Baseline Wavefront Sensor Work Package Description

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1.0 Introduction and General Requirements

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

1.1 Introduction

The wavefront sensor shall be based on the Shack-Hartmann configuration. In this configuration the input pupil is divided into several square subapertures by an array of small lenses; the number of subapertures is determined primarily by the atmospheric turbulence conditions and the compensation wavelength of the adaptive optics system. Each lens focuses the light from a guide star on a section of a detector array, e.g. 4 x 4 pixels, and the position of the focused spot's centroid is measured. The average phase gradient for each subaperture (when expressed in radians/subaperture) is determined by dividing the centroid shift of the focused spot by the effective focal length of the lens. Corrections are usually applied for wedge effects in the lens arrays and spatial non-uniformities in the detector-array characteristics. 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.

For many adaptive optics applications the subaperture size is sufficiently small that tilt is the only significant wavefront aberration present and thus each focused spot on the detector array is essentially diffraction limited. This will not be the case for all operating conditions of NAOMI. For this system the phase gradient will be measured in the 0.4 µm to a maximum of 1.0 µm spectral region whereas the compensation will be applied at longer wavelengths, generally from 1 µm to 2.2 µm. Although the higher-order aberrations over each subaperture may be small at the compensation wavelength, this is not necessarily so at the measurement wavelengths. Thus the wavefront sensor design must be designed to handle focused spot sizes and centroid motions that vary with the atmospheric turbulence conditions.

Subject to the results of the UK Joint Observatories Site Evaluation (JOSE) programme, the sensor should operate under conditions where the atmospheric coherence length, r_0 , at a wavelength of 0.55 µm is greater than 8 cm. Provisions to accommodate this range of conditions are discussed later.

The wavefront sensor shall normally operate with a lenslet array providing 7.35 subapertures across the telescope pupil diameter; the subaperture width as projected at the WHT aperture is 57.1 cm. The capability to operate occasionally with a nominal 3.68 subapertures per pupil diameter is also required; the WFS supplier should determine the optimum configuration (see Section 2.2). A Fried geometry is required, i.e. the ELECTRA deformable-mirror segments must map exactly on to the WFS subapertures. Note that lenslet arrays will be larger than 7.35 x 7.35 and the nominal 3.68 x 3.68 subapertures respectively to accommodate an upgrade to a turbulent-layer conjugation capability. Turbulent-layer conjugation is not a function of the baseline design. Further information on the lenslet array formats is given in Section 2.2. The sensor's lenslet array will focus the guide star radiation from each subaperture on a high-performance, low-noise CCD.

The CCD camera and its controller will either be supplied by the UK adaptive optics project or they will approve the choice. If the choice of a camera cannot be made readily then two WFS camera designs may be carried through to the PDR. The CCD should have 80 x 80 pixels for flexibility when imaging a dominant turbulent layer as part of the AO system upgrade. Although the CCD will provide a maximum of 8 x 8 pixels for use by each Hartmann spot, this pixel configuration may seldom be used except for acquisition purposes or in a spot-tracking mode if a very low noise CCD is available. Baseline operation will use 4 x 4 pixels (unbinned with a guard "ring"). The use of 6 x 6 pixels is anticipated for acquisition purposes in moderate to strong turbulence. The capability to change the pixel configuration, e.g., from 4 x4 to a quad cell, without losing lock is required. For preliminary design purposes the CCD pixels may be assumed to be 24 µm square unless the WFS supplier already has selected a specific CCD configuration.

A high performance 4-port CCD with low readout noise and high quantum efficiency is required. The serial data stream of pixel intensities from the CCD camera head will be fed to a wavefront processor which from a functional viewpoint may be regarded as an integral part of the wavefront sensor. The wavefront processor will be provided by the project as part of another work package. The main functions of this processor are to correct the raw intensity data, e.g. for spatial variations in the CCD response, and to calculate the phase gradients. The latter are then sent to the wavefront reconstructor which calculates the wavefront phase. The processor also calculates the intensity at each subaperture; these data are sent to a real-time display and a recording system. The reconstructor, display and recording systems are covered by other specifications. The processed wavefront data will be used to perform at least the three functions below; these functions are described primarily for information purposes.

1. Tip-tilt data will be sent to the fast steering mirror except for DC and large, low-bandwidth tilts which will be unloaded to the WHT control system (See Baseline Optical Chassis WPD AOW/SUB/5.0/07/96 for further information).

2. Higher-order wavefront data will be used to control the system's deformable mirror except for telescope focus errors as noted in the third function.

3. Focus error will be offloadable to the telescope to keep the telescope wavefront focus peak-to-valley error < 0.2 µm.

The sensor design will also incorporate equipment for calibration and alignment as specified in Section 5.0.

1.2 Overall Size, Opto-Mechanical Interfaces and Configuration

The WFS pick-off design will maintain the guide star on the WFS optical axis regardless of its position within the field of the telescope. The WFS pick-off must allow the acquisition of a guide star anywhere within the unvignetted Nasmyth field.When needed it must also support dithering using the selected guide star.

The following description gives a pick-off specification which is couched mostly in terms of a preferred implementation. Note that the pick-off specifications are intended to apply to the positioning of the WFS as a complete assembly and thus the WFS design should not compromise the required pick-off performance in any way. Minor changes to described implementation concept are allowed provided they do not affect the overall operational concept. The NAOMI system engineer should be informed of any proposed changes.

The guide-star pick-off will be mounted on a remotely controlled 2-axis stage with motion in the x and y axes. The stage axes are defined relative to the corrected f/16.8 focal plane with the y-axis in a vertical plane. Motion in the x-y plane allows the guide star to be selected by translating the pick-off mirror(s) and its mounting plate(s) to the designated field point. This motion also allows the dithering mode to be supported. Table 1 gives the pickoff specifications for the x and y axes. All ranges are minimum values and they do not allow for alignment errors or the need to accommodate the WFS calibration source; consideration must be given to providing additional range as appropriate. Two dithering ranges with different repeatabilities are required by Clause 4 and these are addressed in Table 1.

Table 1. Specifications for x and y axes of the WFS pick-off.

FUNCTION	REQUIREMENT
Acquisition	Range: ± 32.5 mm
	Step size: ? 7 µm
	Accuracy: ? 3.4 µm
	Maximum Speed: ? 1.9 mm/second
Dithering	Repeatability:
	a) ± 3.4 µm (± 0.01 arcsecond) or better for a total dithering range of 1.7 mm (5 arcsecond)

	b) ± 8.5 µm (± 0.025 arcsecond) or better for a total dithering range of 6 mm (18 arcsecond) Amplitude accuracy: ± 17 µm (± 0.05 arcsecond) or better

The specifications given in Table 1 apply to sidereal objects. As a design goal the WFS should be able to operate with non-sidereal objects, e.g. Jupiter's satellites or asteroids.

When using a non-sidereal object for wavefront sensing and observing a different non-sidereal science object, the maximum differential rate for the x and y axes shall be 2.3 µm/sec (0.007 arcsec/sec); a typical rate may be about 0.8 µm/sec (0.0023 arcsec/sec). When observing sidereal science objects and performing wavefront sensing with a non-sidereal object, the maximum rate shall be 13 µm/sec (0.04 arcsec/sec); a typical rate may be 4.5 µm/sec (0.013 arcsec/sec). In both modes an accuracy of ± 0.02 arcsecond or better shall be a design goal. The tracking accuracy should be maintained over at least a 5-minute period with a goal of > 10 minutes. If multiple exposures are required, e.g. several 5-minute exposures, then the pick-off position shall be reset at the end of each exposure to remove any cumulative offset. Repositioning to within 0.01 arcsecond is required. Any effort expended in meeting or attempting to meet these goals should they prove very difficult must not significantly increase costs. If such a problem is anticipated an alternative approach may be considered that, although not complying completely with these specifications, still provides a potentially useful capability. Approval must be received from the project before alternatives are implemented.

The z axis is defined as the optical axis and for the WFS it will be folded in a horizontal plane at 90 degrees to the optical axis of the second off-axis paraboloid. The Main WFS assembly will be divided into two modules mounted on a common slide (or rails) but with independent position control. The slide will define the direction of travel for the z axis. One module will consist of a collimating lens, an atmospheric dispersion corrector (ADC), spectral and neutral density filters, and lenslet arrays. The other will support a relay lens, shutter, the WFS camera and probably the controller. When changing lenslets the latter unit will be moved to the image focus of the selected lenslet array. When moving the pickoff to different field positions the two modules will move together to maintain focus. Note that the removal of field curvature will be accomplished in this manner. The range of motion should be sufficient to cover at least the field curvature over the entire field, together with any initial positioning error, but need not handle the large focal shift (about 53 mm) associated with laser guide stars (system upgrade). The positional accuracy of the two WFS movable modules shall be such that each module remains within the depth of focus and the performance specifications are satisfied. The maximum z-axis speed shall be : ? 1.9 mm/second.

An EPICS interface shall be provided for all three axes. The software latency shall be less than 100 µsec to provide good performance under dynamic conditions. Further information on electrical interfaces and software requirements will provided in the Interface Control Documents and Software Requirements Document when available.

Figure 1 shows the two-dimensional space allocation for the WFS . Note that for the laser upgrade the WFS specified in this work package description may be used as a tip/tilt sensor and, if so, a new WFS would then be constructed for use with laser guide stars (LGS). Thus Figure 1 also shows space for the LGS WFS upgrade.Figure 1 is also available as an AutoCAD file from Colin Dickson and in the Drawings area of the NAOMI BSCW facility. at ROE. The drawing number is 00A03L and the last revision is dated 19 December 1996. Detailed dimensions are contained in this file and the file shall be treated as part of the WPD. Note that a recent proposal to mount the WFS calibration source on the field-lens/dichroic assembly is under consideration and, subject to agreement between all parties involved, the space envelope drawing will be updated as soon as possible to include this change. The equipment height should not extend more than 1 metre above the table surface. The AO-system optical axis will lie at 150 mm above the table surface.

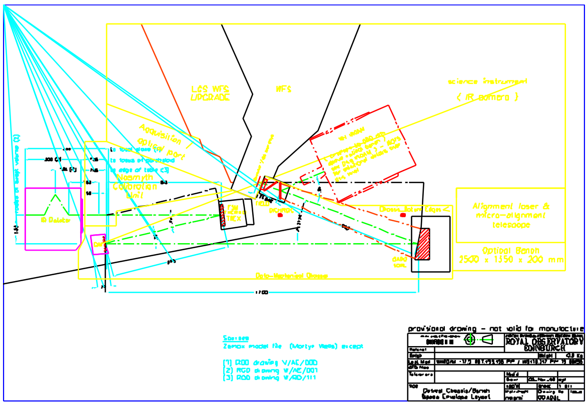

Figure 1. Space allocations on GHRIL table .

Although the tip/tilt sensor (TTS) is planned as part of the system upgrade for laser-guide-star operation, there is a remote possibility that a TTS may also be required in the near term system. The WFS supplier should ascertain that a simple TTS such as fibre-coupled APDs in a quad-cell configuration could be incorporated in the NAOMI optical train, e.g. at the optical science port. Any anticipated performance limitations, e.g. using only separate guide stars for tracking and higher-order wavefront sensing, should be stated. Significant effort should not be expended on this task. The intent of these specifications is only to establish feasibility and these specifications should not be interpreted as a requirement for a TTS.

Note that to keep the weight of the moving assemblies to a minimum, some components, e.g. power supplies, need not be mounted on the moving assembly. Any proposal to mount such components elsewhere requires approval by the project.

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The WFS module will register against the adjacent optical-chassis module. The registration repeatability should be < 50 µm in all three axes. The design of this interface should be the result of collaboration between the optical-chassis and WFS suppliers. The project expects that the initial global alignment of the WFS to the optical chassis will be done with mechanical spacers and/or shims.

The WFS assembly shall have the capability to pivot in azimuth and elevation about the axial f/16.8 focus for the initial angular alignment to the optical chassis. The adjustment range and accuracy shall be determined by the WFS supplier. The adjustment mechanism must allow continous viewing of the illuminated pupil relative to the pupil fiducial mask described later in Section 5.2.1. A functionally equivalent approach is acceptable provided it does not violate the preceding condition.

1.3 Main WFS Assembly

The main WFS assembly includes the components from the pick-off optics to the CCD, all mounts and adjustment mechanisms for these components, covers and baffles. Components beyond the pick-off optics include a collimating lens, interchangeable spectral and neutral-density filters, an atmospheric dispersion corrector (ADC), a shutter, interchangeable lenslet arrays, and a relay (or transfer) lens. The mounting plate or optical bench to support the components listed above is the responsibility of the WFS supplier. Note that this description of the main WFS assembly is intended as a guide and it is not necessarily complete.

1.4 Measurement Accuracy and Range

The phase-gradient measurement accuracy along any axis shall 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 specification includes the effects of sensor noise, photon noise and other sources of error.

At low light level with reduced sensor noise, i.e., the conditions for Clause 2, the measurement accuracy shall be equal to or better than 0.14 $?_C$ rms (where $?_C$ = 2.2 µm) over each subaperture when operating with ? 40 photons per subaperture per measurement incident upon the CCD when used in a quad-cell mode. These measurement accuracy specifications apply to a visible atmospheric coherence length of 20 cm.

Under worst-case conditions (visible r_o of 8 cm) the phase gradient measurement range shall be at least ± 1.5 waves/subaperture (2.2-µm wavelength) when operating in a 4 x 4 pixel mode. This range assumes Kolmogorov turbulence characteristics and it includes the effects of the specified AO-system wavefront errors, residual tilt but not the contributions from the WHT optics (presently unknown). For operation under favourable conditions (visible r_o ? 13 cm) a range of at least ± 1.5 waves/subaperture over 8 x 8 pixels is acceptable.

The capability to operate over the required range of atmospheric turbulence shall be demonstrated in the laboratory with simulated turbulence; the use of phase screens is acceptable for this purpose. The test shall demonstrate that the wavefront sensor can cover the required range without significant spill-over of the focused spots into regions of the CCD used by other subapertures.

1.5 Reliability

Clause 16 requires that the WFS camera shall have an operational lifetime of > 10,000 hours. All other components shall exceed this lifetime requirement. As required by Clause 19, where appropriate the same type of electronic components should be used as are already in use at the ING. Where other components are used a minimum of one spare for each type shall be supplied. Any exceptions shall be subject to a specific agreement with ING.

1.6 Health and Safety

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

2.0 Optical Design

2.1 General Requirements

The input to the WFS will be the image of a guide star located at the corrected f/16.8 focus. A field stop compatible with the sensor’s maximum acquisition range is required. The pick-off optics direct the guide-star light to the WFS. The pick-off optics are expected to consist of a plane, parallel-sided glass plate with a small mirror or prism mounted on one optical surface which directs the guide-star light into the WFS. The plate’s optical surfaces will be perpendicular to the optical axis at the corrected f/16.8 focus. The mirror or prism may be moved anywhere within the field to pick off the guide star light. Mounting approaches other than a parallel-sided glass plate require project approval.

The light from the guide star is collimated by the WFS collimating lens and passes through a selected filter (see Section 2.3) before reaching a lenslet array. The axial position of this array will be coincident with an image of the deformable mirror. A relay (or transfer) lens will produce a demagnified image of the lenslet’s Hartmann spots at the CCD. The demagnification will be chosen to place each spot ideally at the centre of each pixel array for an on-axis input point source. The optical system aberrations shall not displace any spot from an evenly spaced array by more than 20% of the CCD pixel size. Note that the allotment to the WFS optics alone will be determined when analysis of the system optical design is complete. Determination of this allotment will be the responsibility of the optical chassis supplier; the allotment will be subject to project review and approval. The relay lens and CCD will also have sufficient axial travel to allow the lenslet array to be imaged at the CCD for alignment purposes. An atmospheric dispersion corrector (ADC) is also required . Specifications for this component are given in Section 2.4.

The wavefront sensor shall operate over the 0.4 µm to 1.0 µm spectral region. Transmission and scattering losses into the optical train shall be kept to a minimum by following good optical design practices including the use of high efficiency coatings and low scatter surfaces. The WFS transmission shall be ? 90 per cent averaged over the 0.5 µm to 1.0 µm spectral region. The transmission below 0.5 µm shall be on a “best-effort” basis without requiring any coating development.

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

Optics needed for calibration purposes are discussed in Section 5.1.

2.2 Lenslet Arrays and Relay Optics

Three lenslet arrays and associated relay (or transfer) lens(es) shall be provided to image the Hartmann spots on the CCD. The lenslet arrays shall be interchangeable under remote control in less than 5 minutes; this requirement includes any time needed for realignment and recalibration. Any lens adjacent to the CCD shall have a minimum back focal length of 10 mm to provide sufficient clearance from the CCD window. Note that this specification is being revisited at the request of RGO and, if necessary, it will be changed as soon as possible. A pupil fiducial mask is also required (see Section 5.2.1) in the lenslet holder as an alignment aid.

Two of the arrays shall each have at least 10 x 10 lenslets when operating with 7.35 subapertures across the telescope pupil; 14 x 14 lenslets are strongly preferred if they can be provided at no significant additional cost. The smaller number of lenslets allows a partial but potentially very useful turbulent-layer conjugation capability to be implemented as a minimal-cost upgrade. The larger number would be needed for conjugation over the full field but further modifications to the WFS would be required to realise this capability fully (see Section 2.7). One of the arrays shall be designed for use with moderate to good seeing conditions (r_O ?13 cm) and the other shall be for poor seeing conditions (r_O < 13 cm). The size of each lenslet (subaperture) is expected to in the range 0.5 x 0.5 mm^2 to 2 x 2 mm^2. This range should be consistent with commercially available arrays and keep aberrations to a minimum. The third array will have a nominal 8 x 8 lenslets when operating with a nominal 3.68 subapertures per pupil diameter. It is intended for occasional use when such an array may provide a performance advantage, e.g. at very low light levels. The WFS supplier shall determine the number providing optimum performance; assistance and advice may be sought from the project if required. Selection of the number of subapertures for spatial descoping is subject to project approval.

The lens arrays shall have a fill factor of ? 98 percent. When used with monochromatic radiation of wavelength ? ?(where ?= 0.65 µm), the wavefront quality shall be better than ?/4 peak-to-peak. Chromatic aberration shall not increase the image size at the detector focal plane by more than 10% of the diffraction limit at a wavelength of 650 nm. Each lens in an array shall not diffract or scatter more than 2 percent of the incident light into adjacent subaperture pixel arrays of the CCD.

Ideally the Hartmann spots formed at the CCD should be ? 1.8 times the CCD pixel size to give a smooth transfer curve when operating with ? 4 x 4 pixels/subaperture (see also the "Calibration and Alignment " section.) Note that, for the purposes of these specifications, the diffraction-limited spot size for a square subaperture is defined as 2 x ? x focal length / subaperture width. Because the subaperture sizes will usually be larger than the visible r_O and the sensor can operate over a broad spectral band, the project recognises that the spot size will not necessarily be optimum for all atmospheric turbulence conditions and spectral bandwidths. For design purposes, a wavelength of 0.65 µm shall be used when calculating spot size.

Note that all other WFS optics should be sufficiently large to allow full utilisation of the lenslet array sizes selected, i.e. no hardware changes should be required to implement at least a limited turbulent-layer conjugation capability as discussed in Section 2.7. Note that turbulent-layer conjugation is a system upgrade and it is not a function of the baseline design.

2.3 Spectral and Neutral density Filters

All filters shall be remotely interchangeable. The following spectral filters shall be provided.

Wavelength Range (µm at FWHM)
0.6 to 0.7
0.5 to 0.8
0.4 to 1.0 (Blank space acceptable)

The peak transmission of each filter shall be ? 80% with a goal of ? 90 %. At 0.2 µm outside of the FWHM points and beyond the filters shall transmit ? 0.1 %. This choice of filters is nominal and it should be reviewed as part of the work package. Any change from the nominal specifications requires project approval. Neutral density filters of 1.0 ± 0.1 density and 2.0 ± 0.1 density shall also be provided. The spectral filters and neutral-density filters shall be independently selectable, i.e., separate filter wheels or slides for each type. Provision shall be made to accommodate an additional three spectral filters, e.g. broad band and notch filters with the latter eliminating scattered light from the DM figure monitor. All filters shall be manually removable from their holders for replacement by other filters of the same size if desired by the user.

2.4 Atmospheric Dispersion Corrector

An atmospheric dispersion corrector (ADC) shall be provided to correct for atmospheric dispersion at zenith angles up to 60 degrees over at least the 0.5 µm to 0.8 µm spectral region. The residual dispersion after correction shall be ? 0.025 arcsecond in object space. Any pupil shift caused by the ADC shall be ? 3% of a subaperture width subject to the conditions given in paragraph below. The ADC shall have a clear aperture equivalent to at least 14 subaperture widths (for 7.35 subapertures/pupil) to accommodate off-axis guide stars when conjugating to the turbulent layer. The ADC shall be remotely controlled with a rotational accuracy of ? 1 degree.

If difficulty is encountered in meeting the pupil-shift specification, then the following approach is acceptable to the project. Before starting an observation the ADC is set for the mean guide-star angle and, if necessary, the deformable mirror is laterally aligned to the lenslet array using its x-y stage. The differential pupil shift (chromatic and mean position) over the duration of the observation (1-hour maximum) must then satisfy the 3% specification.

The optical quality shall be such that the requirements of Section 2.1 are satisfied. Any pointing error introduced by the ADC shall not exceed 0.05 arcsecond in object space for any zenith angle change of at least 15 degrees within the specified range of 60 degrees. An EPICS interface is required for control of the ADC,

2.5 Shutter

An electronic shutter is required. The shutter response time shall be < 75 milliseconds to prevent CCD damage if the NCU He-Ne laser is inadvertently focused on the CCD under worst-case conditions. An EPICS interface shall be provided for external control of the shutter. In the absence of electrical power the shutter shall be closed. The shutter’s location in the optical train is not critical provided the optical path beyond the shutter is properly enclosed to prevent any stray light from reaching the CCD.

2.6 Optics for Calibration and Alignment

Optics shall be provided for various calibration purposes as specified in Section 5.0 on Calibration and Alignment.

2.7 Upgrade to Turbulent-Layer Conjugation

The combination of the 80 x 80 pixel CCD with a 10 x 10 lenslet array will allow the upgrade to a turbulent-layer conjugation capability to be carried out with no hardware changes to the WFS. With this configuration a field of at least 102 arcseconds diameter without vignetting can be covered for a dominant turbulent layer at a height of 3 km above the telescope. If 14 x 14 lenslet arrays are provided, the feasibility of installing remotely-driven stages to allow the CCD/relay-lens assembly to track the illuminated lenslet area should be assessed. A concise technical explanation should be given if this is not practical . This task should not involve significant design effort. Note that turbulent-layer conjugation is not a function of the baseline NAOMI system and the installation of such stages, if feasible, would be an upgrade.

3.0 CCD Camera and Controller

The WFS CCD camera and its controller will either be supplied by the adaptive optics project or they will approve the choice. The specifications are based on performance claims for existing high performance CCDs.

A CCD with a minimum of 4 ports is required. The CCD should have two readout rates that will be electronically switchable without recabling; a moderate priority goal is for on-the-fly (loop closed) switching. 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 should have ? 3 noise electrons/pixel with a goal of ? 2 noise electrons/pixel and at the maximum readout rate the readout noise should be ? 7 noise electrons/pixel with a goal of ? 5 noise electrons/pixel. The maximum readout rate applies when operating with 4 x 4 binning (with guard "ring") over all subapertures with a latency of ? 250 µsec.

The binning of pixel arrays, e.g. to operate in a quad cell mode, for readout-noise reduction is required. Readout formats should accommodate selection of sub-arrays of pixels within each subaperture array, e.g. 6 x 6 (acquisition only), 4 x 4 pixels.

The quantum efficiency should exceed 80 % over the 0.5 µm to 0.8 µm spectral region with a peak of > 90 %.

The pixel intensity data should be digitized to 12 bits.

4.0 Wavefront Processor (Note: The wavefront processor will be part of RTCS and thus this section is included primarily for information purposes .)

The wavefront processor must perform several functions. First it provides a corrected intensity value for each CCD pixel in the subaperture arrays. This correction takes into account any background offset and variations in the quantum efficiency of the CCD pixels. The corrected intensity I_p for a pixel p is given by the following equation.

$$I_p = (C_p - B_p) G_p$$

where C_p = uncorrected intensity
B_p = background offset
G_p = inverse of pixel quantum efficiency.

The wavefront processor shall have a serial output port to provide the corrected pixel intensity data to a real-time display and a data recording system. The processor shall have the capability to set a low light level flag for any pixel data that fall below an operator-selected limit, e.g. 100 photons per pixel. In this event the operator shall also have the option to set the calculated phase gradient value to zero.

The phase gradients for each subaperture shall be calculated separately for the x and y axes of the CCD. The algorithm used to calculate the phase gradient will depend on the pixel configuration selected, e.g. 4 x 4 pixels, 2 x 2 pixels. With the provision that the performance specifications must be satisfied, the wavefront sensor supplier may select the algorithm for each pixel configuration. The centroid position shall then be converted to a phase gradient value through a tilt gain. This tilt gain is predetermined for the x and y axes of each subaperture as part of the calibration process (see section on calibration and alignment).

The final step performed by the wavefront processor shall be to correct for non-common path aberrations and focused-spot offsets caused by errors in the lens array. This step allows for effects seen only by the wavefront sensor that must not be included in the correction provided by the deformable mirror. The approach to the calibration of non-common path aberrations will be determined by the optical chassis supplier. These values shall be subtracted from the phase gradients measured during normal operation.

The wavefront processor shall maintain the 12-bit precision of the CCD camera data. The time to read out the CCD data and provide the phase gradients shall not exceed 250 µsec with 4 x 4 pixels/subaperture. The capability to sample the data stream at all stages of the processing shall be provided.

5.0 Calibration and Alignment

5.1 Calibration

The design shall allow several calibration functions to be performed. These shall include at least the following:

1. The determination of WFS transfer curves. (Range, linearity and tilt gain information can be obtained from these curves.)

2. The calibration of WFS errors, e.g. Hartmann spot offset errors due to aberrations in the WFS optics.

3. The calibration of CCD camera errors.

Provision shall be made to inject a reference wavefront from a light source at or close to the AO-corrected f/16.8 focus. As a design goal the WFS calibration unit feed should be over the top of the pickoff or in its vicinity. If packaging constraints present significant problems, the WFS supplier has the option of inserting the source beyond the pick-off but before the WFS collimating lens provided the calibration functions are shown to be still valid. This source will be used to perform the first two calibration functions specified above and possibly the third. Light from this source will pass through the WFS collimating lens to produce a plane wavefront. The tilt of this plane wavefront shall be remotely and independently variable in the x and y axes over the maximum operational phase gradient range of the wavefront sensor. This function may be provided by the WFS pick-off stage. The wavefront tip/tilt shall be calibrated by independent means to an accuracy at least a factor of two (2) better than that required for the wavefront sensor. The spectral bandwidth of the source shall cover 0.4 µm to 1 µm. Its radiant intensity integrated over this bandwidth shall be at least 3 x 10^{-8} W ster^{-1} but it shall not be high enough to saturate any CCD pixels. The radiant intensity should be uniform over the f/16.8 beam. The spectral distribution shall match that of a star in the spectral class range G0 to K0. A slot shall be provided for the manual insertion of an additional filter if the need arises to modify the source brightness or spectral characteristics. The space and interface requirements for this source shall be provided to the optical-chassis supplier to avoid any potential conflict with the optical chassis design.

Transfer curves shall be generated to assess the linearity and range of the wavefront sensor. A transfer curve is defined as a plot of the measured phase gradient versus the actual input-wavefront phase gradient for a subaperture. The ideal sensor should have a transfer curve that passes through the origin with a slope of unity. Except when operating in a 2 x 2 pixel mode, the transfer curve should vary by less than ± 15 percent to provide adequate servo stability.

A radiometric calibration source shall be provided to calibrate the pixel responsivity of the CCD pixels, i.e. to perform flat fielding. The source may be the same source used to generate the plane wavefront for the phase-gradient calibration. In this event provision must be made to easily remove and replace the lenslet array , i.e. to allow the central region of the collimated beam to fall on the CCD. Any diffusers that may be required to produce the required illumination uniformity may be inserted manually as flat fielding is expected to be an infrequent operation. The source brightness shall be equivalent to at least a magnitude-8 star. The source shall allow measurements of the relative gain of each pixel to be measured over any 0.1-µm region within the 0.4 µm to 1.0 µm spectral band. The accuracy of the gain calibration shall be ? 1% rms. The CCD shall have a remotely controlled shutter to allow measurement and recording of the fixed pattern noise. The background offset of each pixel (see Section 4.0) shall be determined to within 1 electron per sensor integration period (usually < 25 ms); the ability to determine the average offset over several (>10) consecutive frames is required. The probability that the measurement error is ??1 electron shall be ?0.3.

5.2 Alignment

5.2.1 Alignment of Lenslet Arrays

A manual adjustment capability to initially centre each lenslet array on the WFS optical axis must be provided. Note that the adjustment may be performed using an external jig or alignment fixture. . The resolution of the adjustment mechanism should be sufficient to achieve an alignment accuracy of better than 0.025 of the deformable-mirror centre-to-centre segment spacing. The remote adjustments to switch between the lenslet arrays shall maintain these alignment accuracy requirements. Note that in routine operation fine adjustment of the deformable mirror image to the lenslet arrays will be performed by moving the deformable mirror on a 2-axis remotely controlled stage.

A pupil fiducial mask, interchangeable with the lenslet arrays, is required as an alignment aid. The mask shall indicate the required position of the optical system's exit pupil at the location normally occupied by a lenslet array. The mask may consist of a circle inscribed on a glass plate with the circle diameter equal to the desired pupil diameter. The optimum design for this mask shall be determined by the WFS supplier in consultation with the optical-chassis supplier.

5.2.2 Transfer Lens and CCD (as an assembly) Alignment to Lenslet Array

The z-axis (or focus) range shall be sufficient to allow imaging of either the Hartmann spots or the lenslet array on the CCD. A 10% range contingency should be added.

All adjustments must have sufficient resolution and range to satisfy the measurement range and accuracy requirements given in Section 1.4.

5.2.3 CCD Adjustments

The CCD should have x and y adjustments for initial positioning of the CCD to the optical axis of the relay lens(es). These adjustment may be manual. The manual z-axis motion should be sufficient to accommodate any departure of the relay-optic focal length from its nominal value and to adjust the reduction factor as required.Note that the use of shims for the fine adjustment of the CCD to relay lens separation is acceptable.

5.2.4 Filter Adjustments

The filter lateral positions are not critical provided each is positioned so that all light falls within the clear aperture. Any wedge in the filters must be such that all specifications are satisfied.

5.2.5 Atmospheric Dispersion Corrector (ADC)

The rotation accuracy of the ADC should be < 1 degree. The alignment shall also satisfy the relevant requirements of Section 2.4.

5.2.6 Shutter

The shutter position is not critical provided its aperture does not vignette any beam.

6.0 Independent Control Module

An independent control module is required for laboratory tests of the WFS as a separate assembly. This module should exercise sufficient control to demonstrate the basic WFS functions.

7.0 Environmental Requirements

7.1 General Requirements

The overall requirements are driven by Clauses 17 and 21.

All WFS components within the GHRIL shall operate within specification over a temperature range of -10°C to 25°C in relative humidity from 10% to 90%. Any prediction of failure to satisfy this requirement shall be briefly documented and submitted to the AO project manager. An environmentally conditioned enclosure for the WFS will not be part of the baseline system. Note that while certain components, e.g. rack-mounted electronic components, may be housed in environments with temperature excursions less extreme than specified above in normal operation, the system must be able to cope with a start-up from a lengthy powered-down state within the GHRIL environment. For example the heat generated by electronic components in normal operation may keep the interior of a rack well above -10°C when powered up and therefore apparently allow components specified to 0°C to be used, but these components could fail on a cold start. Any special measures to control the temperature of components must not only comply with Clause 21 but also require project approval. The maximum free atmosphere temperature variation expected within the GHRIL is TBD °C / hour; this variation is important when designing the WFS to meet the requirements of Clause 5 (see Section 7.2 below). All WFS components within the GHRIL shall be able to survive relative humidity of 100%. Protective measures may be employed, subject to project approval, to guard against extreme conditions when the equipment is not operating.

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

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

The baseline WFS will have only a cover over the module that can be sealed for dust protection when the system is not in use.

There will be local cooling of all heat sources in the GHRIL, either by liquid or air. The heat will be taken to the global GHRIL environment heat removal system. Global control of the GHRIL environment is the responsibility of ING. The WFS supplier will be expected to work closely with ING and the AO project in this area. All electronic heat sources not associated with motors or drivers which must be on the bench should be above or away from the bench. In accordance with Clause 21, the combined opto-mechanical bench, DM, FSM and WFS thermal sources must not degrade the uncorrected local seeing by more than 0.1 arcsecond with a goal of no detectable degradation.

Any equipment installed in the WHT control room must operate to specification over a temperature range of 10°C to 30°C.

7.2 Vibration and Stability

All AO components and their mounts shall exhibit good stability consistent with the optical and environmental requirements. In particular the WFS shall be designed such that the performance specified in Clauses 1, 2 and 3 is achieved for integrations up to 1 hour without recalibration, provided the telescope alignment and focus stability does not limit the system performance. This requirement is driven by Clause 5. As a design goal the WFS position should not drift over a 1-hour period by more than 5 µm in any axis relative to the intersection of the AO system's optical axis with the corrected f/16.8 focal plane. For design purposes the optical axis shall be assumed to remain fixed relative to the GHRIL table over this period.

Uncorrectable tip/tilt jitter induced by WFS vibration sources shall not exceed 17 nrad rms (0.0035 arcsecond rms) in object space. Uncorrectable tip/tilt jitter is jitter beyond the response of the AO system. Microphonic effects are also included in this specification.

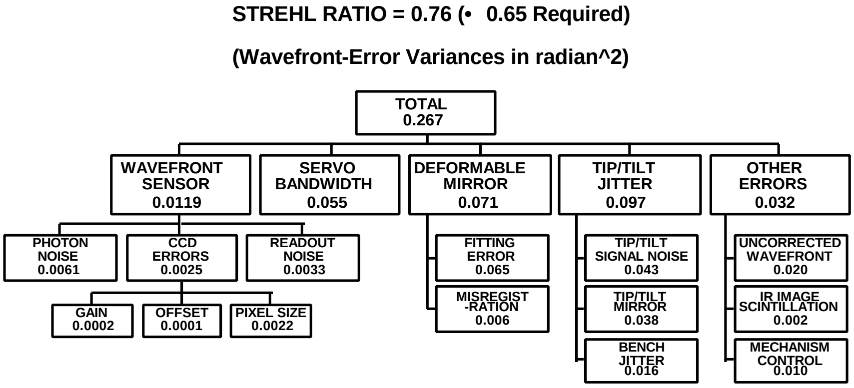
7.3 Cleaning Procedures

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

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

8.0 Error Budgets

Figures 2 and 3 show the system error budgets for Clauses 1 and 2 respectively. For consistency all errors have been expressed as phase variances in radian^2 at a wavelength of 2.2 µm. In parts of some work packages the errors have been converted to units that are more appropriate and easier to interpret. The error budgets are similar to those shown and discussed in earlier documents except that the ELECTRA DM's smaller fitting error and the effect of the larger subaperture size (57 x 57 cm^2) have been taken into account.


STREHL RATIO = 0.76 (• 0.65 Required)

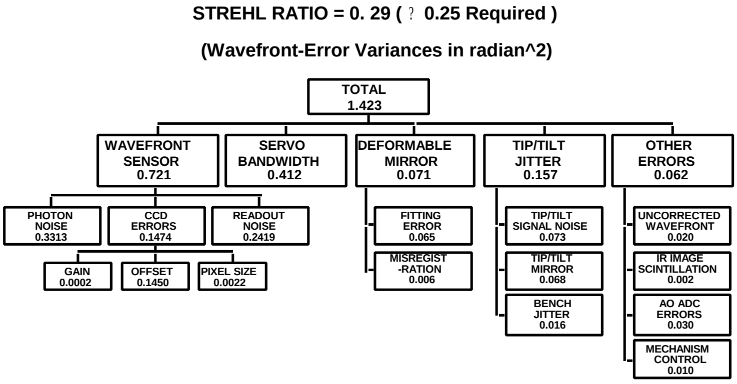
(Wavefront-Error Variances in radian^2)

Figure 2. Clause 1 error budget.

Figure 2 shows the Clause 1 error budget. With the change from a continuous facesheet DM to the segmented ELECTRA DM, fitting error is no longer the dominant effect. Because the light level is high, i.e. magnitude 8 star, the wavefront sensor errors are small. The budget assumes that the wavefront sensor CCD has been calibrated to specification and the pixel size errors do not exceed 1 µm rms. A conventional centroiding algorithm was used in determining the budget for the CCD errors. The tip/tilt jitter includes an allowance of 30 nrad (0.006 arcsec) rms for jitter on the optical bench induced by telescope motion and moving bench components; this jitter is in addition to the 70-nrad (0.015 arcsec) rms residual jitter from the WFS-FSM subsystem. The "misregistration" box refers to errors associated with the incorrect mapping of the mirror actuators at the wavefront-sensor lenslet array, e.g. due to a non-zero incident angle at the deformable mirror. The optical design is such that the deformable mirror is imaged at the lenslet array. The allowance for the uncorrected wavefront error includes only those errors specified for the AO system. The contribution from the WHT optics was not known at the time of writing but this information is being sought.

The error budget in Figure 2 gives a Strehl ratio of 0.76 which is comfortably above the specified value of 0.65 for Clause 1

The ability to satisfy Clause 2 requires that the system operate with faint stars, e.g. visual magnitude of at least 15 or 16. The error budget shown in Figure 3 is for an


STREHL RATIO = 0. 29 (? 0.25 Required)

(Wavefront-Error Variances in radian^2)

Figure 3. Clause 2 error budget.

on-axis visual magnitude 16 guide star; operation with a dichroic beamsplitter that allows the WFS to be used over its maximum spectral bandwidth was assumed. Section 5.4.2 of the NAOMI technical description document (AOW/GEN/AJL/7.0/07/96) presents the expected number of detected photons for various spectral classes of 16th magnitude stars; several classes exceed the error-budget number. An integration time close to the assumed atmospheric time constant was used. In accordance with Clause 2, the time constant assumed atmospheric conditions equivalent to a single turbulent layer moving at 10 m/sec at 3 km above the telescope. The error budget assumed that two benefits of the long integration time were a slower CCD readout rate and reduced readout noise. Specifications on readout rates and noise are covered in Section 3.0 above**.** The Clause 2 error budget takes into account the increase in sources of error such as photon noise expected at these low light levels. The Clause-2 analysis brought out the need for accurate calibration of the CCD background offset as covered in Section 5.1 above.

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

9.0 Additional Support and Interface Requirements

This section covers support and interface requirements not addressed above.

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

Documentation shall be supplied in accordance with Clause 14.

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

As required by Clause 20, NAOMI software shall be written to standards agreed with the ING. Note that any references to software in this WPD refer to the software needed for the WFS mechanism control. A draft software standards document has been prepared by Paul Rees. See the latest version for guidance.

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

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

10.0 Reviews and Procedures

The work package will be subject to Preliminary Design and Critical Design Reviews. The document AOW/MAN/AJL/8.0/07/96 CoDR, PDR and CDR Definitions gives some guidelines as to what levels of design, modelling and costing are expected at each of these stages. It also gives guidelines on the preparation of procedures, e.g. for alignment and calibration, and the level of detail required. Further PDR information is given in AOW/WFS/RAH/1.1/01/97/ Wavefront Sensor PDR Requirements. In addition to the PDR and CDR, the WFS supplier will also be expected to participate in the System Design Reviews. These are also covered in the document AOW/MAN/AJL/8.0/07/96. The first System Design Review is addressed in AOW/SYS/AJL/6.0/01/97/ 1st Design Review Requirements.

11.0 Deliverable Items

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

The delivery location is the WHT, La Palma. Intermediate delivery to the location for system integration (TBD) is also required.