which the NAOMI specifications make about the telescope and its instruments.

14.1 Telescope

Final end-to-end performance predictions will require the following telescope data:

1. Formal values for the amplitude of WHT aberrations up to Zernike radial degree three. Interim values have been available for system design. Errors on these scales are correctable by NAOMI and so the issue is one of DM stroke.
2. The phase variance on spatial scales corresponding to less than 57cm on the primary (i.e. errors which NAOMI cannot correct).
3. The accuracy within which the telescope focus can be maintained (i.e. the resolution and stability of focus). NAOMI can correct focus errors and so the issue is one of DM stroke (and the requirement for off-loading focusing signals).

14.2 HAP

The improvement of intrinsic WHT seeing to free-atmosphere levels is regarded as outside the scope of the NAOMI project. The exception to this is Clause 21 which constrains introduction of additional seeing by the NAOMI systems themselves.

NAOMI performance predictions strongly support efforts to reduce local seeing.

14.3 JOSE

The taking and reduction of JOSE data is a high priority requirement for the NAOMI project. It is the primary means by which more effective optimisation algorithms can be developed [Clauses 2,6] and by which the accuracy of AO performance modelling can continue to be improved.

14.4 GHRIL

GHRIL issues are partly covered by section 16 (see also clause 17). The following NAOMI requirements with respect to the GHRIL are noted here.

1. Global (GHRIL-wide) EMC screening strategy
2. Assurance testing on GHRIL earthing
3. GHRIL global dust control
4. Thermal insulation of GHRIL optics room from GHRIL control room
5. GHRIL heat removal policy and general minimization of heat sources in the GHRIL area

14.5 Instruments

Information on any specific instruments to be supported should be supplied by ING.

15. Software and computing standards; maintenance issues

See the requirement in Clause 14.

The software for ELECTRA which is taken into NAOMI is being developed according to the distributed ELECTRA standards. These include a coding standard, source code control standards, and the use of DTM, Motif and Open/GL.

Coding standards for NAOMI AND ELECTRA will be adjusted and revised to the provided ING standards. A DRAMA-mitigated and ING-compliant procedural layer will be provided as part of NAOMI. See Figure 14.

15.1 Revision Specification

An revision of all software to future ING standards may be provided.

16. Handling and operational support requirements

16.1.1 Introduction

As can be seen from Clause 13 these requirements are largely driven by standards set by ING. The optical chassis design allows a modular implementation mechanically, with electronics also in a small number of racks with built-in cooling systems leading to air ducts. The air ducts should feed a global GHRIL cooling system (see section 14.4). The concept is that the racks and opto-mechanical modules can be removed mostly by hand (two people) but a small hoist is likely to be required for some modules. Removal and installation is expected to take several hours with this model. Installation on a similar optical bench elsewhere to allow pre-use alignment, fault tracing and maintenance will be similar to the GHRIL procedure. These issues are currently covered by a Strawman Support Engineering proposal, given below.

16.1.2 Specification

	Reference	Comment
Driving Science Requirement	Clause 13	
Detailed Specification	Opto-mechanical chassis	See also Straw Man proposal below
Performance Modelling	N/A	

16.1.3 Upgrade Specification

An upgrade is possible to the most efficient long term way for use of NAOMI which would be for it to have its own optical platform, a handling rig and attachments which enables it to be lifted out of GHRIL while fully assembled (including mounted electronics racks) and one or two ‘umbilicals’ for quicker connection to external facilities such as power and coolants. The GHRIL infrastructure and project funds do not allow this approach *ab initio*.

16.2 Support Engineering Strawman

16.2.1 **Dust control**.

The proposed system is to have covers over modules; the number and shape chosen to fit final layout but with a goal of not more than four.

An upgrade to an ideal system would require a design study of positive pressure environment with filtered input.

16.2.2 **Thermal control of GHRIL optics room components**

This is control of heat generated by bench components and nearby electronics (see Clause 21).

The proposed system is local cooling of all heat sources, either by water or air; heat taken to global GHRIL environment heat removal system. All electronics heat sources not associated with motors and drivers which must be on the optical bench should be above or away from the bench.

16.2.3 **Thermal control of GHRIL control room electronics**

This is control of computing and any other equipment required to be in vicinity of the GHRIL room especially the GHRIL control room (see Clause 21).

Ideal system: (i) good insulation between the two GHRIL room and other heat source;

(ii) local cooling of other heat sources with heat removed either by the GHRIL environment system or the equivalent for the appropriate area.

The proposed system is: (i) establish good insulation between the GHRIL optics and control rooms as soon as possible; (ii) monitor the GHRIL seeing performance during E0 and E1 tests, testing for local heat sources and trying effects of fans blowing across optical bench etc., (iii) ensure that the GHRIL global environment heat removal system is able to deal with other local heat sources.

Reasons: (i) a global heat removal system from the GHRIL area is certain to be required, especially if the concept of an enclosed GHRIL room is maintained.

(ii) the GHRIL area must not be allowed to warm up because (a) an excess temperature in GHRIL over that of the dome air of more than one or two degrees is likely to induce significant seeing degradation at the temperature interface and (b) the infrared thermal background increases with temperature and affects progressively shorter wavelengths.

16.2.4 **Thermal control of optical component surfaces**

This refers to control of optical component surfaces (see clause 17).

The Ideal would be that optical surfaces could be cooled to ambient (dome) air temperature and stable to < 1?C (although the concept of cooling to close to dew point would reduce thermal emission even more, it would also induce local convection currents which would be a worse problem than the thermal emission).

The proposed solution is to control only local heat sources and to remove heat from GHRIL generally but not to control directly the optical surface temperatures. The *Reason* is that given the number of surfaces which cannot be cooled (telescope) or it would not be wise to cool (DM, FSM), the differential gain from cooling the remaining two surfaces before the IR instrument would be negligible.

16.2.5 **EMC control and protection**

See Clause 18.

(this section to be developed further after current investigation by the project engineer into EMC suppression and rejection are completed).

The *Ideal* is (i) to reduce EM emissions in the GHRIL environment (Faraday cage?) and (ii) to have integrated system electronics grounding design and to take all standard precautions such as keeping signal and power cables well separated throughout system.

It is Proposed: (i) to measure the properties of the current EM environment at GHRIL; (ii) use E0 and E1 opportunities to learn more about the EM environment; (iii) to have integrated system electronics grounding design and to take all standard precautions such as keeping signal and power cables well separated throughout system; and (iv) to assign a group as responsible for EMC overall, including full system grounding.

This is standard practice in any case; note the as yet unknown sensitivity of DM and TTM to EM emissions.

16.2.6 System Testing and Installation.

Ideal: Fully integrated stand-alone GHRIL bench with ‘umbilical’ attachment to environment control; can be lifted as a unit after removing umbilical, placed on a handling trolley, taken to separate lab and operated fully with (e.g.) its calibration unit for alignment and testing.

Proposed: Modular build; goal of not more than five independent but accurately re-locatable modules on the optical bench and ~ five electronics racks; power and other (water cooling, pneumatic ?) supplies connected through well-designed umbilicals. Removal generally by hand if weight allows (see Email of 10/06/96 from SAB re support engineering) but realistically some units must need hoist for lifting; simplest possible handling trolley to allow safe transport of components; use another optical bench to re-assemble modules for testing; this bench must have attachments for NAOMI electronics, power and signal I/O as per GHRIL bench.

Reason: system design now allows reasonable opto-mechanical modules to be defined; some work needs to be done on estimation of electronics racks requirements. (This solution is likely to be the cheapest which meets the La Palma requirements for instruments).

17. Lifetime and downtime

See clause 16.

The adaptive optics components and associated electronics will be designed for a minimum of 3000 hours of operation with a goal of 10,000 hours. Parts that will fail before that time will be identified , together with the cost and delivery of replacement parts.

As a goal no more than 5% of the available observing time should be lost to AO facility failures.

18. Maintenance

System maintenance will be performed in accordance with ING procedures (see, for example, Clause 13)

19. Safety

See Clause 13.

Potential safety hazards will be identified and the appropriate measures will be taken to protect personnel, e.g. warning notices, covers with interlocks. Handling procedures and simple lifting aids, e.g. eye bolts, will be provided for heavy items. Only a simple handling trolley will be needed.

20. Documentation

See Clause 14.

Documentation will be include a Users' Manual, full system engineering diagrams as built, maintenance procedures and trouble shooting guidelines. The WP specifications and the WP Cover document define these requirements in more detail. The documentation approach will be to recognize that the system must be supported by staff who have good appropriate mechanical, electronics and software engineering skills but who did not build the system.

21. Future Development

The baseline project will provide an AO correction system for the WHT which is capable of doing state-of-the art worthwhile science. However the design has compromised important features, particularly sky cover and observing efficiency, to meet the budget. Throughout this document reference has been made to upgrade possibilities. The system design has, where reasonably possible, followed routes which will allow these compromises to be recovered. This will not be as cost-efficient as having built them in from the start but will allow system development largely by add-ons with no or minimal system re-design. Key development areas will be:

?? improved TCS and Instrument Control System interfaces, giving increased observing efficiency

?? more sophisticated real-time control system, allowing better optimisation between system performance and conditions.

?? introduction of a tip-tilt sensor, giving greater system stability and a laser-use capability

?? turbulent layer conjugation facility

22. References

1. R.W.Wilson and C.R.Jenkins, "Adaptive Optics for Astronomy: Theoretical Performance and Limitations", MNRAS 278, p39 (1996)
2. E. Gendron and P. Lena "Astronomical Adaptive Optics 2. Results of an Optimised Modal Control", Astron. Astrophys Supp., 111, p153 (1995).

23. Modelling Assumptions

The performance of NAOMI has been modelled using a number of techniques:

1. Using established scaling laws (RAH; RMM)
2. By analytical methods (CRJ, RWW)
3. Using numerical techniques (APD)

The common assumptions have been Kolmogorov turbulence and a constrained level of aberration in the WHT (i.e. the models are not *end-to-end*).

Input data on timescale and C_n^2 turbulence profile and strength parameters have been limited up to the present but this will change dramatically as JOSE statistics become available over the coming season. The use of the JOSE database with the existing models will give NAOMI a world-leading position amongst astronomical AO systems in the scope and accuracy of its modelling. It will remove virtually all assumptions about the atmosphere and telescope.

24. Deliverables List (TB completed)

24.1 Optical/mechanical components

The opto-mechanical on-bench components of NAOMI are listed in section 8. Work package divisions are indicated in the following subsections.

24.1.1 WFS Opto-mechanical

RGO-OptoMech-

24.1.2 Deformable Mirror

DUR-OptoMech-

24.1.3 Other Opto-Mech

ROE-Opto-Mech- : all other listed components including F/11 calibration unit and FSM.

24.2 Electronics

24.2.1 Mechanism control electronics

All the mechanisms listed in section 8 (apart from the DM and FSM) are controlled using EPICS via an ING standard set of VME cards and EPICS drivers. Work package divisions are as follows.

24.2.1.1 Mechanism EPICS rack

ROE-ElecRack-:

1. ROE-ElecRack-Crate. TBD-slot VME-rack, PSU, enclosure.
2. ROE-ElecRack-Proc. MVME-167 68040 VME processor card.

24.2.1.2 WFS mechanism control electronics

RGO-Elec-WFSMech

24.2.1.3 WFS camera electronics

RGO-Elec-WFSCam

24.2.1.4 Other Mechanism electronics

ROE-Elec-

24.2.2 Real-time control processors and electronics

24.2.2.1 C40 rack

Dur-C40Rack-:

1. DUR-C40Rack-Crate. TBD-slot VME-rack, PSU, enclosure.
2. DUR-C40Rack-Proc-68040. MVME-167 68040 VME processor card.

This rack is NOT the same as ROE-ElecRack-.

24.2.2.2 C40 processors

Dur-C40Proc:-

The nine TMS320C40 processors will be provided on Arial VME boards.

24.2.2.3 DM driver interface

Dur-DMDrivers:-

DM driver electronics will be provided in 6U electronics racking for all channels. PSUs and C40 comms port interface will also be provided. Digital DM strain gauge feedback circuitry will also be provided for all channels along with an interface to the C40 system.

24.2.2.4 WFS data interface

RGO-WP_WFSInterface:-

A C40 comms port based interface will be provided for the WFS data.

24.2.2.5 Optimisation and Visualization Interfaces

Due-OptVisInt:-

Interfaces shall be provided for transmission of optimisation to/from the host and visualization data to the console.

24.3 Workstations

24.3.1 NAOMI host workstation

DUR-SPARC Sun SPARCstation to be selected by ING. Development will use (Durham) SPARCStation 10 with 32MB. ING choice guideline: should equal or exceed specification of the development unit; lesser configurations may be tested. Functions of this workstation:

1. Host for EPICS system
2. GHRIL Engineering console
3. Host for C40 (real-time) system. Booting, control interfaces and services.
4. Host for C40 (real-time) software development and debugging
5. Can run AO PROC (Portable)

Displays generated by this workstation will be available via X-windows at other locations.

In the baseline implementation this unit must be located in the GHRIL control room due to the limitation in the lead length between the XDS/JTAG SPARC interface and the C40 processor rack. (If the CLRC WFS camera is adopted then the current telemetry (transputer) interface to ELECTRA involves a similar connection length to the SPARC). Any such restrictions may be overcome via an upgrade if required operationally.

24.3.2 NAOM I console workstation

Dur-console. Unix workstation to be selected by ING.

The functions of this console are:

1. Provide WHT control room access to NAOMI user interfaces.

2. Provide higher speed graphics for visualization functions.
3. Can run AO PROC (Portable)

The speed-critical visualization software may be ported and quantitatively evaluated on a demonstration/loan unit and compared with criteria confirmed during development. The fallback position for this unit is an ING-furnished X-server.

24.4 WHIRCAM adapted for use with NAOMI

(if required)

24.5 Software

24.5.1 Real time

Dur-RTSoft:-

C40 real-time software

24.5.2 User interface

Dur-GUI Soft:-

Host GUI software

24.5.3 Procedural

RGO-PROC:-

DRAMA-based procedural layer and interface with scripting capability.

24.5.4 Telescope interface

RGO-TelInt:-

DRAMA-based TCS interface.

24.5.5 Science Header DATA interfaces

RGO-SciHeadInt:-

DRAMA-based ICS science data header interface.

24.6 Operating manuals

24.6.1 Engineering

Proj-TroubleDoc:

System level Trouble shooting document

Proj-EngDiagDoc:

System Level Engineering Diagrams document

Proj-MaintProcDoc:

System Level Maintenance document

ROE-TroubleDoc:

Trouble shooting document

ROE-EngDiagDoc:

Engineering Diagrams document

ROE-MaintProcDoc:

Maintenance document

RGO-TroubleDoc:

Trouble shooting document

RGO-EngDiagDoc:

Engineering Diagrams document

RGO-MaintProcDoc:

Maintenance document

Dur-TroubleDoc:

Trouble shooting document

Dur-EngDiagDoc:

Engineering Diagrams document

Dur-MaintProcDoc:

Maintenance document

24.6.2 User

Proj-UserDoc:

System Level User document

ROE-UserDoc:

User document

RGO-UserDoc:

User document

Dur-UserDoc:

User document

25. Summary of NAOMI upgrade paths

25.1 Summary

NAOMI may be upgraded in the following ways:

?? A full implementation of turbulence conjugation: a method of extending the sky coverage available with natural reference stars (and also of controlling the field-dependence of the adaptively-compensated point spread function).

?? Complete integration into the observatory software and control systems.

?? Full laser-beacon compatibility.

25.2 System Level

Greater observing efficiency (Clause 6) will be possible if full image analysis facilities are available to the AO system to allow automated calibration and image size minimization to be carried out in a loop mode.

If a conjugation facility is implemented via a full concave lens (as opposed to a lens with a hole passing the science field unchanged) at the first Nasmyth focus, then the instrument will need a cold stop with adjustable position along the optical path and probably adjustable size.

25.3 Control Optimisation Processing hardware

Future optimisation algorithms requiring higher processing capacity may be implemented on additional processors in the real-time control computer rather than on the host workstation.

25.4 Observatory Interface Software

The software architecture will be designed such that the long term URD requirements can be implemented within the existing architecture. This upgrade would add the capabilities for the AO system procedures to control and co-ordinate all DRAMA-available functionalitity of the telescope and of other instruments AND for AO system functionality to be available to external process such as instrument control and TAG tasks.

An integrated telescope control - instrument control - NAOMI control GUI would be part of a software upgrade.

The long term goal is to have a fully integrated NAOMI, Telescope and Instrument interface mitigated by DRAMA.

25.5 User Interface

An upgrade route is available such that a full function GUI and visualization system may be provided which is fully compliant with ING standards.

25.6 Real-time computer

The system is readily upgradable by addition of further processors.

The real-time processing system can be upgraded to accept tip-tilt sensor data input via either C40 comm port or VME bus. The data can be processed to provide FSM, DM and TTS signals.

25.7 Analysis and alignment software

Greater observing efficiency (Clause 6) will be possible if full image analysis facilities are available to the AO system to allow automated calibration and image size minimization to be carried out in a loop mode. Improving the functions implemented and extending the number of them is expected to occur as a continuing process driven by what is learned from the initial delivered system. The purchase of an upgraded acquisition camera and more sophisticated software to implement point-and-drag acquisition would significantly improve user efficiency.

25.8 Software Specifications

An revision of all software to future ING standards may be provided.

25.9 Tip-tilt sensor

Provision is maintained for adding a tip-tilt sensor. This will extend NGS performance (with the faintest guide stars) and will provide a laser beacon capability.

25.10 Acquisition Camera

The low-cost camera at the optical/acquisition port 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.

Automation of acquisition procedures (e.g. using ‘drag-and-click’ on visible sources to position either the telescope or WFS stages) will be possible with an upgraded implementation of the acquisition software and acquisition camera.

25.11 Handling and Support

An upgrade is possible to the most efficient long term way for use of NAOMI which would be for it to have its own optical platform, a handling rig and attachments which enables it to be lifted out of GHRIL while fully assembled (including mounted electronics racks) and one or two ‘umbilicals’ for quicker connection to external facilities such as power and coolants. The GHRIL infrastructure and project funds do not allow this approach *ab initio*.

25.12 Dust Control

An upgrade to an ideal system would require a design study of positive pressure environment with filtered input.