W. M. Keck Observatory Next-Generation Adaptive Optics Facility: Science Operations

David Le Mignant[a,b], Christopher R. Neyman[a] , and Elizabeth J. McGrath[b]

[a] W. M. Keck Observatory, 65-1120 Mamalahoa Hwy, Kamuela, HI – 96743 - USA
[b] Center for Adaptive Optics, UC Santa Cruz, 1129, High St., Santa Cruz – CA 95064

ABSTRACT

The W. M. Keck Observatory is currently engaged in the conceptual design of a powerful new adaptive optics (AO) science capability providing precision AO correction in the near infrared (NIR) and visible and faint object multiplexed integral field spectroscopy. In this poster, we present the conceptual design of the Science Operations for this Next Generation Adaptive Optics (NGAO) facility. We summarize the main requirements for science operations resulting from the science cases and the Observatory requirements. We give an overview of the science operation paradigm and design that will meet these requirements. We then illustrate the pre-observing, observing and post-observing interfaces by looking into various observing scenarios. We conclude by briefly outlining the project milestones.
Keywords: Telescope operations, laser guide star, adaptive optics, W. M. Keck Observatory

1. INTRODUCTION

The W. M. Keck Observatory (WMKO) is very active in the development, integration[1,4,3] and science operations[4] of Adaptive Optics for astronomy: while the current generation of Keck NGS and LGS AO systems are successfully used by the Keck astronomers[5], the Observatory and its major partner institutions (University California, UC and the California Institute of Technology, Caltech) started investigating the future of Keck AO astronomy. The team from WMKO, UC and Caltech completed in April, 2008 the system design (similar to the conceptual design phase) for the Next Generation AO (NGAO) facility, which could start science operations in ~ 2015. A series of papers in the 2008 SPIE report on the NGAO project: an overview of the NGAO facility is given in Wizinowich et al. [6]; Max et al. [7] present the Science Case for NGAO; Gavel et al. [8] report on the concept developed for the NGAO; finally, the present paper reports on the science operations for NGAO. We briefly introduce the science cases, the top-level requirements and the NGAO concept in the current section. Section 2 presents our approach to selecting the observing model and Section 3 describes the requirements for science operations. We report on the conceptual design for the system operations in Section 4, and present the system control in Section 5.

1.1 Science case overview

The NGAO science cases and their main requirements are presented in [7]. We list the key-science cases below:

- The study of galaxy assembly and star formation history of $0.5 < z < 3$ through spatially resolved spectroscopy. The main top-level requirements are 1) to obtain a SNR ≥ 10 for a z=2.6 galaxy in an integration time ≤ 3 hours for a spectral resolution R=3,500 with a spatial resolution of 70 mas; 2) the ability to observe 200 galaxies in less than 3 years.; 3) encircled energy at 50% in 70 mas for sky coverage of 30%.
- The study of nearby active galactic nuclei: correlation of the black hole mass and bulge mass and velocity dispersion & study of the host galaxy. The main top-level requirements are 1) Required spectral resolution of R~3000 over observing wavelengths from 850 to 2,500 nm with two resolution elements per spatial sampling; 2) PSF calibrations to allow for 5% relative photometry through the night.
- The measurements for general relativity effect in the galactic center. The main top-level requirements are 1) astrometric accuracy of ≤ 100 μas for objects ≤ 5″ from the Galactic Center ; 2) radial velocity accuracy ≤ 10 km/sec for objects ≤ 5" from the Galactic Center.
- Imaging and characterization of extrasolar planets around nearby stars. The main top-level requirements are: 1) ability to observe several hundreds of targets over 3 years (> 20 targets / night); 2) companion sensitivity of

Δ H = 10 at 0.2″ (this requirement varies depending on the target sample: nearby field brown dwarf, nearby young and solar type stars).

- Solar system formation through the study of multiplicity of minor planets. The main top-level requirements are: 1) $\Delta J \geq 5.5$ mag. at 0.5″ separation for a $V \leq 17$ asteroid (asteroid size < 0.2″) with a proper motion of ≤ 50 arcsec/hour and a relative photometric accuracy of 5% ; 2) target sample ≥ 300 asteroids in ≤ 4 years (≥ 25 targets per 11-hour night).

1.2 Overall architecture

These top-level requirements lead to a pre-selection of science instruments for the NGAO facility: diffraction-limited imagers in the visible and the near infrared, a narrow field integral field spectrograph similar to the K2AO-fed OSIRIS instrument, and a multiplexed/deployable integral field spectrograph (d-IFS) with the ability to observe up to 6 targets simultaneously.

The NGAO facility is designed to provide much improved image performance in the near infrared: higher sensitivity (the total background seen at the science instrument focal planes shall be less than 130% of the current unattenuated sky plus telescope background) and high spatial resolution (≤ 170 nm rms of residual wavefront for the narrow field science cases and ≤ 260 nm for the d-IFS science cases). In addition, the facility will be designed to provide stable PSF and simultaneous PSF calibrations for improved performance for astrometry and photometry.

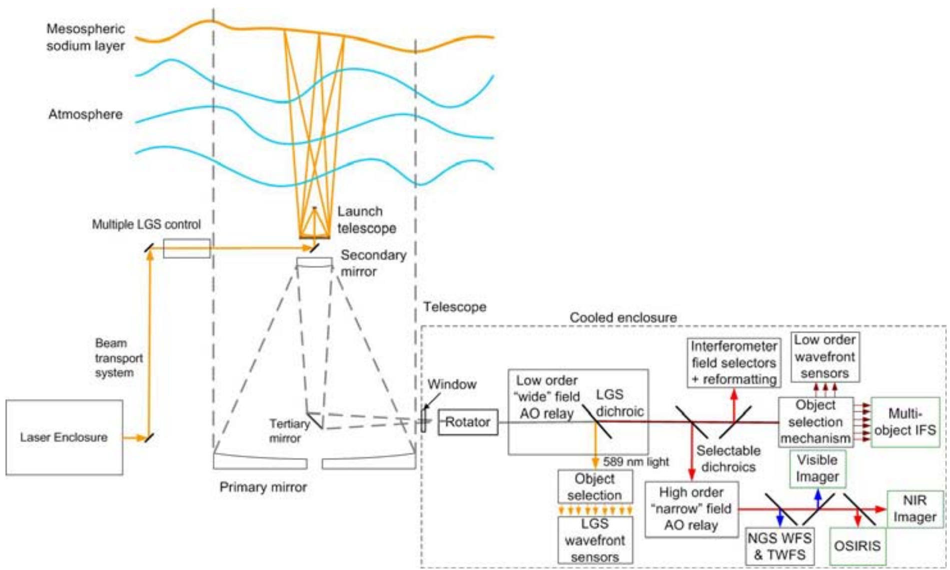

Figure 1: NGAO block diagram. The NGAO facility includes four science instruments: visible and NIR imagers, OSIRIS (narrow-field IFS), and a deployable Integral Field Spectrograph. It also feeds the interferometer. The Na light returned from the 9 lasers used for wavefront sensing (6 to cover the science fields, and 3 for correcting the natural guide stars) is sent to the LGS wavefront sensors in the 150 arcsec "wide" field relay. Objects for the low-order WFS and deployable IFS are selected within the 150 arcsec diameter relay as well. The higher-order "narrow" field relay feeds the imagers and OSIRIS and hosts the NGS WFS.

The concept we have selected for the NGAO system is described in [8] and a block diagram is shown in Figure 1. The architecture for the NGAO facility includes the following main features:

- The system will be located on the Nasmyth plateform under constant gravity vector and the AO system will be enclosed in a cooled environment.
- The system will work in LGS and NGS modes. The LGS mode is based on multiple (6) sodium laser guide star tomographic wavefront sensing to overcome the cone effect. One to three natural guide stars will be required to sense tip-tilt, focus, astigmatism on the low order WFS (LOWFS) and higher orders for the true wavefront sensor (TWFS).

- To maximize sky coverage, a laser will be pointed at each natural guide star and each LOWFS fed by a corrected beam, allowing for sharper image of the natural guide stars on the near infrared LOWFS. [9]
- The overall concept is a cascaded wide-field to narrow-field relay. The LGS mode will feature a wide field of view (150″ diameter) science capability with the d-IFS, the 9 lasers and the three natural guide stars. The narrow field of view science capability (30 arcsec diameter) would still include the 150 arcsec relay for the selection of the three natural guide stars and the 9 lasers (whose geometry will be optimized according to the field of view and the turbulence profile).
- A woofer-tweeter approach was selected, including a conventional DM in the wide field relay combined with open loop MOAO-corrected narrow science fields to the d-IFS and the narrow field science instruments to maximize image quality on small field of views.

2. SCIENCE OPERATIONS MODEL

The overall goal of NGAO science operations is to maximize the science return from the allocated observing time, given i) the science cases, ii) a performance budget for the instrument suite, iii) an operation cost for the Observatory and iv) a scientific skill set for the astronomers. There exists a wide range of science operations models to accomplish this overall goal, as a function of the instrument functionalities, the Observatory budget and the *modus operandi* and size of the scientific community. Two important aspects were studied during the system design: the observing model and the science operation requirements.

2.1 Trade study on the observing model

As part of the system design study, we performed a trade study of possible observing models for the Keck NGAO facility. The first step for the trade study was to quantify and analyze the operations performance of the 2004—2007 LGS AO operations: we found that ~60% of the nights had photometric conditions and allow for LGS operations. An additional ~15% of the nights were marginally affected by weather (LGS used between 2 to 9 hours through the night, NGS useable with variable clouds extinction). On the other hand, for ~25% of the night the laser was used less than 2 hours due to bad weather, including ~20% of the nights where no observing of any kind could be done. We found these numbers were very much in agreement with study on weather and photometric conditions for Mauna Kea. For the nights where we able to operate, we found that the observing overheads remained a severe limit to better efficiency, for several reasons: most observing and calibrations sequences require coordination between telescope, AO, and science instrument only performed though serial commands to different sub-systems, each sub-system adds its own contribution to the total overheads; the performance for the Keck telescope pointing and acquisition systems lead to significant overhead during field acquisition; the design & implementation for AO nodding & dithering leads to relatively poor centering and positioning errors, leading to observing overheads. On the other hand, the relatively small size of the Keck AO users' community allow for flexible observing programs and efficient communication between the Keck support staff and the community. The observers are the astronomers and they use their observing time in a way that optimizes *their* science return, for most observing conditions: astronomers can switch targets, programs and instruments with great flexibility during the night.

In our observing mode trade study report, we compared the current classical observing model to service and queue service observing. We ultimately recommended that the NGAO science operations follow the Keck classical observing model for the following reasons: 1) the Keck astronomers require to be present during the observations and be able to make on-the-fly decisions on the observing strategy; 2) as of 2007, AO instruments are the least used in queue scheduling and service observing modes at other observatories (even though they would benefit from better seeing conditions, both observers and support staff are still learning NGS and LGS AO observing and need to be present during the observations); 3) the Keck Observatory does not have the budget to develop the tools for queue scheduling nor the staff for service observing.

2.2 Observing model: classical with built-in flexibility tools

The observing model we recommend for the NGAO facility is a classical model with built-in flexibility tools. In this model, the observing nights are scheduled and allocated 6-month in advance. Astronomers, assisted by Keck Observatory support personnel, perform the observations remotely either from Keck headquarters in Waimea or from a partner institution: the astronomers-observers are therefore fully engaged in their observations and can make decisions for the observing strategy. The support staff work with the astronomers and benefit from this interaction as well.

The suite of NGAO pre-observing tools including simulation and observations planning tools should allow the astronomer to easily and quickly assess the feasibility of a scientific program during the observing proposal submission phase or any phase prior to the observations, and make the best use of the allocated time. Astronomers will want to adapt the scientific program with the observing conditions for the scheduled observing night(s). Using the planning tools, they can make on-the-fly decisions for the observing strategy and take advantage of the various observing configurations with NGAO: NGS/LGS switch, AO science instrument switch, non-AO instrument switch during any night.

One of the limitations encountered with the classical observing model is that the data collected be incomplete (e.g., due to bad weather or low observing efficiency) preventing the astronomers from fully exploiting the data and publishing, resulting in a lower science return and visibility for the AO instruments. Our model trade study proposes a scenario that can be phased in with NGAO science operations with low impact on the Observatory support: Each TAC may decide to encourage its astronomers' pool to collaborate for a subset of TAC-allocated nights: the scientific programs could be ranked as a function of required observing conditions, and be given observing priorities untill the data is complete. This level of schedule flexibility would likely benefit the overall science return while maintaining Observatory operation costs. The flexibility and scheduling burden would be distributed among the astronomers within the partner institutions. This observing model experiment could be stopped at any time should it not be satisfactory.

3. SCIENCE OPERATIONS REQUIREMENTS

3.1 The science operations requirements

The requirements from the NGAO science cases and the observing scenarios for these science cases (from the astronomer point-of-view), and the operational requirements from the Observatory led to the following set of requirements for the science operations:

- Provide an extensive set of tools for instrument performance simulation and observing preparations.
- Assuming a classical observing model and adequate observing conditions for the science program, more than 80% of the observing time is spent on collecting science-quality data for the deployable science instruments.
- Assuming a classical observing model and adequate observing conditions for the science program, more than 70% of the observing time is spent on collecting science-quality data for the narrow-field science instruments.
- The NGAO system must be capable of supporting 200 nights/year of science operations and keep the total annual operational personnel within the 5-year plan Observatory operation budget, including non-personnel costs.
- Document and update the instrument performance at an appropriate level to support observing preparations.
- Provide the required calibration methods and tools to achieve the astrometry, photometry performance requirements
- Provide the required calibration methods and tools to achieve the PSF characterization requirements.
- Develop a plan for data archival.

3.2 Observing efficiency

One of the most important requirements is the percent of time spent collecting science quality data. Our goal is to achieve at least 80% open shutter science time for "faint field" observing program (programs requiring 1 to 4 hours of total integration time with individual integration time of > 20 min) and 70 % for "bright field" observing programs (programs requiring less than an hour of total integration time and including many fields through the observing night).

Note that in accounting for the open shutter science time, we make the following assumptions:

- Weather impact, including cloudy conditions preventing laser propagation, is not included in the calculation of the open shutter science time. We will track the statistics from time losses due to weather in both LGS and NGS mode. Yet given the Observatory option for the classical observing model, this loss cannot be accounted against the NGAO science operation efficiency. The weather statistics will be included in a more general discussion on observing models.
- Open shutter time spent on science acquisition, centering the object, checking the SNR, etc is considered overhead.
- Open shutter time spent for on-sky telluric, photometry, astrometry, PSF calibration is considered science time but we will keep track of its contribution to the total time.

While developing the observing scenarios, we have created a simple efficiency budget tool that can be used for each science case and provide a preliminary assessment on the observing efficiency. A snapshot of the tool is presented in Figure 2. The details for the estimates for the overhead during the course of an observing program are not reproduced here. We have considered minimum, median and maximum estimate for each of these contributions and calculate a weighted average equivalent to (min + 4*med + max) / 6. We estimate for the current study that the maximum values represent instances of technical difficulties. Therefore we have not allocated any additional time for technical problems. These estimates have also been checked against current performance.

	A	B	C	D	E	F	G	H
4			Time (min)					
5			min	med	max	(min+4*med+max)/6	**Total**	
6								
7	Galaxy Field 1	Telescope slew	1	3	6	3.17		
8		Adjust pointing	0.5	1	2	1.08		
9		NGS acquisition	0.5	1	4	1.42		
10		NGAO acq	2	4	6	4.00		
11		Fine centering	1	2	4	2.17	**11.83**	
12		Ind. Science integration	15	20	30	20.83		
13		Total Science Integration	90	150	240	155.00	**155.00**	
14		repeat	6	7.5	8	7.44		
15		Re-Fine centering	1	2	4	2.17		
16		# of re-centering	0	2	4			
17			0	4	16	5.33	**5.33**	
18		Dither/setup/readout	0.08	0.25	1	0.35		
19		x # of repeats	0.48	1.875	8	2.58	**2.58**	
20								
21	Telluric calibration 1	Telescope slew	0.25	0.5	1.5	0.63		
22		Adjust pointing	0	0	0	0.00		
23		NGS acquisition	0.5	1	2	1.08		
24		NGAO acq	1	2	3	2.00		
25		Fine centering	0	0	0	0.00	**3.71**	
26		Ind. Science integration	1	2	3	2.00		
27		Total Science Integration	2	4	8	4.33	**4.33**	
28		repeat	2	2	2.67	2.17		
29		Dither/setup/readout	0.08	0.25	1.00	0.35		
30			0.16	0.5	2.67	0.75	**0.75**	
31								
32	**Total field #1**	**Total Observing**					**183.54**	
33		**Total Open Shutter**					**159.33**	**0.87**
34								
35	Flux standard	Open shutter				4.33		
36	(eq. to telluric std)	overhead				0.75	**5.08**	
37		repeat per night					**2**	
38	**Total Std Flux**	**Total observing**					**10**	
39								
40	**LTCS interrupts**	ind integration time	20.83	20.83	20.83			
41		re-fine centering	2.17	2.17	2.17			
42		# of interrupt	0	1	3			
43			0	23	69	26.83	**26.83**	
44								
45								
46								
47								
48	Available hours/night		9.1	10.25	11.3	10.23		
49			546	615	678	613.50	**613.50**	
50								
51	Number of field/night					3.14		
52								
53								
54								
55								
56	**Efficiency**	**Total Observing**					**613.50**	
57		**Total Open Shutter**					**509.14**	
58		**Total overhead**					**104.36**	**613.50**
59		**Observing efficiency**					**0.83**	
60								

Figure 2. Efficiency estimate for the high-z galaxies science case.

NGAO can reach ~83% observing efficiency on the d-IFS, including calibrators. There are still a few contributors to the total overhead whose impact is difficult to mitigate. Any dedicated time for calibration standards has a strong impact on observing efficiency since these objects are "bright field" observed for a few minutes (< 5 to 10 min), with ~100% time overheads (slew, acquisition, SNR check, etc).

3.3 Laser operations: a potential risk for observing efficiency

In the Figure 2 example we have estimated ~27 min for any overhead due to the Laser Traffic Control System (LTCS). LTCS interrupts are due to either 1) a plane flying in the vicinity of the beam, 2) beam collision with other telescopes, 3) planned request for no-propagation (closure event) from the Laser Clearinghouse (LCH), and 4) on-the-fly phone call request for no-propagation at all from the LCH.

The number of interrupts due to planes is estimated to ~2 per year, making it a non-issue. The number of interrupts due to beam collision with other telescopes may be reduced once the new "first on target" LTCS rule is agreed upon and applied for all Mauna Kea telescopes (currently the new rule is used between the Keck telescopes).
The planned LCH requests for closure on a specific target direction can be included the observing planning tool and can result in minimal impact on the observing time losses *as long as they are less than 10 min and rare*. LCH closure requests were rare and insignificant from 2003 to 2007. LCH has recently released its new "SPIRAL 3" software that uses new rules for possible laser impact (not documented), a half-cone angle of 1.5º for the no-propagation zone and estimates no-propagation time windows for a particular direction. This has resulted in a dramatic increase of up to hundreds of events per night.[5] Tools have been developed by the WMKO AO operations team to minimize the impact. As it stands, this new LCH closures rate would significantly impact NGAO observing efficiency for extragalactic targets. This issue will require more attention for NGAO.
Last minute phone call request for no-propagation from LCH have a huge impact on efficiency for the given night since this stops all LGS operations for a certain time period. This happens ~ 5 times per year when using LGS 140 nights/year.
Last but not least, the ability to abort a science exposure quickly and either get ready for a new exposure or move to a new target faster should contribute to reduce the impact from LTCS events.

4. CONCEPTUAL DESIGN FOR SYSTEM OPERATIONS

4.1 Operation Control Infrastructure

The current Keck II LGS system feeding NIRC2 or OSIRIS performs routinely with ~ 30 - 50% overhead depending on the science program. Its limited efficiency as an integrated system is primarily due to the serial architecture for the commands and the lack of multi-system coordination sequences (e.g., reading out the camera during telescope offset). To address the efficiency requirement with NGAO, we are proposing a new integrated design. The three main components of the NGAO science operations are 1) the pre- and post- observing tools, 2) the operation control Graphical User Interfaces (GUIs) and 3) the multi-system command sequencer (MCS). In Figure 3, we present a block diagram for the science operations architecture using a view that complements the architecture information from [8].

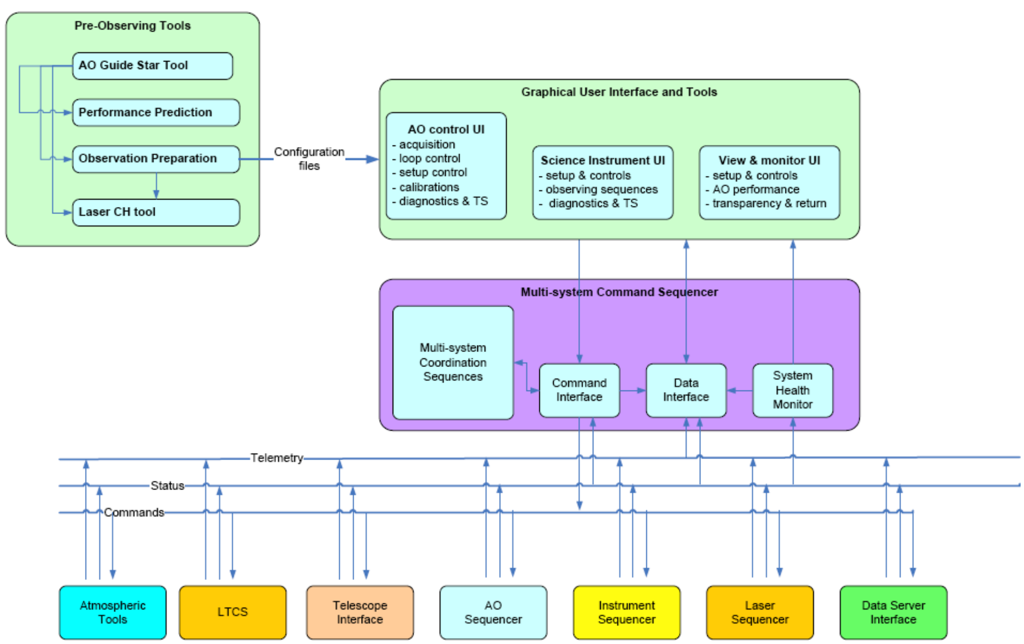

Figure 3. Science operations tools block diagram.

The configuration for the NGAO and the science instrument depends on the science program and the observing strategy and is determined during the pre-observing phases. The NGAO system configurations represents a total of 10 different configurations in NGS mode and 11 in LGS mode for acquisition, calibrations and science observations with one or two of the science instruments (interferometer, visible and NIR camera, OSIRIS, d-IFS). Some of the configurations include more options (e.g., rotator mode in fixed field or fixed pupil, LGS asterisms narrow, medium or wide, etc). Using a set of planning tools, the astronomer will develop the detailed observing plan and save all relevant parameters in configuration files. These configuration files can be loaded by the Operation Control GUIs. From the Operation Control GUIs, the operator and the observer will command & control the observation sequences: AO & science acquisition, system tune-up, observing sequences (snapi, dither, offset, filter, etc). The MCS can address the sub-systems in parallel (e.g., offset the telescope as the science instrument write the FITS file to disk) and each sequencer for each subsystem (AO, laser, science instrument) can quickly and reliably handle complex command for a given subsystem (e.g., set AO subsystem for NGS field acquisition). Note that the post-observing tools have been omitted in Figure 3. The pre- and post- observing tools are described in more detail in the next section.

4.2 System Calibration: Routine and Maintenance Calibrations

The calibrations for the NGAO will be defined in the Preliminary Design (PD) and Detailed Design (DD) phases. They include 1) routine calibrations, and 2) maintenance calibrations. The routine calibrations are calibrations that are required on run-to-run or night-to-night basis such as fine laser alignment and power calibrations, DM to lenslet registration, non-common path aberrations, etc. The maintenance calibrations are performed following a schedule and may include detector response, noise and offsets calibrations, tip-tilt (TT) and DM interaction matrices (poke matrices), motion control tune-ups, throughput, etc. We anticipate that the daily calibrations will be performed by the observing support team using the high-level science operation tools. The maintenance calibrations may be implemented at the subsequencer level when applicable. The detail requirements and the algorithm for each routine and non-routine calibration will be developed during the PD and DD phases. The corresponding calibration sequences will be coded and implemented at the MCS and/or at the subsystem sequencer level. Note that the use of the keyword architecture as currently implemented at Keck will allow the NGAO development team to easily prototype and validate the calibration algorithm using their programming language of choice during the Integration and Testing (I&T) phases.

4.3 System Operations: Acquisition

The NGS and LGS acquisition requirements and conceptual design were developed, including a trade study between near-IR and visible detector technologies. This study demonstrated that a commercial CCD is sufficient for the NGS acquisition task and that a single camera design is feasible for LGS and NGS acquisition. The specifications for the acquisition conceptual design were detailed and high level requirements and interfaces to other NGAO subsystems were discussed. The NGS acquisition will rely on data retrieval from multi-color astronomical catalogs (USNO-B, GCS-II and SDSS). Finally, the report discusses the possible risks during the acquisition process and concludes that telescope pointing accuracy is currently the largest single risk for the NGS acquisition. Table 1 presents a generic description for the acquisition sequence for NGAO with an emphasis on parallel steps. The NGAO planning tools will assist the astronomer in selecting the next science target. All relevant configuration information will be loaded by the Operation Control (OC) tools.

Step	Observing Step	Parallel Steps
0	Select next target: - assess science priority - check target elevation range - check observing conditions - check LTCS conditions	Complete integration on current science target or calibrator. When target selected from Planning Tools, then information is loaded in OC tools.

1	Upon completion of readout of science array, LGS is shuttered, AO loops open and key-system feedback parameters are saved then the operation control tools trigger the telescope slew.	OC tools parses information, and get ready for execution: - NGS parameters for acquisition - AO configuration - Instrument configuration
2	Telescope slews	The OC tools send commands to the multi-system sequencer. Setup sequences are executed as appropriate by the AO, laser & science instrument sequencers.
3	Telescope Pointing Adjustment on one of the NGS (brightness allowing). This step is automatically performed by the NGS acquisition subsystem with the visual check of the Observing Assistant (OA). Upon success, pointing corrections are applied and next telescope slew is commanded from the OC tools.	There is no need to use the acquisition camera for the LGS acquisition: LGS pointing model is accurate enough to get all laser spots centered within the capture range for the HO WFS.
4	Telescope coarse registration on the science field. NGS acquisition subsystem runs an automated routine to record and process image, ID the NGS in the field with respect to catalog data then compute required offset. Visual check of process by OA. Upon success, position offsets are applied to telescope.	LGS propagation and acquisition steps initiated. Laser pointing correction and uplink TT correction loops closed with very low gain. Pickoff mirror positioning and LOWFS setup complete including background.
5	Telescope fine registration on the science field: If photons not detected at the expected SNR on the LOWFS (or NGS not on Pointing Origin), then NGS acquisition subsystem runs a 2nd iteration. Visual check of process by OA. Iterate if necessary (to be detailed). Upon completion adjust telescope pointing model.	Pick-off mirrors for science and TWFS in position
6	AO subsystem control: 1) low gain on woofer & MEMs, 2) increase gain on UT, 3) start telescope guiding, 4) adjust woofer & MEMs gain, 5) initiate TWFS + tomography optimization	Science instrument is setup: optics and read modes are set and confirmed. May record first exposure to check centering with point-source and expected SNR/coadd. Monitor image quality and assess optimization progress.
7	Science integration starts	

Table 1. Generic NGAO Acquisition Scenario.

The main contributions to the centering error budget during NGAO acquisition in LGS mode are:

1. The accuracy for the knowledge of the separation distance and position angle between the stars and the galaxies from the literature.
2. The pickoff arm positioning accuracy for each science target with respect to the TT closed-loop reference position for the LOWFS, which is the total of:
    a. The internal positioning accuracy and position stability for each individual pick-off arm (science and LOWFS) – the requirement is ≤ 0.005"
    b. Registration accuracy and stability between LOWFS and science arms including TT stage positioning accuracy.
3. The differential atmospheric refraction between the LOWFS and the science instrument.

4. The total contribution from the optical distortions due to thermal gradient, alignment error, woofer and MEMs positioning between the science array and the LOWFS.

4.4 System operations: dithering and offsetting

Several approaches to dithering and offsetting were proposed and discussed during the study. The rationale for reviewing the dithering and offsetting scenarios comes from the important overhead (~30 seconds per move) it currently takes to perform these important observing steps. The selected approach recommends avoiding any telescope move and AO pause/resume sequence, unless necessary. Most field repositioning on the science array is performed to account for pixel/spaxel response, background emission or super-sampling and are of relatively small amplitude (< 2"). They could be performed by moving one of the NGAO internal fast-steering optics: tilt on the individual MEMS for the d-IFS, tilt on the second-relay MEMS for the narrow field science, repositioning of the probe arms for the d-IFS. This implementation would leave the LOWFS, TWFS and HOWFS closed during the entire observing sequence, and would allow for maximum flexibility and efficiency for centering the science target, tracking, correcting for DAR, etc. We believe that these internal optics have the required pointing accuracy and could result in minimal overhead (< 5 second).

An alternate scenario that does not require the telescope to move would require a global tilt on the woofer, and a counter motion for the LOWFS/TWFS, HOWFS probe arms. This requires pausing and resuming the AO operations and may require ~ 5 to 10 seconds. Alternatively, offsets of larger amplitude are performed by requesting a telescope offset, repositioning the probe arms at a different field location and re-acquiring the guide stars on the AO sensors. This may take about ~ 15 to 30 seconds depending on the detailed implementation. We are planning to examine these scenarios during the PD and DD phases and develop the detailed requirements. We are confident that the combination of these scenarios with the possibility of parallel commands to different subsystems will address the efficiency requirement for dithers and offset for the key science cases.

5. SYSTEM CONTROL

The high-level control of the system is performed through the Operation Control GUIs and executed by the Multi-system Command Sequencer (MCS). A schematic view for these controls was presented in Figure 3.

5.1 Multi-system command sequencer

The MCS is the main interface between the Operation Control GUIs (configured and controlled the by AO operator, the expert user and the observer) and the control of each subsystem. The MCS has four main components: a library of multi-system coordination sequences, a command interface, a data interface and a system health monitor. The multi-system coordination sequences are at the core of the MCS, they are a collection of functions which implement complex sequences of commands for the underlying control subsystems (AO, Laser, etc). A multi-system coordination sequence allows the user to send a simple command to the MCS, while it commands and coordinates all of the many tasks required by this command and returns the status to the user. The coordination sequence receives a command from the user and then sends multiple commands appropriate for the task to be accomplished by underlying multi-systems using the main command interface discussed below. Examples are: the LGS setup sequence that is used during slew to startup, initialize and setup AO, Laser and science instrument for the next LGS acquisition sequence. Note that we will likely require some flexibility in the management of this sequence library as we plan to add sequences to the library, mostly diagnostic and troubleshooting sequences, during the I&T and early operation phases of the system. The reliability and efficiency of NGAO operations strongly rely on the successful implementation of the multi-system coordination sequences.

5.2 Operation control GUIs

The operation control GUI is the main interface between the Users (AO operator, expert user and observer) and the control of components and execution of sequences with the NGAO and science instrument. The detailed design for the operation control GUIs for the science instruments is not a component of the science operation tools. Yet, we will work with the science instrument teams and define a common design. We have opted for the following preliminary set of design choices:

- The GUIs will be modular and include three main parent components: 1) NGAO controls, 2) science instrument controls and views, and 3) system-view and performance monitoring displays.

- The implementation of these tools should be fully compatible with the pre- and post- observing tools.
- The standard practice in the observatories (Gemini, ESO, STScI, Keck) for the implementation of these operation tools is to use Java and XML programming languages. We would recommend using these standard practices and other similar ones being developed in the context of Virtual Observatories (VO) and National VO.
- Several GUIs may be required during the operations per parent component. We will attempt to limit the total numbers of GUIs. Due to the limited integrated software development, our current LGSAO control includes as many as 30 displays and leads to some confusion during LGS operations.
- The control GUIs will include two type of command controls: controls for direct commands with no parameters e.g., open AO loops, (re-)close AO loops and controls for more complex commands requiring some parameters e.g., an acquisition sequence using a configuration file.
- The operation control GUIs will be designed to be users-friendly and include/display the minimal complexity. All complex commands will be implemented at the lower levels in the MCS and subsystem sequencers. Additional complex commands could be controlled using from specific call to a different set of GUIs (e.g., a somewhat complex calibration widget could be called from the NGAO GUI).
- The user can select the parameters for complex command either by loading a previously saved configuration file (these configuration files are also the outputs of the planning tools) or by manually entering values in the configuration fields.

5.3 Pre and post-observing tools

The pre-observing tools will allow the observer to simulate, evaluate and plan for an observing program using the NGAO and the science instrument(s) any time prior to the observations, particularly during the observing time proposal submission process. The astronomer will likely go through a second phase of observation planning in the month prior to, and days leading to the observations. During the observing night, the observer may use the same sets of tools to check and refine the observing strategy, if necessary.

The pre-observing tools are:
- The AO Guide Star Tool to search adequate astronomical catalogs for natural guide sources, identify and select them, and save all relevant information on the NGS and the science field required to simulate and acquire the target.
- The NGAO Simulation tool to estimate the NGAO performance in terms of Strehl ratio, encircled energy, full-width at half-maximum, etc as a function of the NGAO mode and setup.
- The Exposure Time Calculator to estimate the SNR / seconds and dominant noise regime for the science instruments.
- The Observation Preparation tool to prepare, review and save the observing sequences and estimate the observing efficiency.
- The Laser Clearinghouse Planning tool to automate the coordination tasks with the laser clearinghouse.

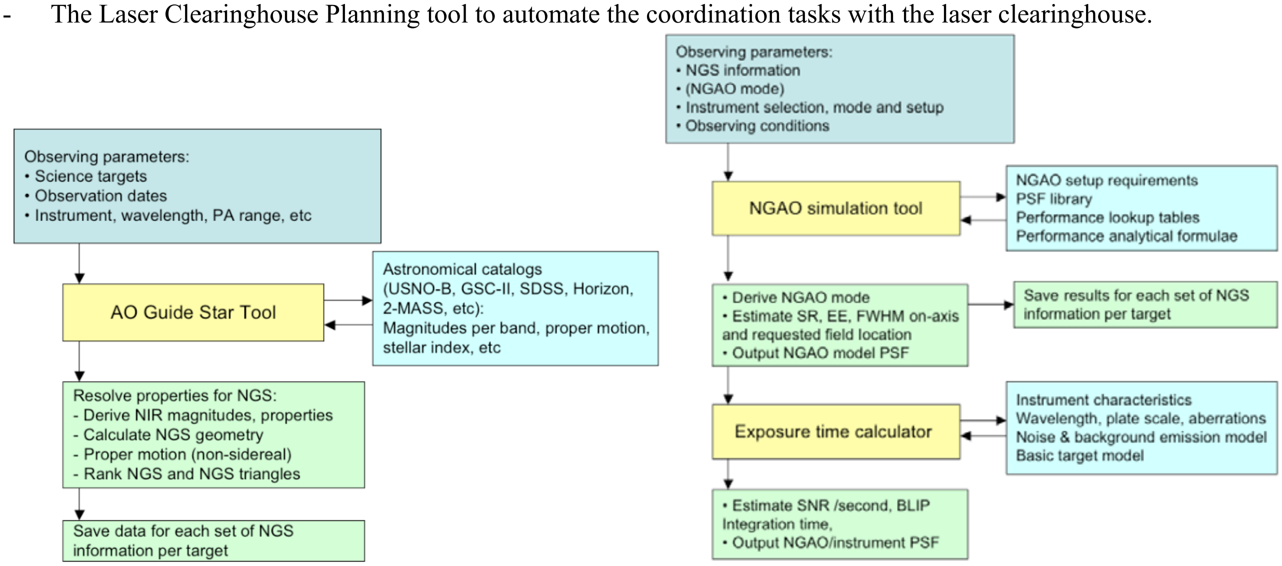

Figure 4. Left: AO guide star tool workflow.

Right: NGAO performance estimation tool and exposure time calculator workflow.

During the proposal phase, the AO Guide Star, the NGAO Performance Estimator, the Exposure Time Calculator and the Observation Preparation tools need to assist the astronomer in identifying suitable Guide Stars and providing a first order estimate for the image quality, the exposure time and expected SNR and the observing strategy, given a basic science instrument setup. The information saved by the user might be inserted in the technical justification of the proposal. The tools need to be users' friendly and easily portable on most computers' OS. During the detailed observation planning, the same tools will be used to evaluate, optimize and prepare the observations sequences. The output parameters for the guide stars and instrument configurations will be saved in a format shared by the NGAO observing tools. The information will be loaded by the observing tools during night time operations. Finally, during the observations, these tools may be used to preview and assist the on-going observations and for any on-the-fly change to the observing strategy. Figure 4, and
Figure 5 succinctly present the workflow for the AO guide star tool, the performance simulation and exposure time calculator, and the observation preparation tools, respectively. The AO Guide Star Tool will be used for both LGS and NGS cases. It is a versatile tool that will make requests to astronomical catalogs, resolve target names, find and select AO guide stars for the NGAO science cases based on their derived NIR brightness and save the results. It is required to find a single star for NGS and sets of triplets for LGS. The sets of triplets will be ranked according to the estimated total residual error on the estimation of the TT mode and quadratic null modes. The results will be saved in telescope and tool valid formats.

The NGAO performance estimation tool will take as inputs the AO guide star(s) information, the AO mode, the selected instrument and the (anticipated) observing conditions. As it will run on the host computer, or through a web-server, it will not be able to (re-)run a full NGAO simulation for each new observing program. Instead, it will make use of a combination of PSF libraries, performance lookup tables and analytical formulae to estimate AO quantities such as SR, EE, FWHM and possibly a 2-D NGAO model PSF for the science field(s). The tool will allow the user to compare performance results from different AO Guide Star(s) and different LGS asterisms configurations. The output results and the parameters used for the simulations will be saved in a file. The parameters and the algorithm(s) for the simulation tools are yet to be defined. Once the AO performance is estimated it will then possible to calculate the exposure time to achieve a desired SNR given the instrument selection and setup, the detector read mode, a model for the noise and background emission, as well as a (simple) flux distribution model for the target. The tool will also estimate the background limited performance time and check that the detector is used in its linear range.

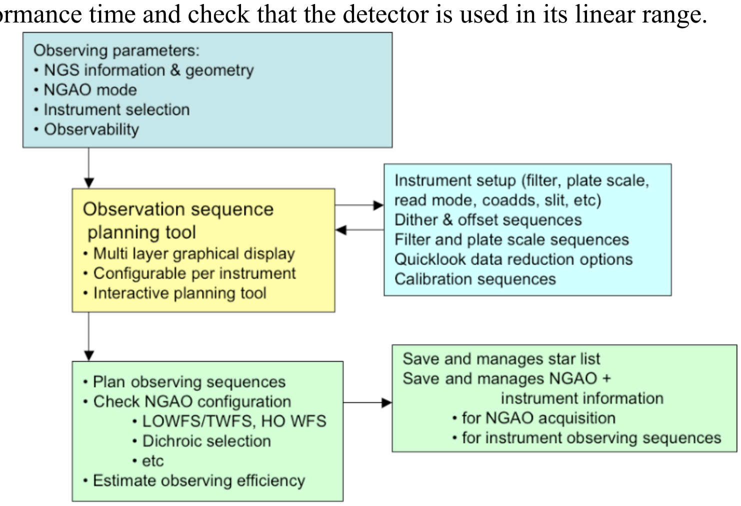

Figure 5. Observation preparation tool workflow.

The observation preparation tool will take as inputs the information from the selected AO guide star(s), the NGAO mode, the instrument selection and when required, the observability of the target. The astronomer will define the parameters for the observing sequences that are possible for this observing mode. These pre-observing tools will check the NGAO configuration e.g., dichroic configuration and expected NGS flux on the LOWFS compatible with the selected observing wavelength. The tools are anticipated to allow for flexible and versatile use of the science instruments. The configuration for the observing sequences will be saved in files that will be loaded at the time of the observations. We have yet to define how these files will be managed. A manual management for these various configuration files (guide star and science targets information, NGAO configuration, instrument configuration, observing sequence information, etc) could lead to confusion. We will consider implementing an automated file management from the observing proposal phase to the final execution at the telescope.

5.4 Post-observing Tools

The post-observing tools and interfaces are:

- Data quality metrics: the purpose of this tool is to reduce and analyze data collected during the observations and output quantities such as total residual wavefront error, seeing, photometric stability, Na return, observing efficiency, etc. These quantities have yet to be defined during the PD and DD phases. The results will be saved and stored with the final data product.
- Data product management tool: the observer and the support staff will use this tool to define which data needs to be saved and stored with the science data. This data product management may also help manage the data that does not need to be stored and can be deleted.
- PSF reconstruction tool: based on the WFC data stored on the data server, the Cn2 information, and other system parameters the PSF reconstruction tool will provide an estimate for the PSF in specific locations in the science field. The algorithms for the PSF reconstruction are yet to be defined. We have started the development of a prototype algorithm for the current NGS and LGS system for the on-axis and off-axis cases.[10]

6. CONCLUSIONS

In this paper we have presented the conceptual design for the NGAO science operations. This design will be developed and detailed in the next two development phases. Assuming funding can be made available we hope to have first light for NGAO in 2014.

7. ACKNOWLEDGEMENTS

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REFERENCES

1. P.L. Wizinowich et al., "The W.M. Keck Laser Guide Star Adaptive Optics System: Overview," PASP 118, 297-309 (2006).
2. M. A. van Dam et al. "The W.M. Keck Laser Guide Star Adaptive Optics System: Performance Characterization," PASP 118, 310-318 (2006).
3. E. Johansson et al., “Updating the Keck AO Systems with a Next Generation WaveFront Controller,” Proc. SPIE 7015, 7015-0121 (2008).
4. D. Le Mignant et al., “LGS AO Operations at the W. M. Keck Observatory, ” Proc. SPIE 6270, 7270-12 (2006).
5. R. Campbell et al., “AO Operations at the W.M. Keck Observatory,” Proc. SPIE 7016, 7016-2 (2008).
6. P.L. Wizinowich et al., “The W.M. Keck Observatory Next Generation AO Facility,” Proc. SPIE 7015, 7015-36 (2008).
7. C. Max et al., “The Science Case for the Next Generation AO System at W.M. Keck Observatory,” Proc. SPIE 7015, 7015-225 (2008).
8. D. Gavel et al., “Concept for the Keck next-generation adaptive optics system,” Proc. SPIE 7015, 7015-226 (2008).
9. R. Dekany et al., “Sharpening low-order NGS using patrolling laser guide stars,” Proc. SPIE 7015, 7015-76 (2008).
10. R. Flicker, D. Le Mignant, “Adaptive Optics PSF reconstruction at the W.M. Keck Observatory,” Proc. SPIE 7015, 7015-10 (2008).