Keck Adaptive Optics Note 559

Keck Next Generation Adaptive Optics
Interim LOWFS and LGS Object Selection Mechanism conceptual study report

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1 Introduction

The Next Generation Keck Adaptive Optics system is a multiple guide star Adaptive Optics system with a two stage reflective OAP relay designed to work between 100-170 nm wavefront error. This report presents concept solutions for the Object Selection Mechanisms (OSM) for the interim Low Order Wavefront Sensor assembly and Laser Guide Star assembly.

The LOWFS OSM is summarized in Section 2 of this report, followed by a description of the LGS OSM in Section 3. A summary of the assumptions regarding acquisition and dithering are presented in Section 4. Acronyms and document references are contained in sections 5 and 6 respectively.

2 Low Order Wavefront Sensor OSM

The Low Order Wavefront Sensor (LOWFS) assembly is located at the focus of the first relay and contains as a minimum 2 Tip/Tilt WFS, 1 TTFA WFS, 1 TWFS WFS and 1 PSF monitor. The NGAO LOWFS assembly is a critical part of the NGAO system as it initiates acquisition and all subsequent observation modes such as on and off-chip dithering, including sub-pixel dithering, and non-sidereal tracking at exquisite levels of performance.

2.1 The interim LOWFS assembly

The interim LOWFS assembly contains a 4-channel Object Selection Mechanism (OSM) feeding 2 Tip/Tilt WFS, 1 combined TTFA/Truth WFS and a wide field PSF monitor. Shown in Figures 1-3 the assembly attaches directly to the NGAO optical bench. The assembly can be viewed as two separate entities: the OSM consisting of a stable structural plate that supports the 4 roaming probe arms and the 4 beam-fed units located behind the structural plate that are fixed during an observation. This report is concerned with the specification and design of the OSM.

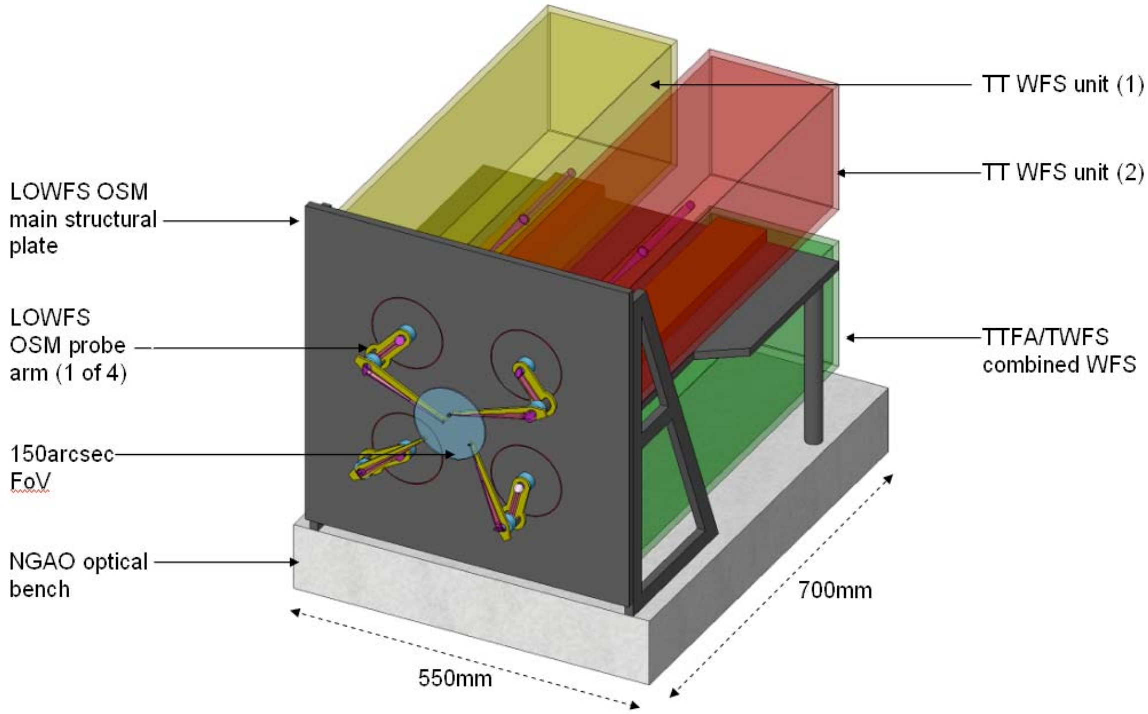

Figure 1: The Low Order WFS assembly for NGAO contains (a) a 4-probe arm Object Selection Mechanism sand (b) 4 units comprising 2 Tip/Tilt WFS units, 1 combined TWFS/TTFA unit and 1 PSF monitor (hidden by main structural plate above). The LOWFS WFS assembly is roughly 500mm by 550mm by 700mm deep in volume.

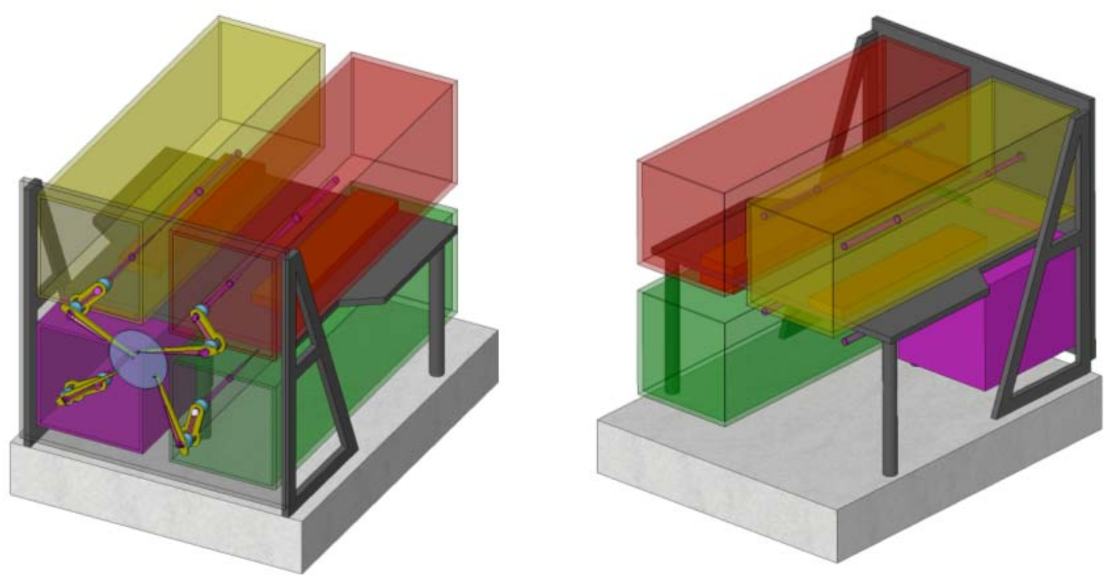

Figure 2: The rear of the LOWFS assembly showing the layout of the 4 units fed by the LOWFS OSM. The units, shown as volume indicators only, are color coded as follows: TT WFS 1 (red); TT WFS 2 (yellow); TWFS/TTFA combined unit (green) and; the PSF monitor (purple).

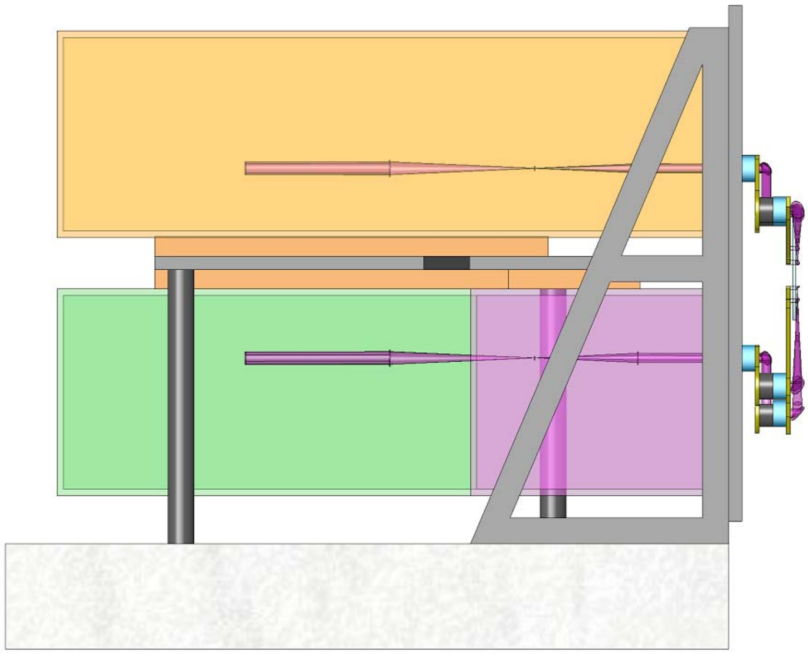

Figure 3: A side view of the interim LOWFS assembly. The optical beams shown terminate at the formation of a pupil image of size equivalent to the deformable MEMS mirror found in each of the LOWFS rear units

2.2 The interim LOWFS OSM versus the d-IFS OSM

The interim LOWFS assembly refers to a 4-pickoff WFS assembly that satisfies all requirements for the NGAO AO-assisted narrow field science instrument suite. The wide-field deployable Intergral Field Spectrograph, d-IFS, is undoubtedly the most complex instrument envisaged for NGAO and by field requirement must be located very close to the LOWFS assembly. Given the proximity it was found a restriction on the design freedom of the d-IFS to separate the spectrograph and LOWFS OSMs.

Given this, and the possibility that the d-IFS will be a second generation instrument not present for first light, we concentrate here on an interim LOWFS assembly, much simpler in design than the d-IFS OSM, that satisfies the narrow field requirements only. It is hoped that parts of this report will be helpful to the development of the d-IFS OSM and furthermore will serve as requirements for the d-IFS OSM.

2.3 LOWFS OSM Requirements

2.3.1 Basics

At the most basic level of functionality the LOWFS OSM must select 4 natural guide stars distributed randomly across the 150arcsec field of view delivered to the LOWFS location by the 1st NGAO optical relay. Each NGS is fed to a different unit, three of which are for low order wavefront sensing and one for PSF monitoring. There is no specific clustering requirement placed on the interim LOWFS unit, a value of 5 arcsec was assumed as a reasonable estimate for this study.

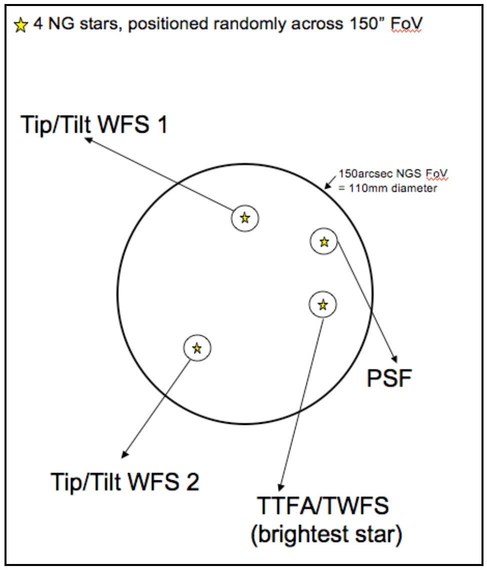

Figure 4: The layout of the LOWFS field of view delivered by the 1st NGAO relay. The LOWFS OSM must select 4 NG stars positioned randomly across the 150arcsec (110mm physical size) field. The brightest star is directed to the combined TTFA/TWFS channel.

2.3.2 Science requirements

2.3.2.1 The "rainbow" chart

The science requirements flowdown, nicely summarized in KAON 548, provides the starting point to the LOWFS OSM performance requirements. Summarized in Table 1 below are the required science performances for acquisition and dithering *at the science detector*. As the LOWFS assembly, that contains the OSM, is the acquisition and dither initiator for the NGAO concept stage the performance requirements for the assembly itself must provide as a minimum this level of accuracy. This is discussed further in Section 2.3.2.3 below.

The acquisition and dither requirements are displayed in units of mas, physical distance in the LOWFS F/15 focal surface and, for interest, physical distance in the F/45 narrow field science focal surface. Requirements that are given as a function of observing wavelength are presented for Hα, J, H and K. The most stringent requirements correspond naturally to the micro-dither movements on the science detector for the shortest observing wavelength, that of Hα at 656nm. Here we see a dither accuracy of 6.8mas, a physical size of just under 5μm at the LOWFS OSM and 15μm at the narrow field science instrument. This is accompanied by a corresponding term called "position knowledge", representing the error in the knowledge of the micro-dither movement at the science detector. For such cases, the position knowledge is only 1μm at the LOWFS OSM corresponding to 3μm at the narrow field science instrument.

Table 1: A summary of the science requirements that are relevant to the design of the LOWFS Object Selection Mechanism. Requirements that are wavelength specific are presented for each NIR band at both the F/15 LOWFS focus and for interest the F/45 narrow field science focus (NA=Not Applicable)

	Acquisition accuracy: slit	***Acquisition accuracy: imager***	***Acquisition accuracy: IFU***	***on-chip dither maximum distance***	***off-chip dither maximum distance***	***dither accuracy***	***dither time (max)***	***Target position knowledge on detector***
	0.25λ/D	200mas	200mas	3arcsec	15arcsec	0.5λ/D	3s	0.1λ/D
@ F/15	NA	145μm	145μm	2.2mm	7.3mm	NA	NA	NA
@ F/45	NA	435μm	435μm	6.6mm	21.9mm	NA	NA	NA
λ=656nm(Hα)	3.4mas	NA	NA	NA	NA	6.8mas	NA	1.4mas
λ=1220nm(J)	6.3mas	NA	NA	NA	NA	12.7mas	NA	2.5mas
λ=1630nm(H)	8.4mas	NA	NA	NA	NA	16.8mas	NA	3.4mas
λ=2190nm(K)	11.4mas	NA	NA	NA	NA	22.8mas	NA	4.6mas
λ=Hα @F/15	2.5μm	NA	NA	NA	NA	4.9μm	NA	1.0μm
λ=J @ F/15	4.6μm	NA	NA	NA	NA	9.2μm	NA	1.8μm
λ=H @ F/15	6.1μm	NA	NA	NA	NA	12.2μm	NA	2.5μm
λ=K @ F/15	8.3μm	NA	NA	NA	NA	16.6μm	NA	3.3μm
λ=Hα @F/45	7.5μm	NA	NA	NA	NA	14.7μm	NA	3.0μm
λ=J @ F/45	13.8μm	NA	NA	NA	NA	27.6μm	NA	5.4μm
λ=H @ F/45	18.3μm	NA	NA	NA	NA	36.6μm	NA	7.5μm
λ=K @ F/45	24.9μm	NA	NA	NA	NA	49.8μm	NA	9.9μm

2.3.2.1.1 Spectrograph slit acquisition accuracy

For immediate clarity it is noted here that the stringent acquisition accuracy of any slit based narrow field spectrograph, listed as 0.25λ/D in Table 1, will be provided by the science instrument itself. The LOWFS OSM will provide substantially better than 200mas acquisition accuracy as discussed in Section *, however, it is assumed that if a narrow slit based spectrograph is to be part of the NGAO instrument suite it must include an internal steering mirror or similar mechanism.

2.3.2.2 Further requirements

2.3.2.2.1 Chromatic effects

There is no atmospheric dispersion corrector in the wide field first relay of NGAO to increase throughput to the d-IFS. Instead, each LOWFS unit incorporates a mini-ADC that corrects the atmospheric dispersion across the LOWFS observing band to sufficient accuracy. However, there are further chromatic effects that cannot be corrected by the unit mini-ADCs and are described here.

2.3.2.2.1.1 Tilt error

This refers to the separation between the science target at the narrow field instrument and the location of the LOWFS stars in the wide field focus. The NGS are selected by a full field dichroic that directs the science target in the correct photometric band towards the narrow field instrument while passing NGS light in a different photometric band to the LOWFS OSM. The consequence is that if the LOWFS OSM were to track according to the location of the tip/tilt stars, the science target would move on the narrow field instrument detector as a function of elevation angle. The mini-ADCs likely will not correct this multi-band effect to the required level of accuracy. Another concern is that the accuracy of positioning a science object for position knowledge for co-adding images, only 1.4mas for the shortest visible mode, will be affected by this error.

→ Proposed solution: the LOWFS WFS units will be tracking devices that provide the variable offset required between the tip/tilt stars and science target.

2.3.2.2.1.2 LOWFS Dichroic aberration

The tilted full field dichroic used to separate the LOWFS and science target light introduces both astigmatism and a lateral chromatic aberration to the LOWFS beam. Astigmatism is an MEMS-correctable error within each LOWFS unit while the chromatic dispersion is not. The magnitude of the effect is shown in Figure 4. The lateral dispersion created by the angled dichroic is roughly 50mas between Hα and H band, with J band roughly centered between the two.

→Proposed solution: the chromatic dispersion can be corrected using a glass wedge inserted into each of the LOWFS units at the expense of roughly double the astigmatism. The latter aberration can be corrected by the MEMS deformable mirror that is internal to each LOWFS unit.

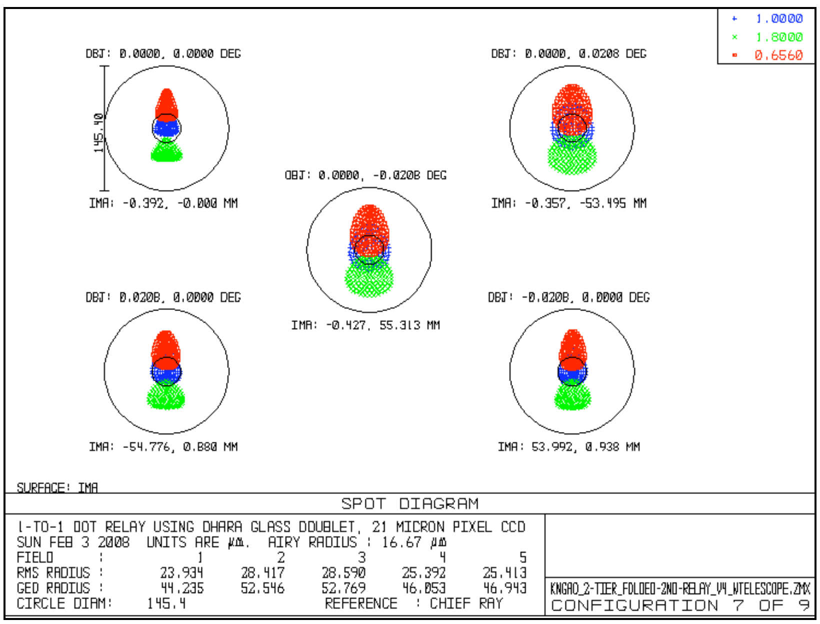

Figure 5: Chromatic and astigmatic aberration created by the LOWFS dichroic element in the 2-tier model. The fused silica element is 20mm thick and orientated at an angle of 20^{o} to the incoming beam. The large black circle corresponds to a sky angle of 200mas; the smaller inset circle is the airy disk for J band. The atmospheric dispersion is zero.

2.3.2.2.2 Non-sidereal tracking

There are observing modes that require the science target to be non-sidereal, such as Kuiper Belt Objects (KBOs). This results in a variable offset pointing between the tip/tilt stars and the science target during the science observation.

→ Proposed solution: the LOWFS WFS units will be tracking devices that provide the variable offset required between the tip/tilt stars and non-sidereal science target.

2.3.2.3 Discussion

It is important to note here that the science requirements listed in Table 1 refer to the performance as measured *at the science detector*. For example, a required science target acquisition accuracy of 200mas is the total error budget for a series of terms of which only 1 component is the acquisition accuracy of a single LOWFS TT unit fed by the LOWFS OSM. Other considerations that affect this error budget are misalignment inaccuracies in the dichroic interchange; AO enclosure thermal gradients; fold mirror interchange inaccuracies; instrument optical distortion; inaccuracy in the element performing the counter-dither motion such as the TT stage of the woofer; plus several other terms.

A full error budget analysis is a goal for the next phase of NGAO. Instead, we take a decision here to design the LOWFS OSM to be as accurate as it can possible be with off-the-shelf components or components already incorporated into the design, such as the very accurate TT stages of the deformable MEMS mirrors.

2.4 Basic design philosophy

With science requirements in mind, the LOWFS assembly followed the following design principles:

- Keep as much of the WFS unit as fixed as possible, especially during an exposure
- Be as modular as possible
- Assume the AO enclosure temperature is adequate for all LOWFS unit optics from an emissivity point of view, with the exception of the detector
- The preferable orientation, from a throughput perspective, of the LOWFS assembly, and hence OSM, is horizontal as shown in the 1-tier layout in Figure *
- The LOWFS assembly, and hence OSM, does not rotate as a whole
- The LOWFS assembly is the acquisition and dither initiator of the NGAO system. This is discussed further in Section 4.
- The pick-off arms (that guide the NGS to the respective fixed WFS unit) are designed to be as good as possible with off-the-shelf components. This is based on the prior knowledge that this is likely good enough for a positioning accuracy of around 40mas in the focal surface of the LOWFS assembly
- Fine positioning to better than 40mas or so is initiated by the Tip/Tilt stage of the MEMS deformable mirror, one being located in each WFS unit. The exact division between a TT stage sky movement and pick-off movement is not critical at this stage so long as it is smaller than the range of the stage mechanism. Software initiated dithering at this level is a further option though is not considered here
- Though not essential, we assume that providing an easily accessible location for the probe arm pupil is advantageous. For example, if the exit pupil is located close to the main structural plate a cold stop can be simply attached to the plate rather than the roving probe arm for the purpose of reducing background if deemed required.

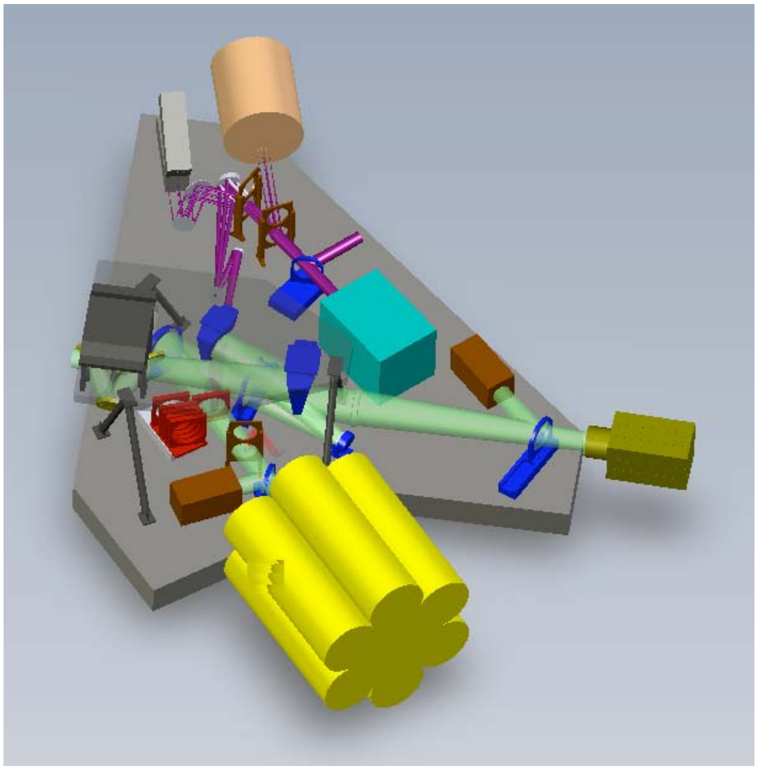

Figure 6: A schematic of the NGAO layout showing the location and orientation of the interim LOWFS unit change to interim LOWFS

2.4.1 LOWFS OSM flowdown requirements

Summarized in Table 2 are the specifications for the LOWFS OSM probe arms. With an NGAO enclosure temperature of -20°C and the assumption that none of the LOWFS optics requires cooling to less than this value, we have a reasonable set of requirements for the start of the conceptual design of the LOWFS OSM.

Table 2: LOWFS OSM probe arm specifications for NGAO

Name	Number	Location	Mechanism type	Short arm length (mm)	Long arm length (mm)	Patrol field (arcsec/m	Arm FoV (arcsec)	Acquisition accuracy (mas/μm)	Stability (mas/μm)	Dithering implimentation (>40mas)	Dithering implimentation (<40mas)
TT star	2	Interim LOWFS	θ/ϕ	55	125	150/110	5	40/30	1.4/1	Probe arm	MEMS TT stage
TTFA/TWFS	1	Interim LOWFS	θ/ϕ	55	125	150/110	5	40/30	1.4/1	Probe arm	MEMS TT stage
PSF monitor	1	Interim LOWFS unit	θ/ϕ	55	125	150/110	5	40/30	1.4/1	Probe arm	MEMS TT stage

2.4.2 The LOWFS OSM theta/phi probe arm

We introduce an object selecting probe arm that is a simplified version of the TMT-IRMOS (University of Florida team) feasibility study.

2.4.2.1 Conceptual design and operation

The LOWFS OSM probe arm is a 2-motor device shown in Figures 7 and 8. The 2 degrees of freedom arm consists in reality of 2 arms: a crank arm and a lever arm, driven by 2 corresponding rotation motors: the crank and lever motor. *Enter further description.*

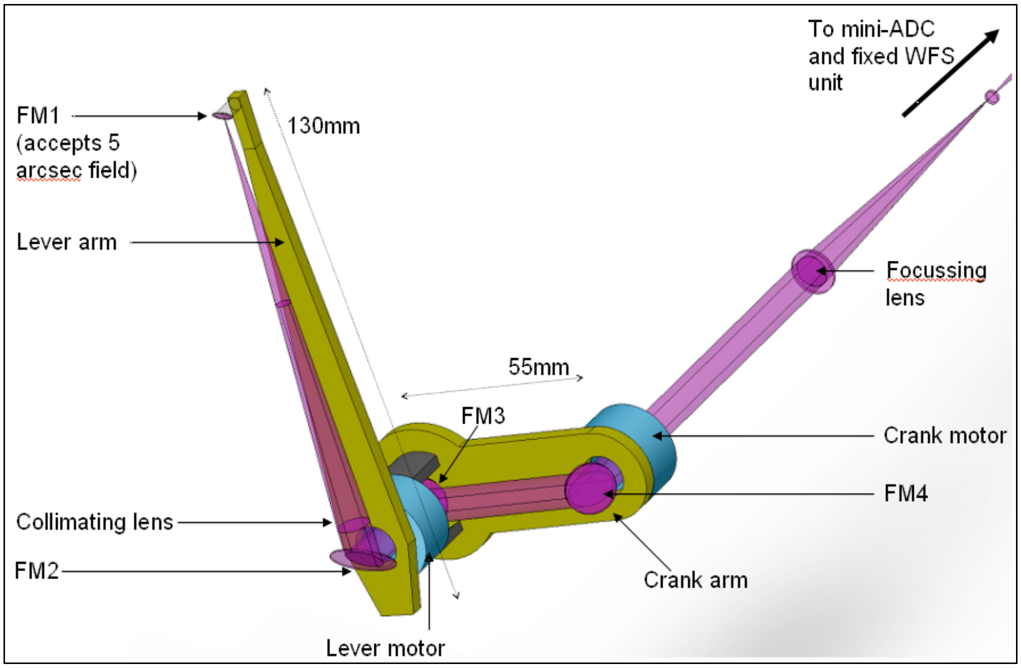

Figure 7: The LOWFS probe arm with dimensions and major items identified. The probe arm relays NGS light from any location within a 150arcsec field of view to a fixed rear unit, the direction of which is indicated by the arrow to the top right.

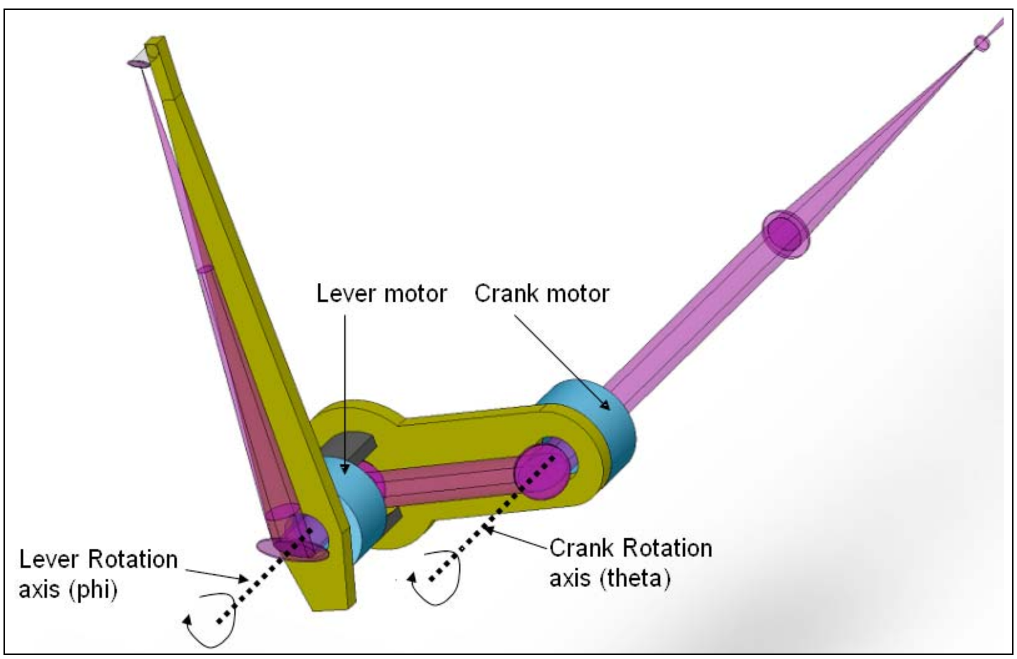

Figure 8: The LOWFS probe arm has 2 rotational degrees of freedom provided by 2 motors, as shown above. See text for further details.

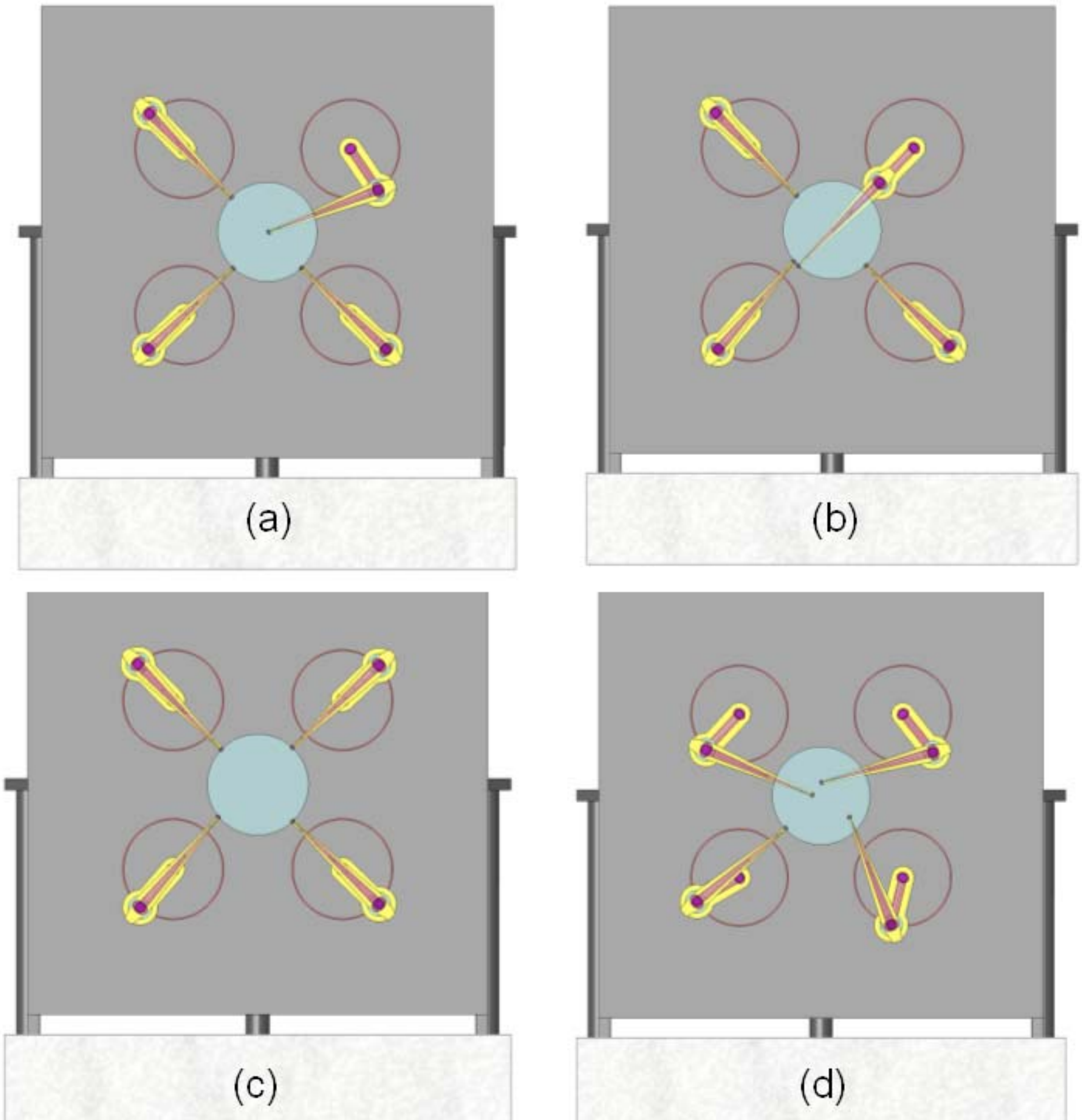

Figure 9: Four configurations for the LOWFS OSM probe arms: (a) One TT on-aixs with remaining 3 probes unused; (b) Showing the full range of the probe arm; (c) the OSM in the "home" position and; (d) a random field with all 4 probe arms in operation.

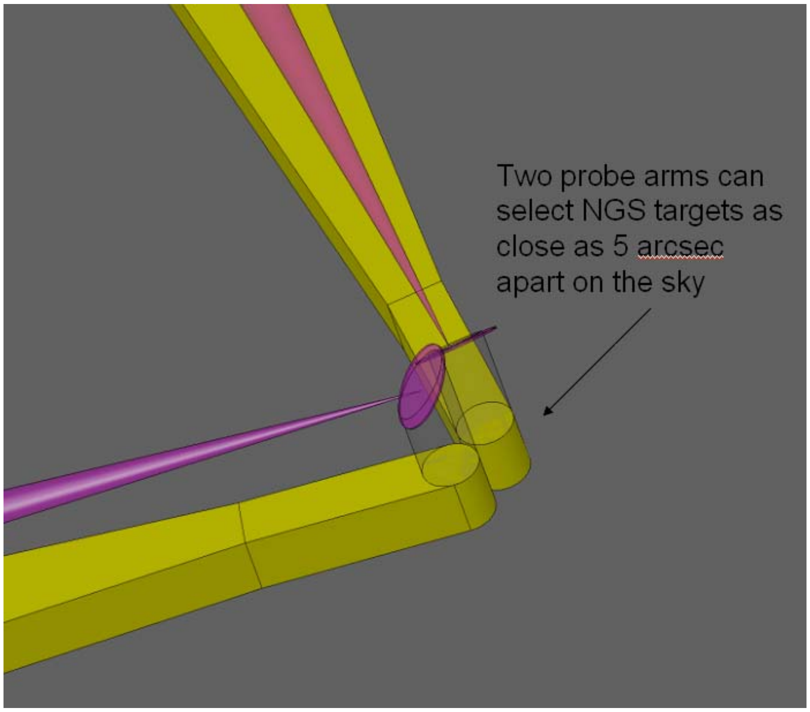

Figure 10: The tips of the LOWFS probe arms can be positioned to 5 arcsec separation on the sky

2.4.2.2 Zemax model of theta/phi arm for interim LOWFS OSM

We present the optical design of the LOWFS OSM probe arm. The telecentric feed from the AO system makes the optical design relatively simple.

2.4.2.2.1 Delivered field to interim LOWFS OSM

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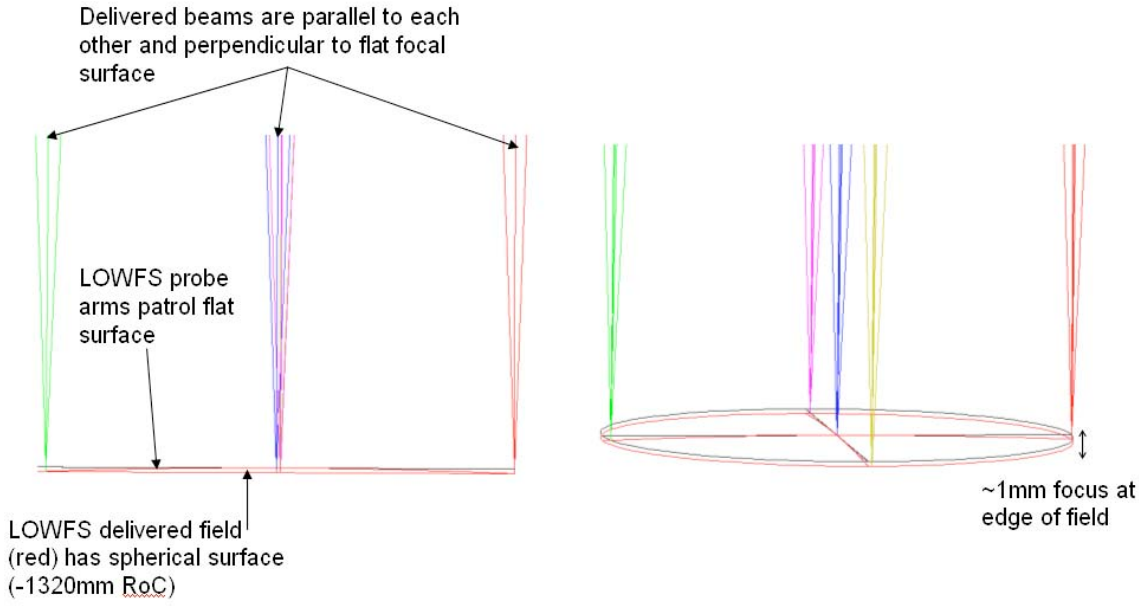

(a) (b)

Figure 11: (a) The LOWFS field of view is a spherical surface of radius -1320mm whereas the probe arms patrol a flat surface. The delivered optical beam is telecentric however, a benefit to the probe arm design.. (b) The field curvature results in a probe arm being defocused by around 1mm when patrolling at the edge of the field of view. See text for further details.

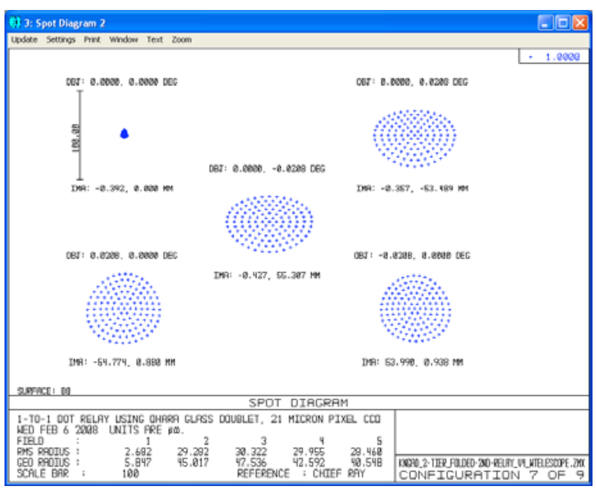

Figure 12: The image defocus at the edge of the field of view due to the probe arm patrolling a flat surface corresponds to an image broadening of only 70microns. This defocus is compensated by a small adjustment of the WFS or PSF monitor unit prior to NGS acquisition.

2.4.2.2.2 Zemax model of theta/phi arm

General description: the probe arm is optically a simple relay with lens as collimator to prevent beam broadening. The Focal length of the lens is governed by wanting the exit pupil to be close to the main structural plate – in case a cold stop is required to reduce thermal background/filters etc. The probe arm can have a smaller cross section otherwise, however this 4 probe arm OSM benefits from having 1/2inch optics that are easier to align than mm sized optics for example.

A field of view of 5 arcsec was chosen as a reasonable size of field to be large enough to always hit the target, but small enough that clustering tagets to 5 arcsec separation offers a large flexibility. The field can be stopped at the WFS/PSF monitor unit internally if required.

The designers of the WFS/PSf monitor units have the flexibility to choose the focal length of the focusing lens in (a). It is shown here to be the same as the collimating lens therefore providing a 1:1 relay, however this does not have to be the case. This flexibility may be of use.

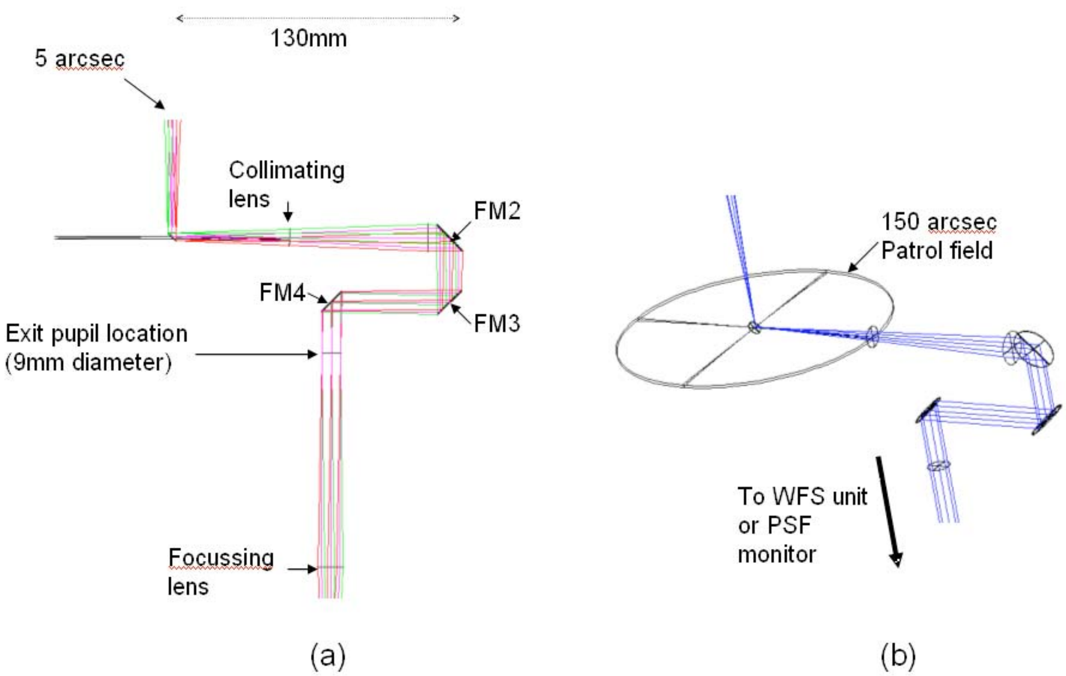

Figure 13: (a) Zemax model of interim LOWFS probe arm that relays a 5 arcsec field of view to a fixed exit pupil location; (b) the probe arm patrols a 150 arcsec field

2.4.2.3 Advantages/Disadvantages of theta/phi arm

The advantages of this design are:

1. The optical pathlength is naturally and accurately preserved as a function of field position.
2. As only 4 pick-offs are required one can allow larger mechanisms than otherwise allowed, resulting in readily available off-the-shelf rotary mechanisms using conventional worm gears rather than custom piezo or hybrid devices.
3. The theta/phi arm naturally allows for a fixed feed to the non-tracking WFS unit.

4. The arms can be balanced about the center of mass for each arm if this is an advantage to fine positioning in the future

There are two disadvantages of a theta/phi mechanism:
1. The pupil rotates as a function of field position, by up to * degrees. This creates a varying rotation of the woofer DM with respect to the lenslet arrays inside the TTFA and TWFS unit. The TT and PSF monitor units contain no lenslet arrays and the effect can be calibrated in software. As with the High Order LGS WFS discussed in Section 4, a solution to this is to include an extra non-tracking rotation mechanism in the WFS unit that rotates the entire unit about the z axis as a function of field position.
However, the low order nature of the TTFA and TWFS units is most likely sufficient that this mechanism is not required in the LOWFS assembly, and we therefore propose the effect to be calibrated in software.
2. In general, linear motors are more accurate than rotary.

2.4.2.4 Motor specifications

A critical component of the LOWFS probe arm is the motor, in particular the phi motor that operates the longer lever arm. The motor is shown conceptually in Figures 7 and 8 to be 1 inch diameter disks with a clearance hole of roughly 0.5inch for passage of the optical beams, and is identical for each rotation axis. The diameter of the motor can in practice be as large as 3 inches.

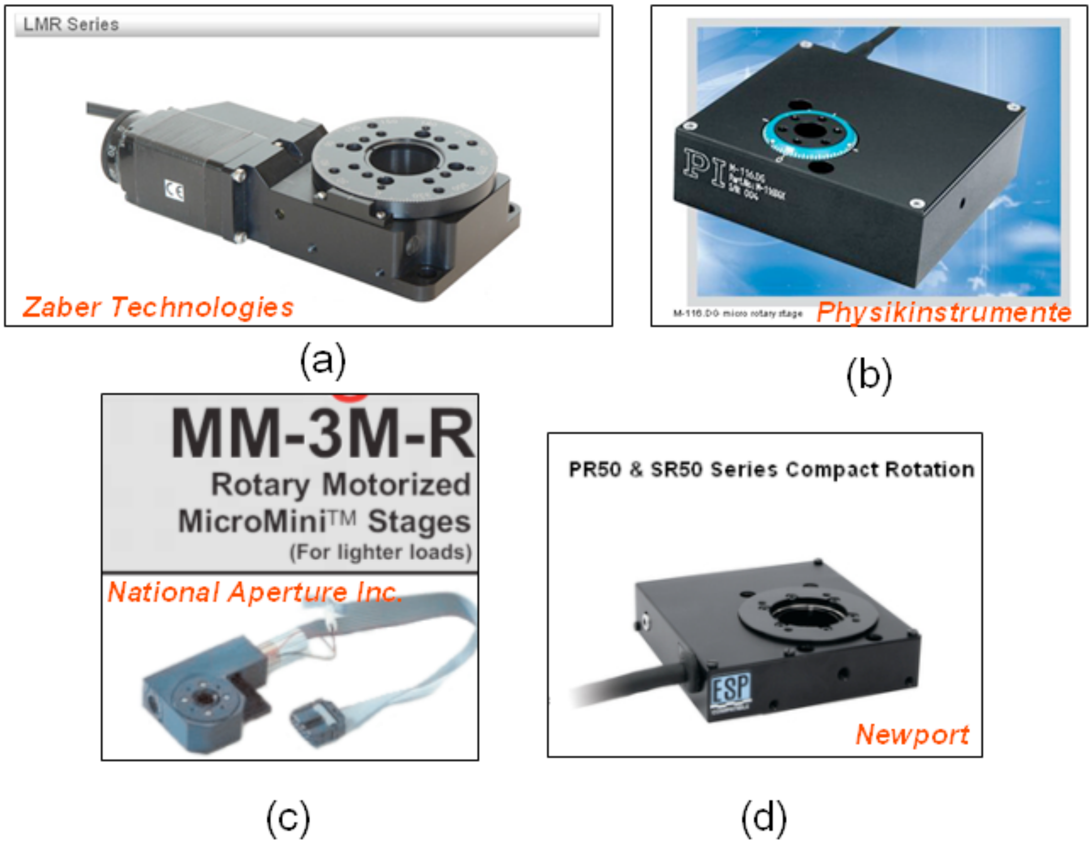

Figure 14 (a) – (e): Examples of off-the-shelf rotary motor packages as a possible solution for the phi/theta motors of the LOWFS OSM probe arm. References to each motor can be found in Section 6.

There are many approaches to the implementation of the phi and theta mechanisms. These range from off the shelf dc motors, to Ultrasonic motors found in high-end camera zoom lenses; to piezo based high precision linear motors driving the crank arm round a circular track.

Given that all fine positioning (<40mas moves) is assumed to `be implemented by the TT stages of the internal MEMS mirrors, we consider here off-the-shelf package dc-motor solutions for the gross movements of the LOWFS OSM probe arms. The advantage of such solutions is that they incorporate control electronics and software for positioning and encoding, therefore an advantage over developing a custom solution.

2.4.2.4.1 DC motor feasibility

A single worm gear with 70:1 reduction using 1.8^{o} stepper motor employing factor of 10 microstepping will have a 0.005^{o} minimum step size (9 arcsec). DC servo variants require feedback from an encoder, either inside the motor itself or preferably an encoder measuring the *actual* movement of the probe arms. As long as the encoder provides the level of accuracy required a well designed DC servo system should in theory be as good as a stepper motor driven equivalent. Furthermore, encoders measuring the actual movement of the arms rather than the motor rotation itself, will fair much better. In summary, it is feasible to consider DC motor solutions for the LOWFS OSM probe arms that incorporate a single high precision worm gear.

Table 3: Specifications for the off-the-shelf compact motor solutions for the LOWFS OSM probe arm. Resolution refers to the fineness of the encoder, whereas Step Size refers to the minimum repeatable mechanical step of the motor. The resulting movement at the probe arm tip for movements of the crank and lever arms of the smallest step size are presented, and this assumes a perfect system.

Motor name	**Dimensions (mm)**	**Step size (minimum. in arcsec))**	**Speed**	**Motor type**	**Resolution (arcsec)**	**Crank min movement at tip (μm/mas)**	**Lever min movement at tip (μm/mas)**
PI M-116.DGH	70x66x23.5	±10	20°/s	DC servo or Stepper Motor	0.5	±2.7/3.7	±6.4/8.8
NAI MM-3MR	76.2x36x12.7	±15	1.5°/s	DC servo, brush	0.4	±4.0/5.5	±9.4/12.9
Newport SR50	80x77x21	±14.4	1.6°/s	2 phase stepper motor	3.6	±3.8/5.2	±9.0/12.3
Zaber LMR Series	129x64x29	Not stated	33.6°/s	2 phase stepper motor	0.3	-	-

Shown in Figure 14 are the basic specifications for a rotary motor package of size suitable for this application. All contain precision worm gears. As expected the motors are comparable in performance. Assuming perfect systems (zero hysteresis; perfect meshing between gears; zero stage wobble) the step size error as measured at the probe arm tip is worst case ±14mas (±10.2μm). We assume a factor of 3 performance degradation in reality at this early stage, hence an approximate error of 40mas.

The Zaber LMR series motor contains a higher gear ratio than the others and is suitable for several kilogram loads, therefore maybe a little larger than required, in particular for the lever arm motor as it must be situated on the shorter crank arm (55mm pivot to pivot distance).

In summary, an off-the-shelf DC motor package is a reasonable starting point for the drives of the LOWFS OSM probe arms, when it is assumed that the TT stages of the MEMS deformable mirrors are capable of performing all fine positioning moves.

2.4.2.5 Temperature effects

The NGAO enclosure will be controlled to a temperature of -20°C with an accuracy of 0.3°C. A worst case scenario is that this corresponds to a temperature differential across the LOWFS OSM main structural plate, to which all components such as the probe arms and WFS units are structurally attached. Assuming a steel plate roughly 500mm square this corresponds to an expansion δl of ($0.3\times0.5\times11E^{-6}$) or 1.7μm. This equates to 2.4mas on sky or ×5.7 the diffraction limit at Ha, for the most stringent of science cases.

Such a variation is of no immediate concern, however, careful consideration must be given to temperature induced variations between the LOWFS assembly and the narrow field science instrument that could be situated several meters away. This should become part of the error budget analysis for the preliminary design.

2.5 Calibrating the LOWFS OSM

In this concept design the LOWFS OSM dictates the pointing of the telescope as viewed by the science instrument. In the majority of cases this is an open loop system, as in there is no star at the science detector that can be used to ascertain the delivered image position. As such accurate calibration of the OSM is an important issue.

2.5.1 What needs calibrating?

The following require calibration:
1. The LOWFS OSM to the telescope field of view
2. The NGAO acquisition camera to the LOWFS OSM
3. The LOWFS OSM to the narrow field science instrument

For a well calibrated acquisition camera one in theory does not require step 1 as it is already well calibrated to the telescope field of view. We assume here that all 3 steps are required.

2.5.2 Method of LOWFS OSM calibration

We envisage a simple device located in the NGAO calibration unit that consists of a well defined grid of illuminated points spanning the 150 arcsec telescope field of view. This unit could consist of an etched piece of glass with 1 arcsec or so diameter transparent holes arranged to sub-micron level accuracy in a pre-defined grid. With illumination from behind, using electroluminescence sheet if a suitable wavelength exits, the grid of points will be re-imaged simultaneously at the LOWFS OSM focal surface and narrow field instrument, or acquisition camera with the camera fold mirror in place. This device could be used to provide transformations between LOWFS OSM probe arm positions to acquisition camera pixel coordinate and to narrow field detector pixel coordinate.

During commissioning the use of on-sky targets such as globular clusters would be useful in providing the final link between the calibration unit itself and the telescope field of view, as well as incorporating Keck telescope performance into the calibration procedure.

2.6 Hardware table for LOWFS OSM

Table 4 lists the required hardware for the LOWFS OSM. Note this does not include the rear WFS and PSF monitor units that are detailed in the relevant KAON.

Table 4: List of hardware items for the LOWFS OSM

Item	Dimensions (for 5arcsec FoV)	Quantity	Comments
FM1	5.4mm diameter	4	Elliptical mirror for 5 arcsec FoV
Collimating lens	14.6mm diameter	4	Circular lens
FM2	19mm diameter	4	Elliptical mirror for 5 arcsec FoV

FM3	17.8mm diameter	4	Circular mirror
FM4	16.0mm diameter	4	Elliptical mirror for 5 arcsec FoV
Focussing lens	13.4mm diameter	4	Set by WFS unit designers, can be variable. Current value assumes 1:1 imaging
Crank motor (theta axis)	Less than 5" diameter by 1-2inch height	4	360^o range; minimum step size of ~15 arcsec. Position measurement to 2 arcsec.
Lever motor (phi axis)	Less than 2-3 inch diameter by 1 inch height	4	Length can be 4 inches or more if aligned to crank arm. 360^o range; minimum step size of ~15 arcsec. Position measurement to 2 arcsec.
Main structural plate and support	500mm square steel plate	1	
Probe arm structure		4	Support structure for probe arm elements

2.7 Preliminary costing for LOWFS OSM

A preliminary costing for the hardware items is presented. The costing assumes the motor definition to be adequate for the probe arms: this is a definite task for the preliminary design. It is expected that a certain amount of prototyping for one probe arm to be performed which includes assessing assembly tolerances and testing viable motors. This is not costed in the table below.

Table 5: Preliminary costs estimate for LOWFS OSM hardware

Item	**Quantity**	**Cost/item**	**Total cost**
Optics	4 sets	1,000	4,000
Motors	8	5,000	40,000
Main structural plate and support + labor	1	20,000	20,000
Probe arm structure	4 sets	5,000	20,000
			84,000

3 Laser Guide Star OSM

4 Acquisition and Dithering

A summary of the acquisition and dithering basics for NGAO from a LOWFS and LGS OSM perspective is discussed in this section. This by no means should replace the relevant KAONs describing the NGAO acquisition and observing modes.

General Flow diagram of acquisition and dithering assumed for this study

4.1 Optimizing dithering strategy for NGAO

No thought so far to existing software, difficulty to interface to telescope pointing software, delays and errors in telescope repoints etc. Requires a study in the next phase.

5 Acronyms

On-chip dither
Off-chip dither

ADC
KBO
LOWFS
TT
TWFS
TTFA
PSF
NGAO
OSM
LGS assembly
NGS
LOWFS assembly
LGS unit
LOWFS unit
KAON
MEMS

6 References

Viswa WFS KAON
Sean A NGAO passbands
Reni’s optical report
Rainbow chart latest version
Chris Neyman acquisition
David – observation modes?
Chris Lockwood – EASM file
Steve E IRMOS probe arm
MM-3M-R reference website
Zaber motor website
PI motor website
NAI motor website
Jim Bell private communication